Optimizing of bread quality and sustainability: Evaluating the impact of conventional, microwaves and hybrid baking methods

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Abstract

Baking is a final and one of the most important stages in the breadmaking process, shaping product quality, energy performance, and overall sustainability. Conventional baking methods is widely adopted but it is energy-intensive and often results with uneven heat distribution. This study evaluates the effects of three baking methods including conventional oven (CB), industrial solid-state microwave (IM), domestic microwave (DM) baking, and evaluates the sensorial and physicochemical properties of the resulting breads including moisture content, hardness, colour, specific volume, cell structure, and acrylamide levels, as well as energy consumption, cost, and greenhouse gas (GHG) emissions. A hybrid baking approach, combining CB with microwave baking (applied separately for IM and DM), was also investigated, and the resulting breads were analysed for the same quality attributes. In addition, temperature distribution and moisture variation were monitored during the baking processes for all baking modes. Response Surface Methodology (RSM) was employed to optimise the baking parameters and identify the best baking conditions to maximise improved quality and sustainability performance. The results indicated that IM baked bread achieved the highest moisture content, while domestic microwave led to pronounced moisture loss. Colour analysis revealed that microwave- baked samples developed lighter crusts, whereas CB produced darker crusts due to the higher surface temperatures. Texture analysis showed that IM baking generated softer bread, while DM baking resulted in significantly highest hardness. Although conventional baking achieved the highest specific volume, microwave-baked breads exhibited more irregular crumb structures and lower acrylamide levels. Among all baking modes, IM baking proved to be the most energy-efficient and cost-effective, generating the lowest GHG emissions and therefore representing a more sustainable alternative. It also provided rapid and uniform heating with improved moisture preservation, whereas DM baking caused surface drying and poor internal hydration. Hybrid baking, particularly when incorporating IM, improved thermal uniformity and moisture preservation compared to CB. RSM optimisation further identified IM as the optimal method, achieving highest moisture retention, low hardness, and a desirability score of 0.865.

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Acronyms

CB	Conventional Baking
IM	Industrial Microwave Baking
DM	Domestic Microwave Baking
IMCB$_1$	Industrial Microwave (5 min) + Conventional Baking (5 min)
IMCB$_2$	Industrial Microwave (5 min) + Conventional Baking (10 min)
DMCB$_1$	Domestic Microwave (5 min) + Conventional Baking (5 min)
DMCB$_2$	Domestic Microwave (5 min) + Conventional Baking (10 min)
TPA	Texture Profile Analysis
GHG	Greenhouse Gas
RSM	Response Surface Methodology
R^2	Coefficient of Determination
ANOVA	Analysis of Variance
LC-MS/MS	Liquid Chromatography Tandem Mass Spectrometry
LOD	Limit of Detection
LOQ	Limit of Quantification

Chapter 1 Introduction

1.1 Background

Baking is the most important phase in the breadmaking process which involves the transfer of heat throughout the dough, starting a series of changes that are responsible for the typical features of bread (Purlis, 2011). At first, dough is transformed into crumb due to starch gelatinization and protein denaturation followed by thermal expansion of carbon dioxide (produced by leavening agents) and water vapour. After that, crust begins to form as a result of water evaporation and browning which is related with flavour and harmful compounds (such as acrylamide) formation (Mondal and Datta, 2008; Vanin et al., 2009). The final quality of bread is largely determined by baking time, baking temperature, and the heat source used (Chhanwal et al., 2012; Panirani et al., 2023). Conventional ovens are the most popular baking mode, but they are often energy-intensive and provide non-uniform heating, which may affect the overall quality and consistency of the final product (Bou-Orm et al., 2021). Because the baking method strongly affects the final product quality, the baking industry is increasingly exploring non-conventional technologies to speed up production, improve yield, enhance product quality, and reduce both processing costs and environmental impact (Chhanwal et al., 2012). Infrared baking is one of the non-conventional baking technologies which allows for fast and uniform heating. It can reduce baking time and lower energy consumption. However, it may influence crust formation and the development of texture in the final product (Chhanwal et al., 2019). Panirani et al. (2023) investigated how infrared baking influences the qualitative and quantitative characteristics of bread compared with a conventional oven. Their findings showed that specific volume expansion, firmness, and shearing force were all higher in breads baked using infrared heating than in those baked conventionally. In addition, infrared baking achieved the greatest energy efficiency, whereas the conventional oven had noticeably higher energy consumption. Ohmic heating is another emerging technology that offers several advantages compared with conventional baking methods. In this process, heat is generated quickly and uniformly throughout the product because the heating occurs volumetrically, rather than through conventional mechanisms such as conduction, convection or radiation (Varghese et al. 2014; Jaeger et al. 2016). Mattioli et al. (2024) studied a comparative effect of ohmic baking on quality characteristics of gluten free sponge cake with conventional oven. Their findings indicated that ohmic system achieved significantly higher energy efficiencies, reaching nearly 60%, compared to only 4.1% for conventional baking. Ohmic-baked cakes showed higher weight loss, which was linked to a greater number of cells in their spongy structure, resulting in increased volume expansion and reduced density. The remaining quality characteristics, such as colour, hardness, cohesiveness, and elasticity, were not significantly different. Today, microwave baking has gained popularity in the processing of food products through its ability to achieve volumetric heating, higher heating rates, a significant reduction in baking time, safe handling, ease of operation, and reduced maintenance. However, the number of factories that use microwave baking for producing baking product is minimal (İçöz et al., 2004; Bou-Orm et al., 2021). One of the most attractive aspects of domestic microwave baking is its ability to significantly decrease the preparation and baking time. Furthermore, because the energy penetrates the product and heats it from the inside, the entire dough reaches the desired temperature more quickly than in a conventional oven which can help preserve some of the product's moisture and resulting in a softer texture (Sumnu et al., 2005). It also has ability to minimize the formation of harmful compounds such as acrylamide contributing to improved food safety due to its lower processing temperature compared to conventional oven. Al-Ansi et al. (2019) studied the effect of conventional and microwave baking on the physical and nutritional properties of baked biscuits. According to the results, the biscuits baked by microwave showed higher antioxidant activities, higher moisture content and lower acrylamide compared to those biscuits baked by conventional oven. However, domestic microwave presents certain drawbacks including non-uniform heating and inability of the microwave to induce browning crust (Bou-Orm et al., 2023). The cool ambient temperature inside a microwave oven causes low surface temperature which prevents Maillard browning reactions that are responsible for the production of many flavoured and coloured compounds (İçöz et al., 2004). To address this limitation, hybrid baking has been developed by combining different baking techniques with the aim of reducing baking time and improve energy efficiency and product quality (Datta & Rakesh, 2013). Most research in literature used microwave as one of the baking modes combined with conventional oven, infrared or jet impingement.

Chhanwal et al. (2014) studied the effect of electrical and hybrid baking (infrared combined with conventional oven) on physicochemical properties of baked bread. Results showed that breads baked in hybrid baking mode showed 28% higher moisture content, higher volume, and lower crumb hardness compared to those baked in only conventional oven. Furthermore, baking time has been reduced by 28% in hybrid baking. In another study, Keskin et al., (2004) investigated the effect of halogen lamp combined with microwave oven on sensorial and physical properties of the bread. According to their results, halogen lamp microwave combination reduced the baking time of breads by about 75% compared to conventional baking. Also, those breads baked in hybrid baking showed lower specific volume, higher weight loss, higher hardness and lightness compared to other samples. Industrial solid-state microwave technology is an emerging and highly promising innovation that has the potential to serve as an effective alternative to conventional oven baking. This advanced system is designed to deliver more uniform and controlled heating which could help to achieve a better textural structure for final product. In contrast to domestic microwaves that function at a fix frequency, leading to non-uniform heating and potential overbaking or undercooking of baked products, solid-state systems provide precise control over both frequency and power. This led the energy to be adjusted in real time based on the product's properties and specific heating requirements (Atuonwu & Tassou, 2018). Another advantage of solid-state microwaves is their improved energy efficiency, faster heating rate, shorter processing time and lower energy loss in either the oven cavity or the surrounding air (Atuonwu & Tassou, 2019; Dinani et al., 2020). The shorter processing time also means that overall energy use is reduced, making it more cost-effective and environmentally friendly. Although previous studies have investigated microwave-assisted bread baking, most have focused primarily on selected quality attributes such as moisture, texture, volume, and colour, often using domestic microwave systems and evaluating only a limited number of parameters. Consequently, there remains a lack of comprehensive studies comparing conventional, industrial microwave, domestic microwave, and hybrid baking technologies under identical conditions. Furthermore, limited information is available regarding real-time temperature distribution during baking, acrylamide formation in microwave and hybrid systems, and the simultaneous assessment of product quality, food safety, energy consumption, and environmental impact. In addition, the integration of these parameters within a systematic optimisation framework has received little attention. Therefore, a significant knowledge gap exists regarding the holistic evaluation and optimisation of alternative baking technologies for sustainable bread production, which this study aims to address. Furthermore, the application of industrial solid-state microwave technology in food processing has received very limited scientific attention compared with conventional magnetron-based microwave systems. Consequently, there is insufficient understanding of its effects on product quality, process efficiency, and sustainability, particularly in bread baking applications. The aim of this study is to investigate the effect of different baking modes including industrial solid-state microwave, domestic microwave and conventional oven on the physicochemical and sensory properties of baked bread. In addition to those baking modes, hybrid baking which combines conventional oven with both industrial and domestic microwaves is also examined to evaluate its effect on bread quality. Furthermore, this study explores the environmental and economic impacts of each baking method, providing insights into how emerging technologies can improve energy efficiency and sustainability in the baking industry. This project also examines the process conditions during baking, such as temperature variations and moisture changes, to better understand the thermal behaviour of bread under different systems. Finally, Response Surface Methodology (RSM) is applied to optimise the baking process, aiming to enhance product quality and overall baking performance.

Aim

The overall aim of this study is to systematically evaluate and compare the performance, sustainability, and scientific principles of various baking technologies including conventional, domestic microwave, industrial solid-state microwave and hybrid approach to optimize baking processes for improved product quality, energy efficiency, and environmental impact. This is achieved through comprehensive experimental, analytical, and techno-economic investigations, leading to the development of evidence-based recommendations for the design and operation of sustainable industrial baking solutions.

1.2 Objectives

1. Establish a comprehensive understanding of baking science and technology by conducting in-depth literature review of small scale and industrial baking processes, mapping the state of the art in conventional and emerging baking technologies and define the main physicochemical and sensory attributes that characterise high-quality bread products.

2. Systematically investigate and compare the performance of multiple baking technologies including conventional, domestic microwave, industrial solid-state microwave, and hybrid baking systems through a structured approach of controlled experimental trials.

3. Characterise physicochemical and textural properties of the baked breads produced under each baking mode using advanced analytical methods and determine the influence of processing conditions on product quality, uniformity and process efficiency.

4. Analyse critical process parameters such as temperature profile and humidity across all baking modes to develop fundamental scientific understanding into moisture migration, and structural transformation during baking.

5.Quantify of acrylamide formation across different baking technologies using advance high-performance liquid chromatography to assess food safety implications and identify the best baking mode that minimises the harmful contaminant.

6. Evaluate and compare energy consumption, greenhouse gas (GHG) emissions, and cost performance of each baking technology through detailed techno-economic and environmental analyses and identify the most sustainable and resource- efficient baking technology capable of delivering high- quality breads.

7. Develop date- driven recommendations for industrial implementation proposing optimal design, control and operational strategies of the studied baking technologies, to improve product quality, energy efficiency, and environmental performance for large scale production.

1.3 Thesis structure

Chapter 1 introduces the use of microwave and hybrid baking and how they affect the final product quality, highlights the advantages and disadvantages of each method and presents the research gap, aim and objectives of the thesis.

Chapter 2 is a literature review on various baking technologies, covering both conventional and non-conventional methods. It explores the advantages and disadvantages of each with a focus on how non-conventional systems compare to traditional baking in terms of performance, efficiency, and product quality.

Chapter 3 outlines the research design and methodology used across all experiments. It details how key parameters were measured including moisture content, texture, volume, cell structure, colour values, acrylamide content, energy consumption, and greenhouse gas (GHG) emissions. This chapter also explains how process conditions such as temperature distribution and moisture movement during baking were monitored and analysed to support a comprehensive understanding of the baking performance under different technologies.

Chapter 4 presents the sensorial results from each experiment conducted in this study. It includes detailed findings on the physicochemical properties of the baked breads such as moisture content, texture, volume, cell structure, colour. The outcomes from different baking methods including conventional oven, domestic microwave, industrial solid-state microwave, and hybrid systems are compared to highlight their effects on bread quality and physicochemical properties.

Chapter 5 presents the results of process conditions during baking including temperature distribution and moisture movement within the bread. It details how these factors were measured across different baking methods, including conventional, domestic microwave, industrial solid-state microwave, and hybrid systems. This chapter provides insights into how heat and moisture behave throughout the baking process and how these dynamics influence the overall quality of the final product.

Chapter 6 focuses on the results related to acrylamide content in the baked bread samples. It presents a comparison of acrylamide levels across different baking methods, including conventional, domestic microwave, industrial solid-state microwave, and hybrid systems.

Chapter 7 explores the environmental and economic impacts of the different baking methods used in this study. It evaluates and compares energy consumption, greenhouse gas (GHG) emissions, and operational costs associated with conventional, domestic microwave, industrial solid-state microwave, and hybrid baking systems. This chapter provides a perspective on the sustainability and cost-effectiveness of each method, offering valuable insights for selecting energy-efficient and environmentally responsible baking technologies.

Chapter 8 focuses on optimising baking conditions with the goal of improving product quality using Response Surface Methodology (RSM). This chapter details the experimental design and analysis conducted using RSM software to identify the most effective combinations of baking parameters such as moisture level and hardness for achieving desirable product characteristics.

Chapter 9 presents the conclusion of the thesis and recommendations for future research.

Chapter 2 Literature review

2.1 A review on a different baking technology used for baking bread

Baking is a highly heat-sensitive process in which temperature conditions strongly influence the quality of the baked product (Chhanwal et al., 2019; Khatir et al., 2015). It consists of various stages including mixing, proofing, baking, and cooling which contributes to the quality of the final product (Cauvain & Young, 2003). The baking process strongly influences key quality characteristics of the final bread, such as hardness, moisture content, colour properties value, and loaf volume. Many key bread quality characteristics depend on temperature, meaning they can be managed by adjusting and optimizing the baking temperature (Therdthai and Zhou 2003). At the end of baking, the dough forms two distinct layers including crumb and crust with its own textural properties. The brown colour of bread crust develops through non-enzymatic browning reactions that occur when the surface reaches high temperatures (Chhanwal et al. 2012; Vanin et al. 2009). The quality of baked products improves significantly when oven conditions are optimised, as factors such as temperature distribution, efficient heating, baking time, and moisture levels all have a major influence on the final outcome (Zhou and Therdthai 2007). The baking industry is looking forward to non-conventional technologies to speed up the baking process, improve product quality, and reduce environmental impact. Several non-conventional technologies have been used in the baking process, including vacuum baking, microwave baking, infrared baking, and jet impingement. Therefore, this chapter discuss different non-conventional baking techniques used in baking process and their impact on physical and sensorial properties of baked products and acrylamide formation during baking. Table 2.1 presents a summary of studies that have investigated the effects of different non-conventional, conventional and hybrid technologies on physicochemical properties and acrylamide content of various baked products. These alternatives, such as microwave, vacuum, infrared, or hybrid ovens, offer faster processing times, better product quality, and potential reductions in energy consumption.

2.1.2 Jet impingement

In jet impingement baking, hot air is blown onto the product's surface through specialised nozzles in the oven. Instead of traditional nozzles, small holes are used to apply high-speed air straight onto the food. This method can shorten baking times and lower the required air temperature, depending on the product characteristics and nozzle design. By reducing the boundary layer between the surface of the product and the heating medium, the fast-moving air markedly increases heat transfer efficiency, resulting in more even baking at reduced oven temperatures (Altay et al., 2023; Chhanwal et al., 2019). The characteristics of impingement ovens versus conventional ovens have been studied by many researchers and mentioned in Table 2.1. The key advantages of jet impingement include improved heating, shorter baking process, less moisture loss and enhanced product porosity (Sarkar& Singh, 2004; Olsson et al., 2005; Altay et al., 2023). The large variation in the heat transfer coefficient on a product's surface is one of the disadvantages of using jet impingement systems which can lead to certain quality attributes. According to previous studies, jet impingement may lead to temperature non-uniformity, causing both hot and cold regions on the surface of the food (Sarkar & Singh, 2004; Banooni et al., 2008). Moreover, the complexity of jet impingement systems, including the need for specialized nozzles and control units, can lead to higher equipment costs and maintenance requirements. The noise generated by high-speed air jets may also pose a consideration in production environments (Li et al., 2013). Despite these limitations, jet impingement baking is increasingly used in industrial bakeries due to its speed, efficiency, and ability to produce high quality baked products with consistent surface characteristics.

2.1.3 Vacuum baking

Vacuum baking is a non-conventional technology that involves the processing of baked products at a reduced pressure environment, usually below atmospheric pressure levels (60Kpa) (Devu et al., 2022). It operates like the traditional oven process but requires a lower baking pressure which translates to a significant reduction of the baking temperature. Baking takes place in a vacuum chamber where the boiling point of water is significantly reduced. As a result, vapour is released at lower temperatures from the dough which enables the avoidance of the thermal degradation of heat-sensitive components of the product (Simsek, 2020). Heat transfer in vacuum baking occurs mainly through conduction, as there is limited air in the chamber to support convective heat transfer (Yildiz et al., 2017). One of the main advantages of vacuum baking is its ability to retain product moisture and nutrients, which is especially important for products that are sensitive to drying out or losing flavour during traditional baking. Lower baking temperatures can also reduce the formation of unwanted compounds such as acrylamide, which forms at high temperatures during browning (above 120 °C) (Grenier et al., 2019). However, there are certain limitations that affect its wider application. Because heat transfer is less efficient in a vacuum environment, baking times may be longer compared to conventional baking methods. Equipment costs and energy requirements for maintaining the vacuum also present practical challenges, particularly for large-scale production. Moreover, the lack of browning due to lower surface temperatures may be undesirable for some baked products, requiring additional finishing steps such as surface heating (Bedre-dine et al., 2024).

2.1.4 Infrared baking

Infrared baking is a modern thermal processing technique that uses infrared radiation as the main source of heat to bake food products. In this method, heat is transferred primarily through radiation from infrared emitters positioned above or below the baking surface. Unlike conventional ovens that rely on hot air circulation, infrared ovens use electromagnetic waves to directly heat the surface of the dough (Sumnu et al., 2005). These waves penetrate the outer layers of the product and convert to thermal energy, resulting in rapid surface heating. Infrared baking operates in specific wavelength ranges, typically classified as near, medium, or far infrared, depending on the energy intensity and depth of penetration (Ozkoc et al., 2009(a)). The wavelength used is selected based on the moisture content, thickness, and composition of the product (Sakiyan, 2015). This targeted heating allows for faster baking and can lead to energy savings, as the system does not need to heat the entire oven chamber. A major advantage of infrared baking is the reduction in baking time due to its rapid heat transfer, which can improve production efficiency (Demirkesen et al., 2013). This speed also helps preserve moisture level in the product, resulting in a softer texture and potentially extending shelf life. This method is also useful in achieving desirable browning and crust formation in a shorter time compared to conventional methods due to its rapid surface heating (Sumnu et al., 2005). However, infrared baking presents certain challenges. Since the heating process is mainly surface focused, it can be difficult to ensure uniform heating throughout the entire product. Without proper control, this may result in an overcooked crust and an undercooked crumb (Chhanwal et al., 2014). The baking environment is also less flexible, as infrared heating systems often require precise adjustment of emitter intensity and positioning (Purlis, 2014). Despite these limitations, infrared baking is seen as a promising technology for industrial use, particularly when fast processing and consistent surface quality are priorities. It is especially suitable for thin or flat baked products such as pizza bases, biscuits, or pastries, where internal heat penetration is less critical (Turabi et al., 2008). Ongoing developments in infrared oven design, including the integration of combined heating methods, aim to improve heat distribution and expand its use across a wider range of bakery applications. With proper calibration and process control, infrared baking can offer a balance between efficiency, product quality, and energy savings.

2.1.5 Domestic microwave

Domestic microwave baking has become a popular alternative to conventional baking methods, particularly due to its convenience, speed, and suitability for small scale baking. Unlike conventional ovens that use external heat sources to warm the air inside the chamber and then transfer heat to the product through convection, conduction and radiation, microwave ovens use electromagnetic waves typically at a frequency of 2.45 GHz to generate heat directly within the product. As a result, heat is generated throughout the entire product, rather than only from the surface towards the inside, which helps reduce baking time (Kalla & Devaraju, 2017; Therdthai et al., 2016). One of the most attractive aspects of domestic microwave baking is its ability to significantly decrease the preparation and baking time. Because the energy penetrates the product and heats it from the inside, the entire dough reaches the desired temperature more quickly than in a conventional oven which can help preserve some of the product’s moisture, resulting in a softer texture (Sumnu et al., 2005; Icoz et al., 2004). However, domestic microwave baking shows a number of limitations such as lack of browning, crust formation, unacceptable texture, high moisture loss, and rapid staling. These issues directly affect the sensory qualities of the bread and reduce consumer acceptance (Bou-Orm et al., 2023; Sumnu, 2001). Lack of browning is due to the fact that in microwave ovens, the surface temperature of the food never rises above 120 °C and this relatively cool environment inside a microwave oven leads to surface cooling of the product and prevents Maillard reactions from occurring, which are essential for browning (Bou-Orm et al., 2023). Microwave baking is a fast method, but it does not produce the desired quality in baked products due to its non-uniform heating. Research has shown that the rapid, volumetric nature of microwave heating leads to changes in product characteristics during baking. As a result, combining microwave heating with another rapid surface-heating method, such as infrared or jet impingement, can help achieve better product quality (Chhanwal et al., 2019).

2.1.6 Solid-state microwave

Solid-state microwave baking is a recent development in food processing that offers greater control and flexibility compared to traditional microwave ovens. Unlike domestic microwaves, which operate at a fixed frequency and power level, solid-state microwave systems use semiconductor technology to produce electromagnetic waves with adjustable frequency and power. This allows precise control over the heating process, which is especially important in baking, where temperature sensitivity and uniform heating play a key role in product quality (Dinani et al., 2021). In solid-state microwave baking, heat is generated inside the product through dielectric heating, it can be useful in improving energy efficiency and production speed, particularly for small or individual products (Atuonwu & Tassou, 2018). This internal heating method could also help maintain moisture in the final product, often resulting in a softer crumb and more tender texture. One of the main advantages of solid-state microwave is the ability to adjust the frequency so the energy can be distributed more evenly inside the oven cavity, helping to reduce problems such as non-uniform heating, and overbaked spots that are often associated with domestic microwaves (Dinani et al., 2020). This is especially useful for products with irregular shapes or varying moisture content, where consistent heating is often difficult to achieve. Another advantage of solid-state microwave baking is its potential for combining with other heat sources, such as convection or infrared, to create hybrid baking systems. These systems aim to balance the fast-internal heating of microwaves with the surface browning and texture development achieved by other methods. This combination can result in products that are not only cooked quickly but also have the crust and appearance that consumers expect from baked products. At industrial scale, this can help reduce baking times, lower energy costs, and increase production efficiency without lowering the quality of the product (Atuonwu & Tassou, 2018). However, despite these benefits, solid-state microwave baking also presents certain challenges. The technology itself is relatively new and not yet widely available in markets, which means equipment costs remain high. Additionally, while solid-state microwaves offer improved control, they still operate within the limitations of microwave heating, such as limited surface browning and crust development (Dinani et al., 2020). These characteristics are difficult to achieve without the aid of additional heat sources, which may require more complex and expensive equipment.

2.1.7 Hybrid baking

Hybrid baking technologies represent an important innovation in the baking industry, combining two or more heating methods to reduce the processing time and improve product quality (Datta and Rakesh 2013). These technologies are designed to improve both the efficiency and the quality of baked products by using the strengths of different thermal processes into a single system (Chhanwal et al., 2015). Common combinations include conventional oven-microwave, infrared-microwave, microwave-conventional oven-infrared, and impingement-microwave systems. As it was mentioned before, in conventional ovens heat is primarily delivered through hot air circulation, which can result in slow and uneven heating, especially in thicker or denser products (Schumm et al., 2018). While this method supports browning and texture on the surface, it often leads to extended baking times, increased energy consumption, and potential drying of the crumb. On the other hand, domestic microwave ovens bakefood rapidly by generating energy within the product itself, but they fail to produce the surface browning or crust for many baked products which often resulted in uneven heating, hard textures, and low product volume (Panirani et al., 2023). Microwave baking tends to trap moisture inside the product but often lacks the browning needed for good crust formation (Yolacaner et al., 2017). In hybrid systems, this balance is better maintained. The microwave component heats the product quickly from within, minimising the time water is exposed to high surface temperatures, while the secondary heating method (like convection or infrared) is used to control the drying process at the surface (Chhanwal et al., 2015). This allows for a well-balanced moisture profile, where the interior remains soft and moist and the exterior develops the desired firmness or crispness. This is particularly beneficial for products like cakes, muffins, and breads, which require both moist crumbs and properly set surfaces to meet consumer expectations (Sakin-Yilmazer et al., 2013). One of the critical issues in conventional baking is acrylamide formation, which is a compound that forms under high temperature, low moisture conditions through the Maillard reaction. Hybrid ovens provide a practical solution by reducing the overall baking temperature and time while still achieving the desired colour and flavour development. This means less time spent at critical temperatures for acrylamide formation, reducing the total amount produced. This is a major step forward for improving the health profile of baked goods without compromising on quality (Schumm et al., 2018). Colour development is closely tied to surface temperature and moisture content, both of which can be precisely controlled in hybrid baking systems. Conventional baking supports crust formation and surface browning but may require longer time which increase energy use and may lead to over drying. Microwave baking does not naturally promote surface browning which limits the visual appearance of the product (Yolacaner et al., 2017). Infrared or convection components in hybrid systems help address this by applying direct heat to the surface, promoting browning and crust formation. As a result, baked products using hybrid methods can achieve the golden colour crust and desirable texture that consumers associate with quality without the extended exposure to high heat required in conventional systems (Chhanwal et al., 2014). Beyond this, hybrid baking technologies also contribute to process efficiency and energy savings by reducing baking time through fast internal heating and avoiding the need to preheat large oven chambers. This is particularly valuable on a commercial baking scale, where energy efficiency is a growing concern. Additionally, because hybrid systems provide more control over the baking environment, they support better repeatability and lower rates of product failure, reducing waste and improving production consistency (Patel et al., 2005).

Table 2.1 overview of the works that carried out on baking process using non-conventional baking ovens

Type of baking	Process conditions	Product	Advantages	Disadvantages	Reference
Jet impingement VS conventional	The jet impingement oven operated at 180 and 250 °C with air jets delivered at 7.5 m/s for 1–2 minutes. The conventional oven operated at 180 °C and 250 °C, with baking times set at 2.5, 5, and 10 minutes.	Baguettes	The rapid development of crust in jet impingement baking led to higher moisture levels remaining in the crumb. Quick surface browning	A thinner crust resulted from the reduced jet impingement baking time, while moisture loss was higher during combination baking.	Olsson et al. (2005)
Jet impingement VS conventional	Jet impingement temperatures of 160 °C and 216 °C were used with a conveyor transit time of 8 minutes. Jet velocity was set to 8 m/s for 2 minutes Conventional baking was performed at 171 °C for 20 minutes	Cake	An increase in product loaf volume was observed alongside higher moisture levels in cakes baked with jet impingement	Lighter surface colouring and a somewhat sticky crumb texture	Xue and Walker (2003)
Vacuum VS conventional	Vacuum: The initial baking stage was performed at 101.3 kPa pressure and 180 °C for 15 minutes, after which the process continued at 60 kPa vacuum pressure at 180 °C for an additional 15 minutes. The conventional oven operated at 180 °C for a 20-minute baking period	Bread	Less water loss during vacuum baking, higher browning development on crust and improved textural properties	Higher bread hardness and lower moisture content in vacuum baked bread	Simsek, (2020)
Vacuum VS conventional	Vacuum condition: -65kPa below the atmospheric pressure for 10, 30, 50 and 70 sec Conventional baking conditions consisted of heating at 180 °C for a duration of 30 minutes.	Flat bread	Better colour development, lower hardness and higher moisture content in vacuum baked bread	Increased the staling rate	Bedre-dine et al. (2024)

Infrared–microwave combination VS conventional	The microwave was set to 706 W with baking times of 9, 9.5, 10, and 10.5 minutes. Infrared baking conditions included 50% power applied for 9.0, 9.5, 10, and 10.5 minutes, and 70% power applied for 7, 7.5, 8, and 8.5 minutes. The conventional oven operated at 175 °C for a 24-minute baking period.	Cake	Enhanced browning, reduced baking time, and softer texture in combined infrared-microwave baked cake	Decreased specific volume and higher weight loss	Sumnu et al., (2005)
Infrared–microwave combination VS microwave VS conventional	The microwave was set to 706 W for a 2-minute baking period. The infrared–microwave combination was operated at 1500 W for a duration of 8 minutes. The conventional oven operated at 200 °C for a 13-minute baking period.	Bread	Lower hardness, setback viscosity, and crystallinity values and decreased the rapid staling in infrared-microwave combination baking	--	Ozkoc et al. (2009)
Infrared-microwave oven VS conventional	Baking using the infrared–microwave setup was conducted at 682 W for a 15-minute period. The conventional oven operated at 200 °C for a 35-minute baking period.	Bread	More even pore distribution, more consistent crumb structure, a higher overall number of pores with a wider range of pore sizes, and reduced starch-granule breakdown in infrared–microwave baked breads	Infrared–microwave baking produced rice-flour bread with noticeably smaller pores, whereas chestnut-flour bread baked conventionally formed much larger pores.	Demirkesen et al. (2013)
Infrared-conventional oven vs conventional	The infrared–conventional combination oven operated at 700 W for a duration of 5 minutes.	Bread	Lower hardness, higher moisture and volume in infrared-conventional combination baked breads	A paler crust and a lower number of cells in infrared-conventional baked breads	Chhanwal et al. (2014)

	The conventional oven operated at 220 °C for an 18-minute baking period				
Infrared-microwave oven VS conventional	The infrared–microwave system operated at 706 W for durations of 8, 9, and 10 minutes. The conventional oven operated at 175 °C for a 24-minute baking period.	Cake	Lower weight loss, higher specific volume values and shorter baking time in infrared-microwave baked cakes.	A paler crust, firmer texture, and reduced moisture content	Sakiyan (2015)
Microwave-toaster oven VS conventional	Microwave baking was performed using a low-power stage initially (204 W for 120 s), then a high-power stage (937 W for 70 s). Conventional baking conditions involved heating at 180 °C for a duration of 35 minutes.	Cake	Greater volume, increased luminosity, and reduced hardness in microwave-baked cakes	Lower crumb cell number of the cake	Sánchez-Pardo et al. (2012)
Microwave-conventional vs conventional	The microwave operated between 400 and 600 W at 2,450 MHz for durations of 30, 40, and 50 seconds. Conventional baking conditions involved heating at 225 °C for durations of 8 and 11 minutes.	Cake	Higher specific volume and reduced baking time in microwave–conventional combination baked cakes	Lighter cake colour and less browning development	Bilgen et al. (2004)
Microwave oven vs conventional oven	The microwave operated at a power level of 635 W. The conventional oven operated at 175 and 200 °C for baking times of 10 to 18 minutes, and at 225 °C for baking durations of 4 to 12 minutes.	Bread	--	Increased hardness and accelerated staling, with no browning enhancement, in breads baked by microwave	Icoz et al. (2004)
Halogen lamp-microwave vs	The microwave was set to 706 W during baking.	Bread	Greater volume and enhanced crust browning in microwave baking assisted by a halogen lamp	Higher weight loss and firmness of bread.	Keskin et al. (2004)

conventional oven	The conventional oven operated at 175, 200, and 225 °C for baking durations of 12, 13, and 14 minutes.				
Microwave oven vs conventional oven	Microwave baking was performed at 635 W. Conventional baking conditions involved heating at 225 °C for baking durations of 15 minutes.	Bread	Reduced hardness and increased volume were observed in breads baked by microwave	Lower cell number and a lighter crust colour in the bread	Ozmutlu et al. (2001)

2.2 An investigation on temperature distribution and moisture level during baking

Temperature distribution and moisture variation are the two key factors that significantly affect the quality, texture, and shelf life of baked products. In conventional baking, external heating creates a temperature gradient, with the surface of the product becoming significantly hotter than the centre and as a result the outer layers heat up faster leading to the development of a dry crust (Vanin et al., 2009). Simultaneously, the internal moisture in the dough starts to migrate outward to replace the evaporated water. However, this kind of heat and moisture movement can result in non-uniform baking especially for products with large volume or dense composition. The outer layers may be overcooked while the centre remains under baked. In contrast, microwave baking introduces a different pattern of heat and moisture distribution (Chhanwal et al., 2019). Microwaves generate electromagnetic waves within the dough to vibrate and generate heat internally through dielectric heating. This results in rapid volumetric heating, where the energy is absorbed inside the product rather than starting at the surface. Because of this, the temperature inside the dough can increase more evenly and more quickly than in conventional baking (Ureta et al., 2019). Moreover, moisture retention in microwave baked products is usually higher as the limited surface drying and short baking time do not allow enough evaporation to occur. While this can lead to a softer texture and extended shelf life, it may also produce a soggy texture that consumers find less appealing. In hybrid baking, temperature distribution can be more controlled, and heat can be applied where it is needed most. This results in improved product volume, more uniform crumb structure, and desirable surface characteristics (Besbes et al., 2013). Moisture migration in hybrid systems is also more balanced. For instance, in microwave-conventional oven hybrid baking, the microwave ensures that water within the product is heated and partially retained which leads to a softer crumb, while the conventional oven helps reduce surface moisture to create the desired browning and appearance. Because of this dual mechanism, hybrid baking technologies are especially effective in addressing common challenges such as uneven baking, moisture imbalance, and poor surface colouration, making them suitable for a wide range of baked products (Dessev et al., 2020). In baking technologies, monitoring internal temperature distribution helps improve consistency and prevents undercooked area. Moreover, tracking moisture levels in real time can aid in reducing energy consumption by avoiding overbaking and maintaining product texture.

2.3 The effect of different baking technologies on acrylamide formation

Acrylamide is a chemical compound that forms in certain foods during high temperature processes, such as baking, roasting, or frying. It is created as a by-product of heat-induced chemical reactions, particularly the Maillard reaction, which is responsible for browning and flavour development in many baked products (Keramat et al., 2011). Acrylamide is formed mainly from the reaction between free asparagine, a naturally occurring amino acid found in cereal grains, and reducing sugars like glucose or fructose when foods are exposed to temperatures typically above 120°C in low moisture environments (Nahid & Bhuiyan, 2025). This reaction pathway becomes more active as the surface of bakery products heats up and loses moisture, which creates the ideal dry and hot conditions required for acrylamide formation. As a result, products such as bread crusts, cookies, crackers, biscuits, and breakfast cereals are commonly identified as sources of acrylamide (Mesias & Morales, 2016). The crusty or browned parts of baked products generally contain higher concentrations, while the inner moist crumb contains less, due to the difference in heat exposure and moisture retention. In the context of baking, acrylamide formation is most often associated with conventional thermal processes where heat is applied to carbohydrate-rich products (Aouzelleg & Ojinnaka, 2023). The outer layers of dough, as they are exposed to high temperatures and surface drying, become sites for intense Maillard reactions, which not only generate colour and aroma but also facilitate the formation of acrylamide. This means that conventional ovens, which rely on convective and radiant heat, provide the most common conditions for acrylamide to form (Streekstra & Livingston, 2020). The longer the baking time and the higher the temperature, the greater the potential for acrylamide formation. Factors such as baking temperature, time, formulation, and water activity are key variables that influence the amount of acrylamide produced. For instance, extended baking time at a temperature above 180°C can significantly increase acrylamide levels in thin or flat baked products, such as biscuits or flat breads, which have greater surface area exposed to air and less internal moisture to inhibit the reaction (Keramat et al., 2011). Similarly, formulations with high sugar content, often added for flavour and browning, are more prone to form acrylamide during baking. Certain alternative or non-conventional baking technologies have shown potential to reduce acrylamide formation by altering the thermal environment or processing time. For example, microwave baking, particularly in domestic or solid-state microwave systems, involves rapid volumetric heating that does not produce the same level of surface heating and high surface temperatures as conventional oven baking (Mesias & Morales, 2016). Because microwave energy heats food from the inside out, the surface temperature often remains lower, which can inhibit or delay the Maillard reaction and reduce acrylamide formation. However, this also results in a lack of browning and crust formation, which may be undesirable for certain products (Sarion et al., 2021). Vacuum baking is another method that has demonstrated reduced acrylamide levels, due to the lower pressure environment that allows water to evaporate at reduced temperatures. This means baking can occur at lower overall temperatures, which helps prevent the development of acrylamide even in products that would typically be high in risk (Baskar & Aiswarya, 2018). Similarly, hybrid ovens combining infrared and microwave heating, or impingement systems with precise temperature and moisture control, offer more flexibility in managing surface conditions, allowing for maintaining product quality while minimising the formation of harmful compounds (Sarion et al., 2021). The health concern surrounding acrylamide is linked to its classification as a probable human carcinogen by the International Agency for Research on Cancer (IARC), a branch of the World Health Organization (WHO). Although most research has been conducted on animals, and the evidence in humans is still under investigation, studies suggest that long-term exposure to high levels of acrylamide could increase the risk of certain cancers (Gokmen, 2015). Additionally, acrylamide is considered to have neurotoxic and genotoxic effects in laboratory settings, leading to increased regulatory interest in limiting its presence in foods. As baked products represent as one of the major sources of acrylamide in the average diet, especially for children and adolescents, reducing its formation during processing has become a public health priority. In response to these concerns, food safety authorities have established guidelines and recommendations to help producers control acrylamide levels in baked products (Bušová et al., 2020). In the European Union, acrylamide levels in food are regulated under Commission Regulation (EU) 2017/2158, which sets benchmark levels and mitigation measures for different food categories, including bakery products. For instance, the benchmark level for soft bread is 50 µg/kg, while for biscuits and crackers it ranges between 150 and 350 µg/kg, depending on the specific product type and ingredients (Amrein et al., 2007). These benchmark levels are not maximum legal limits but are intended as reference points that food producers should aim to stay below by applying best practices and mitigation strategies. In the United States, the Food and Drug Administration (FDA) has issued guidance to help the food industry reduce acrylamide levels, but there are currently no mandatory limits in place (Barutcu et al., 2009). Several strategies are available to control acrylamide formation without compromising the quality of baked products including choosing cereal flours with naturally lower asparagine content, incorporating additives like calcium salts that can interfere with the Maillard reaction, or using asparaginase enzyme treatments to reduce precursor levels before baking. Adjusting the baking temperature, time and avoiding overbaking, can also help manage acrylamide levels. In addition, careful moisture control during processing can reduce acrylamide, as higher water activity tends to slow down the Maillard reaction (Baskar & Aiswarya, 2018). However, these changes must be carefully balanced to maintain consumer expectations around product colour, taste, and texture. For example, while reducing baking temperature may help lower acrylamide, it could also result in pale, underdeveloped crusts or soggy textures that consumers find unpleasant. Therefore, the challenge lies in developing baking processes that minimise acrylamide without lowering product quality (Alija et al., 2024). Figure 2.1 illustrates the proposed mechanism for acrylamide formation during the Maillard reaction. The reaction begins with the interaction between free asparagine and a reactive carbonyl compound derived from reducing sugars. This condensation reaction produces a Schiff base, accompanied by the elimination of one molecule of water. The Schiff base acts as a key intermediate in the acrylamide formation pathway and can undergo several subsequent reactions. One pathway involves the decarboxylation of the Schiff base to form an azomethine ylide, which can subsequently decompose directly to produce acrylamide. Alternatively, the azomethine ylide can rearrange to form a decarboxylated Amadori compound, which further degrades during heating to generate acrylamide. The Schiff base may also undergo hydrolysis to form an aminoketone (commonly identified as 3-aminopropionamide, 3-APA), which upon further thermal degradation and deamination produces acrylamide. These parallel pathways demonstrate that several reaction intermediates contribute to acrylamide formation during thermal processing. The formation of acrylamide is strongly influenced by processing conditions. High baking temperatures, prolonged heating time, and reduced moisture content favour the Maillard reaction and increase acrylamide production. Since free asparagine is the principal amino acid involved in this reaction, the concentrations of free asparagine and reducing sugars in the dough are considered the primary precursors determining the extent of acrylamide formation. Understanding these reaction pathways is essential for developing baking strategies that minimise acrylamide formation while maintaining the desired quality characteristics of bread.

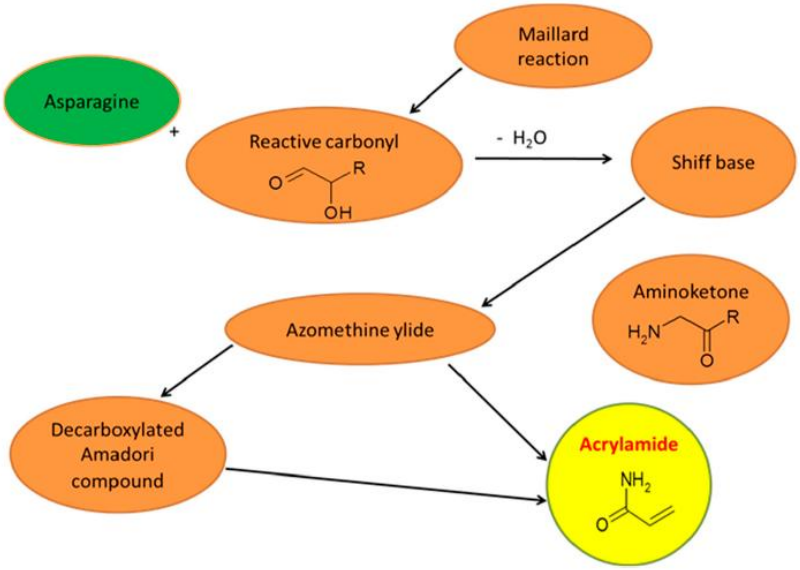


Figure 2.1 acrylamide formation mechanism by Maillard reaction (Michalak et al., 2020)

Table 2.2 Effect of different baking process on acrylamide content in different food products

Type of baking	Process conditions	Product	Advantages	Disadvantages	Reference
Microwave frying VS conventional frying	Microwave: 365W, Temperature: 180± 1 ℃ for 1.5 min Conventional frying: 180± 1 ℃ for 5 min	Batter	Microwave frying resulted in lower acrylamide formation	-	(Barutcu et al., 2009)
Vacuum baking VS conventional	Vacuum: at 10 for 10, 11, 12, 13,14 min. at 120 ◦C, for 10, 11 and 12 min. at 130 ◦C, for 6, 7, 8, 9 and 10 min at 140 ◦C, for 6, 7, 8 and 9 min at 150 ◦C, for 5, 6 and 7 min at 160 ◦C Conventional baking: at 180 ℃ for 4, 5, 6, 7 and 8 min. at 190 ◦C for 3, 4, 5, 6 and 7 min. at 200 ◦C for 3, 4, 5, 6.	Potato chips	Vacuum baking decreased acrylamide level by 98%	Vacuum baking led to lighter colour of potato chips	(Akkurt et al., 2021)
Vacuum baking VS conventional VS combined vacuum-conventional	Vacuum: at160,180, 200 °C and at 500 mbar for 17 min Conventional baking: at 180, 190, 200 °C for 15min	Biscuit	The combination process prevented the formations of acrylamide and HMF in biscuits.	Lack of browning development of biscuits in combination baking	(Mogol & Gökmen, 2014)

	Combination baking: 220 °C for 2, 3, and 4 min, and then they were post-baked in the vacuum oven set at 180 °C and 500 mbar for 6, 5, and 4 min,				
Vacuum-conventional VS conventional	Vacuum: 101 kPa for 12 min. Conventional baking: at 180 C for 20 min	Cookie	Combined vacuum baking decreased acrylamide content by 33% compared to conventional baking	Vacuum combination baking showed lighter cookie colour compared to conventional baked cookies	(Yıldız et al., 2017)
Vacuum-conventional VS conventional	Vacuum: 7.5 min under 101 kPa Conventional baking: at 205 °C for 11 min	Cookie	Combination baking led to lower acrylamide formation compared to conventional baking. It also showed lower hardness	-	(Palazoğlu et al., 2015)
Vacuum-microwave VS infrared baking VS conventional	Vacuum-microwave combination: at 60◦C for 7.5 min Infrared baking: at 76◦C for 10 s Conventional oven: at 230◦C for 25 min	Bread	Vacuum microwave baking led to higher formation of smaller size particles.	Both vacuum microwave and infrared baking led to higher acrylamide formation compared to conventional oven	(Juodeikiene et al., 2018)

Microwave VS conventional	Microwave: 700 W for 90 s Conventional oven: 190 °C for 10 min	Biscuit	Microwaved baked biscuits showed significantly lower acrylamide content	Microwave-baked biscuits showed several defects from a consumer perspective including an irregular upper surface with noticeable bulges, and an uneven texture, with the edges being hard and the centre remaining soft, particularly in the control samples.	(AL-Ansi et al., 2019)

2.4 An investigation on energy efficiency, production cost and greenhouse gas emission of different baking technologies

Energy efficiency, greenhouse gas emissions (GHG), and operational costs are becoming important factors in the evaluation of baking technologies both at industrial and domestic scales. These concerns are closely tied to the environmental and economic impact of food production. Conventional ovens are often considered energy intensive due to its need to preheat large chambers, maintaining high temperature (typically between 160°C and 250°C), and operate for extended periods contributes to high energy consumption (Bermúdez et al., 2015). These ovens are also less energy efficient due to heat losses through oven walls, and lengthy baking cycles. As a result, conventional ovens can have relatively high GHG emissions especially when powered by fossil fuels. The cost associated with this energy use is significant, particularly at industrial settings where multiple ovens operate continuously (De Pilli & Alessandrino, 2020). Despite these drawbacks, conventional ovens generally produce high quality baked products with well-developed texture, colour, crust and volume. In contrast, microwave ovens specially those used in domestic scales are more energy efficient for short baking or reheating tasks. They heat food by generating electromagnetic waves that cause water molecules in the product to vibrate and produce heat internally (Contreras et al., 2017). This direct, volumetric heating allows microwave ovens to reach the required temperatures much faster than conventional ovens and reduces the need for preheating. As a result, energy use per unit of food is generally lower and GHG emissions are also reduced when electricity is sourced from renewable energy (El-Adly et al., 2015). Hybrid baking systems, which combine two or more heating methods such as microwave and convection, or infrared and impingement, are designed to improve both energy efficiency and product quality. By integrating rapid internal heating with targeted surface heating, these systems allow for shorter baking times while still achieving browning, texture, and volume similar to conventional baking. For example, a combination of conventional oven and microwave hybrid can bake a product faster using microwave energy and then apply convection heat to the surface to develop crust and colour (Cappelli et al., 2021). This approach reduces total energy input and shortens processing time leading to lower operational costs and reduced GHG emissions. Infrared baking is another method gaining attention for its energy capability. Infrared energy is absorbed directly by the outer layers of the product, which allows for rapid surface heating with minimal heat loss to the surrounding air. This targeted heat transfer reduces baking time and lowers energy requirements particularly in continuous baking systems. Infrared ovens also tend to have lower GHG emissions when operated efficiently although their effectiveness depends on precise control of wavelength, intensity, and exposure time (Bermúdez et al., 2015). However, because the heat penetrates less deeply into the product, it may not be ideal for thicker baked items unless combined with another method such as microwave or conventional oven. In such cases, a hybrid infrared-microwave system can deliver fast, efficient internal heating alongside surface browning with reduced energy consumption (Khatir et al., 2013). Vacuum baking also represents a promising approach in terms of energy and quality of baked products by reducing the pressure inside the baking chamber which allows baking to occur at reduced temperature. GHG emissions from vacuum baking can be lower depending on the energy source used and system design. However, vacuum baking systems are costly to install and operate, and they may not be suitable for all product types due to the lack of browning and crust formation. To address this, some manufacturers are exploring vacuum systems combined with surface-heating methods like infrared which adds complexity but can result in well-balanced energy use and product quality (Devu et al., 2022). Jet impingement baking is known for its fast-baking times and high heat transfer efficiency. The focused air flow allows products to reach target temperatures quickly and reducing overall energy consumption. In terms of GHG emissions, the efficiency of jet impingement systems depends on how the heat is generated but the shortened bake times generally contribute to lower emissions. When optimised, jet impingement systems provide a strong balance between energy efficiency and consistent product quality, making it a suitable technology for a variety of bakery products. As energy prices rise and environmental concerns grow, baking technologies must not only deliver desirable product characteristics but also align with sustainability goals (Banooni et al., 2008).

Chapter 3 Research design and methodology

3.1 Research design

The research design of this thesis includes: 1) A comprehensive literature review, 2) Bread baking using different baking modes which includes dough preparation, proofing and baking , 3) Sensorial properties analysis including texture, moisture content, C-cell structure, colour and volume measurement, 4) Evaluation of process conditions including temperature and moisture during baking 5) Evaluation of acrylamide formation 6) Energy consumption, cost and greenhouse gas emission measurement 7) Optimisation of baking conditions using RSM design expert software. The following provides a visual representation in the form of a flow diagram, which conveys the design of the programme of research (Figure 3.1)

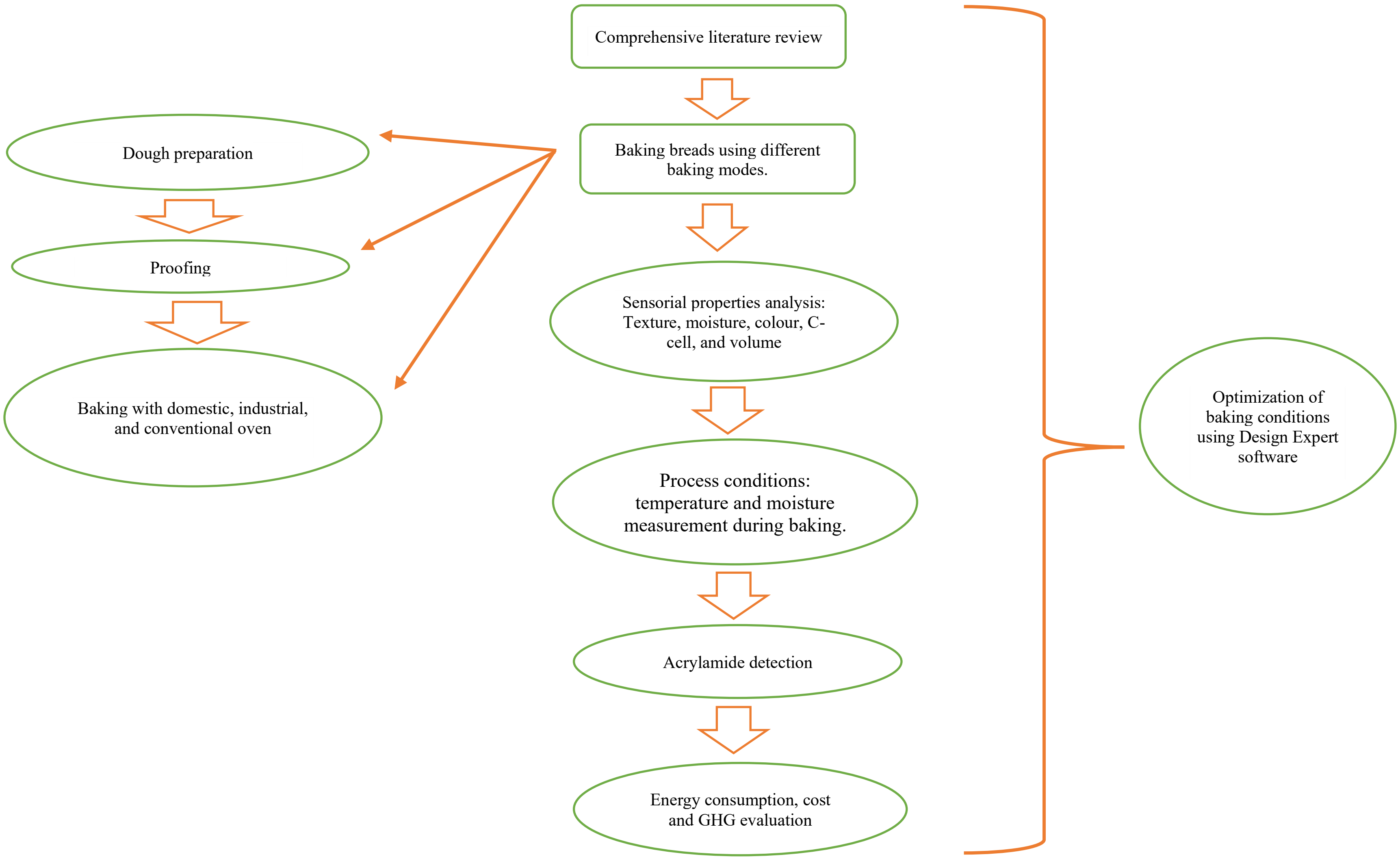


Figure 3.1 Research design of the project

3.2 Methodology

3.2.1 Dough preparation and baking process

The formulations used for breadmaking processes in this study are presented in Table 3.1. The ingredients including wheat flour (Shipton mill, United Kingdom) with the composition (w/w) of 11% protein, 1.2% fat, 0.5% sugar, 79% starch and 3.3% fibre, vegetable oil (local supermarket, UK), dry yeast (Allinson, United Kingdom), lukewarm water, salt and sugar (purchased from the local supermarket). The dry ingredients were mixed with water in a food processor (Acuma Stand Mixer, United Kingdom) using a S-shaped hook geometry at the speed of 100 rpm/min for 1 min then second speed of 200 rpm/min for another 1 min. Factors such as flour composition, water absorption, yeast concentration, sugar content and fat level influence bread quality attributes. To eliminate formulation as a confounding factor, a single standard bread recipe was used throughout the present study, ensuring that observed differences could be attributed solely to the baking technologies employed.

Table 3.1 Bread formulation for baking based on the wheat flour weight

Ingredients based on flour weight	Amount (%)
Water	58-60%
Dry yeast	3
Salt	2.3
Sugar	6
Vegetable oil	4

The resulting dough was divided into 9 pieces and placed into the greased pans, proofed in a steam oven (Eco catering equipment, Rational SCC61E, 5 Senses, United Kingdom) for 55 mins at temperature of 30°C and humidity of 85% then baked using conventional oven (Eco catering equipment, Rational SCC61E, 5 Senses, United Kingdom), domestic microwaves (Panasonic NN-CD87KSBPQ combination microwave oven, Japan) and industrial solid- state (Industrial microwave system, United Kingdom). All the equipment used for different baking modes are shown in Figure 3.2. The bread formulation employed in this study and proofing condition were adapted from (Stojceska & Ainsworth, 2008), who demonstrated suitable dough development and bread quality characteristics using this recipe. Preliminary experiments were conducted to determine suitable baking durations for both microwave baking. Microwave treatments between 3 and 7 min were investigated. Baking durations shorter than the selected conditions resulted in incomplete baking, whereas longer durations produced excessive moisture loss and crust darkening. Based on these observations, 5 min microwave baking were selected for the main experiments.

Figure 3.2 The equipment used for different baking modes a) Conventional oven b) domestic microwave and c) industrial solid-state microwave

Overall, 21 bread samples (7 x 3 replicates) were baked using different baking modes, as follows:

- 3 bread samples were baked using a conventional oven at 220°C for 20 minutes (CB). These samples were used as reference samples.

- 3 bread samples were baked using a domestic microwave oven at a med-high W and frequency of 2450 MHz for 5 min (DM).
- 3 bread samples were baked using an industrial solid-state microwave with similar conditions as DM samples, at 706 W and at a frequency of 2450 MHz for 5 min (IM).
- 3 samples were baked using a hybrid approach of DM for 5 min + CB for 5 min ($DMCB_1$)
- 3 samples were baked using a hybrid approach of DM for 5 min + CD for 10 min ($DMCB_2$)
- 3 bread samples were baked using a hybrid approach of IM for 5 min+ CB for 5 min ($IMCB_1$).
- 3 samples were baked using hybrid approach of IM for 5 min + CB for 10 min ($IMCB_2$).

After baking, breads were cooled for 2 hours at room temperature of 22 °C. The image of the baked breads is presented in Figure 3.3.

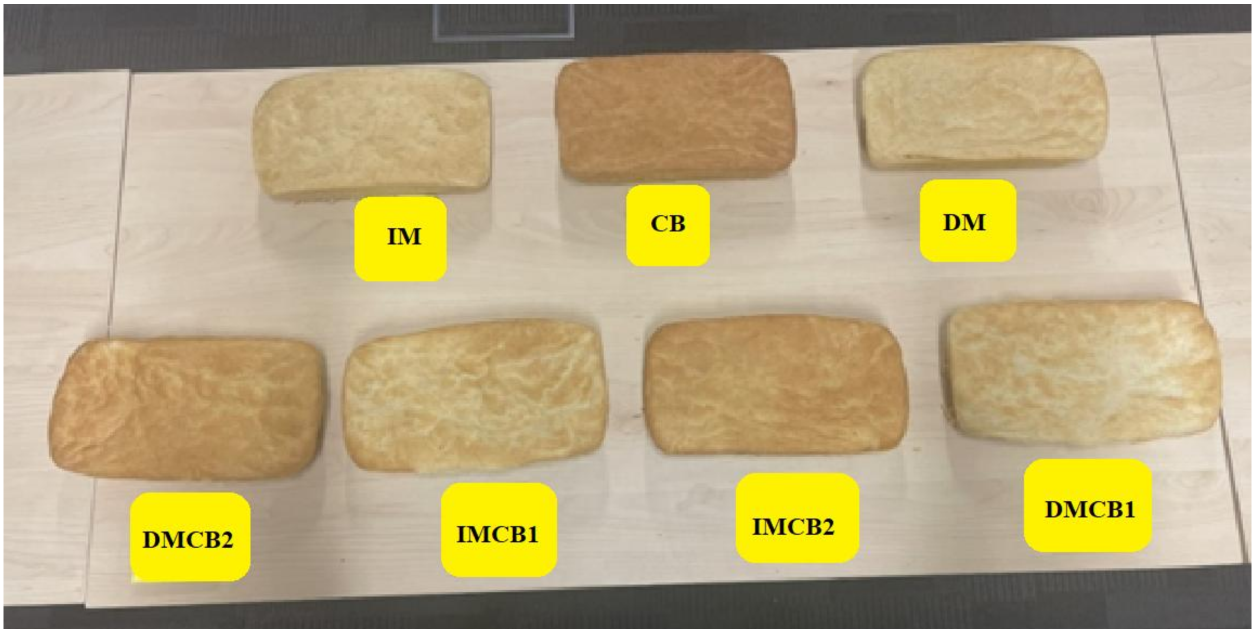


Figure 3.3 The images of the baked breads with different baking modes (CB- conventional oven; DM - domestic microwave baking; IM- industrial solid-state microwave baking; DMCB - (DM + CB baking); IMCB - (IM + CB baking))

3.2.2 Moisture content

The moisture content of the baked breads, including both crust and crumbs, were evaluated on the first, fifth and eight days of the baking using a moisture analyser (Ohaus, BM 25, United States) (Figure 3.4). The analyses were performed using 3g of each sample to dry at 120 ℃ for 9 mins. Three replicates were carried out to ensure the accuracy of the analyses.

Figure 3.4 Moisture analyser for measuring moisture content

3.2.3 Colour measurement

Bread crust colour was measured using a colourimeter (Chromameter CR-400, Konica Minolta, Tokyo, Japan) (Figure 3.5), and the results were reported according to the CIELAB colour system (illuminant C, 10° viewing angle). The colour parameters assessed included lightness (L-value), redness (a*), and yellowness (b*) (Bolger et al., 2021; Minolta, 2007).

Figure 3.5 Chromameter for measuring colour values

3.2.4 Texture analysis

Bread samples have been sliced using slicing machine (Buffalo meat slicer 220 mm, United Kingdom) (Figure 3.7) and tested using TA-XT2i Texture Analyzer (A-XT2, Plus-Upgrade, Stable Micro Systems, Godalming, UK) (Figure 3.8) coupled with Exponent Connect Lite software, version 6.1.16.0 (Stable Microsystems, Godalming, UK) using a 35 mm aluminium plunger and 20 mm tick bread-slices. Hardness testing was performed in the centre of the bread slices using a 5 kg load cell and 6 mm cylinder. A double compression test was carried out at a test speed of 1 mm/s, using a constant speed of 2.0 mm/s for the pre-test, main test, and post-test stages. The trigger force was set to 5.0 g, and the compression distance was fixed at 40% of the slice thickness. From the force–time curves obtained in the Texture Profile Analysis, hardness (defined as the maximum peak force during the first compression cycle) was determined using the Exponent software (version 6.1.18.0, Stable Micro Systems, UK). The measurements were performed in triplicate, and the recorded forces were expressed in grams (Bolger et al., 2021).

Figure 3.6 Slicing machine for cutting the breads

Figure 3.7: TA-XT2 texture analyser used for measuring textural properties of the breads

3.2.5 Bread volume, specific volume, and length

Volume, specific volume, length and weight of whole breads were measured using a Stable Micro Systems Volscan Profiler (Volscan profiler, Stable Micro Systems, England) (Figure 3.8) 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).

Figure 3.8: Volfscan profiler volume analyser

3.2.6 Cellular structure of the breads

Breads were cut in multiple slices with 15 mm thickness and scanned using scanner (HP Scanjet G2710, HP Inc., Palo Alto, CA, USA) (Figure 3.9) and subsequently the digital pictures were provided. The images were used to analyse average cell area (in mm^2) and cell number of the bread using ImageJ Software (National Institutes of Health, Bethesda, MD, USA).

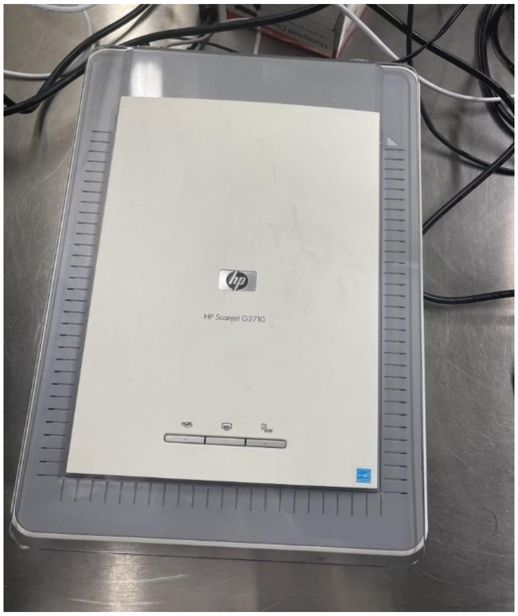


Figure 3.9: HP scanner used for taking picture of bread slices

3.3 Temperature measurement during baking

Conventional oven temperature measurement of bread while baking was carried out using three thermocouples (K-type, 0.2 mm in diameter, TC SA, France) with USB serial interface, PicoLog software (PicoLogsoftwareversion5.25.3, Picolog Technology, TX, USA). They were placed at the bottom, centre and top of the breads over 20 minutes for CB mode and 5 and 10 minutes for the hybrid baking modes. Regarding domestic and industrial solid-state microwave, fibre optic sensors (2m PTFE coated fibre optic temperature sensor) and Portable 4 channel FOM-H201-4 Fibre Optic Monitor (Omega, United Kingdom) have been used to measure temperature at the bottom, centre and top of the breads over 5 minutes for IM and DM breads. The analyses were repeated three times at each position (Top, centre and bottom) aligned each other.

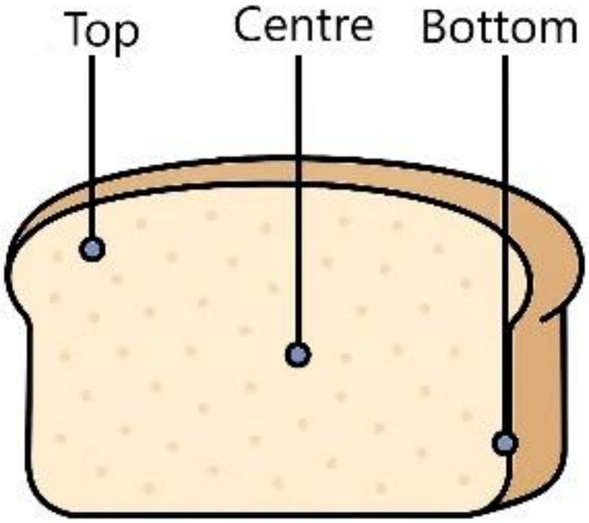


Figure 3.10 Sensor positions in bread while baking

3.4 Moisture measurement during baking

Humidity measurement was carried out using fibre optic AM2315C humidity sensor (Ec-electric, Iran, Tehran) with both 24 VDC & 115-230 VAC power supply, 0-100% volumetric humidity reading in a display and 4-20 mA output signal. PicoLog software (PicoLogsoftwareversion5.25.3, Picolog Technology, TX, USA) for recording data. The analyses were repeated three times at each position (Top, centre and bottom) aligned each other.

3.5 Acrylamide formation 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- Parmar 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, 2ml 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 x 3.0 mm i.d., 5µm film thickness) with a Hypercarb precolumn (10 x 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 5µL. 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 (N2collision 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).

3.6 Energy consumption, GHG emissions and overall cost

The energy efficiency, environmental impact and energy cost of the baking processes examined in this study were evaluated by analysing energy consumption and GHG emissions and energy costs associated with the conventional oven as well as domestic and industrial solid-state microwave technologies. Electrical energy consumption for the conventional oven and microwave systems was recorded at10-second intervals using a Fluke 345 energy logger (Washington, USA). Since the conventional oven and industrial solid-state microwave are powered by a three-phase supply, the logger monitored the voltage of each phase and measured the corresponding line currents independently using induction-based current measurement. Similarly, for the domestic microwave, which operates on a single-phase power supply, the Fluke 345 energy logger (Washington, USA) recorded the phase voltage, current, power factor, power, and cumulative energy at 10-second intervals. Energy consumption of the microwave and conventional oven baking was calculated using Equation 1:

$$E_t = P \times t \tag{1}$$

where E_t represents the total energy consumption for baking (kWh), P is the output power (kW), and t is the baking time (h)

The electrical cost of baking, are calculated using the Equation 2:

$$\text{Energy cost for baking} = E_t \times Unit\ rate \tag{2}$$

where E_t represents the total energy consumption for baking, measured in kilowatt-hours (kWh). The unit cost of electricity is assumed to be £0.34 per kWh, based on a fixed rate from Npower (2022).

The carbon footprint accounts for all greenhouse gases released, including methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), perfluorocarbons (PFCs), sulphur hexafluoride (CF_6), and hydrofluorocarbons (HFCs) (Carbon Trust, n.d). It was estimated by multiplying the relevant conversion factor by the amount of energy used (kWh), as shown in equation (3). The energy conversion factors were adopted from the Department of Environment, Food and Rural Affairs (2022) and are shown in Table 3.2.

$$\text{GHG emission} = E_t \times X \tag{3}$$

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

Table 3.2 Energy consumption factors (Department of Environment, Food and Rural Affairs, 2022)

Emission incurred per unit energy consumed (kWh)	**kg CO_2 e**	**kg CO2**	**kg CH4**	**Kg N_2O**
	0.1912	0.1933	0.0008	0.0013

3.7 Statistical analysis

Sensory properties, acrylamide levels, and environmental analyses were conducted in triplicate, and results are expressed as mean ± standard deviation. Prior to statistical analysis, the assumptions of normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests, respectively. As these assumptions were satisfied, one-way analysis of variance (ANOVA) was used to compare treatment means at a 95% confidence level ($P < 0.05$), followed by Duncan's multiple range test using SPSS 22.0 software (SPSS Inc., Chicago, IL, USA). One-way ANOVA was selected because it provides an appropriate method for comparing the means of multiple independent groups when its assumptions are met. If these assumptions had been violated, the Kruskal–Wallis test would have been considered as a non-parametric alternative. Optimisation of baking process using response surface methodology.

3.8 Optimisation of baking process using response surface methodology

The experimental data were analysed using Response Surface Methodology (RSM), central composite design of Design-Expert software version 25.0 (Stat-Ease Inc., Minneapolis, USA) to determine the optimum baking conditions for the measured parameters. The quality of the fitted model was evaluated using ANOVA at a significance level of $p < 0.05$ to evaluate the statistical significance of each model. The statistical indicators presented model F-value, P-value, adjusted R^2, and R^2 which evaluate the strength and adequacy of each model. The F-value is used to test the overall significance of the model, and a large F-value suggests that the model or factor has a strong and statistically significant effect on the response. The goodness of fit of the model was checked by a coefficient of determination (R^2) and higher R^2 values (close to 1) means the model predicts the results very well. The adjusted R^2 should be close to R^2 value to confirm that the model fits the data well and does not include unnecessary variables. P-values were used to check the significance of each coefficient and smaller P-values show stronger effects, and values below 0.05 indicate that the model terms are statistically significant. The independent variables considered in this study were the baking time for different baking modes, while the response variables include moisture content, hardness, loaf volume, cell structure, colour (L-value), acrylamide and GHG emissions. Moisture content and hardness data were taken on the first day after baking as presented in Figure 4.1 and 4.3 respectively. The average final baking temperature, calculated from measurements taken at the top, surface and bottom of the breads has been used for each baking mode, as it showed in Table 3.3.

Table 3.3 The range of time and temperature for different baking modes

Baking mode	Temperature (℃)	Time (min)	Source
CB	114	20	Figure 5.1
IM	102	5	Figure 5.2
DM	95	5	Figure 5.3
$IMCB_1$	105	10	Figure 5.4
$IMCB_2$	104	15	Figure 5.5
$DMCB_1$	104	10	Figure 5.6
$DMCB_2$	115	15	Figure 5.7

Table 3.4 shows the set goals for each factor and response variable considered in the optimization process. Although each response variable falls within an experimentally defined range in the optimization, a specific target value was selected as long as it did not exceed that range. The target for moisture content was set at 29% because this level produced breads with a soft and pleasant texture while maintaining safety against microbial growth, as breads with moisture levels above

35% have been shown to promote microbial activity (Alpers et al., 2021). The target for hardness was set at 1000 N because it was the lowest hardness and softest bread among all samples (Figure 4.3). In terms of bread loaf volume, although no significant difference was observed and all values were relatively high, the target was set to the maximum measured volume (1191 mL), as high volume is the main indicator for desirable bread quality (Różyło & Laskowski, 2011). The target for lightness (L-value) was set at 55, as this level represents an appealing golden-brown crust. The bread produced by conventional baking showed the darkest crust (lower L-value), while both microwave - baked samples were notably paler with L> 70 (Figure 3.3 and Figure 4.2). Therefore, setting the target at 55 aimed to achieve a visually attractive, lightly browned crust indicative of proper baking. For crumb structure, the uniformity was prioritised as the key quality attribute; therefore, the target cell number was based on the conventional baking sample (250), which exhibited the most uniform cell distribution (Figure 4.5 and Figure 4.7). The targets for acrylamide levels (1.88 µg/kg) and GHG emissions (0.006) were set to have the lowest observed levels to reduce the formation of harmful compounds and environmental impact (Figure 6.1 and Table 7.1 respectively). These targets enabled the optimisation software to identify baking conditions that best balanced product quality with environmental performance. The importance level for most responses was set to 5, highlighting their critical role in achieving optimal baking results. Table 3.4 The optimization process set goals for each response.

Table 3.5 The optimization process set goals for each response

Name	Target goal
Hardness (N)	29
Moisture (%)	1000
Loaf volume (ml)	1191
Cell number	250
Lightness (L-value) (%)	55
Acrylamide (µg/Kg)	1.88
GHG (%)	0.006

The final experimental design incorporated all variables, resulting in 21 experimental runs, generated by the RSM design matrix. These runs combined different time and temperature conditions, as shown in Table 3.4.

Table 3.6 Final experimental RSM design

Run	Conventional baking time (min)	Industrial microwave baking (min)	Domestic microwave baking (min)	Temperature (℃)	Moisture (%)	Hardness (N)	Volume (ml)	Cell number	L value (%)	Acrylamide (µg/Kg)	GHG (%)
1	20	0	0	124	26.3	1299.7	1176	249	73.23	22.41	0.086
2	10	5	0	104	25.1	1687.9	1171	351	57.76	15.87	0.038
3	5	0	5	104	21.7	1795.51	1179	340	63.41	8.2	0.041
4	10	0	5	115	18.1	2223.5	1175	338	57.74	16.11	0.055
5	0	5	0	104	29.9	1062.5	1166	378	63.46	1.98	0.006
6	5	0	5	104	21.9	1748.69	1182	339	63.32	8.27	0.039
7	5	5	0	105	27.8	1267.98	1191	351	47.21	7.91	0.021
8	0	0	5	98	15.2	2356.87	1188	379	71.89	2.06	0.025
9	10	5	0	104	24.5	1545.55	1179	353	57.81	15.95	0.039
10	0	0	5	98	15.4	2498.47	1181	382	71.81	2.05	0.033
11	5	0	5	104	21.8	1771.94	1185	339	63.35	8.31	0.041
12	20	0	0	124	27.1	1379.53	1181	251	73.29	22.15	0.089
13	5	5	0	105	29	1301.45	1179	353	47.29	7.96	0.017
14	0	0	5	98	16.3	2497.62	1183	382	71.92	2.11	0.027
15	0	5	0	102	29.3	1087.6	1185	382	63.42	1.88	0.006
16	10	0	5	115	18.2	2249.87	1178	341	57.79	16.03	0.061
17	5	5	0	105	28.1	1329.76	1171	354	47.33	7.99	0.022
18	20	0	0	124	26.8	1345.65	1186	250	73.37	23.11	0.087
19	10	0	5	115	18.7	2387.51	1186	341	57.85	16.09	0.064
20	10	5	0	104	24.4	1611.23	1184	353	57.72	15.89	0.029
21	0	5	0	102	29.1	996.8	1182	380	63.48	1.92	0.008

Chapter 4 Results and Discussion – Evaluation of process conditions including temperature and humidity variation during baking

This chapter presents the work that has been conducted on the effect of the process conditions during baking on the quality of the baked breads. In order to understand the effect of the process conditions on the quality of bread baked using different baking modes, the temperature variation and moisture changes inside the bread during baking were studied.

4.1 Temperature measurement

Fig. .1 shows the temperature variation in the CB breads during baking over 20 minutes at three different zones including top, centre and bottom of the bread. It can be seen that there was a linear increase of the temperature on the top that varied from 25°C to 120°C, centre from 20°C to 100°C and bottom part from 20 to 118°C. During the first 5 minutes, there is a sharp increase in temperature for all three zones, indicating rapid heat absorption in the conventional oven. However, as baking continues, the increase in temperature decreases, especially in the centre where heat moves inward from the hotter outer layers (Besbes et al., 2013). Because the top surface of bread is directly exposed to both convection and radiation which cause the temperature to rise quickly in this zone (Fehaili et al., 2010). The resulting temperature gradient between the surface and centre induces conductive heat transfer within the bread (Lostie et al., 2002; Fehaili et al., 2010). As the baking time extends beyond 15 minutes, the centre temperature reached a plateau at 100 °C and remained constant slightly above 90°C, while the top and bottom continued increasing beyond 120°C. This behaviour could be attributed to a maximum evaporation where most of the heat supplied to the bread was used for water vaporization at the surface (Fehaili et al., 2010). At the end of baking, the top and bottom zones reached nearly 120°C, while the centre was around 100°C. This shows that conventional baking resulted in non-uniform heating, where some areas of the bread (top and bottom) became hotter while the centre remained cooler.

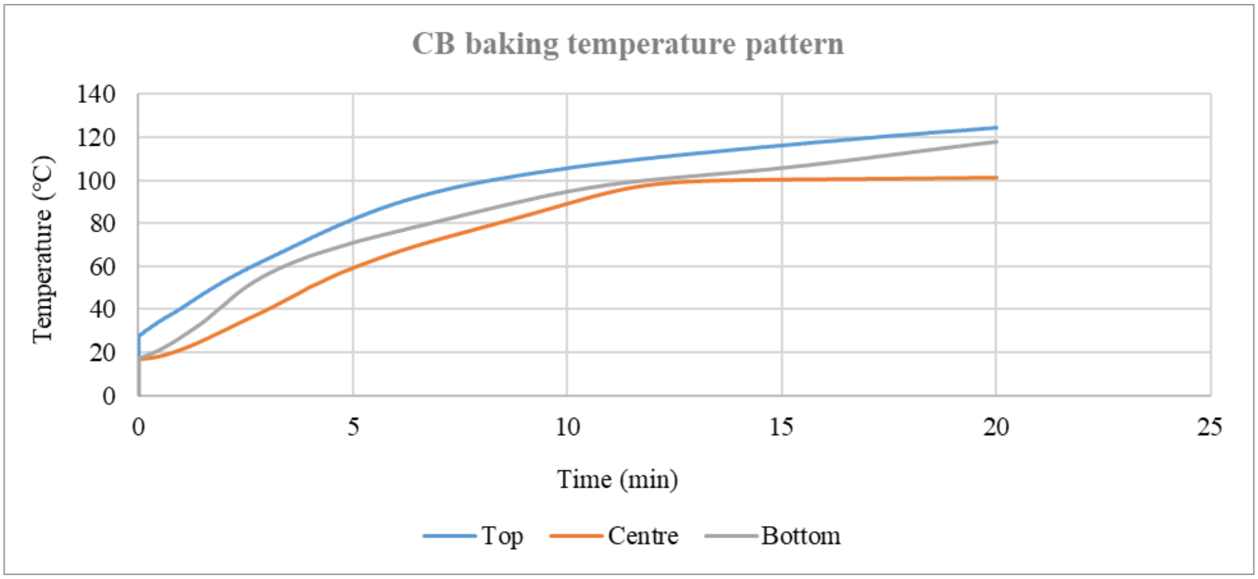


Figure 4.1 Temperature distribution in CB breads during baking

Fig. 4.2 shows the temperature variation in the industrial solid-state microwave baking over 5 minutes at three different zones including the top, centre and bottom of the bread. It can be seen that the temperature was ranging from nearly 22 °C to 100 °C during baking in all three measured zones. Within the first two minutes, the temperature in all three zones increased rapidly, with the top surface of the bread reaching 100°C showing that the heating rate in IM surpasses that of a CB which took more than 15 minutes to reach the same temperature. Because there is limited research on the temperature measurement of IM, it is assumed that the uniform heating achieved by the IM system contributed to this higher heating rate (Atuonwu & Tassou, 2019). Also, the emission of electromagnetic waves in microwave baking penetrates the bread and causes the water molecules to vibrate, generating heat evenly throughout the product. This process excites the water molecules, allowing the bread to heat much faster than in conventional ovens, which rely on slower surface heat transfer methods. (Megahey et al., 2005; Bou-Orm et al., 2023). The high moisture content in the bread dough also prevented the internal temperature from increasing much beyond 100 °C (Fig 5.7) (Baik et al., 2000). The bread's surface is directly exposed to microwave radiation and the bottom being in contact with the baking tin, which leads to greater absorption of microwave energy at these areas (Megahey et al., 2005). Consequently, the top and bottom heat up more, while the centre remains at a lower temperature. At the end of baking, it can be seen that the temperature resulted in a close alignment of temperatures across different zones (top, centre, and bottom), suggesting that the uniform heating of an industrial solid-state microwave caused minimal variation in these zones.

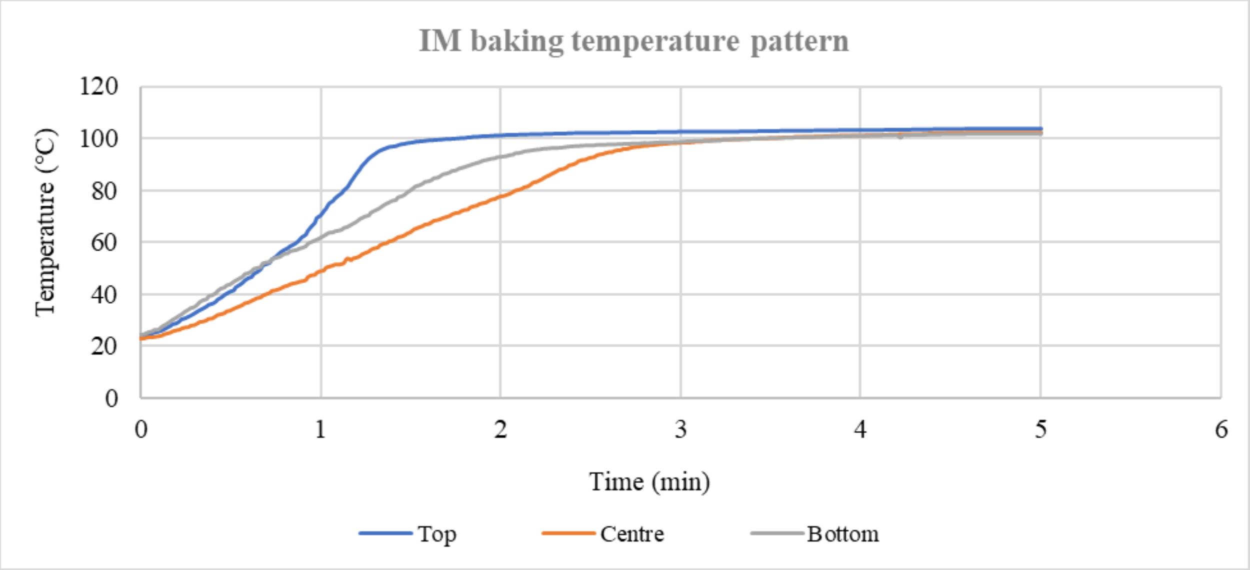


Figure 4.2 Temperature distribution in IM baked breads

Fig. 4.3 shows the temperature variation in the domestic microwave baking over 5 minutes at three different zones including the top, centre and bottom of the bread. It can be seen that the DM breads showed different temperatures across various zones of the bread during baking. The temperature of the bread's top ranges from 20°C to 100°C while the bread's centre from 20°C to 80°C, resulting in 20°C lower temperature compared to the bread's top. These findings are consistent with those of Vadivambal and Jayas (2010), who reviewed temperature distribution during domestic microwave baking and reported that microwave baking often results in wide temperature variations, depending on the type and properties of the materials used. It can be seen that the temperatures measured at the top and bottom showed different values during the baking, but they were synchronised by the end of the baking process, which was not a case with the temperature measured at the centre of the breads. Since domestic microwaves heat food by exciting water molecules, areas with higher moisture content heat up faster, leading to localized overheating and excessive moisture loss from the surface layers, while the centre remains at a lower temperature for a prolonged period (Wilson et al., 2002). Also, this could be due to the direct exposure of the bread's surface to microwave radiation and the contact of the bottom layer with the baking tin, causing the top and bottom of the bread to absorb more microwave energy (Chandrasekaran et al., 2013). As a result, the temperature is higher at the top and bottom and lower at the centre of the bread (Pitchai et al., 2012). Tong and Lund (1993) found that the internal temperature of microwave-baked bread rose steadily over time, reaching around 100°C, and this pattern was not affected by the microwave power level.

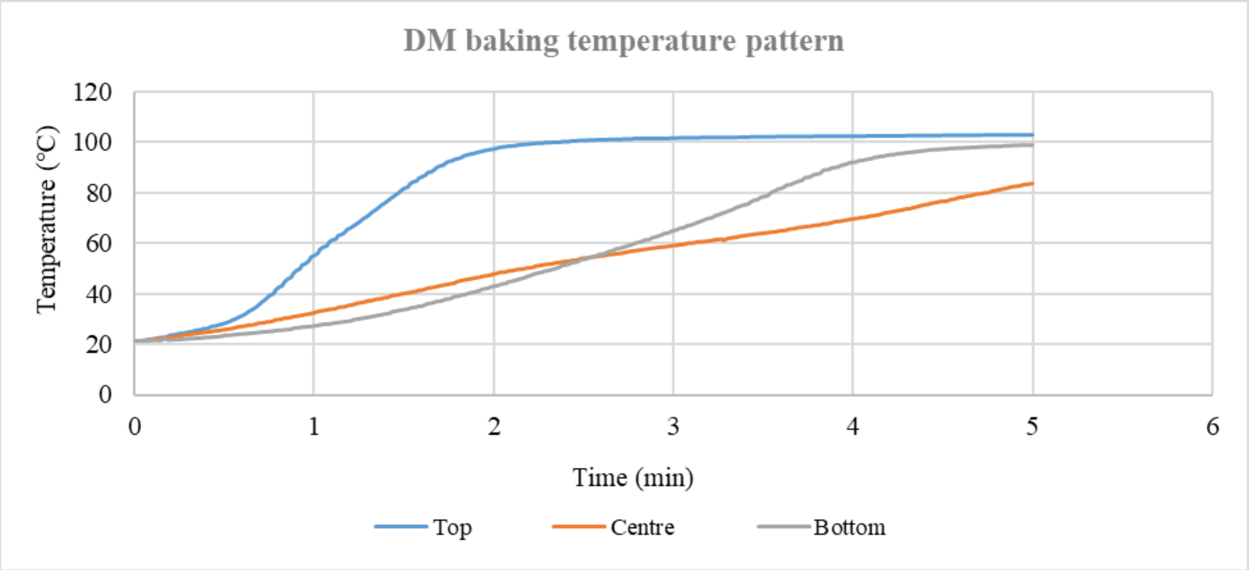
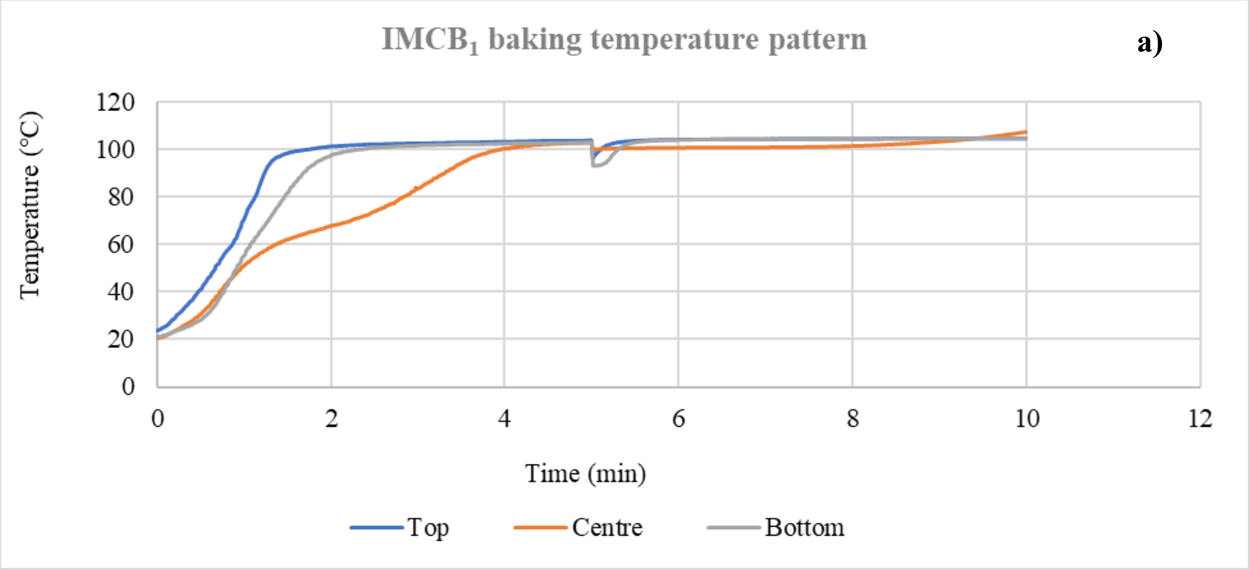


Figure 4.3 Temperature distribution in DM breads during baking

Figs. 4.4 (a and b) show the temperature variation in $IMCB_1$ and $IMCB_2$ over 10 and 15 minutes of baking at three different zones including top, centre and bottom of the bread. It can be seen that there was variation of the temperatures across different zones in both samples. Both the top and bottom regions exhibited higher temperatures than the central part due to the direct exposure of the bread to the radiation and baking tin respectively (Megahey et al., 2005).A small dip observed around the fifth minute which was due to the transition phase between industrial solid-state microwave and the conventional oven. During the first few minutes of $IMCB_1$, the top, centre, and bottom zones show a rapid increase in temperature due to the microwave radiation, with the top and bottom reaching around 100°C by minute 3. As baking continued from 2 to 5 minutes, the centre temperature gradually increased, and by the fifth minute, all zones reached a similar temperature of about 100°C, demonstrating that industrial solid-state microwave baking promoted uniform heat distribution throughout the bread loaf. This result agrees with results from Figure 5.2, which showed industrial solid-state microwave baking alone resulted in uniform heating, where the top, centre and bottom were reached to the similar temperature. The centre zone heated slightly slower but eventually reaches a similar temperature, indicating uniform volumetric heating from the industrial solid-state microwave. After 5 minutes of industrial solid-state microwave baking, the temperature remained relatively stable and then slightly increases again when conventional baking started. After 10 minutes of baking, $IMCB_1$ and $IMCB_2$ both showed more uniform internal heating than conventional baking alone, since all three zones reached the same temperature at the end of baking, while the centre of the bread in CB remained significantly cooler than top and bottom. The employment of hybrid baking suggests that the combination of industrial solid-state microwave and conventional oven in $IMCB_1$ and $IMCB_2$ bread effectively balances rapid heating with improved uniformity, reducing the significant temperature gradient often observed in only conventional baking methods.



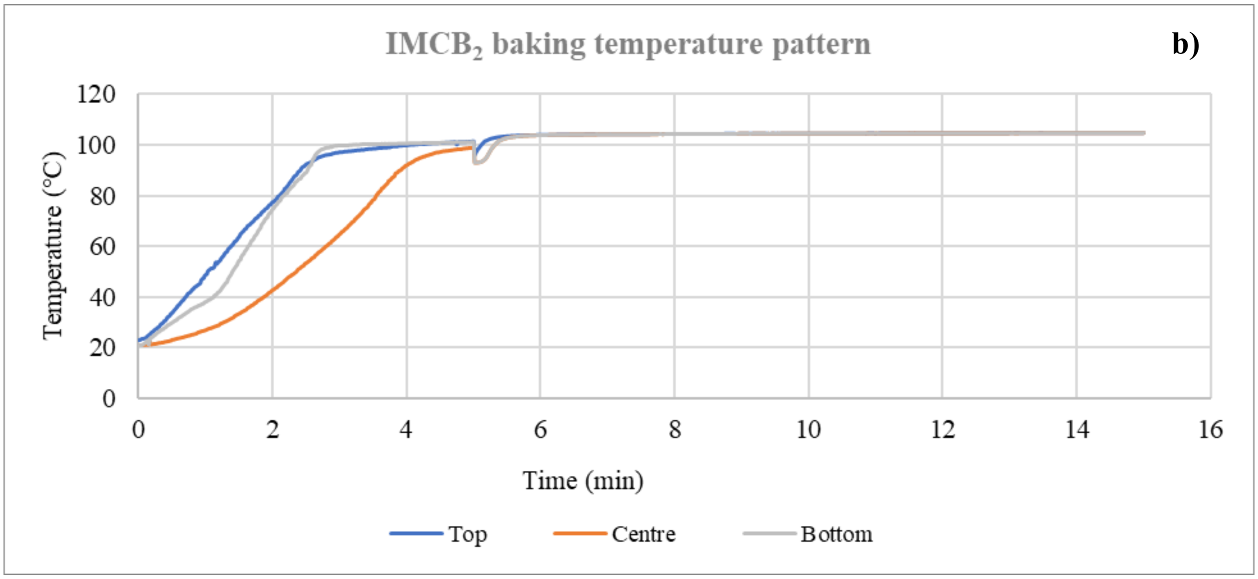


Figure 4.4 Temperature distribution in a) IMCB$_1$ and b) IMCB$_2$ breads during baking

Figure 4.5 (a and b) shows the temperature variation in DMCB$_1$ and DMCB$_2$ over 10 and 15 minutes of baking at three different zones including the top, centre and bottom of the bread. During the first three minutes of baking in both DMCB$_1$ and DMCB$_2$, the top zone showed a sharp and rapid increase in temperature due to domestic microwave electromagnetic radiation, reaching around 100°C by the third minute, while the centre and bottom zones remained cooler. By the end of five minutes of microwave baking, the bottom zone reached almost the same temperature as the top because of its contact with the hot baking tray, whereas the centre remained colder at approximately 70°C. This result agrees with results from Figure 4.3, which showed that domestic microwave baking alone resulted in non-uniform heating, where the top and bottom were much hotter than the centre. After the fifth minute, when conventional baking started, a slight temperature increase was observed from 100°C to nearly 120°C in the top and bottom, and from 70°C to 120°C in the centre. This indicates that the conventional oven helped to balance the temperature across all zones, resulting in more uniform heating without temperature variation.

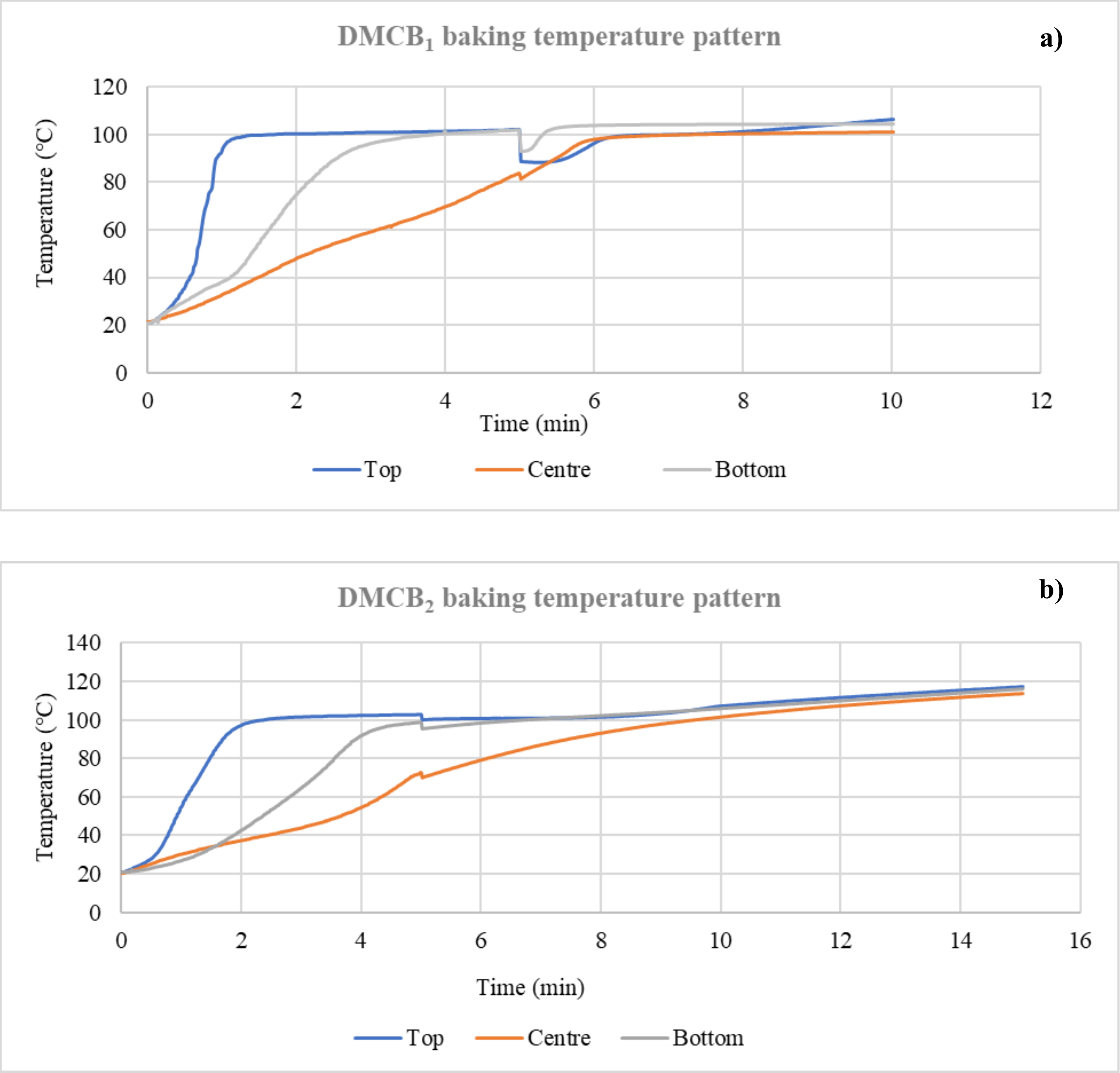


Figure 4.5 Temperature distribution in a) $DMCB_1$ and b) $DMCB_2$ breads during baking

4.2 Moisture changes during baking

Fig. 4.6 displays the moisture content change in the CB bread over 20 minutes of baking at different zones, including the top, centre and bottom of the bread. It is evident that the top and bottom of the bread experience more significant moisture loss compared to the centre. During the first five minutes of baking, all three regions of the bread exhibited a sharp decline in moisture content due to the rapid evaporation of moisture. The substantial moisture loss at the top of the bread can be attributed to its direct exposure to hot air within the oven, which enhances evaporative cooling and contributes to the formation of a crust (Vanin et al., 2009). Over time, as evaporation continues, the top surface becomes progressively drier and firmer, ultimately forming a crust that characterizes conventionally baked bread (Baik, et al., 2000). Also, according to Figure 5.1, the top temperature of the bread increased significantly which can cause moisture loss during baking. The baking pan transfers heat to the dough via conduction, causing the temperature at the bottom to rise more gradually compared to the top surface exposed to radiant and convective heat, which leads to losing more moisture and becoming drier (Chhanwal et al., 2019). The baking pan gradually increases the temperature of the bottom layer, leading to moisture migration toward the surface, where it eventually evaporates (Chhanwal et al., 2019). In contrast, the centre of the bread retains the highest moisture content throughout most of the baking process due to the insulating effect of the outer and surrounding layers, which slows down heat penetration (Zhang et al., 2017). The presence of a temperature gradient between the centre and the surface facilitates the movement of moisture outward, but because the centre remains at a lower temperature for a longer duration, it does not lose moisture as rapidly as the outer layers (Vanin et al., 2009). Even though some moisture is lost from the centre, it remains significantly higher than the moisture content at the top and bottom by the end of the baking process, ensuring that the final product retains a desirable texture with a moist crumb.

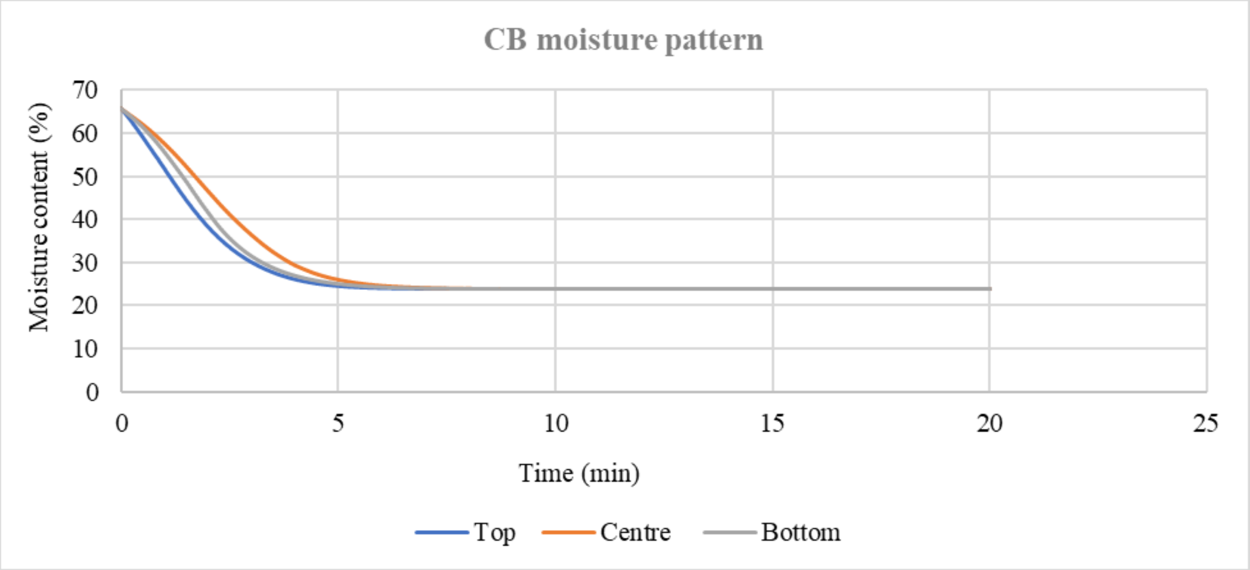


Figure 4.6: Moisture change in CB bread during baking

Figure 4.7 displays the moisture content change in the IM bread over 5 minutes of baking at different zones, including the top, centre and bottom of the bread. During the first 2 minutes of baking, all three parts of the bread experienced moisture loss, followed by a plateau that persisted until the end of baking where most of water evaporated. Unlike conventional baking, where moisture loss varies significantly between the top, bottom, and centre due to heat exposure to the oven hot air, the IM baking process promotes more aligned moisture evaporation across all zones, as evident in the closely aligned moisture curves. Due to the lack of research and study on industrial solid-state microwave in food specially in baking, it can be assumed that the uniform heating of an IM caused minimal moisture loss in these zones which resulted in less variation and close alignment of the top, centre and bottom. The top surface is typically exposed to industrial solid-state microwave radiation and lose moisture quickly due to evaporation (Besbes et al., 2013). As baking continues, the centre will eventually lose moisture, but this typically happens slower than the outer parts. The bottom layer maintains slightly higher moisture content than the top initially due to the heat penetration of microwaves through the baking pan, which reduces localized overheating and excessive drying of specific layers (Chhanwal et al., 2019).

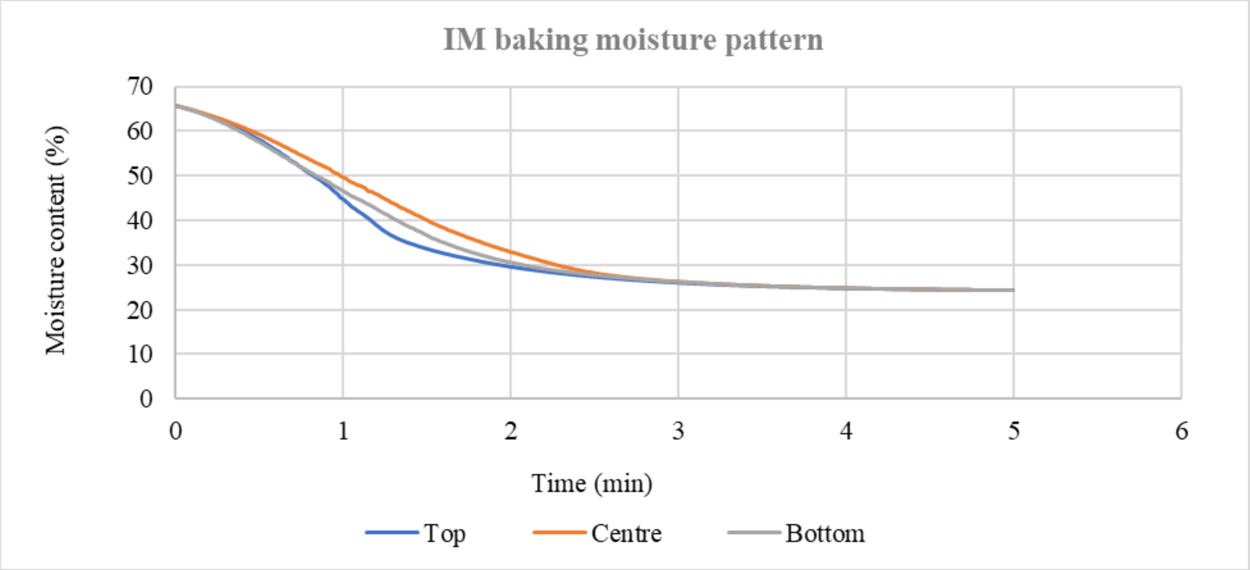


Figure 4.7 Moisture changes in IM bread during baking

Figure 4.8 displays the moisture content change in the DM bread over 5 minutes of baking at different zones, including the top, centre and bottom of the bread. The moisture loss pattern in DM breads exhibited a rapid decrease across all three zones within the first few minutes of baking, with the top losing moisture at the fastest rate. Unlike conventional or industrial solid-state microwave baking, where moisture loss follows a more gradual curve, the DM baking process results in a steep moisture loss within the first two minutes**,** indicating rapid evaporation due to intense microwave energy absorption by water molecules (Ureta et al., 2019). The top layer, which is more exposed to microwave radiation and surface heating, loses moisture at a much higher rate compared to the centre and bottom. This is evident from the sharp decline in the top moisture curve, suggesting that the outermost layer experiences quick dehydration, which can contribute to excessive drying of the top layer compared to bottom and centre (Wilson et al., 2002). The centre of the bread typically retains the highest moisture content during microwave baking. As microwaves penetrate the bread, water molecules in the interior absorb energy and generate heat directly. Since the centre of the bread is insulated by the surrounding layers, it experiences less direct exposure to evaporative forces (Pitchai et al., 2012). The bottom of the bread initially retains more moisture than the top but eventually aligns with the moisture levels of the other zones by the end of baking due to the direct contact with the bread tin while baking (Chhanwal et al., 2019). By the end of the baking process, the moisture content in all three zones stabilizes at a very low level, indicating that DM baking leads to excessive moisture loss in a short time, making it less effective at retaining moisture compared to other baking methods.

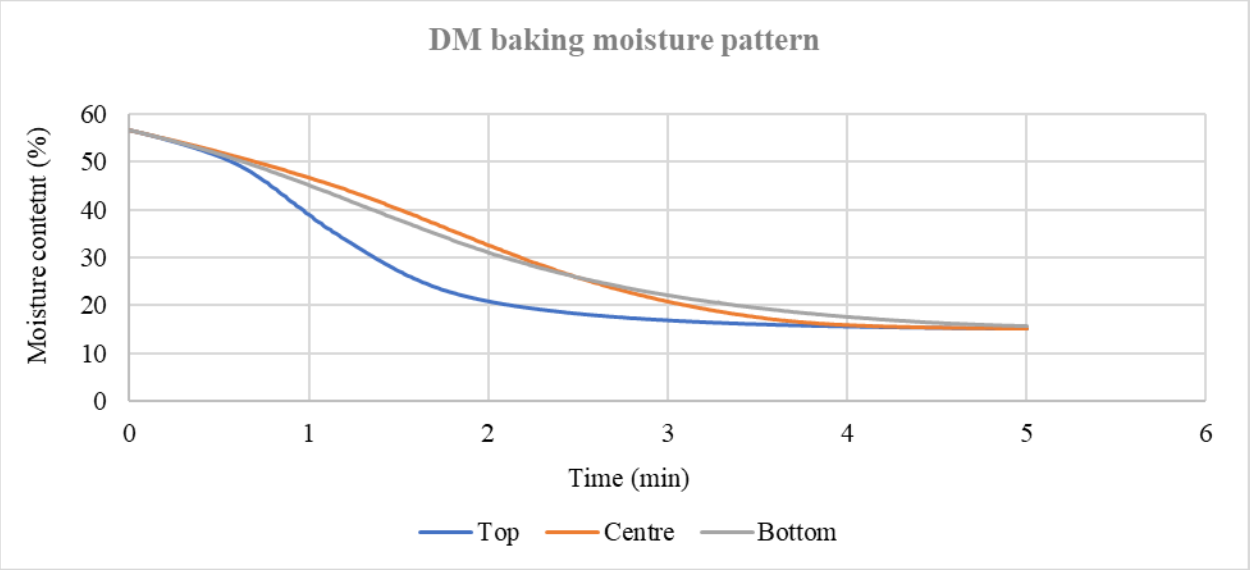


Figure 4.8 moisture change in DM bread during baking

Figure 4.9 (a and b) shows the moisture content changes in $IMCB_1$ and $IMCB_2$ over 10 and 15 minutes of baking at three different zones including the top, centre and bottom of the bread. The moisture loss pattern in IMCB1 and IMCB2 showed a rapid decline in moisture content across all three zones within the first two minutes of baking. The top and bottom layers lost moisture the fastest due to direct exposure to IM electromagnetic radiation and baking pan, which enhances surface heating and evaporation (Ureta et al., 2019). The centre experienced slightly slower but steady decline, indicating that the inner part of the bread retained more moisture compared to top and bottom. The bottom followed a similar trend to the top with slightly less moisture loss due to its direct contact with the baking pan. As mentioned before, due to the lack of research on industrial solid-state microwave in food especially in baking, it can be assumed that the uniform heating of the IM resulted in a more uniform moisture distribution compared to CB, $DMCB_1$ and $DMCB_2$. At the end of baking, $IMCB_2$ showed slightly lower moisture compared to $IMCB_1$ due to the longer baking time and longer exposure to direct heating, which resulted in lower moisture content (Chhanwal et al., 2019).

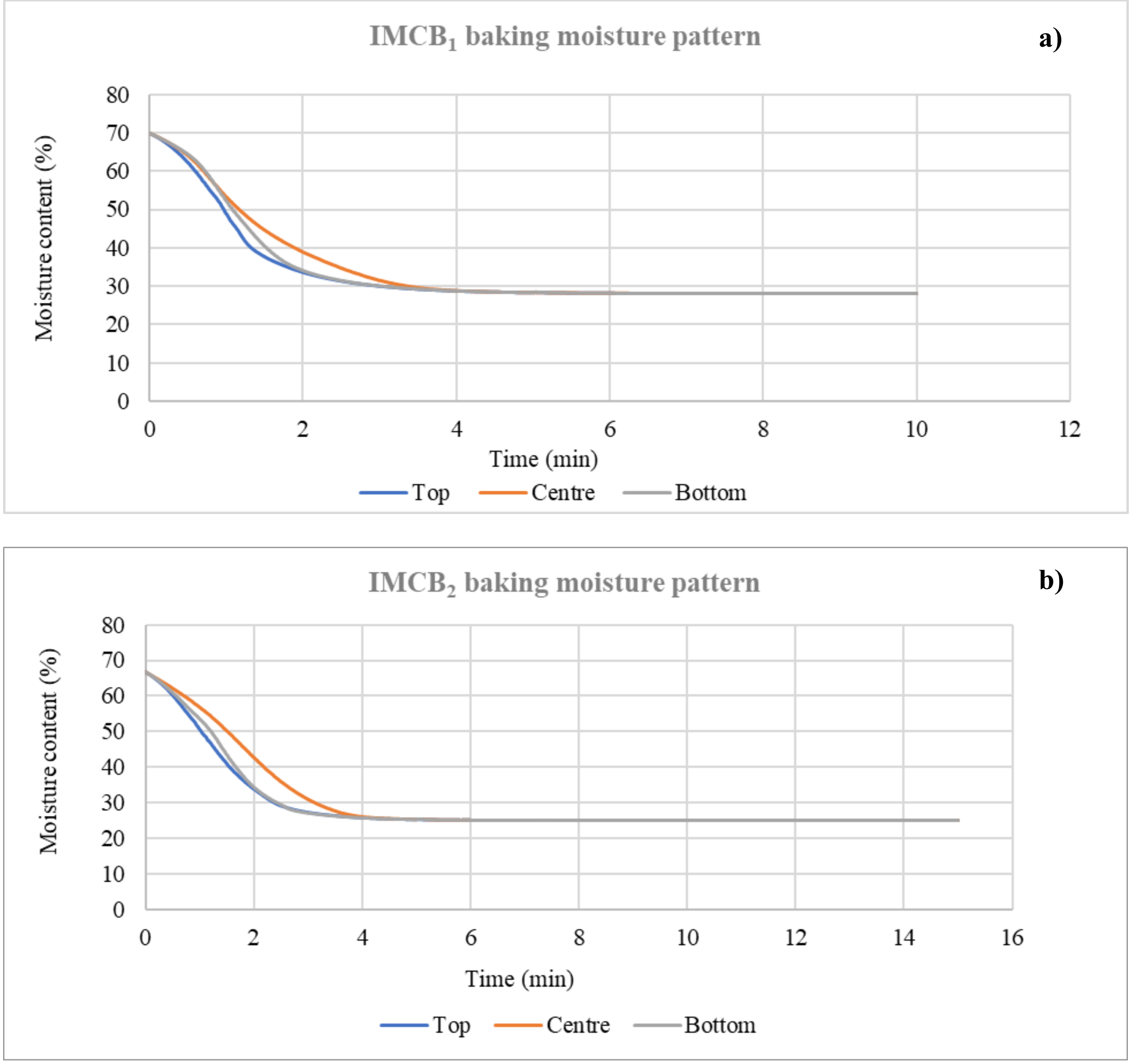
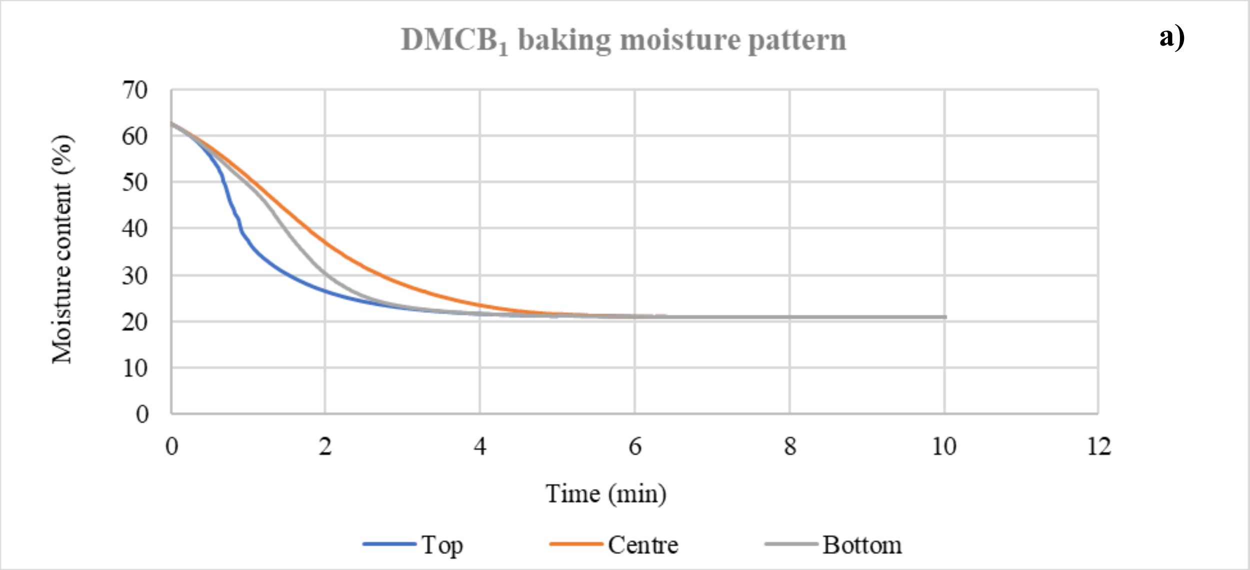


Figure 4.9 Moisture changes in a) IMCB$_1$ and b) IMCB$_2$ breads during baking

Figure 5.10 (a and b) shows the moisture content changes in DMCB$_1$ and DMCB$_2$ over 10 and 15 minutes of baking at three different zones including the top, centre and bottom of the bread. It can be seen that there was a sharp decrease in moisture in the top and bottom of the bread while centre retained more moisture during baking. The top experiences the fastest rate of moisture loss, likely due to direct exposure to microwave radiation which led to rapid surface evaporation (Ureta et al., 2019). The centre showed a slightly slower but consistent decrease in moisture, indicating that the inner part of the bread retained more water than the top and bottom layers. The bottom displayed a similar pattern to the top, though with slightly less moisture loss, likely due to its direct contact with the baking pan (Chhanwal et al., 2019).



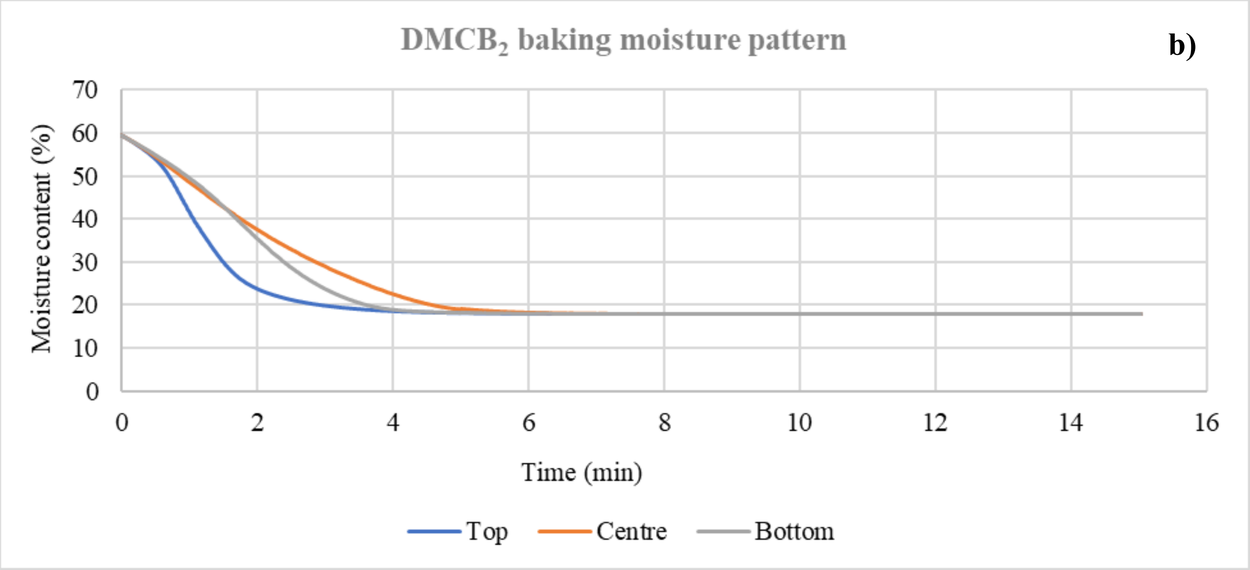


Figure 4.10 Moisture changes in a) DMCB$_1$ and b) DMCB$_2$ breads during baking

Chapter 5 Results and Discussion – sensorial properties of the breads

5.1 Moisture content

Figure 5.1 represents the moisture content of the baked breads using different baking modes at day 1, 5 and 8 after baking (Raw data is provided in appendix 4.1). A significant decrease in moisture content ($p<0.05$) was observed in all breads throughout the storage period, demonstrating a general trend of moisture loss over time. Among these samples, the IM baked breads showed the highest ($p<0.05$) level of moisture content during the 8-day storage period, while the DM baked breads showed the lowest ($p<0.05$) moisture content. In terms of hybrid baking, the $IMCB_1$ and $IMCB_2$ breads showed significantly ($p<0.05$) higher moisture content compared to the $DMCB_1$ and $DMCB_2$ baked breads over 8 days of storage. No significant differences ($p>0.05$) in moisture content between $DMCB_1$ and $DMCB_2$ were observed at day eight. These findings can be attributed to two primary factors associated with the different heating methods used during baking. Firstly, the DM function by emitting electromagnetic waves, which cause rapid excitation of water molecules, leading to an accelerated heating process; this leads to a significantly faster rate of evaporation and moisture loss compared to conventional baking (Bou-Orm et al., 2021). This rapid absorption of microwave energy results in the development of a steep temperature gradient within the bread, where the outer layers heat up much more quickly than the inner crumb; as a consequence, excessive surface drying occurs (Sumnu, 2001), reducing significantly the overall moisture content in DM baked bread samples Secondly, the vapor generation that takes place during DM baking creates high internal pressure and strong concentration gradients within the bread matrix, which further accelerates the migration of moisture from the interior toward the surface, ultimately leading to increased moisture loss during and after baking (Ozkoc et al., 2009(b)). Similar observations were reported by (Demirekler et al., 2004), who demonstrated that bread baked in a DM oven with halogen lamp exhibited a greater degree of moisture loss compared to conventionally baked bread mainly due to the effect of internal pressure created by microwave heating, which forces moisture outward at a faster rate. This explains why DM baked bread consistently exhibited the lowest moisture content throughout the storage period, as it initially started with significantly less retained moisture immediately after the baking process was completed. When comparing the moisture content of IM and CB baked breads, it is evident that IM baked bread maintained more moisture over the eight-day storage period. These results could be attributed to the fact that conventional baking relies on gradual heat transfer via convection and conduction, which enables more controlled evaporation but still leads to substantial moisture loss due to the longer exposure to the heating (Chhanwal et al., 2019). The hybrid baking methods that incorporate industrial solid-state microwave technology (IMCB$_1$ and IMCB$_2$) demonstrated lower level of moisture loss compared to CB breads but higher than IM baked breads, suggesting that the combination of conventional heating and microwave technology offers more balanced approach to moisture retention compared to conventional oven. However, the effectiveness of moisture retention in hybrid baking appears to depend on the type of microwave technology employed. According to Figure 1(a), IMCB$_1$ and IMCB$_2$ showed significantly higher moisture than DMCB$_1$ and DMCB$_2$. Although due to the lack of research on solid state microwave in baking technology, it is assumed that the higher moisture retention in IM baked breads during the 8 days period could be attributed to the uniform heating of industrial solid-state microwave, which limits additional moisture loss during the baking process (Dinani et al., 2020).

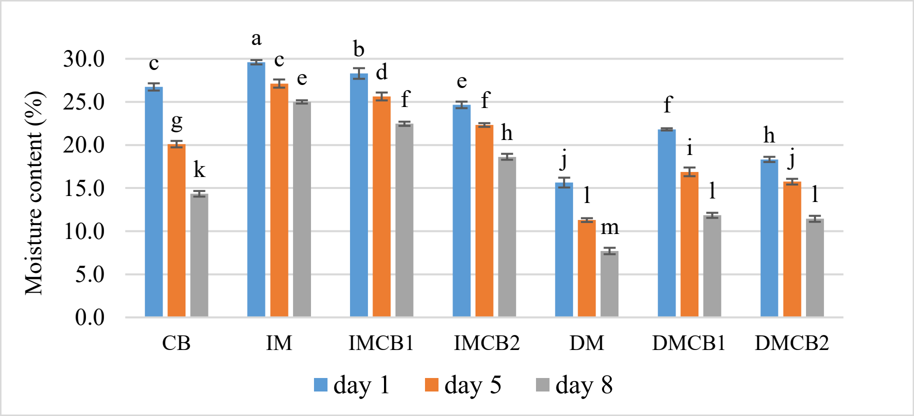


Figure 5.1 Moisture variation of breads baked using different baking modes

Note: Lowercase letters indicated the significant ($p < 0.05$) difference between different bread samples baked with different baking technologies, bread samples baked with different baking technologies including: Conventional oven (CB), Domestic microwave (DM), Industrial solid-state microwave (IM), Hybrid approach of IM for 5 min+ CB for 5 min (IMCB1), Hybrid approach of IM for 5 min + CB for 10 min (IMCB2), Hybrid approach of DM for 5 min + CB for 5 min (DMCB1), Hybrid approach of DM for 5 min + CD for 10 min (DMCB2).

5.2 Colour of baked breads

Figure 5.2 presents the colour parameters of the baked breads using different baking modes (Raw data is provided in appendix 4.2). It can be seen that the L* value, which represents lightness, was significantly higher ($p<0.05$) for breads baked using industrial solid-state microwave and domestic microwave methods compared to those baked using conventional and hybrid methods. There was no significant difference between IM and DM baked breads. Regarding hybrid baking methods, in $IMCB_1$, $IMCB_2$, $DMCB_1$, and $DMCB_2$ baked breads, the L* values were significantly ($p<0.05$) lower than DM and IM but higher than CB baked breads. The same trend was observed for a* and b* values, with DM and IM baked breads showing significantly higher ($p\leq0.05$) values among the other samples, whereas conventionally baked bread exhibited the lowest values. These results align with findings from (Icoz et al., 2004), who investigated the colour and texture of bread during oven and microwave baking and realised that as baking time and temperature increase, the lightness (L*) values decrease, leading to a darker crust. Additionally, Maillard reaction and caramelisation, are responsible for browning, occurs more intensely under higher temperatures, leading to the production of more melanoidin compounds that contribute to a darker crust colour (Dessev et al., 2020). It can be concluded that the higher L* values in both domestic and industrial solid-state microwave bread crusts can be attributed to the inability of the bread surface to reach the necessary temperatures required for the Maillard reaction to produce browning compounds (Yolacaner et al., 2017). In terms of hybrid baking, the conventional oven increases surface temperatures, facilitating the Maillard reaction that contributes to darker crust formation compared to IM and DM breads but still lighter than CB breads due to the shorter baking time in the conventional oven. Figure 4.2 showed no significant difference ($p<0.05$) in a* and b* values among the hybrid-baked bread samples, suggesting that while hybrid methods influence overall lightness, they do not significantly alter the levels of redness and yellowness components in the bread crust.

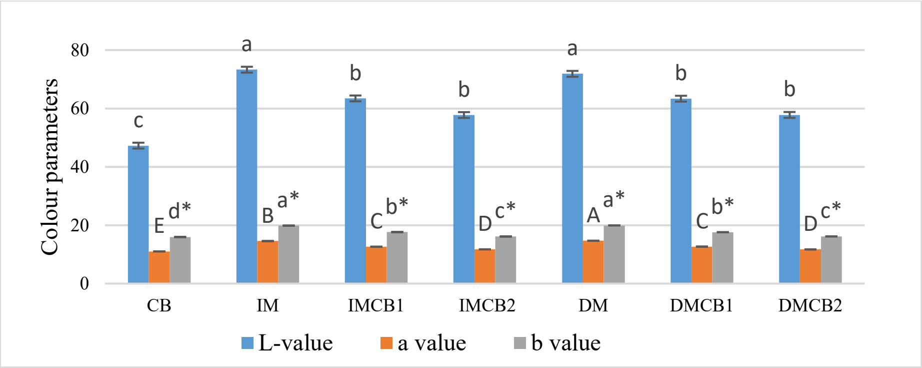


Figure 5.2 Colour values of breads baked using different baking modes

Note: Lowercase letters indicated the significant (p <0.05) difference between different bread samples baked with different baking technologies, *Capital letters indicated the significant (p <0.05) difference in a value colour parameter between different bread samples baked with different baking technologies and lowercase letters with star indicated the significant (p <0.05) difference in b value colour parameter between different bread samples baked with different baking technologies including: Conventional oven (CB), Domestic microwave (DM), Industrial solid-state microwave (IM), Hybrid approach of IM for 5 min+ CB for 5 min (IMCB1), Hybrid approach of IM for 5 min + CB for 10 min (IMCB2), Hybrid approach of DM for 5 min + CB for 5 min (DMCB1), Hybrid approach of DM for 5 min + CD for 10 min (DMCB2).*

5.3 Texture analysis

Figure 5.3 represents the hardness of the baked breads using different baking modes at day 1, 5 and 8 after baking (Raw data is provided in appendix 4.3). Results showed that IM baked breads showed significantly (*p*≤0.05) lower value of hardness during the 8 days of storage compared to the other samples. However, there is limited available studies on the solid-state microwave baking and its effect on the physicochemical properties of breads. One of the rare studies published by Dinani et al., (2020), reported that the solid-state microwaves can deliver uniform heating and modulate radiation strength. Therefore, it is assumed that it could contribute to the production of the breads with the better texture compared to DM baked breads. In contrast, the DM baked breads showed significantly (*p*≤0.05) higher hardness compared to all other samples during the 8-day storage period. According to Figure 4.4, it can be observed that moisture content had a high, linear negative correlation with the hardness with the coefficients of determination for day 1, 5 and 8 are 0.98, 0.96 and 0.97, respectively.

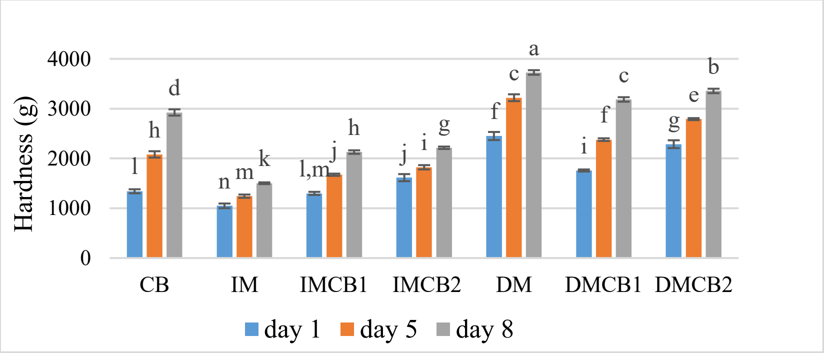


Figure 5.3 Hardness of the baked breads using different baking methods.

Note: Lowercase letters indicated the significant (p <0.05) difference between different bread samples baked with different baking technologies, bread samples baked with different baking technologies including: Conventional oven (CB), Domestic microwave (DM), Industrial solid-state microwave (IM), Hybrid approach of IM for 5 min+ CB for 5 min (IMCB1), Hybrid approach of IM for 5 min + CB for 10 min (IMCB2), Hybrid approach of DM for 5 min + CB for 5 min (DMCB1), Hybrid approach of DM for 5 min + CD for 10 min (DMCB2).

As moisture content decreases, it accelerates the starch–protein interactions and also starch-starch interactions, resulting in a firmer texture (Bou-Orm et al., 2021). The breads baked in the domestic microwave exhibited the lowest moisture content (Figure 4.1) when compared to other heating methods and consequently they showed the highest hardness values (Figure 4.3). The interaction between domestic microwave heating and gluten has been found to have a negative impact on the firmness of breads baked in this microwave (Boukid et al., 2018). Ozkoc et al., (2009(a)), found that the hardness of the domestic microwave baked bread can be affected by hydrogen bonds formed between gelatinized starch and the gluten network, facilitated by amylose molecules leached during baking. As a result, hydrogen bonds can form between retrograded starch molecules and the gluten network which lead to the harder texture of the bread. Also, the higher heating rate of domestic microwaves may also result in an increase in the amount of moisture loss and consequently speed up the interactions between proteins and starches, as well as starches and starches, leading to a firmer texture (Bou-Orm et al., 2021). A similar conclusion was reached by Icoz et al. (2004) who investigated the effect of microwave and conventional oven on bread firmness. They found that the rate of hardness variation in breads baked in microwave oven were higher than those baked in conventional oven. Similar findings were reported by Konak et al.,

(2017) who investigated the effect of microwave, conventional oven and combination of both methods on sensory and quality properties of baked cake and found that cakes baked with microwave showed the highest hardness while the combination of oven and microwave baking reduced the baking time and hardness of baked cake. The CB breads showed significantly ($p \leq 0.05$) higher hardness compared to IM baked breads probably due to the non-uniform heating of conventional oven. It is evident that using IM has significant potential to reduce the hardness of breads that could be applied to the baking process to decrease baking time and improve overall efficiency. In contrast, CB breads showed significantly ($p \leq 0.05$) lower hardness in comparison to DM baked breads due to the lower moisture loss occurring during conventional baking (Icoz et al., 2004). In terms of the hybrid baking using domestic microwave, DMCB1 and DMCB2, bread samples showed significantly ($p \leq 0.05$) lower hardness compared to DM baked breads indicating that the combination of domestic microwave and conventional oven baking partially resolved the quick staling problem of domestic microwave baking. On the other hand, $IMCB_1$ and $IMCB_2$ remained softer than control samples during the 8 days of storage due to the potential capability of IM to decrease hardness and also reduce the baking time with conventional oven.

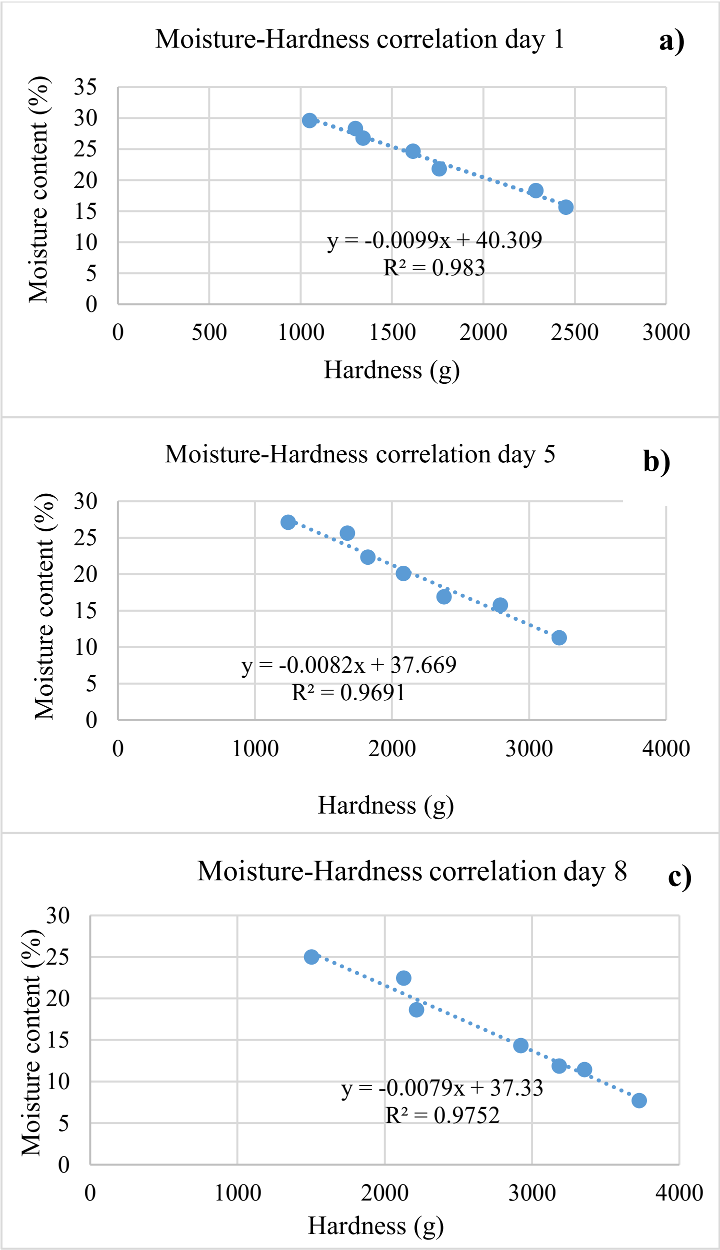


Figure 5.4 Correlation between hardness and moisture content of breads on day 1, 5 and 8 of storage

5.4 Bread volume, specific volume, and length

Table 5.1 presents the bread volume, specific volume and length of the baked breads using different baking modes (Raw data is provided in appendix 4.4). The results indicated that there were no significant differences between volume and length of all baked breads, however there were significant ($p \leq 0.05$) differences detected between the specific volume as a result of different weight of the breads. The CB baked breads showed significantly ($p < 0.05$) higher specific volume in comparison to other samples including both domestic and industrial microwave heating and all hybrid baked breads that exhibited a significantly ($p < 0.05$) lower specific volume. There were no significant differences between both microwave-baked breads and hybrid-baked breads. Achieving optimal bread specific volume and gas retention necessitates a sufficient crumb temperature, typically around 220°C and adequate time for the occurrence of complex reactions involved in the modification of the starch-gluten matrix and the development of the bread structure (Keskin et al., 2004). A conventional oven provides enough time and temperature to generate gas inside the breads resulting in a higher specific volume (Sumnu et al., 2007). As both domestic and industrial solid-state microwave baking fail to provide the required temperature compared to conventional baking, the specific volume in these breads was significantly ($p \leq 0.05$) lower among all samples.

Table 5.1 Volume, specific volume and length of baked bread with different baking modes

Samples	Volume (mL)	Weight (g)	Length (mm)	Specific volume (mL/g)
CB	1177.67 ± 0.87^{a}	337 ± 0.06^{c}	220.2 ± 0.03^{a}	3.19 ± 0.04^{a}
IM	1179.33 ± 0.85^{a}	352 ± 0.07^{a}	221.3 ± 0.05^{a}	3.12 ± 0.04^{c}
IMCB$_1$	1178.00 ± 0.42^{a}	343 ± 0.03^{b}	220.2 ± 0.02^{a}	3.16 ± 0.03^{b}
IMCB$_2$	1178.00 ± 0.56^{a}	343 ± 0.05^{b}	220.7 ± 0.05^{a}	3.16 ± 0.05^{b}
DM	1180.00 ± 0.30^{a}	351 ± 0.06^{a}	221.1 ± 0.04^{a}	3.11 ± 0.06^{c}
DMCB$_1$	1179.00 ± 0.25^{a}	344 ± 0.05^{b}	221.5 ± 0.03^{a}	3.17 ± 0.04^{b}
DMCB$_2$	1179.67 ± 0.48^{a}	344 ± 0.06^{b}	221.8 ± 0.02^{a}	3.17 ± 0.02^{b}

Note: Lowercase letters indicated the significant ($p < 0.05$) difference between different bread samples baked with different baking technologies, bread samples baked with different baking technologies including: Conventional oven (CB), Domestic microwave (DM), Industrial solid-state *microwave (IM), Hybrid approach of IM for 5 min+ CB for 5 min (IMCB1), Hybrid approach of IM for 5 min + CB for 10 min (IMCB2), Hybrid approach of DM for 5 min + CB for 5 min (DMCB1), Hybrid approach of DM for 5 min + CD for 10 min (DMCB2).*

5.5 Cellular structure of the breads

Figure 5.5 and 5.6 present the cell number and average cell area of breads baked using different baking modes (Raw data is provided in Appendix 5.5). Bread baked using industrial solid-state microwave and domestic microwave showed the highest number of cells, indicating a greater degree of expansion and gas retention during baking. This is likely due to the rapid and volumetric heating in microwave systems, which allows the dough to rise quickly before the structure sets (Ozkoc et al. 2009(a)). Such heating encourages the formation of numerous small gas bubbles, resulting in a more aerated crumb. Breads baked using hybrid systems that combine conventional ovens with either industrial solid-state or domestic microwaves ($IMCB_1$, $IMCB_2$, $DMCB_1$, $DMCB_2$) also demonstrated a high number of cells, although slightly lower than those produced by microwave-only methods. This suggests that combining microwave heating with conventional heat can enhance internal structure while maintaining better control over the final texture. In contrast, bread baked in the conventional oven had the lowest cell number, indicating less internal expansion. This may be due to the slower and less uniform heat transfer in conventional ovens, which can result in moisture loss and limited gas retention, ultimately producing a denser crumb (Sumnu, 2001). A similar pattern was observed for average cell area. Breads baked using the industrial solid-state microwave and domestic microwave had the largest average cell sizes, reflecting greater internal expansion and more open crumb structures. The rapid internal heating in these methods promotes cell growth, contributing to a lighter and softer texture. The hybrid baking methods also resulted in relatively large cell areas, although slightly smaller than those produced by the microwave-only systems. This balance suggests that the hybrid approach allows for good expansion while also providing surface setting and structure through the contribution of conventional heat. Based on Figure 5.7, CB baked bread exhibited a more homogeneous cell structure, while IM and DM baked breads had larger, irregular cells and a heterogeneous appearance. These findings align with the observations made by (Sumnu, 2001) who noted that microwave baked products often exhibited larger and more irregular crumb cells compared to conventionally baked goods due to the rapid heating of microwave, which causes swift water evaporation and accelerated gas expansion within the dough, leading to a more heterogeneous crumb structure. This result also agrees with (Bou-Orm et al., 2021) who reported that the rapid heating associated with microwave baking leads to larger and more irregular crumb cells, resulting in a less uniform crumb structure compared to conventional baking methods. In contrast, conventional baking allows for gradual heat penetration, enabling controlled gas expansion and a more stable crumb structure. The slower rate of heat transfer in conventional ovens ensures that gas cells expand more evenly, leading to the formation of smaller, more uniform pores (Baik et al., 2000).

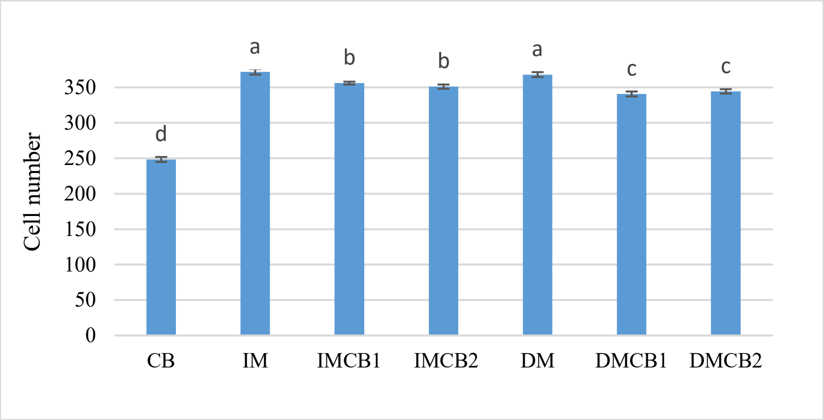


Figure 5.5 cell number of baked breads with different baking modes

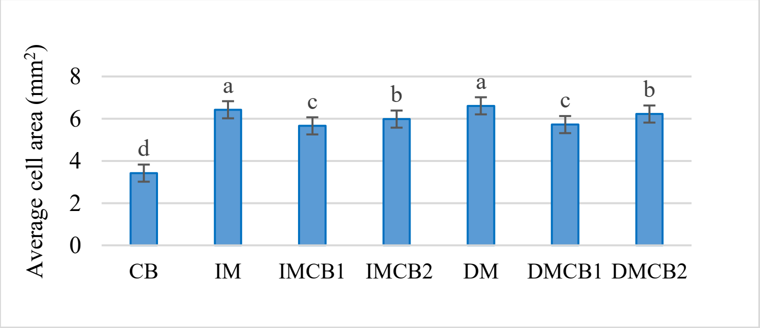


Figure 5.6 Average cell area (mm^2) of baked breads with different baking modes

*Note: Lowercase letters indicated the significant ($p < 0.05$) difference between different bread samples baked with different baking technologies**,** bread samples baked with different baking technologies including: Conventional oven (CB), Domestic microwave (DM), Industrial solid-state microwave (IM), Hybrid approach of IM for 5 min+ CB for 5 min (IMCB1), Hybrid approach of IM for 5 min + CB for 10 min (IMCB2), Hybrid approach of DM for 5 min + CB for 5 min (DMCB1), Hybrid approach of DM for 5 min + CD for 10 min (DMCB2).*

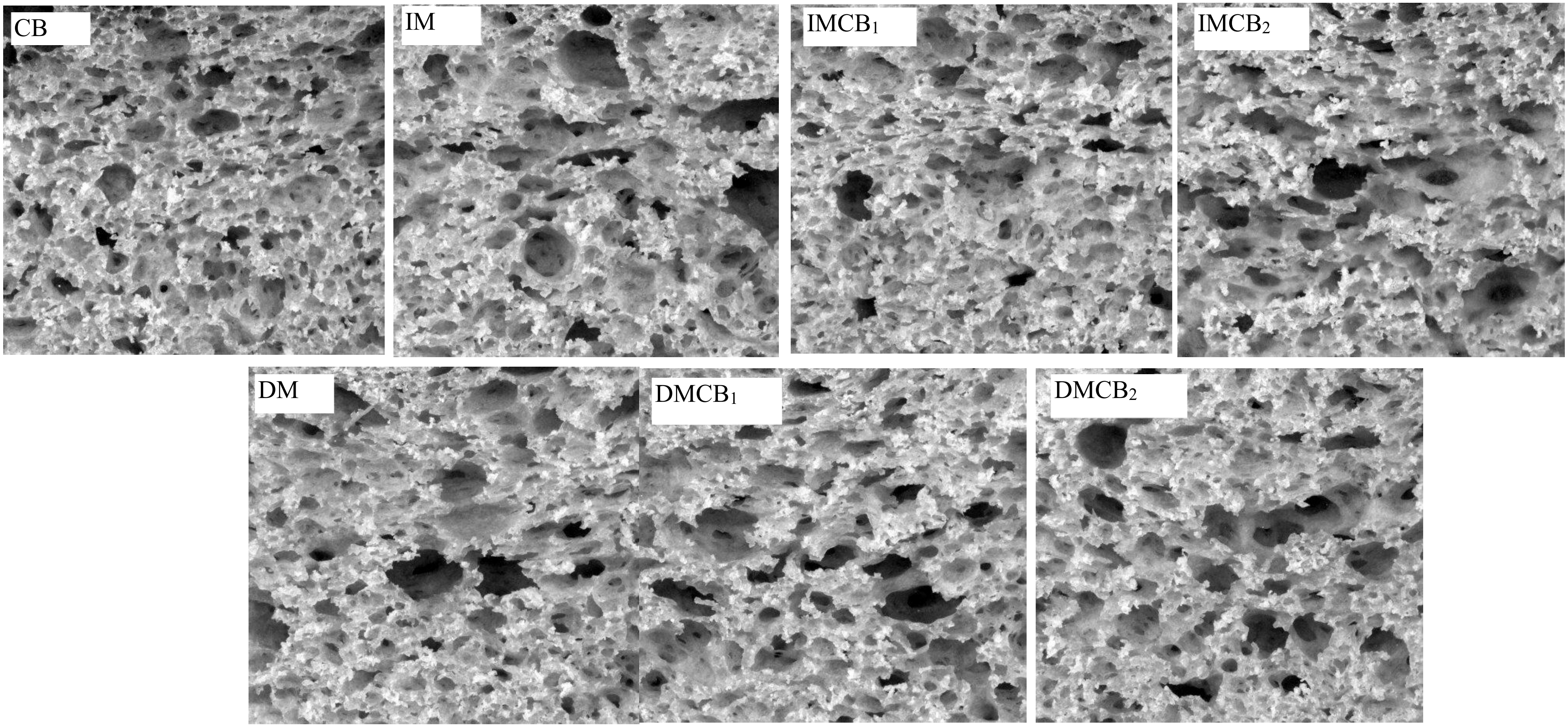


Figure 5.7 Scanned images of bread baked in different baking modes

Chapter 6 Results and Discussion – Acrylamide formation

Figure 6.1 shows the acrylamide levels detected in the breads as a result of the different baking procedures (Raw data is provided in appendix 6.1). Significant ($p < 0.05$) differences were observed as a result of using different baking technologies between all baked breads. However, no significant differences in acrylamide content were observed between IM and DM baked breads or between the hybrid baking methods $IMCB_1$ and $DMCB_1$, as well as between $IMCB_2$ and $DMCB_2$, indicating that acrylamide formation for hybrid baking remained independent regardless of the type of microwave used. However, CB baked breads exhibited significantly higher ($p < 0.05$) acrylamide content compared to those baked with both microwaves, which was particularly evident with prolonged baking time in the conventional oven. Previous studies have shown that the rise in acrylamide levels during conventional oven baking is attributed to the Maillard reaction where acrylamide forms on the outer surface of the bread which is directly exposed to heat (Michalak et al., 2017). According to the Fig.5.1, the temperature profile for CB baked breads indicates a gradual and steady rise in surface and internal temperatures, with the top and bottom surfaces reaching approximately 125–130 °C by the end of the baking period. This thermal behaviour in CB is directly linked to the high acrylamide content observed in conventionally baked bread, the highest among all baking modes. IM and DM baked breads had the lowest acrylamide due to the lower temperature and shorter baking time of microwave. According to Figure 5.2 and 5.3 the temperature distribution observed during IM and DM baking revealed a rapid heating pattern, with the top, centre and bottom reaching approximately 100–105 °C within 5 minutes. In the IM and DM temperature graph, neither the top nor the bottom surfaces exceeded the 120 °C threshold, and the heating time is very short (5 minutes total). Therefore, these conditions reduce the opportunity for browning reactions, thus limiting acrylamide formation. These findings are aligned with studies conducted by Al-Ansi et al., (2019), who investigated the impact of two different baking methods including conventional baking (190°C for 10 min) and microwave baking (700 W for 90 seconds) on acrylamide content in biscuits. Their study revealed that microwave baked biscuits exhibited a 10% reduction in acrylamide levels compared to those baked in a conventional oven, reinforcing the notion that shorter baking times in microwave processing reduce acrylamide formation. Both IMCB_1 and DMCB_1 showed similar acrylamide levels, which were significantly lower than those of the conventionally baked breads, due to their comparable baking times and temperatures (Fig. 5.4 and 5.6). IMCB_2 and DMCB_1 followed a similar pattern and exhibited higher acrylamide levels than IM, CB, and DMCB_1 and IMCB_1 due to their longer overall baking time (15 minutes). However, their acrylamide content remained significantly lower than that of the control samples. Despite these findings, several studies suggest that microwave baking may lead to higher acrylamide formation compared to conventional baking. For instance, Michalak et al., (2017) reported that acrylamide content in microwave-baked croquettes reached significantly higher levels of 420 μg/kg compared to those baked conventionally. One possible explanation for this is that the microwave generates heat by directly exciting water molecules within the food, allowing the internal temperature to rise rapidly without relying on an external heat source. Foods with low thermal conductivity may experience a rapid temperature increase under microwave radiation, leading to conditions that favour acrylamide formation, unlike conventional heating, which gradually raises temperature through conduction and convection. This accelerated heating process could create localized high-temperature regions within the food matrix, potentially promoting acrylamide formation under certain conditions (Michalak et al., 2020). Given the mixed findings in the literature, it is evident that the effects of microwave baking on acrylamide formation are complex and may depend on multiple factors, including food composition, water activity, power levels, and baking duration. Some studies suggest that microwave baking reduces acrylamide due to shorter processing and lower temperatures. This study confirms that both industrial solid-state and domestic microwaves reduce acrylamide formation more than the use of conventional ovens probably as a result of a shorter high-temperature exposure that limits the Maillard reaction.

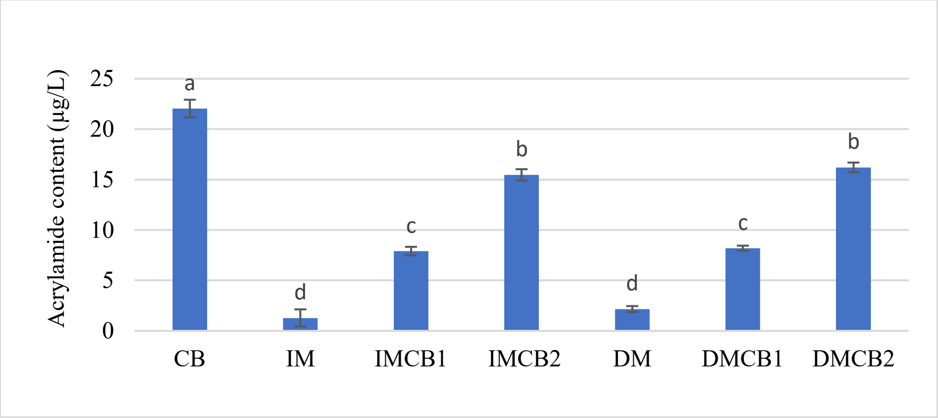


Figure 6.1 Acrylamide content of baked breads with different baking modes

Note: Lowercase letters indicated the significant difference between different bread samples baked with different baking technologies ($p <0.05$) including: Conventional oven (CB), Domestic microwave (DM), Industrial solid-state microwave (IM), Hybrid approach of IM for 5 min+ CB for 5 min ($IMCB_1$), Hybrid approach of IM for 5 min + CB for 10 min ($IMCB_2$), Hybrid approach of DM for 5 min + CB for 5 min ($DMCB_1$), Hybrid approach of DM for 5 min + CD for 10 min ($DMCB_2$).

Chapter 7 Results and Discussion – Environmental and economic impact of different baking modes

Table 7.1 presents the total energy consumption and environmental and economic effects of different baking technologies (Raw data is provided in appendix 7.1). The findings indicate that breads baked in a conventional oven required a higher energy input compared to those baked using domestic microwave, industrial solid-state microwave, and hybrid methods, while breads baked in an industrial solid-state microwave exhibited the lowest energy consumption of all the samples. Also, the energy demand of the hybrid baking process was lower than that of the conventional baking process, primarily because of the reduced baking time of hybrid compared to conventional oven baking. When using a conventional oven, it must first heat the oven walls and cavity to transfer heat to the sample, which leads to a higher energy consumption when using small amounts of samples compared to a microwave. However, microwave heating produces heat within the food material itself, a process known as energy conversion. This means that the sample is heated directly, resulting in much higher efficiency compared to conventional methods, as it avoids or minimises energy losses from heating the oven walls and cavity (Bermúdez et al., 2015). Furthermore, the production of heat in the microwave oven occurs through the interaction of radiation with charged particles and polar molecules present in the food (De Pilli & Alessandrino, 2020; Kutlu et al., 2022). The conversion of energy into heat is more efficient when applied throughout the product, as microwaves have the ability to penetrate into the food rather than being limited to the surface level as a conventional oven does (Contreras et al., 2017). According to Atuonwu and Tassou (2018), microwaves can enhance energy efficiency when drying food compared to conventional methods, as long as the microwave power level is appropriately selected to suit the moisture content and properties of the food being processed, thus reducing reflections. This author also found that the solid-state microwave system is more efficient overall than the domestic microwave system, primarily because of the greatly enhanced absorption efficiency it offers. The use of industrial solid-state microwaves resulted in a correspondingly lower environmental impact than the conventional oven and domestic microwave. Furthermore, as previously mentioned, hybrid-baked breads consume less energy than conventional ovens due to the reduction in baking time, resulting in a reduction in production costs and greenhouse gas emissions. Beyond energy consumption and economic considerations, the environmental impact of different baking methods merits attention (Bermúdez et al., 2015). Conventional baking methods, characterised by their higher energy demand, contribute to increased greenhouse gas emissions and environmental degradation compared to microwave-based methods. The production of heat in conventional ovens involves burning fossil fuels or using electricity generated from non-renewable sources, resulting in carbon dioxide emissions and other pollutants. In contrast, microwave baking processes, particularly those utilizing industrial solid-state microwaves, offer a more environmentally friendly alternative because of their lower energy consumption and reduced reliance on fossil fuels. Furthermore, the reduction in baking time associated with microwave-based methods translates into additional environmental benefits. Shorter baking durations mean lower overall energy consumption and a reduced carbon footprint per batch of bread produced (De Pilli & Alessandrino, 2020). This is particularly significant in large-scale baking operations, where the cumulative environmental impact of energy-intensive processes can be substantial. By adopting microwave technology, bakeries and food manufacturers can contribute to mitigating climate change and promoting sustainability in the food industry. Another aspect worth considering is the potential for technological advancements and innovation in microwave baking to further enhance efficiency and sustainability. Research and development efforts focused on optimising microwave systems, improving heat distribution, and maximising energy conversion rates have the potential to drive significant improvements in the environmental performance of baking processes. For example, advancements in solid-state microwave technology may lead to even greater energy savings and reduced environmental impact compared to conventional microwave systems (Contreras et al., 2017). Additionally, the adoption of microwave baking methods can have broader implications for resource conservation and food security. By reducing energy consumption and production costs, microwave technology makes it more economically viable to produce baked goods, thereby increasing accessibility and affordability for consumers (El-Adly et al., 2015). This can be particularly beneficial in regions where access to traditional baking facilities or reliable energy sources is limited. Moreover, the efficiency of microwave baking processes can contribute to reducing food waste and improving food preservation. Rapid and uniform heating provided by microwaves can help extend the shelf life of baked goods, minimizing spoilage and the need for preservatives. This not only reduces food waste but also enhances food safety and quality, ultimately benefiting both producers and consumers (Cappelli et al., 2021). Regarding the relationship between energy consumption (Table 7.1) and temperature distribution for CB baked bread (Fig.5.1), the conventional oven relies primarily on convection and conduction, which require heating the entire oven cavity including the walls, air, and baking tray before any significant heat is transferred to the bread (Bermúdez et al., 2015). As a result, there is a delayed rise in centre temperature, while the top and bottom surfaces gradually reach around 125–130 °C over a prolonged baking time. Additionally, longer baking durations are required to achieve the desired product quality, which further increases the total energy input (Khatir et al., 2013). The conventional oven consumes greater amounts of thermal energy to maintain consistent temperatures over time, leading to substantial energy losses through the oven walls and door (Le-bail et al., 2010). This is supported by the temperature profile (Fig.5.1), which exhibits slow and prolonged heating, directly correlating with increased energy usage. Therefore, the combination of inefficient heat transfer mechanisms, the need for preheating, and extended baking times collectively accounts for the high energy consumption observed in conventional baking (El-Adly et al., 2015). The industrial microwave baking method recorded an energy consumption of only 0.035 kWh, which is substantially lower than the 0.453 kWh required by the conventional oven. Based on Fig.5.2, this sharp contrast is consistent with the temperature distribution observed in IM baking, where all regions of the bread including the top, bottom, and centre, reached lower baking temperatures (around 100–105 °C) rapidly and uniformly within a few minutes. Due to the lack of literature on solid state microwave, it can be assumed that unlike conventional baking, industrial microwave heating delivers energy directly to the water molecules and other dipoles within the dough through dielectric heating, enabling volumetric and highly efficient heat transfer (Bou-Orm et al., 2021). Because energy is absorbed directly by the product rather than heating the oven environment or surfaces, there is minimal thermal loss. The fast and even heating reduces the total time required to achieve sufficient baking, significantly decreasing energy consumption. Furthermore, solid-state microwave generators used in industrial systems offer enhanced frequency control and uniform electromagnetic field distribution, which improves absorption efficiency (Atuonwu & Tassou, 2018). The temperature profile confirms that effective baking can be achieved without exceeding 110 °C or relying on prolonged heating, making IM a highly energy-efficient alternative to conventional methods. The domestic microwave baking process consumed 0.261 kWh of energy, placing it between the industrial microwave (0.035 kWh) and conventional oven (0.453 kWh) in terms of efficiency. This intermediate energy demand corresponds well with the temperature distribution profile previously observed in DM baking in Fig.5.3. The heating pattern in DM showed a rapid but non-uniform temperature rise, where the surface (especially the top) reached just above 100 °C quickly, while the centre and bottom remained comparatively cooler, stabilizing below 90 °C. Domestic microwaves rely on magnetron technology, which delivers microwave energy in bursts and is often less controlled than solid-state systems used in industrial applications (Kalla & Devaraju, 2017). As a result, non-uniform heating and power cycling reduce efficiency and can lead to local overheating or undercooking. Despite achieving shorter baking times than conventional methods, the lower absorption efficiency, less uniform energy distribution, and higher moisture retention (which demands more energy for water excitation and phase change) contribute to the relatively higher energy use compared to industrial systems (Su et al., 2022). Moreover, unlike the industrial microwave, domestic units do not allow for precise frequency tuning or field shaping, which increases reflected energy and reduces conversion efficiency (Atuonwu & Tassou, 2018). This inefficiency is compounded by potential multiple heating cycles required to achieve consistent doneness, particularly in a complex matrix like bread dough. Therefore, the 0.261 kWh energy consumption in DM baking reflects a balance between faster cooking compared to conventional ovens and lower efficiency compared to industrial microwave systems. The temperature profile highlights these limitations, with inconsistent heating requiring more energy input than expected for what appears to be a short baking process. The $IMCB_1$ baking method, which combines 5 minutes of industrial microwave heating with 5 minutes of conventional oven baking, recorded an energy consumption of 0.118 kWh, which is considerably lower than that of conventional baking and also lower than domestic microwave baking, yet higher than industrial microwave alone. This intermediate level of energy use reflects the hybrid nature of the process, benefiting from the efficiency of microwave heating while still requiring some conventional energy input (Khatir et al., 2013). According to Fig.6.4, the corresponding temperature distribution profile shows a rapid initial temperature increase across all zones during the microwave phase, with the top, bottom, and centre reaching approximately 100–105 °C. The following conventional phase then gradually elevates the surface temperatures, particularly at the top and bottom, while maintaining a relatively uniform thermal gradient. The inclusion of a industrial microwave phase allows the bread to reach baking temperatures faster and more uniformly, reducing the amount of time and energy the conventional oven needs to supply (Atuonwu & Tassou, 2018). As a result, the total process time is halved compared to standard conventional baking, and the system avoids the preheating and thermal losses typically associated with prolonged oven use. Therefore, the 0.118 kWh consumption for $IMCB_1$ demonstrates how hybrid methods can offer a balanced solution, significantly reducing energy costs compared to traditional methods while preserving baking performance and food safety. The $IMCB_2$ baking method, consisting of 5 minutes of industrial microwave baking followed by 10 minutes of conventional oven baking, consumed 0.148 kWh of energy. This energy usage is still substantially lower than conventional oven baking alone but slightly higher than the $IMCB_1$ method, reflecting the extended time spent in the energy-intensive conventional oven. According to Fig.5.4, the temperature distribution graph for $IMCB_2$ illustrates an efficient and rapid heating of the bread during the microwave stage, where internal and surface temperatures quickly approach 95–105 °C across all zones. Compared to $IMCB_1$, the increased duration of conventional heating in $IMCB_2$ increased energy consumption showing that even modest extensions (5 extra minutes) in oven baking duration can contribute to noticeable increases in overall consumption due to the inherent inefficiency of convection-based heating and the need to maintain the oven at a high temperature for longer periods (El-Adly et al., 2015). The $DMCB_1$ hybrid method recorded an energy consumption of 0.231 kWh, which is lower than that of conventional baking but slightly below domestic microwave alone. This reduction can be attributed to the shorter total baking duration and synergistic use of the microwave and conventional oven stages. According to Fig.5.5, $DMCB_1$ exhibited a quick temperature rise at the top and centre due to the initial domestic microwave phase. However, compared to industrial microwave systems, domestic units generate less uniform heating, and temperature penetration is limited (Pitchai et al., 2012). During the following 5-

minute conventional oven phase, the surface temperatures continue to rise gradually but do not exceed 115 °C, while the centre remains relatively cooler. From an energy point of view, the microwave stage contributes efficient volumetric heating, pre-warming the product and reducing the load on the conventional oven (Masanet, 2013). Overall, the 0.231 kWh energy usage in DMCB$_1$ demonstrates an effective compromise between speed and efficiency. The method benefits from the microwave's rapid internal heating while limiting the energy-intensive conventional baking stage to just 5 minutes. The DMCB$_2$ method, involving a 5-minute domestic microwave phase followed by 10 minutes of conventional oven baking, results in an energy consumption of 0.344 kWh. This value is significantly lower than that of conventional oven baking, but notably higher than other hybrid methods such as DMCB$_1$ and IMCB$_2$. Based on Fig.5.5, the corresponding temperature distribution shows that the initial microwave phase leads to a rapid increase in temperature at the surface, though heating remains non-uniform due to the nature of domestic microwave heating (Bou-Orm et al., 2021). This is followed by a prolonged conventional oven phase, during which the surface temperatures (top and bottom) rise steadily to just below 120 °C, while the centre remains cooler. This extended oven exposure increased the thermal load significantly, as conventional ovens require time and energy to maintain and distribute heat, especially to achieve crust formation and moisture loss (Khatir et al., 2013).

Table 7.1 Energy consumption, cost and carbon emission of baked bread

Samples	Energy consumption (kWh)	Total cost (£)	GHG emission (Kg of CO2)
CB	0.453^{a}	0.1532^{a}	0.086^{a}
IM	0.035^{g}	0.0054^{g}	0.006^{g}
IMCB1	0.118^{f}	0.0401^{f}	0.022^{f}
IMCB2	0.148^{e}	0.0503^{e}	0.028^{e}
DM	0.261^{c}	0.0887^{c}	0.049^{c}
DMCB1	0.231^{d}	0.0785^{d}	0.044^{d}
DMCB2	0.344^{b}	0.1169^{b}	0.065^{b}

Note: Lowercase letters indicated the significant difference between different bread samples baked with different baking technologies ($p < 0.05$) including: Conventional oven (CB), Domestic microwave (DM), Industrial solid-state microwave (IM), Hybrid approach of IM for 5 min+ CB for 5 min (IMCB$_1$), Hybrid approach of IM for 5 min + CB for 10 min (IMCB$_2$), Hybrid approach of DM for 5 min + CB for 5 min (DMCB$_1$), Hybrid approach of DM for 5 min + CD for 10 min (DMCB$_2$).

Chapter 8 Results and Discussion – Optimization of bread quality and environmental responses

8.1 Statistical performance of the model

Table 8.1 summarizes the ANOVA results for the linear regression models developed to describe the influence of different baking modes on the main bread quality parameters (optimization process is provided step by step in appendix 8.1). For most bread quality parameters, including moisture content, hardness, cell number, acrylamide concentration, and greenhouse gas (GHG) emissions, the models exhibited extremely high F-values ($F > 50$), very low P-values (<0.0001), and R^2 values above 0.90. These results demonstrate that the linear models provide a highly reliable and statistically robust description of how these responses vary across different baking modes. The close agreement between R^2 and adjusted R^2 values confirms that both models have predictive capability. In contrast, the model for loaf volume exhibited a low F-value (0.51), high P-value (0.72) and very low R^2 (0.27), indicating that loaf volume did not vary significantly with the baking modes tested and is therefore not adequately explained by the model. This is probably as a result of a non-significant difference between loaf volume range across all baked breads in contrast to the other quality parameters which exhibited a clear variation among the baking modes. Loaf volume may be naturally less sensitive to microwave or hybrid heating conditions, or its variation may be dominated by other factors like fermentation activity that are not part of the experimental design. In summary, the statistical evaluation confirms that the linear modelling approach is suitable and reliable for most bread quality attributes, with loaf volume representing the sole parameter not significantly influenced by the baking method.

Table 8.1 Summary of linear model performance for bread quality responses

Parameters	Model	P-value	F-value	Adjusted R^2	R^2
Moisture content (%)	Quadratic	<0.0001*	387	0.99	0.99
Hardness (N)	Quadratic	<0.0001*	184.51	0.98	0.99
Loaf volume (%)	Quadratic	0.72	0.51	0.10	0.27
Cell number	Quadratic	<0.0001*	97.83	0.97	0.96
L-value (%)	Quadratic	<0.0001*	13.90	0.72	0.77
Acrylamide (µg/Kg)	Quadratic	<0.0001*	1172.93	0.99	0.99
GHG (%)	Quadratic	<0.0001*	275.38	0.98	0.98

* Model is significant (P-values less than 0.05 are significant)

8.2 Optimization of the baking parameters

Table 8.2 presents the optimization results produced through Response Surface Methodology (RSM), which identifies the most favourable combinations of conventional baking, industrial microwave, and domestic microwave, to maximise the overall desirability and minimise environmental impact. The predicted solutions consist of 30 combinations ranked by their overall desirability scores, which integrate multiple quality and sustainability parameters. The highest desirability scores (0.860–0.865) were obtained for baking configurations involving a very short CB time (0.20–0.30 min) combined with an IM time (around 4.9–5.0 min) with no contribution from DM baking. This combination produced breads with high moisture content (29%), minimal hardness (1000–1450 N) low acrylamide formation (<2 µg/kg) and desirable brown crust colour (55–59%) while also achieving low GHG emissions (0.06 kg CO_2). These results demonstrate that industrial microwave baking provides efficient and uniform internal heating while minimally promoting surface over-processing or undesirable chemical reactions. As CB time increases beyond 2 minutes or when DM time was introduced, a decline in desirability values (below 0.80) was observed, corresponding to reductions in overall bread quality including hardness and acrylamide levels, and decreased cell uniformity. DM involvement, in particular, contributed to excessive moisture loss and non-uniform heating, corroborating earlier findings on its limitations for high-quality baking. Similarly, solutions involving long CB times (>5 min) and high DM contributions (Solutions 20–30) exhibited substantial reduction in moisture content and L-value, alongside increased acrylamide level (up to 22 µg/kg) and GHG emissions, resulting in the lowest desirability scores (0.32–0.55) reflecting the performance of both quality and sustainability metrics. Overall, the RSM strongly indicates that IM baking alone or IM baking with minimal CB baking represents the most sustainable and high performing baking configuration. This hybrid baking improves product quality, particularly moisture retention, texture, and crust appearance while lowering environmental impact and reducing processing costs. Conversely, extended conventional heating or excessive use of domestic microwave baking adversely affects both product attributes and sustainability outcomes.

Table 8.2 The RSM optimization of baking conditions

Number	CB time (min)	IM time (min)	DM time (min)	Moisture (%)	Hardness (N)	Volume (ml)	Cell number	L value (%)	Acrylamide (μg/Kg)	GHG (kg CO₂)	Desirability	
1	**0.260**	**4.903**	**0.000**	**29.000**	**1307.230**	**1190.289**	**272**	**55.934**	**1.880**	**0.009**	**0.865**	**Selected**
2	0.246	4.924	0.000	29.000	1240.279	1189.544	273	56.873	1.880	0.008	0.860	
3	0.236	4.939	0.000	29.000	1198.360	1189.076	274	57.450	1.880	0.008	0.855	
4	0.206	4.982	0.000	29.000	1092.171	1187.880	276	58.864	1.884	0.007	0.852	
5	0.251	4.960	0.000	28.886	1141.385	1188.287	275	58.376	1.921	0.008	0.849	
6	0.288	4.867	0.000	28.959	1443.498	1191.750	270	54.034	1.889	0.010	0.848	
7	0.282	4.865	0.000	29.000	1456.159	1191.939	270	53.784	1.880	0.010	0.848	
8	0.444	5.022	0.000	29.000	1039.971	1186.856	276	59.352	2.262	0.007	0.847	
9	0.789	5.007	0.000	28.780	1091.357	1186.700	275	58.850	2.726	0.008	0.847	
10	0.682	5.066	0.000	29.000	1000.263	1185.959	276	59.599	2.651	0.008	0.846	
11	0.182	5.029	0.000	28.806	1000.001	1186.639	278	60.297	1.899	0.006	0.846	
12	0.000	4.678	0.487	29.000	1188.616	1188.382	277	57.475	1.884	0.008	0.844	
13	0.000	4.626	0.593	29.000	1333.714	1189.733	276	55.002	1.985	0.009	0.843	
14	1.481	5.148	0.000	28.485	1000.000	1184.058	276	59.463	3.872	0.009	0.821	
15	2.645	4.789	0.000	28.892	1517.846	1188.702	262	53.343	5.066	0.017	0.801	
16	2.547	5.286	0.000	28.568	1000.002	1182.101	274	58.074	5.552	0.012	0.800	
17	0.426	5.038	0.000	27.177	1003.692	1184.802	279	62.363	2.230	0.006	0.798	
18	3.167	5.349	0.000	29.000	1000.002	1181.307	273	56.940	6.509	0.013	0.795	
19	3.973	5.045	0.000	28.998	1210.035	1182.922	264	55.770	7.232	0.018	0.789	

20	2.110	0.000	5.531	29.000	1207.715	1181.984	270	66.815	5.508	0.033	0.724
21	3.191	5.840	0.000	26.544	1008.403	1177.904	280	56.527	7.207	0.010	0.685
22	5.820	5.965	0.000	29.000	1069.403	1175.716	272	51.516	11.075	0.018	0.681
23	6.342	5.781	0.000	29.000	1126.720	1175.962	267	51.832	11.550	0.021	0.679
24	8.977	0.000	3.759	27.807	999.999	1179.532	328	69.160	12.545	0.054	0.607
25	11.242	0.000	3.542	28.407	1000.006	1178.508	318	66.779	15.412	0.061	0.553
26	4.026	0.000	7.557	29.000	1526.686	1177.290	380	49.782	11.171	0.042	0.542
27	12.029	0.000	5.087	29.000	1394.047	1176.313	327	53.463	18.795	0.065	0.463
28	15.457	0.000	2.243	29.000	1000.728	1178.501	389	67.927	19.438	0.074	0.423
29	15.692	2.584	0.000	29.000	2086.354	1181.141	391	55.302	20.214	0.065	0.371
30	15.969	3.888	0.000	29.000	1167.902	1168.924	315	58.506	22.321	0.056	0.327

The relationship between the selected baking parameters and each response for the sample with the highest desirability is presented in Table 8.2 (first row). These plots were generated based on the optimization criteria established for each response.

Figure 8.1 presents the 3D surface plot illustrating the combined effects of CB and IM baking on the predicted moisture content of the optimised bread sample. Under the optimised conditions identified, the predicted moisture content is 29%, which is considerably higher than other samples, indicating a softer texture. In this plot, the vertical axis shows the predicted moisture content, while the horizontal axes show baking time for both IM and CB. The colour gradient, ranging from blue (low moisture) to red (high moisture), represents the variation in moisture retention across different baking times combinations. The surface indicates that shorter CB times combined with longer IM times result in the highest moisture content (red region), whereas longer CB times and shorter IM times correspond to lower moisture levels (blue region). This pattern indicates that conventional baking, which involves prolonged dry heat exposure, tends to cause greater moisture loss, while the industrial solid-state microwave baking helps retain internal moisture due to volumetric heating and shorter exposure duration. The transition from blue to red across the surface suggests a strong interaction between the two factors, where increasing IM time can compensate for moisture loss caused by longer CB exposure.

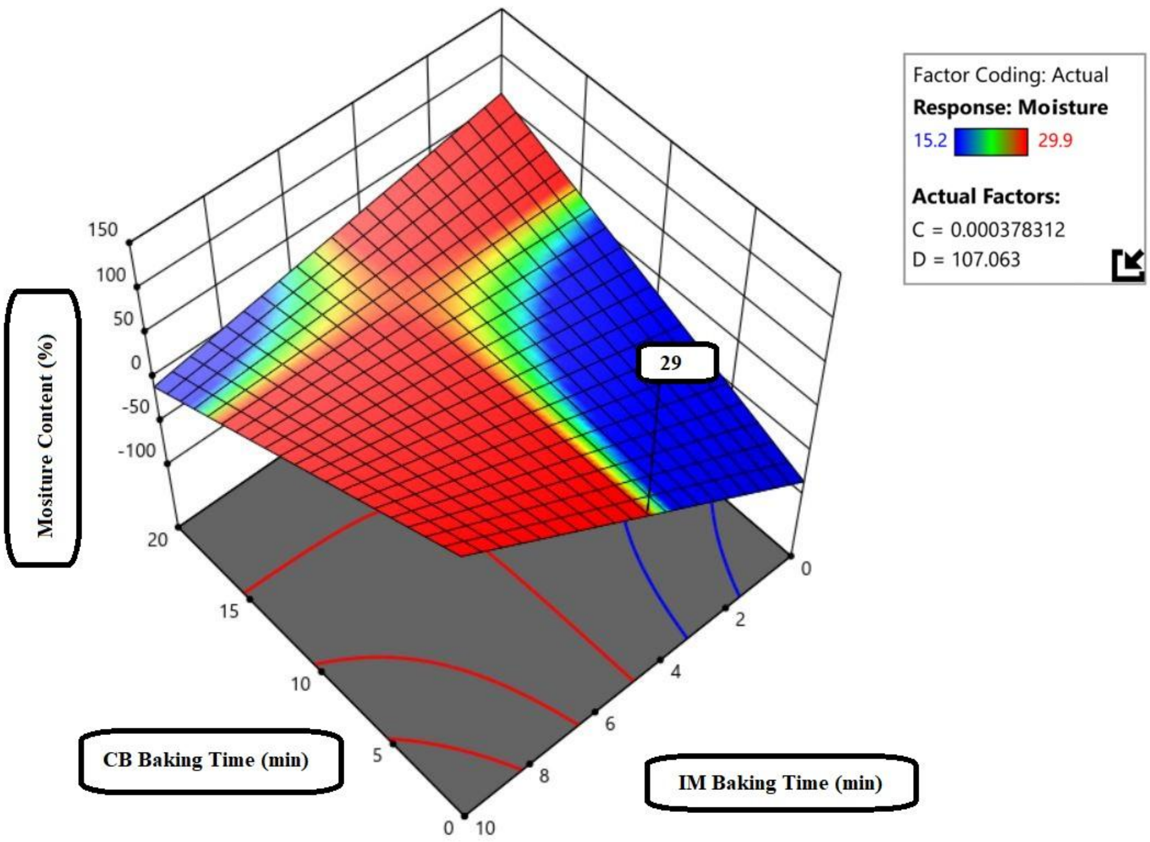


Figure 8. 3D surface plot illustrating the combined effect of conventional baking and industrial microwave baking on the moisture content of bread as predicted by the RSM model in Design Expert

Figure 8.2 presents the 3D surface plot illustrating the combined effects of CB and IM baking on the predicted hardness of the optimised bread sample. The hardness is predicted to be 1307 N showing that the bread retains a good level of internal moisture, which helps maintain softness and freshness. The vertical axis shows the predicted hardness, while the horizontal axes show CB and IM baking time. The colour gradient ranges from blue (low hardness) to red (high hardness), showing how the bread's texture changes under different baking conditions.

As shown in Figure 8.2, the bread's hardness increases with longer CB time and shorter IM time. This occurs because extended conventional baking subjects the bread to dry heat for a longer duration, leading to greater moisture loss and a firmer texture. In contrast, shorter CB times and longer IM times produce softer bread, as solid-state microwave baking helps retain more internal moisture due to its volumetric and uniform heating. The central green–yellow region represents intermediate hardness, suggesting a balance between both baking methods.

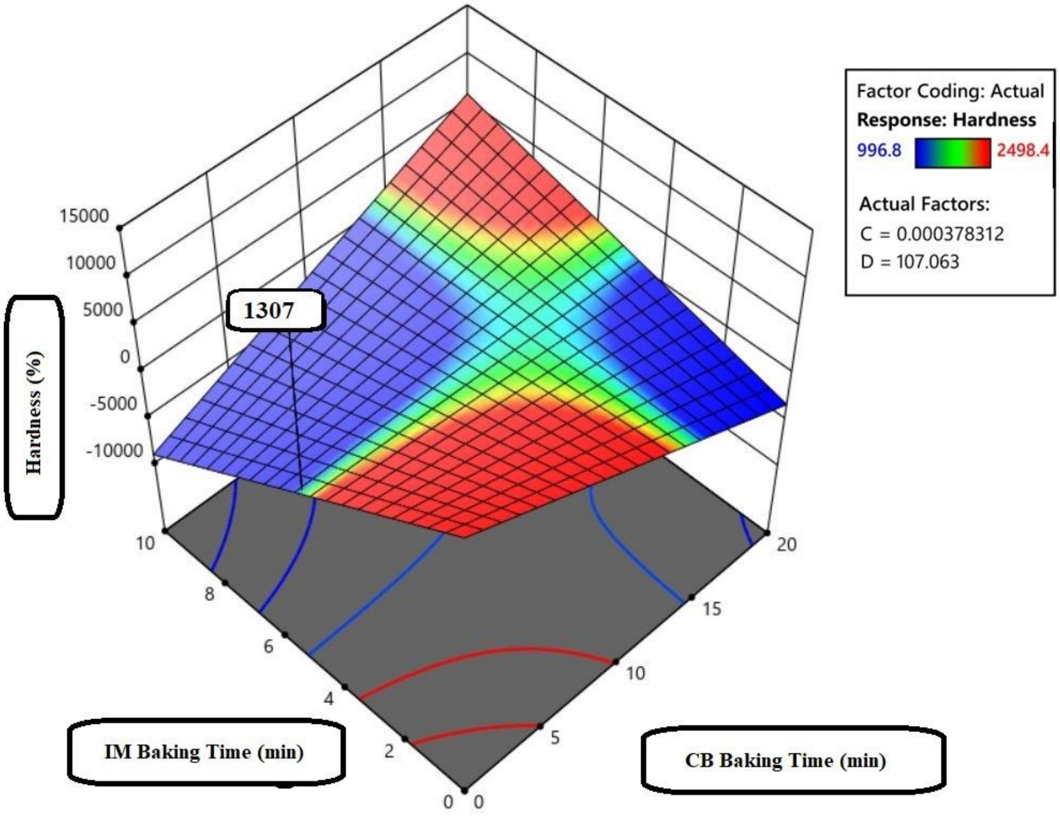


Figure 8 3D surface plot illustrating he combined effect of conventional baking and industrial microwave baking time on the moisture content of bread as predicted by the RSM model in Design Expert

Figure 8.3 presents the 3D surface plot illustrating the combined effects of CB and IM baking on the predicted loaf volume of the optimised bread sample. The predicted bread volume was approximately 1190.85 mL, indicating the overall expansion to get a good volume achieved under the selected baking conditions. In this figure, the vertical axis represents the predicted bread volume, while the horizontal axes correspond to IM and CB baking time. The colour gradient ranges from blue (lower volume) to red (higher volume), visually showing how the bread's volume changes with different baking time combinations. It can be seen that bread volume remains consistent across the tested range, with only a slight increase when IM time is higher and CB time is shorter. This suggests that the effect of both factors on bread volume is minimal. A gentle upward slope along the IM axis indicates that using more microwave heating may slightly improve loaf expansion, while longer CB times show a mild negative effect. The relatively flat surface demonstrates that neither CB nor IM time significantly affected the loaf volume, confirming that the baking time conditions used did not cause major changes in volume expansion. This finding supports the statistical results showing a low F-value and R^2 for volume in Table 8.1, suggesting that other factors have a stronger influence on bread volume than the baking mode or duration. The low F-value and the non-significant model ($p > 0.05$) indicate that baking mode had no statistically significant effect on loaf volume within the investigated range. The low R^2 value further suggests that the model explained only a small proportion of the observed variability, indicating limited predictive capability rather than confirming the absence of an effect

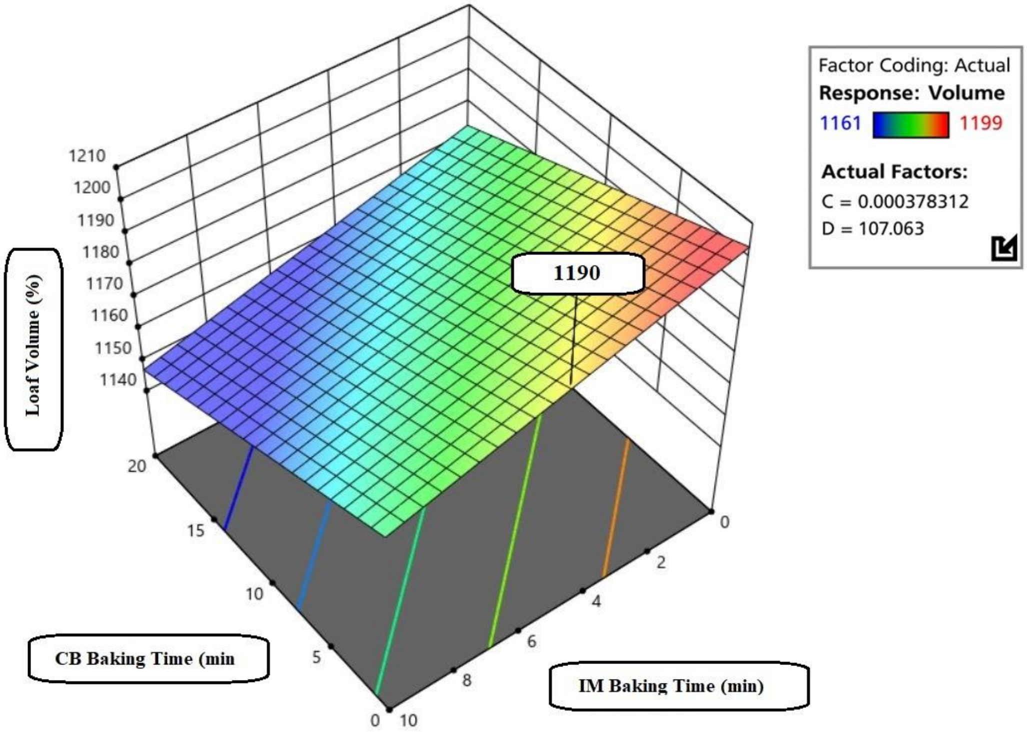


Figure 8 3D surface plot illustrating the combined effect of conventional baking and industrial microwave baking time on the loaf volume of bread as predicted by the RSM model in Design Expert

Figure 8.4 presents the 3D surface plot illustrating the combined effects of CB and IM baking on the predicted cell number of the optimised bread sample. The predicted cell number was approximately 250, representing the number of cells formed within the bread crumb structure under the selected baking conditions. In this figure, the vertical axis (z-axis) represents the predicted cell number, while the horizontal axes correspond to CB time and IM baking time. The colour gradient ranges from blue (low cell number) to red (high cell number), visually indicating the distribution of cell density across different baking conditions. The plot shows that cell number increases with longer IM time and slightly decreases with longer CB time. The red area, located toward higher IM times and lower CB times, represents the maximum predicted cell number, which corresponds to less uniform crumb porosity and lower gas retention. In contrast, the blue and green regions indicate fewer cells, typically observed at longer CB times and greater crumb uniformity. The surface pattern indicates a smooth gradient, implying that the model fits the experimental data well with no sharp irregularities. The overall response surface confirms that the conventional baking plays a more influential role in determining cell structure than industrial solid-state microwave .

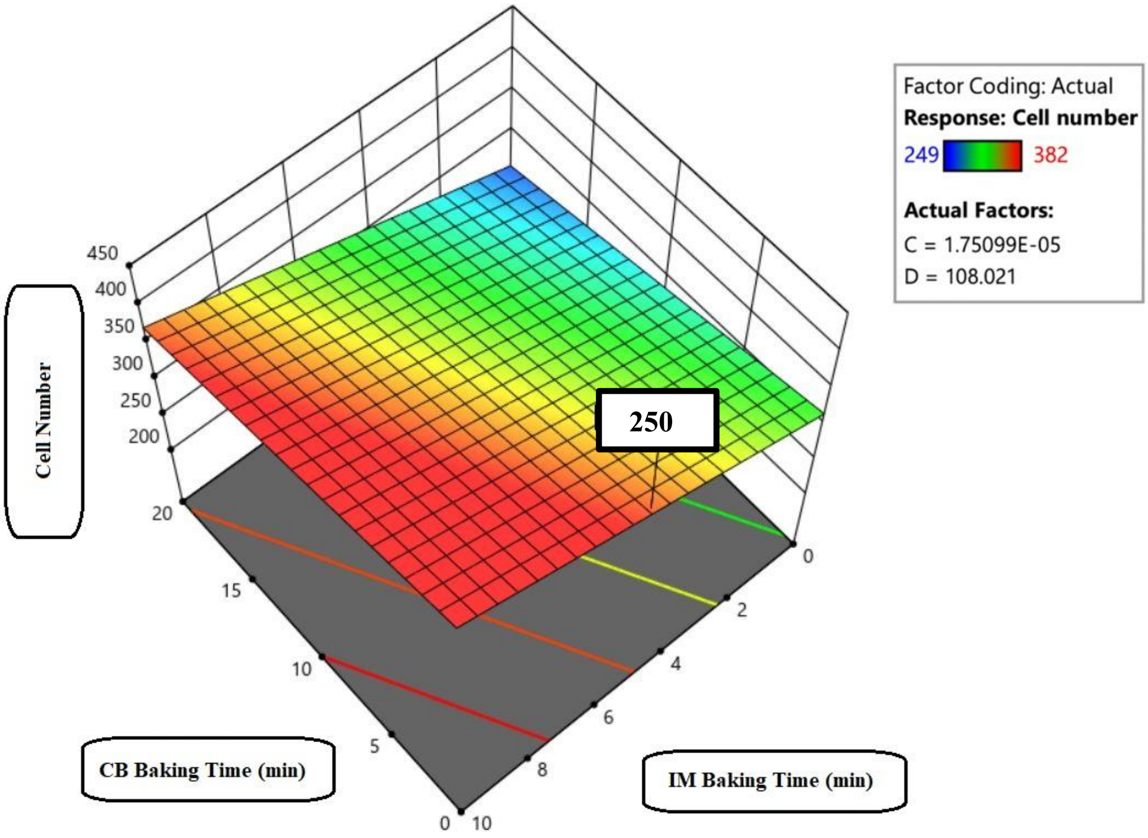


Figure 8 3D surface plot illustrating the combined effect of conventional baking and industrial solid-state microwave baking time on the cell number of bread as predicted by the RSM model in Design Expert

Figure 8.5 presents the 3D surface plot illustrating the combined effects of CB and IM baking on the predicted L-value of the optimised bread sample. In the figure, the vertical axis represents the L-value, which indicates the lightness or brightness of the bread's crust. The horizontal axes represent CB time and IM time. The colour gradient ranges from blue (low L-value, darker crust) to red (high L-value, lighter crust), visually showing how different baking times affect the bread's colour. The predicted L-value for optimum baked bread is approximately 56.07, representing the light browning of the bread crust, where higher values indicate a lighter and paler colour and lower values reflect darker browning.

It can be observed that L-value decreases with longer CB times and increases with shorter CB times or higher IM times. This means that longer conventional baking makes the crust darker, as it exposes the bread to heat for a longer duration, enhancing browning reactions such as the Maillard reaction. On the other hand, shorter CB time combined with higher IM time result in a lighter crust, since microwave heating reduces the exposure time to surface heat. So, in order to get the ldesirable light brown crust, conventional baking involvement is needed since microwave baking does not reach the required temperature for browning.

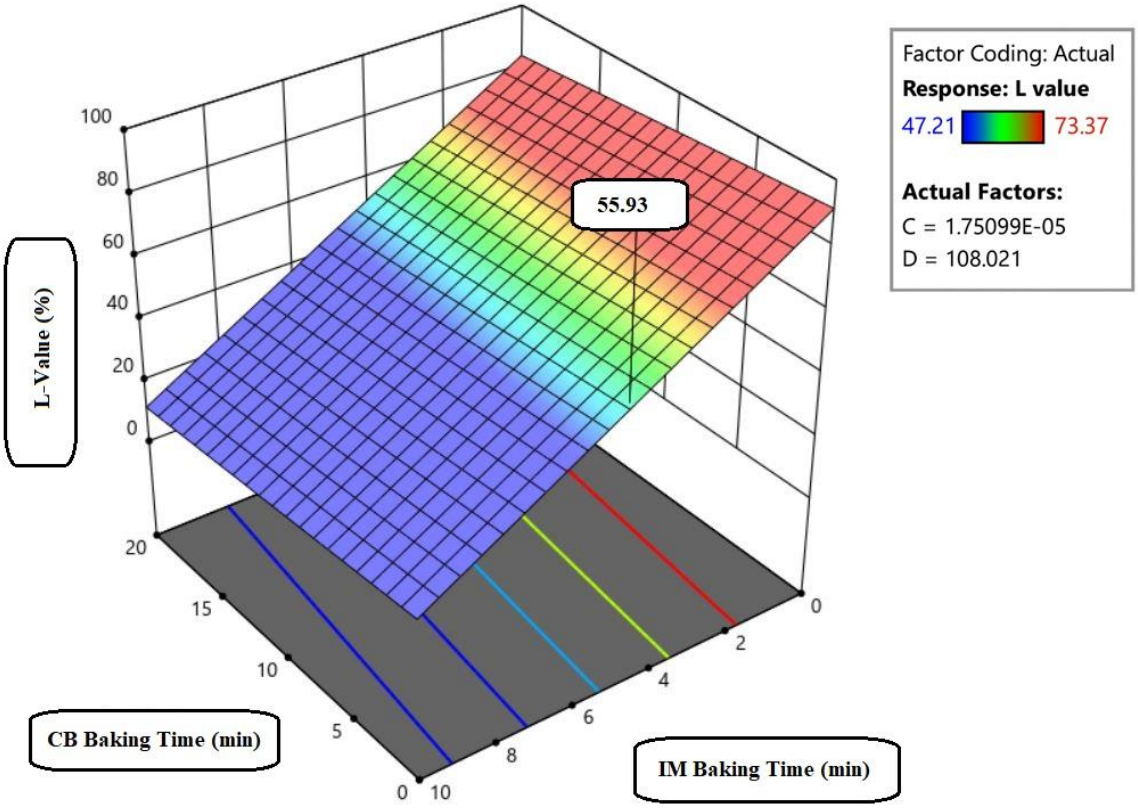


Figure 8 3D surface plot illustrating the combined effect of conventional baking and industrial solid-state microwave baking time on the cell number of bread as predicted by the RSM model in Design Expert

Figure 8.6 presents the 3D surface plot illustrating the combined effects of CB and IM baking on the predicted acrylamide content of the optimised bread sample. The predicted acrylamide level is 1.88 (µg/Kg) suggesting that this condition minimizes the formation of this undesirable compound. The vertical axis represents the predicted acrylamide concentration, while the x-axis and y-axis correspond to CB and IM baking times. The colour gradient on the surface ranges from blue (low acrylamide levels) to red (high acrylamide levels), showing how changes in the baking conditions influence the formation of this compound. From the plot, it can be seen that acrylamide content increases significantly with longer conventional baking, while IM baking led to lower acrylamide formation. The blue region of the surface, corresponding to low CB times and IM times around 5 minutes, shows the lowest predicted acrylamide values (approximately 1.88, as indicated by the data point on the plot). In contrast, the red region at the top of the surface represents high acrylamide formation, which occurs when conventional baking time is extended. This trend suggests that conventional oven baking promotes more intense Maillard reactions, leading to greater acrylamide production, while the industrial solid-state microwave method reduces this effect by providing rapid and uniform heating with shorter exposure times.

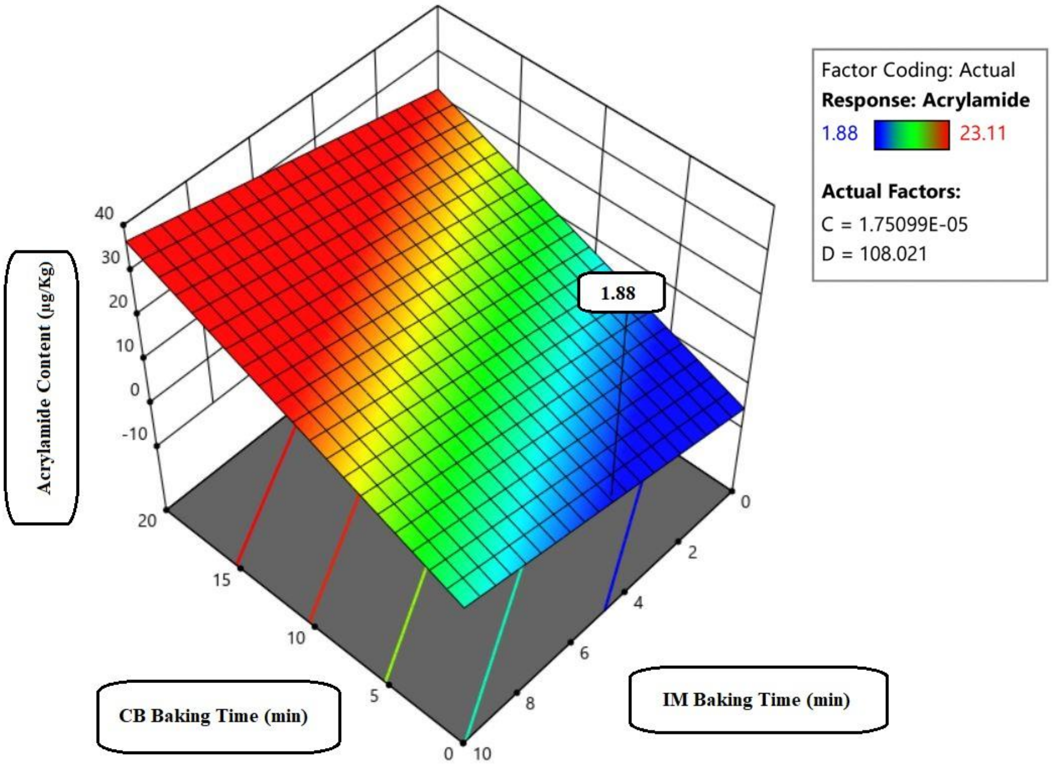


Figure 8 3D surface plot illustrating the combined effect of conventional baking and industrial solid-state microwave on the acrylamide content of bread as predicted by the RSM model in Design Expert

Figure 8.7 presents the 3D surface plot illustrating the combined effects of CB and IM baking on the predicted GHG emission of the optimised bread sample. The predicted GHG emission is 0.008, the lowest among the tested conditions, meaning that the IM baking process is also more environmentally friendly. The vertical axis represents the predicted GHG emission values, while the horizontal axes correspond to CB and IM times, respectively. The colour scale ranges from blue (low emissions) to red (high emissions), providing a visual representation of how changes in baking conditions influence the overall environmental impact of the process. From the plot, it can be observed that GHG emission increase with longer conventional baking times, while shorter CB times combined with moderate IM times result in the lowest predicted emission. The blue region, located at the lower corner of the surface, represents conditions with minimal GHG emission of approximately 0.006 kg CO_2 as shown at the data point near the IM time of around 5 minutes and the CB time close to zero. In contrast, the red region at the opposite end of the plot indicates higher emission levels, which occur when the conventional baking time is extended. This pattern suggests that conventional oven baking consumes more energy and generates higher GHG emissions compared to the industrial solid-state microwave process, which operates more efficiently by reducing baking duration and utilizing targeted volumetric heating. The slope of the surface indicates that CB time has a stronger influence on GHG emissions than IM time. As CB time increases, the emission levels rise sharply, while the impact of IM time remains comparatively mild. The nearly flat response along the IM axis shows that increasing IM time within the studied range does not significantly raise emissions, demonstrating that industrial solid-state microwave baking is both energy-efficient and environmentally sustainable.

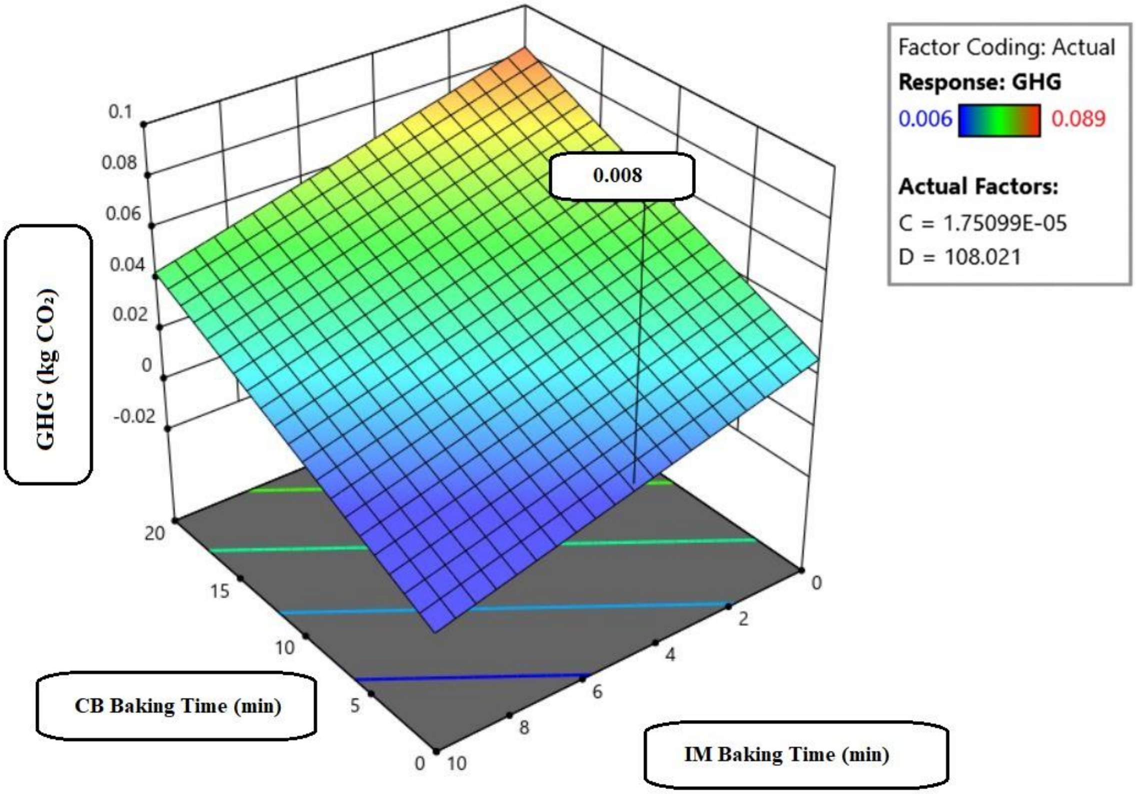


Figure 8. 3D surface plot illustrating the combined effect of conventional baking and industrial solid-state microwave on the greenhouse gas emission of baking bread as predicted by the RSM model in Design Expert

Chapter 9 Conclusion

1) Establish a comprehensive understanding of baking science and technology by conducting in-depth literature review of small scale and industrial baking processes, mapping the state of the art in conventional and emerging baking technologies and define the main physicochemical and sensory attributes that characterise high-quality bread products.

Conclusion: This objective was achieved by conducting a comprehensive review of conventional and emerging bread baking technologies, establishing a detailed understanding of the physicochemical and technological principles governing the baking process. The review identified the advantages and limitations of each baking technology in terms of heat transfer, moisture retention, energy efficiency, product quality, and acrylamide formation. Importantly, it revealed a significant knowledge gap regarding the application of industrial solid-state microwave technology in bakery products, providing the scientific rationale for the experimental work presented in this thesis. The review also established the key physicochemical and quality attributes required to evaluate bread quality, which formed the basis for the experimental design and subsequent analyses.2) Systematically investigate and compare the performance of multiple baking technologies including conventional, domestic microwave, industrial solid-state microwave, and hybrid baking systems through a structured approach of controlled experimental trials.

Conclusion: This objective was successfully achieved through the systematic experimental comparison of conventional oven, domestic microwave, industrial solid-state microwave, and hybrid baking methods under controlled processing conditions. The results demonstrated clear differences in baking performance, with industrial solid-state microwave and hybrid baking providing more uniform heating, improved moisture retention, reduced energy consumption, and lower environmental impact compared with conventional and domestic microwave baking. These findings confirm that industrial solid-state microwave and hybrid technologies represent promising alternatives for improving both baking efficiency and bread quality while supporting more sustainable industrial baking processes.3) Characterise physicochemical and textural properties of the baked breads produced under each baking mode using advanced analytical methods and determine the influence of processing conditions on product quality, uniformity and process efficiency

Conclusion: This objective was successfully achieved through the comprehensive characterisation of the physicochemical and textural properties of breads produced using conventional, domestic microwave, industrial solid-state microwave, and hybrid baking methods. The study demonstrated that baking mode significantly influenced moisture content, hardness, specific volume, cell structure, crust colour, and acrylamide formation. Industrial solid-state microwave baking produced breads with superior moisture retention, softer texture, and lower acrylamide levels, while hybrid baking successfully combined the advantages of microwave and conventional heating by improving moisture retention, texture, and crust colour. These findings confirm that processing conditions play a critical role in determining bread quality and identify industrial solid-state microwave and hybrid baking as effective approaches for improving product quality and process efficiency.

4) Analyse critical process parameters such as temperature profile and humidity across all baking modes to develop fundamental scientific understanding into moisture migration, and structural transformation during baking.

Conclusion: This objective was successfully achieved through the experimental measurement of temperature and moisture profiles at the top, centre, and bottom of bread during baking using different baking technologies. The study demonstrated that baking mode significantly influenced heat transfer, moisture migration, and structural development. Conventional baking produced pronounced temperature gradients and non-uniform moisture distribution, whereas industrial solid-state microwave achieved rapid and uniform heating with improved moisture retention. Hybrid baking, particularly the combination of industrial solid-state microwave and conventional heating, provided the best balance between rapid heating, moisture control, and temperature uniformity. These findings provide a fundamental understanding of the coupled heat and mass transfer mechanisms governing structural transformation during bread baking and demonstrate the advantages of industrial solid-state microwave-assisted baking over conventional and domestic microwave methods.5) Quantify of acrylamide formation across different baking technologies using advance high-performance liquid chromatography to assess food safety implications and identify the best baking mode that minimises the harmful contaminant

Conclusion: This objective was successfully achieved by quantifying acrylamide concentrations in breads produced using conventional, domestic microwave, industrial solid-state microwave, and hybrid baking methods through high-performance liquid chromatography. The results demonstrated that baking technology had a significant influence on acrylamide formation. Industrial solid-state microwave baking produced the lowest acrylamide levels, followed by domestic microwave baking, while conventional baking generated the highest concentrations because of prolonged exposure to high surface temperatures. Hybrid baking methods produced intermediate acrylamide levels, with shorter hybrid treatments resulting in lower acrylamide formation than longer treatments. These findings identify industrial solid-state microwave baking as the most effective technology for minimising acrylamide formation while maintaining product quality, highlighting its potential to improve the safety and sustainability of bread production.

6) Evaluate and compare energy consumption, greenhouse gas (GHG) emissions, and cost performance of each baking technology through detailed techno-economic and environmental analyses and identify the most sustainable and resource- efficient baking technology capable of delivering high- quality breads.

Conclusion: This objective was successfully achieved through a comparative techno-economic and environmental assessment of conventional, domestic microwave, industrial solid-state microwave, and hybrid baking technologies. The analysis demonstrated that baking technology significantly influenced energy consumption, greenhouse gas emissions, and operating costs. Industrial solid-state microwave baking exhibited the lowest energy consumption, GHG emissions, and production costs while maintaining high bread quality, making it the most sustainable and resource-efficient technology evaluated. Hybrid baking methods also improved energy efficiency and reduced environmental impact compared with conventional baking, demonstrating their potential as practical alternatives for sustainable industrial bread production.

7) Develop date- driven recommendations for industrial implementation proposing optimal design, control and operational strategies of the studied baking technologies, to improve product quality, energy efficiency, and environmental performance for large scale production

Conclusion: This objective was successfully achieved through RSM optimisation using Design-Expert software, which integrated key quality, safety, and sustainability responses, including moisture, hardness, loaf volume, cell structure, colour, acrylamide formation, and GHG emissions. The optimisation identified industrial solid-state microwave baking as the most favourable technology, as it provided the best overall balance between bread quality, low acrylamide formation, reduced energy use, and lower environmental impact. The findings support the recommendation that industrial solid-state microwave baking, with or without a short conventional finishing stage, could be implemented as a practical strategy for improving bread quality and sustainability in large-scale production.

Study limitation

Although this study provides a comprehensive comparison of conventional, industrial microwave, domestic microwave and hybrid baking methods, several limitations should be acknowledged. First, only a single bread formulation was evaluated, allowing the effect of baking technology to be isolated but limiting generalisation to other bread formulations. Second, experiments were conducted at laboratory scale, and therefore industrial-scale validation is required before large-scale implementation. Third, sensory evaluation and consumer acceptance were not included and should be considered in future studies. Fourth, storage stability was evaluated up to eight days only, and longer storage periods may provide additional information regarding staling behaviour. Finally, economic assessment was based on historical energy prices and may vary depending on future market conditions and geographical location.

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Appendix

Appendix 4.1: Raw data for moisture content on day 1,5 and 8 after baking with three replicates

Samples	Moisture day 1 (%)	Moisture day 5 (%)	Moisture day 8 (%)
CB	26.3	20.5	14.41
CB	27.14	20.04	14.62
CB	26.76	19.76	13.98
IM	29.67	27.67	24.78
IM	29.32	26.89	25.07
IM	29.81	26.81	25.14
$IMCB_1$	27.79	25.79	22.52
$IMCB_1$	28.98	25.98	22.19
$IMCB_1$	28.11	25.11	22.66
$IMCB_2$	25.08	22.08	18.98
$IMCB_2$	24.5	22.5	18.62
$IMCB_2$	24.37	22.37	18.29
DM	15.2	11.54	7.85

DM	15.43	11.18	7.28
DM	16.28	11.14	7.98
$DMCB_1$	21.67	16.67	12.21
$DMCB_1$	21.92	17.52	11.73
$DMCB_1$	21.84	16.46	11.58
$DMCB_2$	18.09	16.09	11.76
$DMCB_2$	18.17	15.43	11.07
$DMCB_2$	18.71	15.71	11.48

Appendix 4.2: Raw data for L-value, a-value and b-value with three replicates

Samples	L-value (%)	a-value (%)	b-value (%)
CB	47.21	11.06	15.99
CB	47.29	11.01	15.96
CB	47.33	11.01	15.92
IM	73.23	14.52	19.87
IM	73.29	14.61	19.81
IM	73.37	14.57	19.93
$IMCB_1$	63.46	12.68	17.62
$IMCB_1$	63.42	12.65	17.66
$IMCB_1$	63.48	12.59	17.69
$IMCB_2$	57.76	11.77	16.13
$IMCB_2$	57.81	11.75	16.16
$IMCB_2$	57.72	11.7	16.11
DM	71.89	14.67	19.93
DM	71.81	14.71	19.96

DM	71.92	14.69	19.91
DMCB$_1$	63.41	12.61	17.66
DMCB$_1$	63.32	12.69	17.6
DMCB$_1$	63.35	12.71	17.59
DMCB$_2$	57.74	11.72	16.17
DMCB$_2$	57.79	11.66	16.14
DMCB$_2$	57.85	11.75	16.18

Appendix 4.3: Raw data for hardness on day 1,5 and 8 after baking with three replicates

Samples	Hardness day 1 (N)	Hardness day 5 (N)	Hardness day 8 (N)
CB	1299.70	2135.8	2854.2
CB	1379.53	2098.9	2976.6
CB	1345.65	2011.3	2941.3
IM	1062.5	1278.8	1522.2
IM	1087.6	1214.5	1498.1
IM	996.8	1235.9	1488.6
IMCB$_1$	1267.98	1678.9	2098.8
IMCB$_1$	1301..45	1692.5	2167.8
IMCB$_1$	1329.76	1649.6	2120.4
IMCB$_2$	1687.90	1871.9	2236.7
IMCB$_2$	1545.55	1809.2	2189.1
IMCB$_2$	1611.23	1789.7	2218.7
DM	2356.87	3209.1	3778.5

DM	2498.47	3293.9	3713.5
DM	2497.62	3157.7	3690.0
DMCB$_1$	1795.51	2344.5	3127.3
DMCB$_1$	1748.69	2401.2	3211.1
DMCB$_1$	1771.94	2389.8	3217.9
DMCB$_2$	2223.50	2767.6	3356.6
DMCB$_2$	2249.87	2798.9	3311.2
DMCB$_2$	2387.51	2804.8	3399.9

Appendix 4.4: Raw data for Volume, specific volume, length and weight of the bread with three replicates

Samples	Volume (ml)	Specific volume (ml/g)	Length (mm)	Weight (g)
CB	1176.0	3.43	221.1	338.63
CB	1181.0	3.52	220.8	344.75
CB	1186.0	3.56	220.7	348.52
IM	1166.0	3.41	221.3	342.51
IM	1185.0	3.315	219.5	335.38
IM	1182.0	3.28	220.8	332.49
IMCB$_1$	1191.0	3.51	221.2	341.48
IMCB$_1$	1179.0	3.41	221.6	356.94
IMCB$_1$	1171.0	3.35	222.1	359.82
IMCB$_2$	1171.0	3.42	220.6	341.47

$IMCB_2$	1179.0	3.47	221.1	338.85
$IMCB_2$	1184.0	3.39	220.9	348.93
DM	1188.0	3.39	221.7	349.86
DM	1181.0	3.31	221.5	356.62
DM	1183.0	3.40	221.3	347.28
$DMCB_1$	1179.0	3.45	221.4	341.47
$DMCB_1$	1182.0	3.39	221.6	348.58
$DMCB_1$	1185.0	3.43	221.4	344.53
$DMCB_2$	1175.0	3.40	221.8	345.12
$DMCB_2$	1178.0	3.45	221.5	340.94
$DMCB_2$	1186.0	3.40	221.3	348.41

Appendix 4.5: Raw data for cell number and average cell area of the bread with three replicates

Samples	Cell number	Average cell area (mm^2)
CB	249	3.83
CB	254	3.85
CB	257	3.80
IM	378	6.55
IM	382	6.61
IM	380	6.65
$IMCB_1$	351	5.81
$IMCB_1$	353	5.86
$IMCB_1$	354	5.88
$IMCB_2$	351	6.11
$IMCB_2$	353	6.07

$IMCB_2$	353	6.03
DM	379	6.89
DM	382	6.91
DM	382	6.93
$DMCB_1$	340	5.87
$DMCB_1$	339	5.84
$DMCB_1$	339	5.88
$DMCB_2$	338	6.24
$DMCB_2$	341	6.20
$DMCB_2$	341	6.18

Appendix 6.1: Raw data for acrylamide content of the bread with three replicates

Samples	Acrylamide content (µg/L)
CB	22.41
CB	22.15
CB	23.11
IM	1.98
IM	1.88
IM	1.92
$IMCB_1$	7.91
$IMCB_1$	7.96
$IMCB_1$	7.99

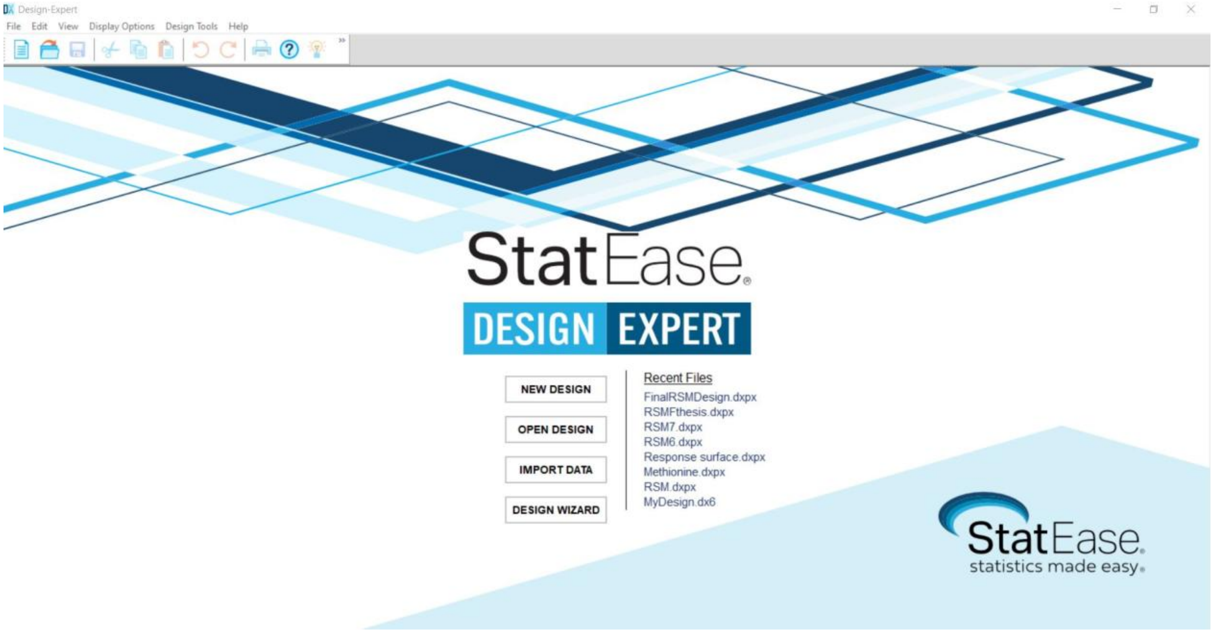
IMCB$_2$	15.87
IMCB$_2$	15.95
IMCB$_2$	15.89
DM	2.06
DM	2.05
DM	2.11
DMCB$_1$	8.2
DMCB$_1$	8.27
DMCB$_1$	8.31
DMCB$_2$	16.11
DMCB$_2$	16.03
DMCB$_2$	16.09

Appendix 7.1: Raw data for energy consumption, total cost and carbon emission with three replicates

Samples	Energy consumption (kWh)	Total cost (£)	GHG emission (Kg of CO2)
CB	0.452	0.1532	0.086
CB	0.459	0.1539	0.089
CB	0.450	0.1530	0.087
IM	0.038	0.0052	0.006
IM	0.033	0.0057	0.006
IM	0.038	0.0055	0.008
IMCB$_1$	0.114	0.0403	0.021
IMCB$_1$	0.123	0.0405	0.017

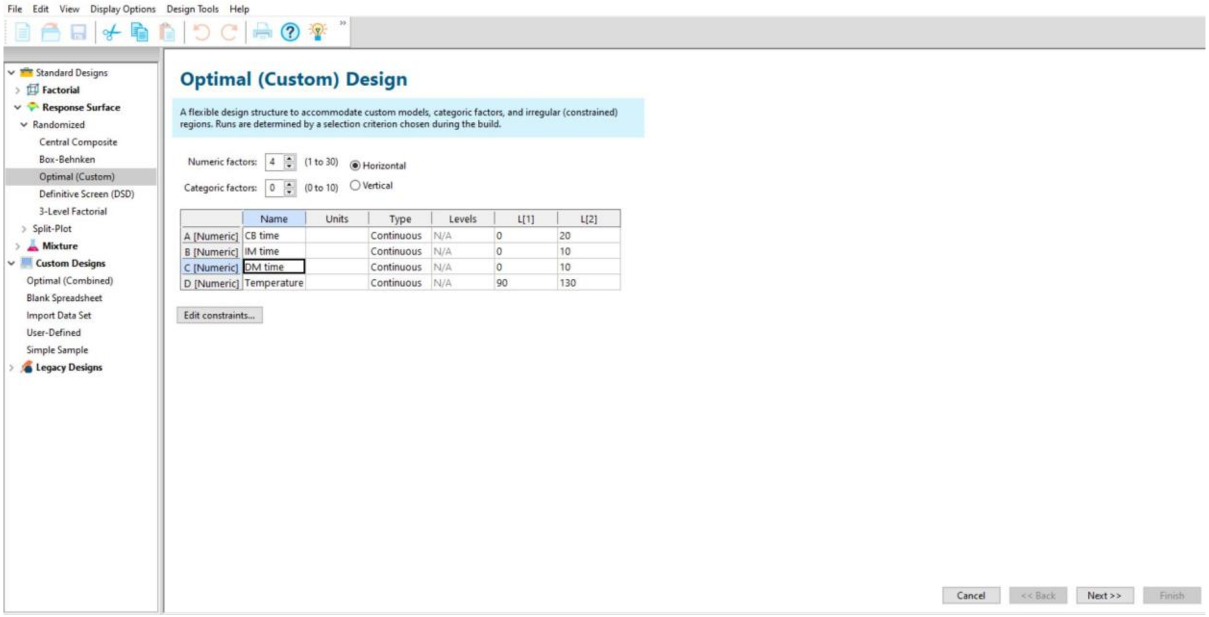
IMCB$_1$	0.121	0.0398	0.022
IMCB$_2$	0.145	0.0503	0.038
IMCB$_2$	0.152	0.0501	0.039
IMCB$_2$	0.149	0.0506	0.029
DM	0.261	0.0884	0.025
DM	0.263	0.0889	0.033
DM	0.258	0.0890	0.027
DMCB$_1$	0.235	0.0788	0.041
DMCB$_1$	0.230	0.0783	0.039
DMCB$_1$	0.233	0.0785	0.041
DMCB$_2$	0.348	0.1165	0.055
DMCB$_2$	0.341	0.1169	0.061
DMCB$_2$	0.343	0.1172	0.064

Appendix 8: Optimisation process using RSM step by step using Design Expert software.



Recent Files
FinalRSMDesign.dxpx
RSMFthesis.dxpx
RSM7.dxpx
RSM6.dxpx
Response surface.dxpx
Methionine.dxpx
RSM.dxpx
MyDesign.dx6

Different baking time for different baking modes and final temperature have been used as independent variables.



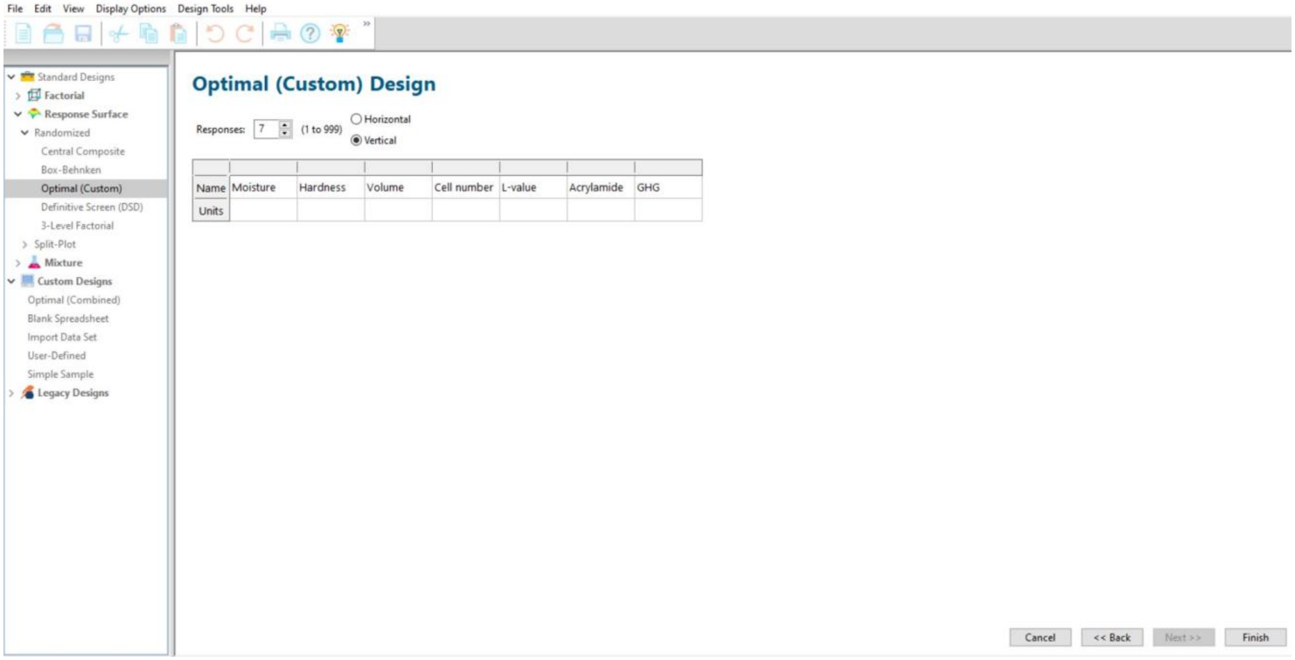
Optimal (Custom) Design

A flexible design structure to accommodate custom models, categoric factors, and irregular (constrained) regions. Runs are determined by a selection criterion chosen during the build.

Numeric factors: 4 (1 to 30) ● Horizontal
Categoric factors: 0 (0 to 10) ○ Vertical

	Name	Units	Type	Levels	L[1]	L[2]
A [Numeric]	CB time		Continuous	N/A	0	20
B [Numeric]	IM time		Continuous	N/A	0	10
C [Numeric]	DM time		Continuous	N/A	0	10
D [Numeric]	Temperature		Continuous	N/A	90	130

Seven responses were selected including moisture content, hardness, volume, cell number, L-value, acrylamide and GHG.

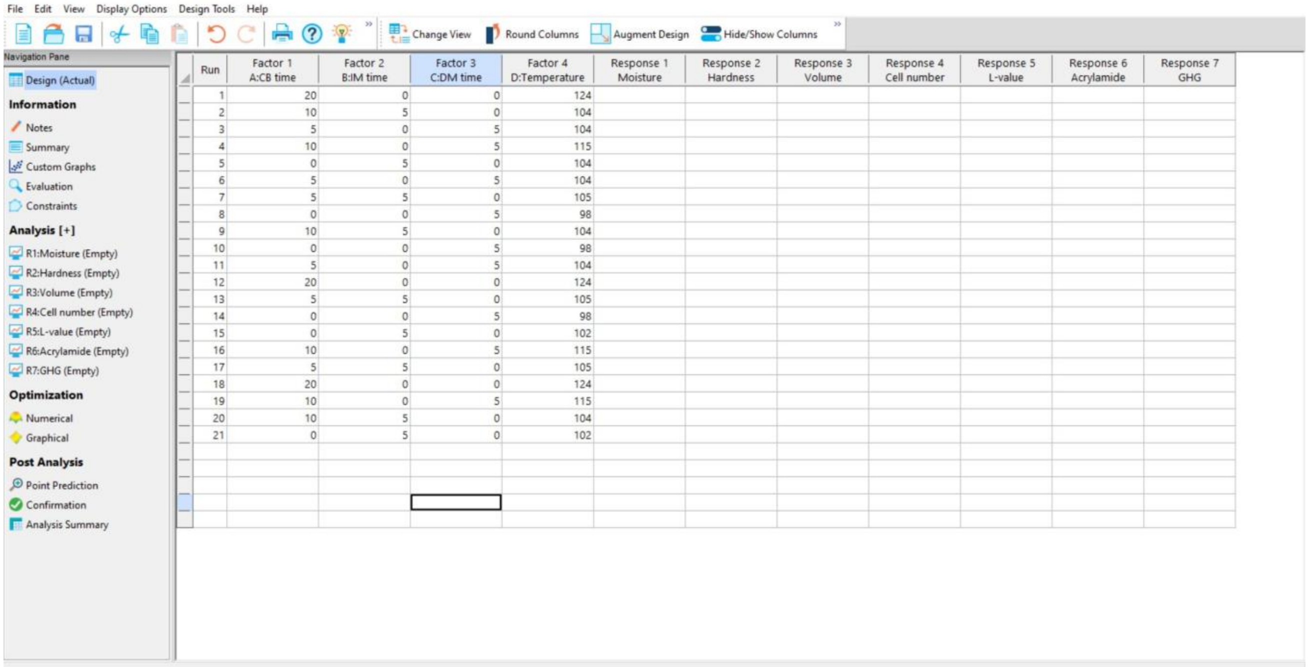


Optimal (Custom) Design

Responses: 7 (1 to 999) ○ Horizontal ● Vertical

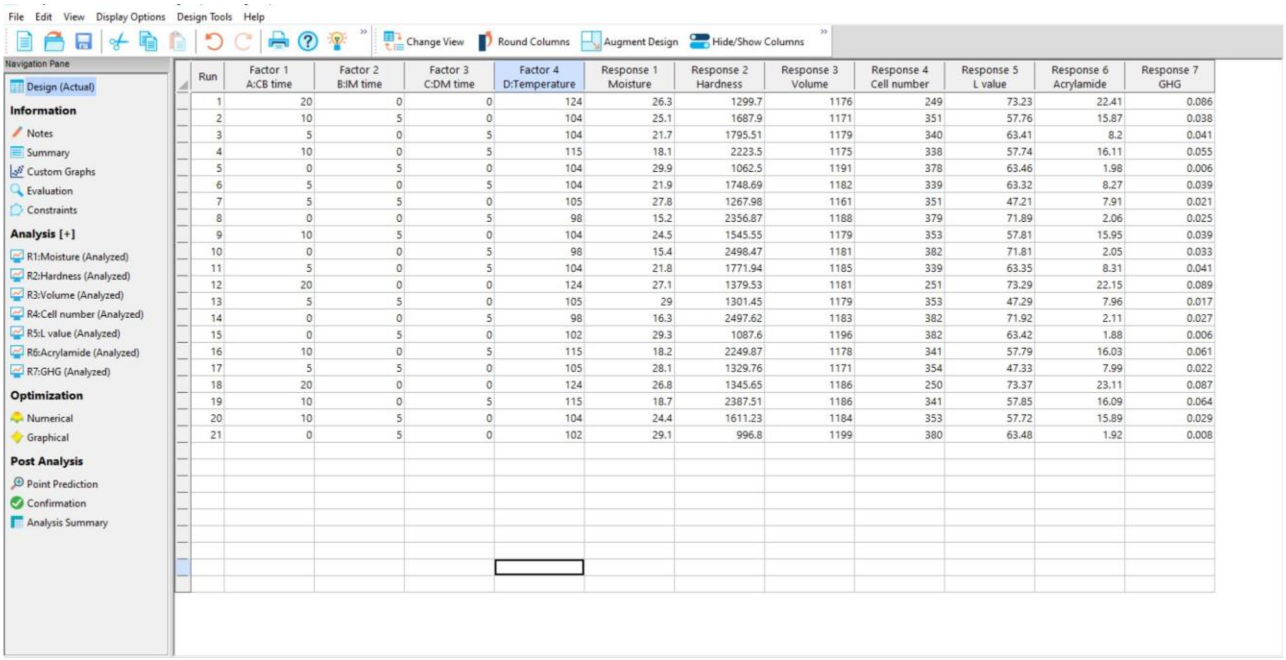
Name	Moisture	Hardness	Volume	Cell number	L-value	Acrylamide	GHG
Units							

A 21-run design, including all defined variables and responses was generated after the factors and model terms were specified. Each row under the "Run" column represents a single experimental trial, and in this design a total of 21 runs has been created.



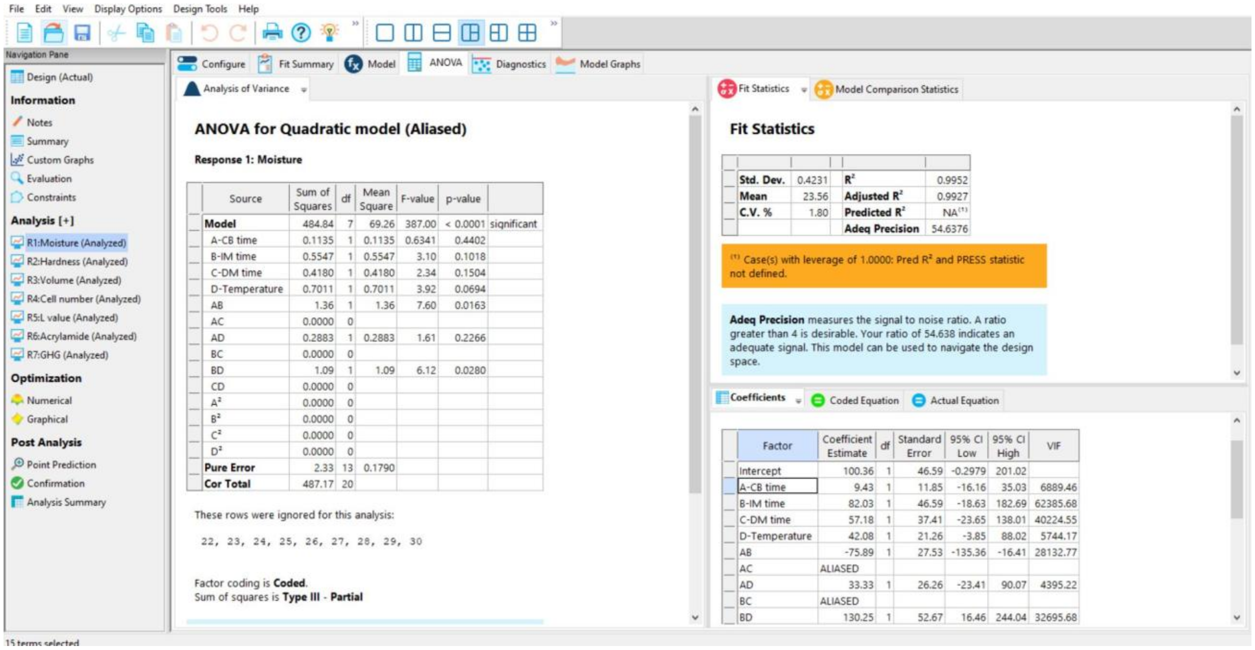
Run	Factor 1 A:CB time	Factor 2 B:IM time	Factor 3 C:DM time	Factor 4 D:Temperature	Response 1 Moisture	Response 2 Hardness	Response 3 Volume	Response 4 Cell number	Response 5 L-value	Response 6 Acrylamide	Response 7 GHG
1	20	0	0	124							
2	10	5	0	104							
3	5	0	5	104							
4	10	0	5	115							
5	0	5	0	104							
6	5	0	5	104							
7	5	5	0	105							
8	0	0	5	98							
9	10	5	0	104							
10	0	0	5	98							
11	5	0	5	104							
12	20	0	0	124							
13	5	5	0	105							
14	0	0	5	98							
15	0	5	0	102							
16	10	0	5	115							
17	5	5	0	105							
18	20	0	0	124							
19	10	0	5	115							
20	10	5	0	104							
21	0	5	0	102							

Experimental data were imported to the design to start the analysis and optimization.



Run	Factor 1 A:CB time	Factor 2 B:IM time	Factor 3 C:DM time	Factor 4 D:Temperature	Response 1 Moisture	Response 2 Hardness	Response 3 Volume	Response 4 Cell number	Response 5 L value	Response 6 Acrylamide	Response 7 GHG
1	20	0	0	124	26.3	1299.7	1176	249	73.23	22.41	0.086
2	10	5	0	104	25.1	1687.9	1171	351	57.76	15.87	0.038
3	5	0	5	104	21.7	1795.51	1179	340	63.41	8.2	0.041
4	10	0	5	115	18.1	2223.5	1175	338	57.74	16.11	0.055
5	0	5	0	104	29.9	1062.5	1191	378	63.46	1.98	0.006
6	5	0	5	104	21.9	1748.69	1182	339	63.32	8.27	0.039
7	5	5	0	105	27.8	1267.98	1161	351	47.21	7.91	0.021
8	0	0	5	98	15.2	2356.87	1188	379	71.89	2.06	0.025
9	10	5	0	104	24.5	1545.55	1179	353	57.81	15.95	0.039
10	0	0	5	98	15.4	2498.47	1181	382	71.81	2.05	0.033
11	5	0	5	104	21.8	1771.94	1185	339	63.35	8.31	0.041
12	20	0	0	124	27.1	1379.53	1181	251	73.29	22.15	0.089
13	5	5	0	105	29	1301.45	1179	353	47.29	7.96	0.017
14	0	0	5	98	16.3	2497.62	1183	382	71.92	2.11	0.027
15	0	5	0	102	29.3	1087.6	1196	382	63.42	1.88	0.006
16	10	0	5	115	18.2	2249.87	1178	341	57.79	16.03	0.061
17	5	5	0	105	28.1	1329.76	1171	354	47.33	7.99	0.022
18	20	0	0	124	26.8	1345.65	1186	250	73.37	23.11	0.087
19	10	0	5	115	18.7	2387.51	1186	341	57.85	16.09	0.064
20	10	5	0	104	24.4	1611.23	1184	353	57.72	15.89	0.029
21	0	5	0	102	29.1	996.8	1199	380	63.48	1.92	0.008

The ANOVA results for each response are shown in the following figures.



ANOVA for Quadratic model (Aliased)

Response 1: Moisture

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	484.84	7	69.26	387.00	< 0.0001	significant
A-CB time	0.1135	1	0.1135	0.6341	0.4402	
B-IM time	0.5547	1	0.5547	3.10	0.1018	
C-DM time	0.4180	1	0.4180	2.34	0.1504	
D-Temperature	0.7011	1	0.7011	3.92	0.0694	
AB	1.36	1	1.36	7.60	0.0163	
AC	0.0000	0				
AD	0.2883	1	0.2883	1.61	0.2266	
BC	0.0000	0				
BD	1.09	1	1.09	6.12	0.0280	
CD	0.0000	0				
A^2	0.0000	0				
B^2	0.0000	0				
C^2	0.0000	0				
D^2	0.0000	0				
Pure Error	2.33	13	0.1790			
Cor Total	487.17	20				

These rows were ignored for this analysis:

```
22, 23, 24, 25, 26, 27, 28, 29, 30
```

Factor coding is **Coded**.
Sum of squares is **Type III - Partial**

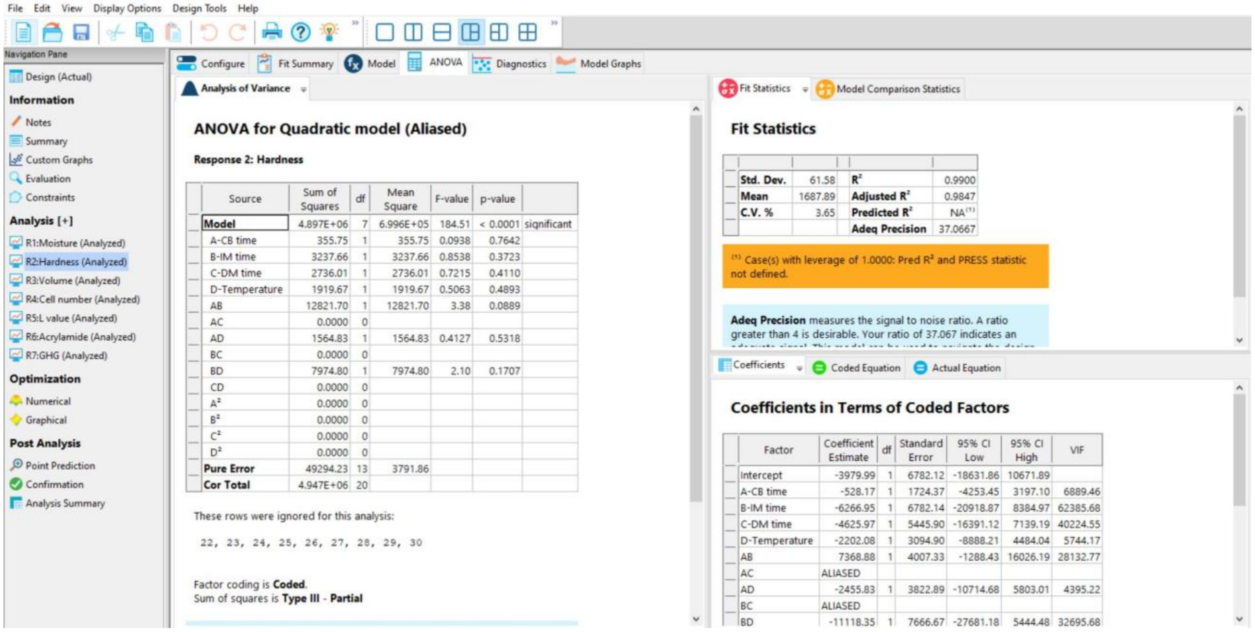
Fit Statistics

Std. Dev.	0.4231	**R^2**	0.9952
Mean	23.56	**Adjusted R^2**	0.9927
C.V. %	1.80	**Predicted R^2**	NA(1)
		Adeq Precision	54.6376

(1) Case(s) with leverage of 1.0000: Pred R^2 and PRESS statistic not defined.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 54.638 indicates an adequate signal. This model can be used to navigate the design space.

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	100.36	1	46.59	-0.2979	201.02	
A-CB time	9.43	1	11.85	-16.16	35.03	6889.46
B-IM time	82.03	1	46.59	-18.63	182.69	62385.68
C-DM time	57.18	1	37.41	-23.65	138.01	40224.55
D-Temperature	42.08	1	21.26	-3.85	88.02	5744.17
AB	-75.89	1	27.53	-135.36	-16.41	28132.77
AC	ALIASED					
AD	33.33	1	26.26	-23.41	90.07	4395.22
BC	ALIASED					
BD	130.25	1	52.67	16.46	244.04	32695.68



ANOVA for Quadratic model (Aliased)

Response 2: Hardness

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4.897E+06	7	6.996E+05	184.51	< 0.0001	significant
A-CB time	355.75	1	355.75	0.0938	0.7642	
B-IM time	3237.66	1	3237.66	0.8538	0.3723	
C-DM time	2736.01	1	2736.01	0.7215	0.4110	
D-Temperature	1919.67	1	1919.67	0.5063	0.4893	
AB	12821.70	1	12821.70	3.38	0.0889	
AC	0.0000	0				
AD	1564.83	1	1564.83	0.4127	0.5318	
BC	0.0000	0				
BD	7974.80	1	7974.80	2.10	0.1707	
CD	0.0000	0				
A^2	0.0000	0				
B^2	0.0000	0				
C^2	0.0000	0				
D^2	0.0000	0				
Pure Error	49294.23	13	3791.86			
Cor Total	4.947E+06	20				

These rows were ignored for this analysis:

```
22, 23, 24, 25, 26, 27, 28, 29, 30
```

Factor coding is **Coded**.
Sum of squares is **Type III - Partial**

Fit Statistics

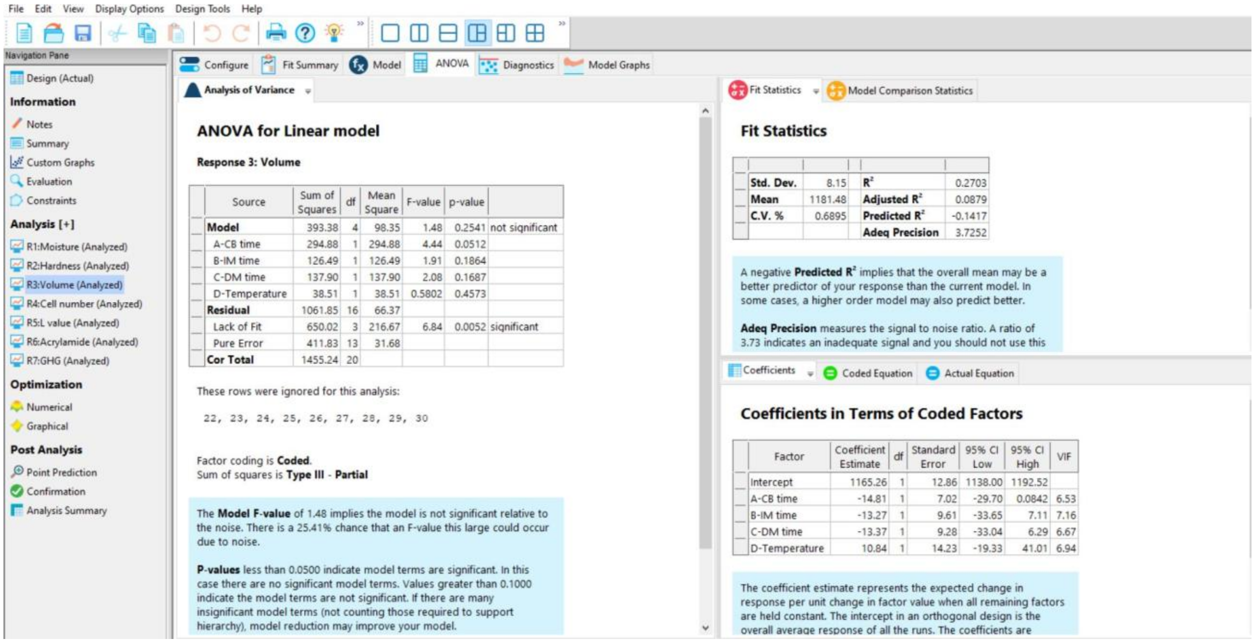
Std. Dev.	61.58	**R^2**	0.9900
Mean	1687.89	**Adjusted R^2**	0.9847
C.V. %	3.65	**Predicted R^2**	NA(1)
		Adeq Precision	37.0667

(1) Case(s) with leverage of 1.0000: Pred R^2 and PRESS statistic not defined.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 37.067 indicates an

Coefficients in Terms of Coded Factors

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	-3979.99	1	6782.12	-18631.86	10671.89	
A-CB time	-528.17	1	1724.37	-4253.45	3197.10	6889.46
B-IM time	-6266.95	1	6782.14	-20918.87	8384.97	62385.68
C-DM time	-4625.97	1	5445.90	-16391.12	7139.19	40224.55
D-Temperature	-2202.08	1	3094.90	-8888.21	4484.04	5744.17
AB	7368.88	1	4007.33	-1288.43	16026.19	28132.77
AC	ALIASED					
AD	-2455.83	1	3822.89	-10714.68	5803.01	4395.22
BC	ALIASED					
BD	-11118.35	1	7666.67	-27681.18	5444.48	32695.68



ANOVA for Linear model

Response 3: Volume

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	393.38	4	98.35	1.48	0.2541	not significant
A-CB time	294.88	1	294.88	4.44	0.0512	
B-IM time	126.49	1	126.49	1.91	0.1864	
C-DM time	137.90	1	137.90	2.08	0.1687	
D-Temperature	38.51	1	38.51	0.5802	0.4573	
Residual	1061.85	16	66.37			
Lack of Fit	650.02	3	216.67	6.84	0.0052	significant
Pure Error	411.83	13	31.68			
Cor Total	1455.24	20				

These rows were ignored for this analysis:

```
22, 23, 24, 25, 26, 27, 28, 29, 30
```

Factor coding is **Coded**.
Sum of squares is **Type III - Partial**

The **Model F-value** of 1.48 implies the model is not significant relative to the noise. There is a 25.41% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case there are no significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Fit Statistics

Std. Dev.	8.15	**R^2**	0.2703
Mean	1181.48	**Adjusted R^2**	0.0879
C.V. %	0.6895	**Predicted R^2**	-0.1417
		Adeq Precision	3.7252

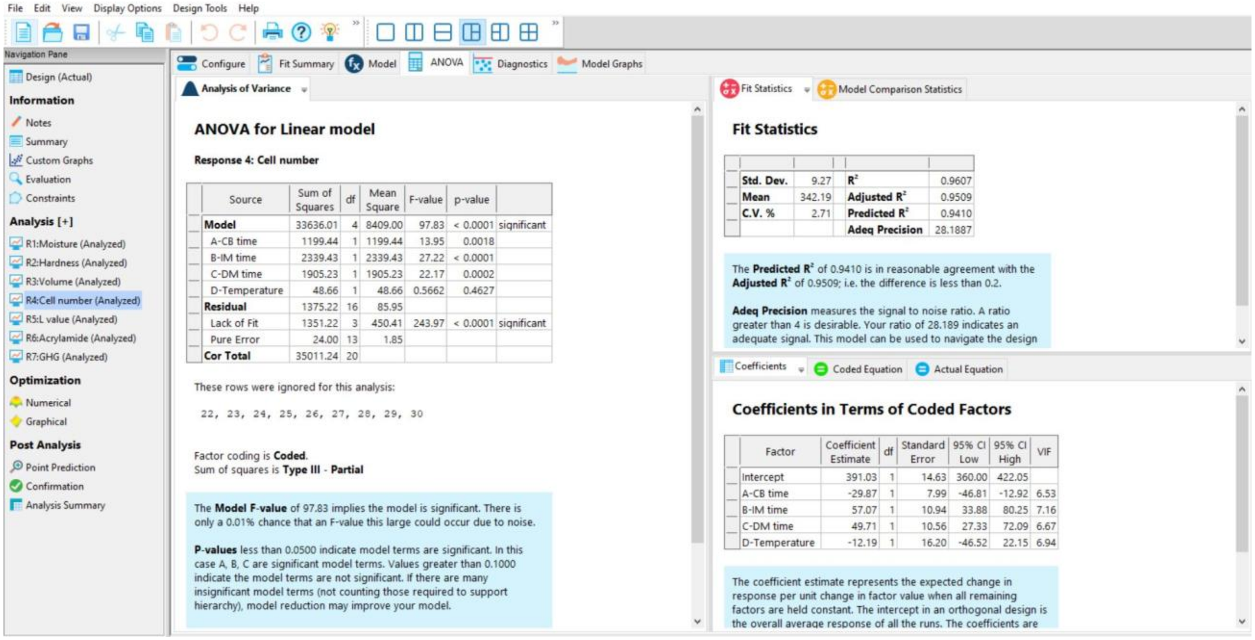
A negative **Predicted R^2** implies that the overall mean may be a better predictor of your response than the current model. In some cases, a higher order model may also predict better.

Adeq Precision measures the signal to noise ratio. A ratio of 3.73 indicates an inadequate signal and you should not use this

Coefficients in Terms of Coded Factors

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	1165.26	1	12.86	1138.00	1192.52	
A-CB time	-14.81	1	7.02	-29.70	0.0842	6.53
B-IM time	-13.27	1	9.61	-33.65	7.11	7.16
C-DM time	-13.37	1	9.28	-33.04	6.29	6.67
D-Temperature	10.84	1	14.23	-19.33	41.01	6.94

The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are



ANOVA for Linear model

Response 4: Cell number

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	33636.01	4	8409.00	97.83	< 0.0001	significant
A-CB time	1199.44	1	1199.44	13.95	0.0018	
B-IM time	2339.43	1	2339.43	27.22	< 0.0001	
C-DM time	1905.23	1	1905.23	22.17	0.0002	
D-Temperature	48.66	1	48.66	0.5662	0.4627	
Residual	1375.22	16	85.95			
Lack of Fit	1351.22	3	450.41	243.97	< 0.0001	significant
Pure Error	24.00	13	1.85			
Cor Total	35011.24	20				

These rows were ignored for this analysis:

```
22, 23, 24, 25, 26, 27, 28, 29, 30
```

Factor coding is **Coded**.
Sum of squares is **Type III - Partial**

The **Model F-value** of 97.83 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case A, B, C are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Fit Statistics

Std. Dev.	9.27	**R^2**	0.9607
Mean	342.19	**Adjusted R^2**	0.9509
C.V. %	2.71	**Predicted R^2**	0.9410
		Adeq Precision	28.1887

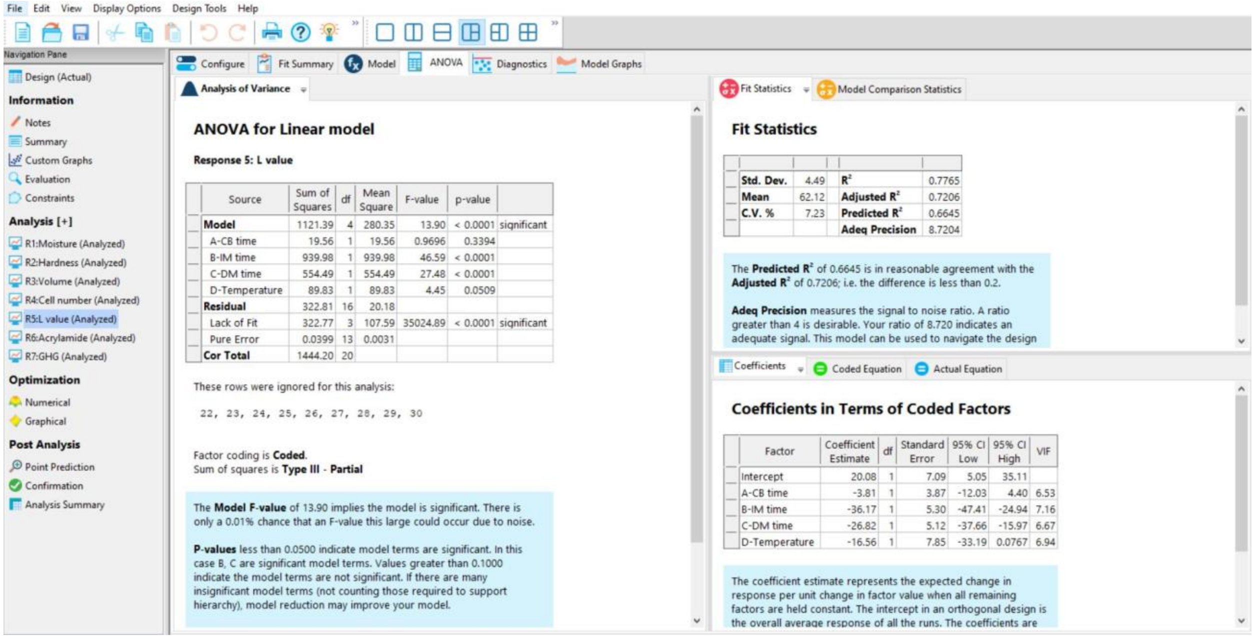
The **Predicted R^2** of 0.9410 is in reasonable agreement with the **Adjusted R^2** of 0.9509; i.e. the difference is less than 0.2.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 28.189 indicates an adequate signal. This model can be used to navigate the design

Coefficients in Terms of Coded Factors

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	391.03	1	14.63	360.00	422.05	
A-CB time	-29.87	1	7.99	-46.81	-12.92	6.53
B-IM time	57.07	1	10.94	33.88	80.25	7.16
C-DM time	49.71	1	10.56	27.33	72.09	6.67
D-Temperature	-12.19	1	16.20	-46.52	22.15	6.94

The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are



ANOVA for Linear model

Response 5: L value

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1121.39	4	280.35	13.90	< 0.0001	significant
A-CB time	19.56	1	19.56	0.9696	0.3394	
B-IM time	939.98	1	939.98	46.59	< 0.0001	
C-DM time	554.49	1	554.49	27.48	< 0.0001	
D-Temperature	89.83	1	89.83	4.45	0.0509	
Residual	322.81	16	20.18			
Lack of Fit	322.77	3	107.59	35024.89	< 0.0001	significant
Pure Error	0.0399	13	0.0031			
Cor Total	1444.20	20				

These rows were ignored for this analysis:

`22, 23, 24, 25, 26, 27, 28, 29, 30`

Factor coding is **Coded**.
Sum of squares is **Type III - Partial**

The **Model F-value** of 13.90 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case B, C are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Fit Statistics

Std. Dev.	4.49	**R^2**	0.7765
Mean	62.12	**Adjusted R^2**	0.7206
C.V. %	7.23	**Predicted R^2**	0.6645
		Adeq Precision	8.7204

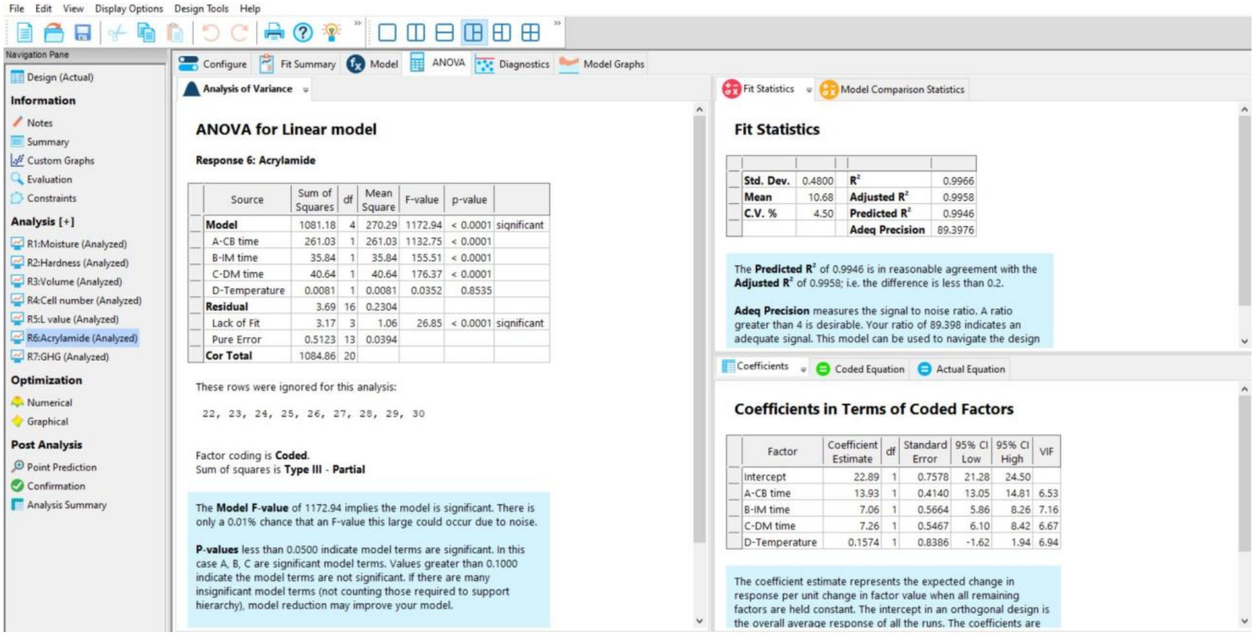
The **Predicted R^2** of 0.6645 is in reasonable agreement with the **Adjusted R^2** of 0.7206; i.e. the difference is less than 0.2.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 8.720 indicates an adequate signal. This model can be used to navigate the design

Coefficients in Terms of Coded Factors

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	20.08	1	7.09	5.05	35.11	
A-CB time	-3.81	1	3.87	-12.03	4.40	6.53
B-IM time	-36.17	1	5.30	-47.41	-24.94	7.16
C-DM time	-26.82	1	5.12	-37.66	-15.97	6.67
D-Temperature	-16.56	1	7.85	-33.19	0.0767	6.94

The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are



ANOVA for Linear model

Response 6: Acrylamide

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1081.18	4	270.29	1172.94	< 0.0001	significant
A-CB time	261.03	1	261.03	1132.75	< 0.0001	
B-IM time	35.84	1	35.84	155.51	< 0.0001	
C-DM time	40.64	1	40.64	176.37	< 0.0001	
D-Temperature	0.0081	1	0.0081	0.0352	0.8535	
Residual	3.69	16	0.2304			
Lack of Fit	3.17	3	1.06	26.85	< 0.0001	significant
Pure Error	0.5123	13	0.0394			
Cor Total	1084.86	20				

These rows were ignored for this analysis:

`22, 23, 24, 25, 26, 27, 28, 29, 30`

Factor coding is **Coded**.
Sum of squares is **Type III - Partial**

The **Model F-value** of 1172.94 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case A, B, C are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Fit Statistics

Std. Dev.	0.4800	**R^2**	0.9966
Mean	10.68	**Adjusted R^2**	0.9958
C.V. %	4.50	**Predicted R^2**	0.9946
		Adeq Precision	89.3976

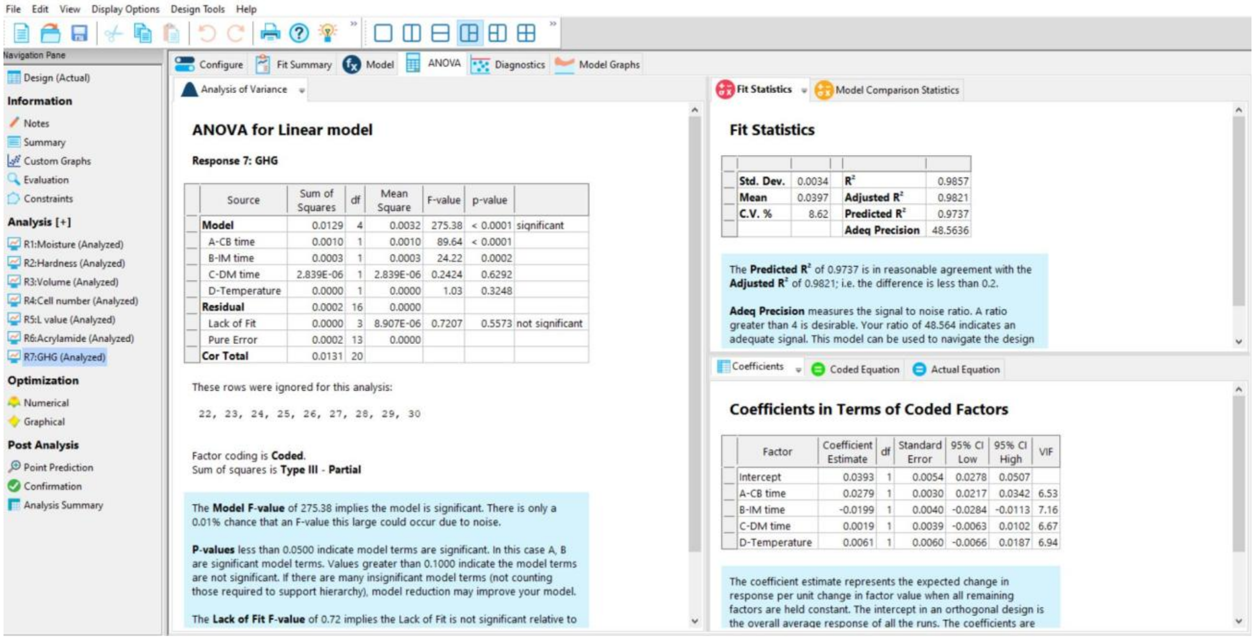
The **Predicted R^2** of 0.9946 is in reasonable agreement with the **Adjusted R^2** of 0.9958; i.e. the difference is less than 0.2.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 89.398 indicates an adequate signal. This model can be used to navigate the design

Coefficients in Terms of Coded Factors

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	22.89	1	0.7578	21.28	24.50	
A-CB time	13.93	1	0.4140	13.05	14.81	6.53
B-IM time	7.06	1	0.5664	5.86	8.26	7.16
C-DM time	7.26	1	0.5467	6.10	8.42	6.67
D-Temperature	0.1574	1	0.8386	-1.62	1.94	6.94

The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are



ANOVA for Linear model

Response 7: GHG

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0129	4	0.0032	275.38	< 0.0001	significant
A-CB time	0.0010	1	0.0010	89.64	< 0.0001	
B-IM time	0.0003	1	0.0003	24.22	0.0002	
C-DM time	2.839E-06	1	2.839E-06	0.2424	0.6292	
D-Temperature	0.0000	1	0.0000	1.03	0.3248	
Residual	0.0002	16	0.0000			
Lack of Fit	0.0000	3	8.907E-06	0.7207	0.5573	not significant
Pure Error	0.0002	13	0.0000			
Cor Total	0.0131	20				

These rows were ignored for this analysis:

```
22, 23, 24, 25, 26, 27, 28, 29, 30
```

Factor coding is **Coded**.
Sum of squares is **Type III** - **Partial**

The **Model F-value** of 275.38 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case A, B are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The **Lack of Fit F-value** of 0.72 implies the Lack of Fit is not significant relative to

Fit Statistics

Std. Dev.	0.0034	**R^2**	0.9857
Mean	0.0397	**Adjusted R^2**	0.9821
C.V. %	8.62	**Predicted R^2**	0.9737
		Adeq Precision	48.5636

The **Predicted R^2** of 0.9737 is in reasonable agreement with the **Adjusted R^2** of 0.9821; i.e. the difference is less than 0.2.

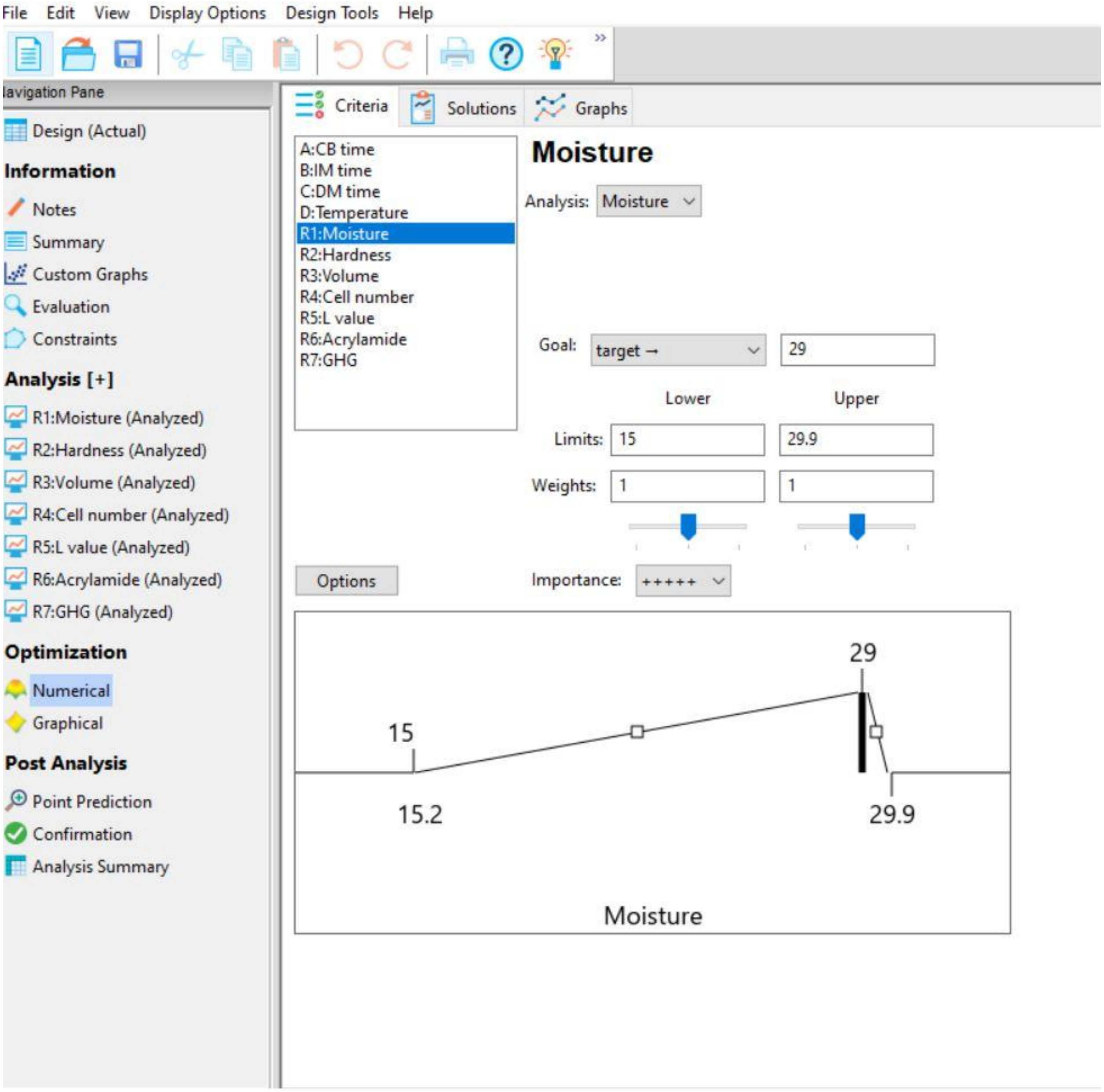
Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 48.564 indicates an adequate signal. This model can be used to navigate the design

Coefficients in Terms of Coded Factors

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	0.0393	1	0.0054	0.0278	0.0507	
A-CB time	0.0279	1	0.0030	0.0217	0.0342	6.53
B-IM time	-0.0199	1	0.0040	-0.0284	-0.0113	7.16
C-DM time	0.0019	1	0.0039	-0.0063	0.0102	6.67
D-Temperature	0.0061	1	0.0060	-0.0066	0.0187	6.94

The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are

Numerical optimisation is the next step, and in this panel the optimisation criteria for moisture content are defined. The goal is set to “target,” for each responses as shown in the following figures.



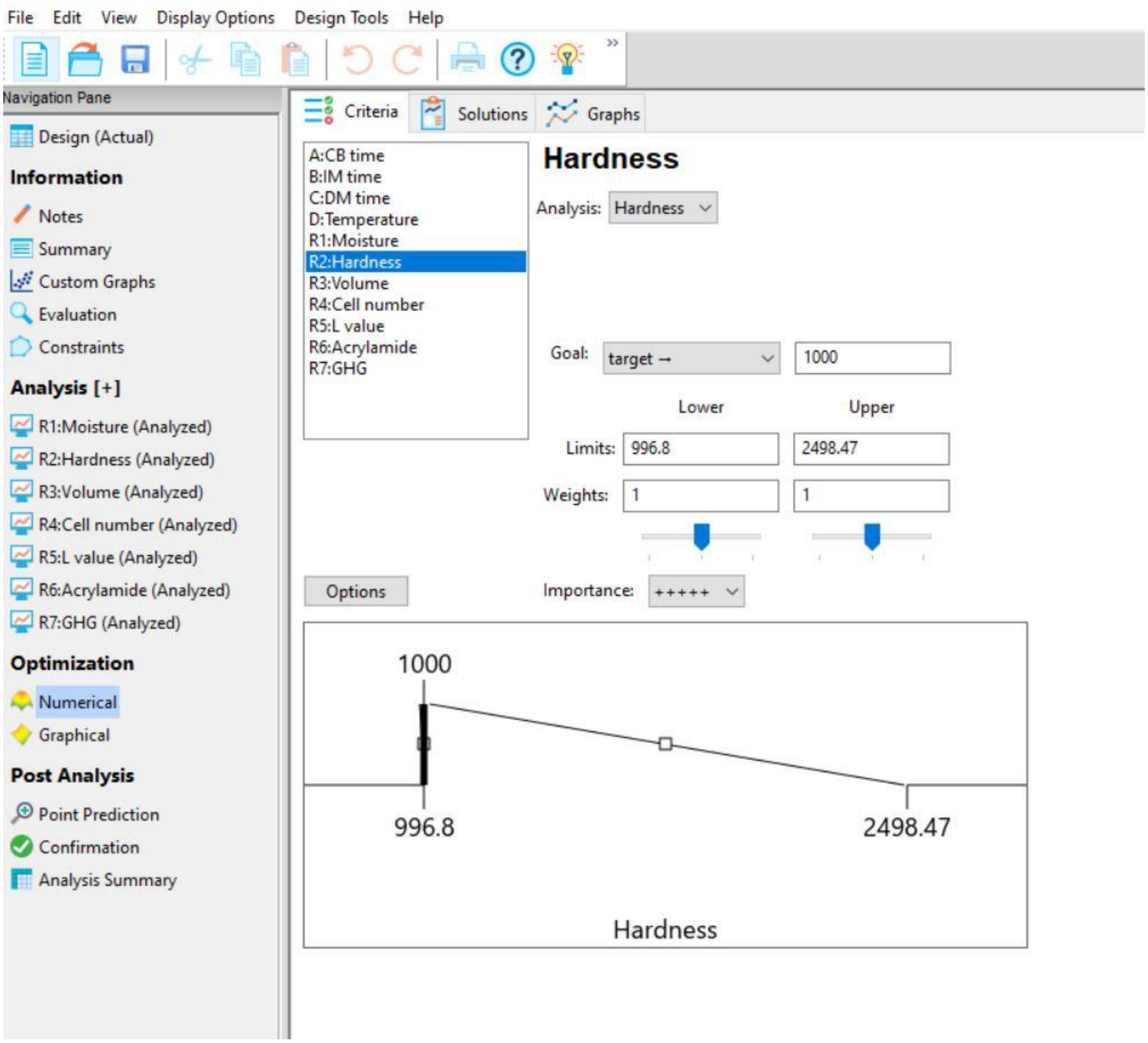
Moisture

Analysis: Moisture

Goal: target → 29

	Lower	Upper
Limits:	15	29.9
Weights:	1	1

Importance: +++++



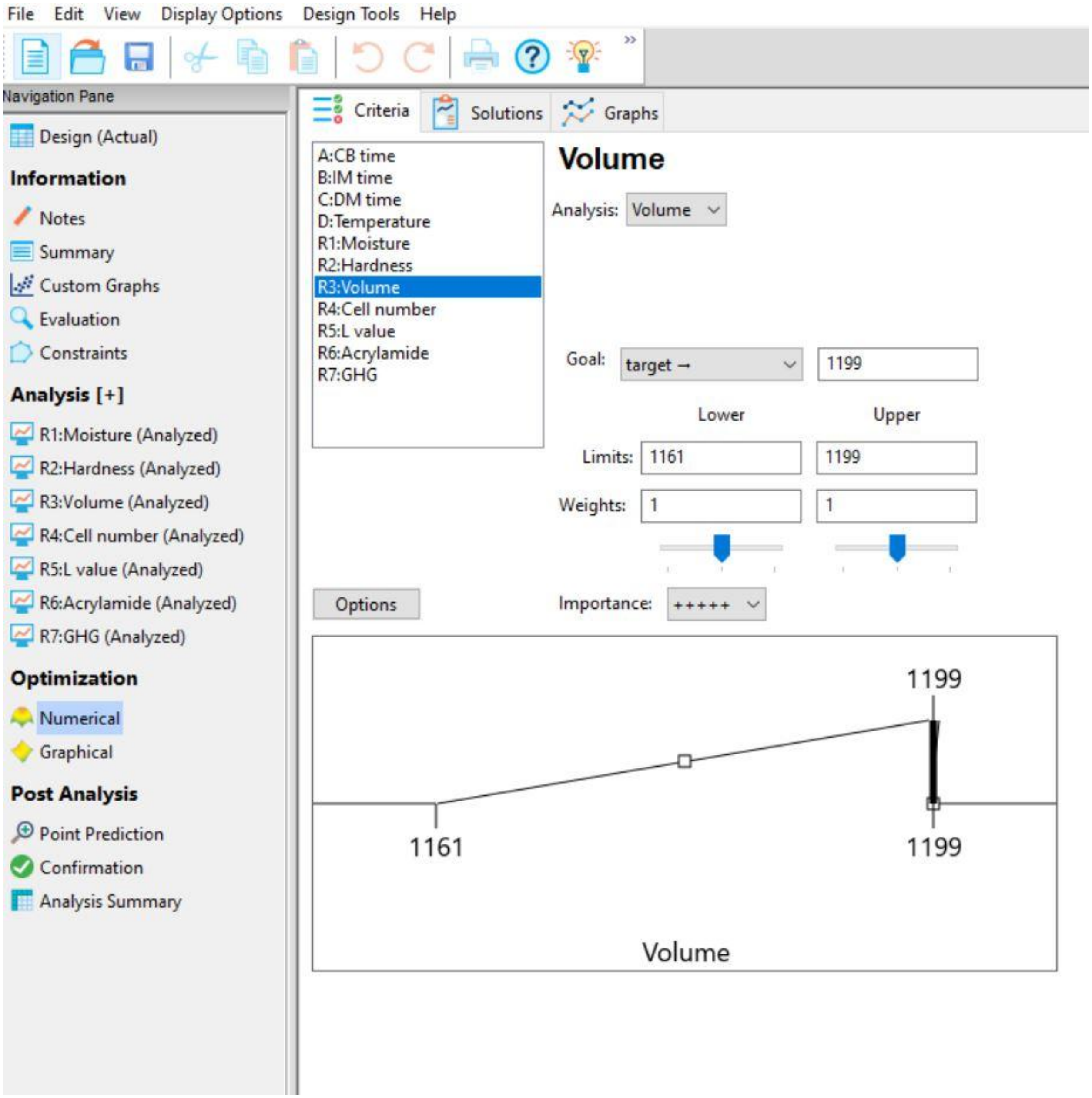
Hardness

Analysis: Hardness

Goal: target → 1000

	Lower	Upper
Limits:	996.8	2498.47
Weights:	1	1

Importance: +++++



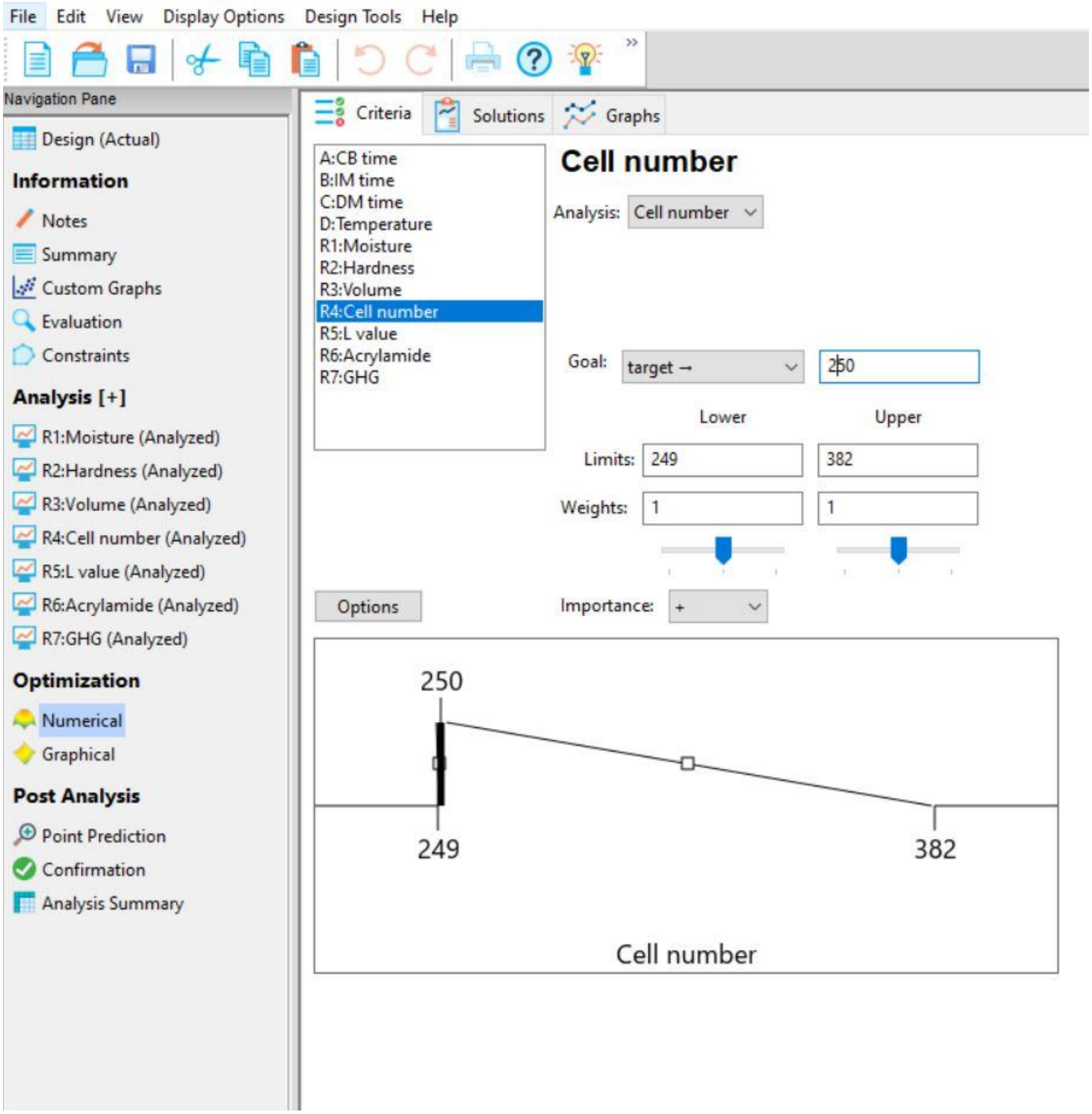
Volume

Analysis: Volume

Goal: target → 1199

	Lower	Upper
Limits:	1161	1199
Weights:	1	1

Importance: +++++



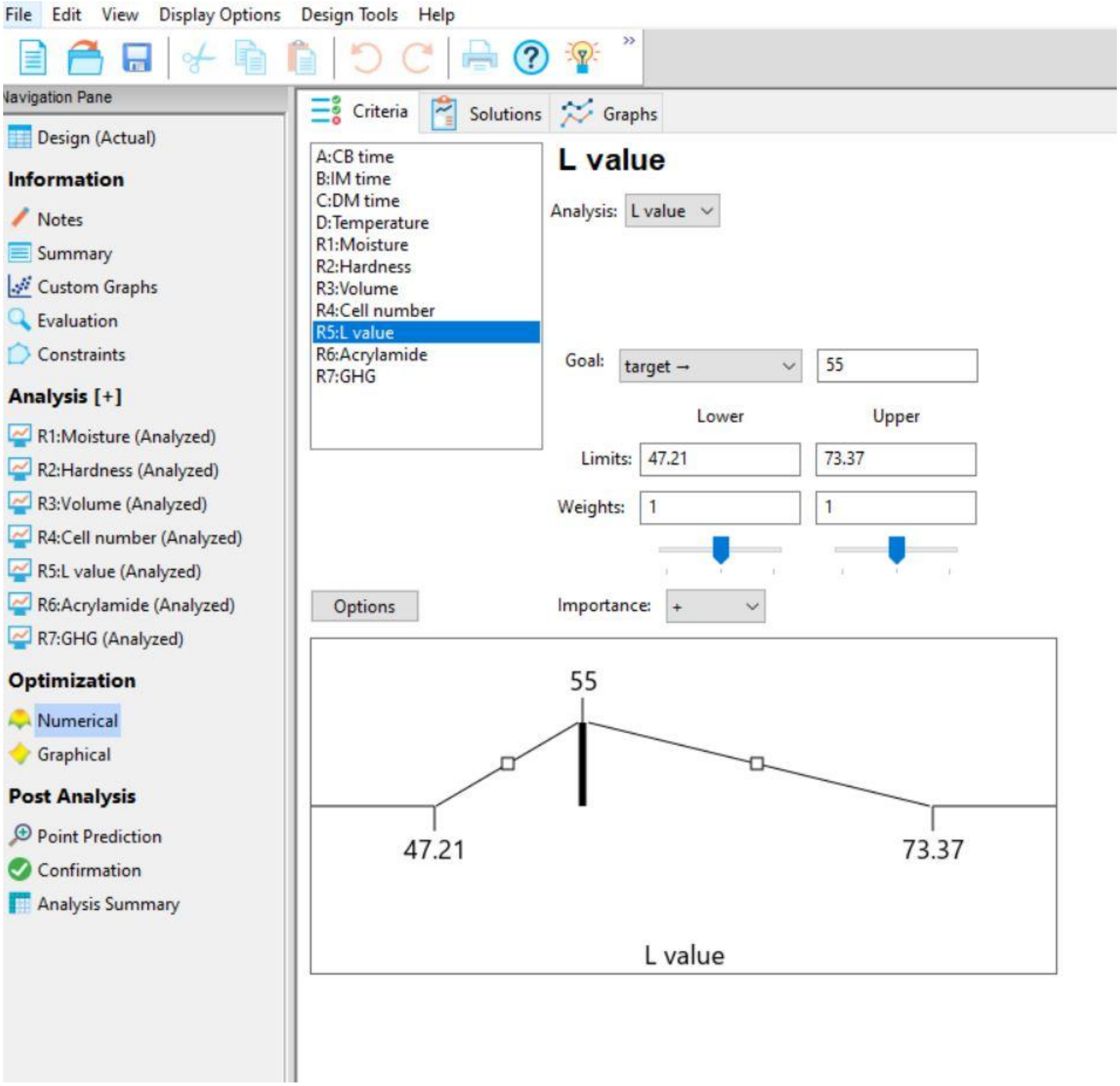
Cell number

Analysis: Cell number

Goal: target → 250

	Lower	Upper
Limits:	249	382
Weights:	1	1

Importance: +



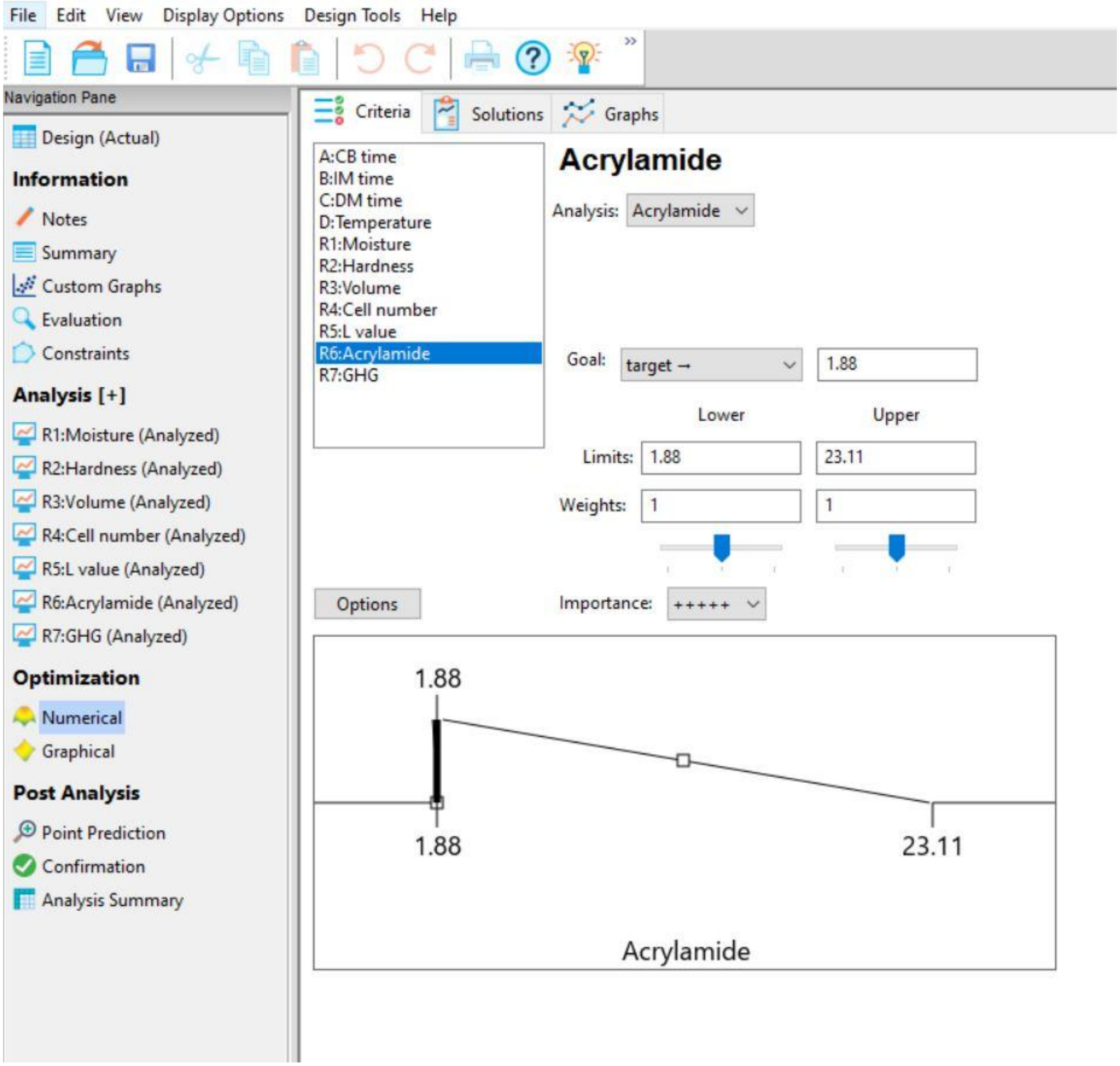
L value

Analysis: L value

Goal: target → 55

	Lower	Upper
Limits:	47.21	73.37
Weights:	1	1

Importance: +



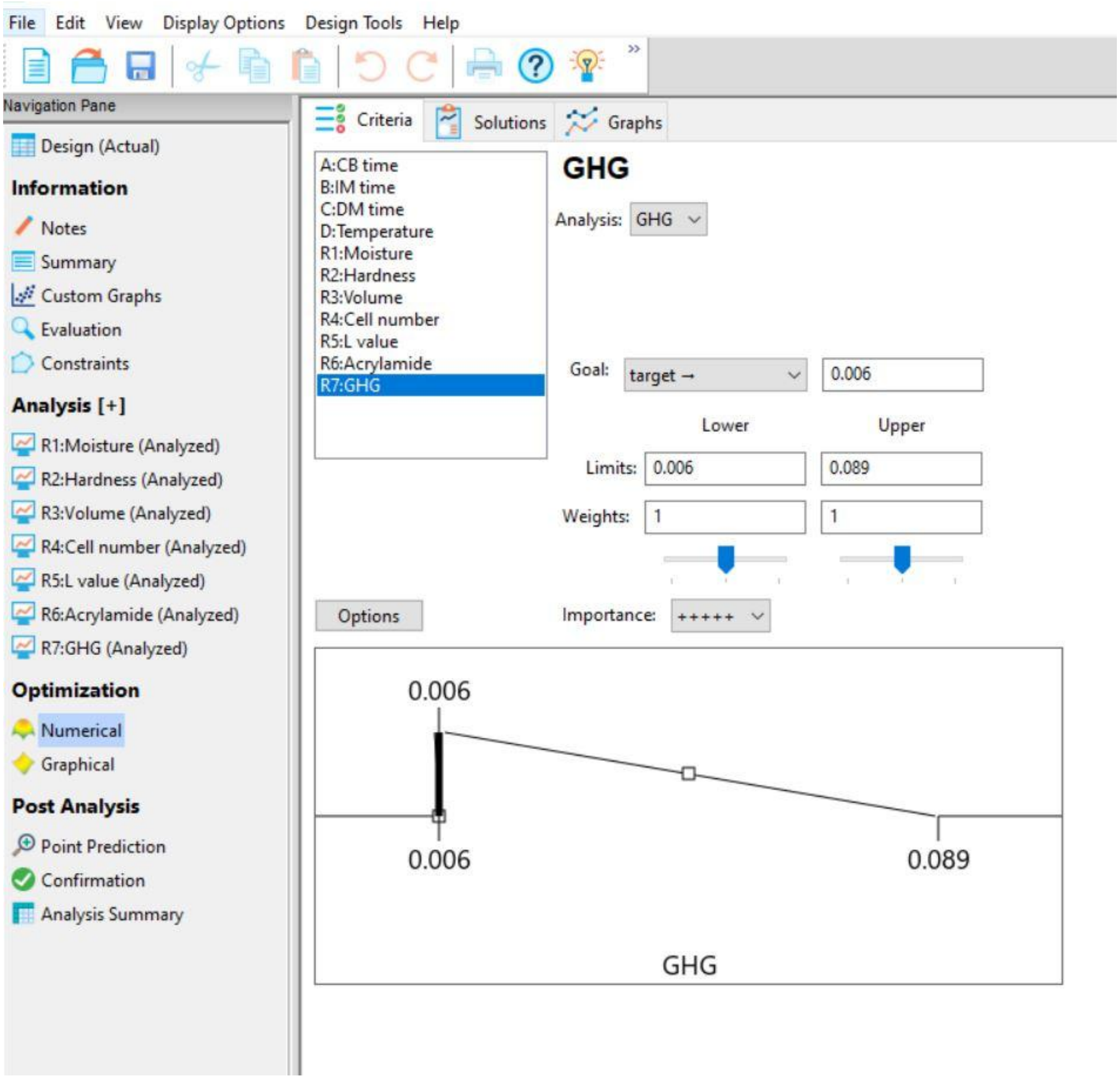
Acrylamide

Analysis: Acrylamide

Goal: target → 1.88

	Lower	Upper
Limits:	1.88	23.11
Weights:	1	1

Importance: +++++



GHG

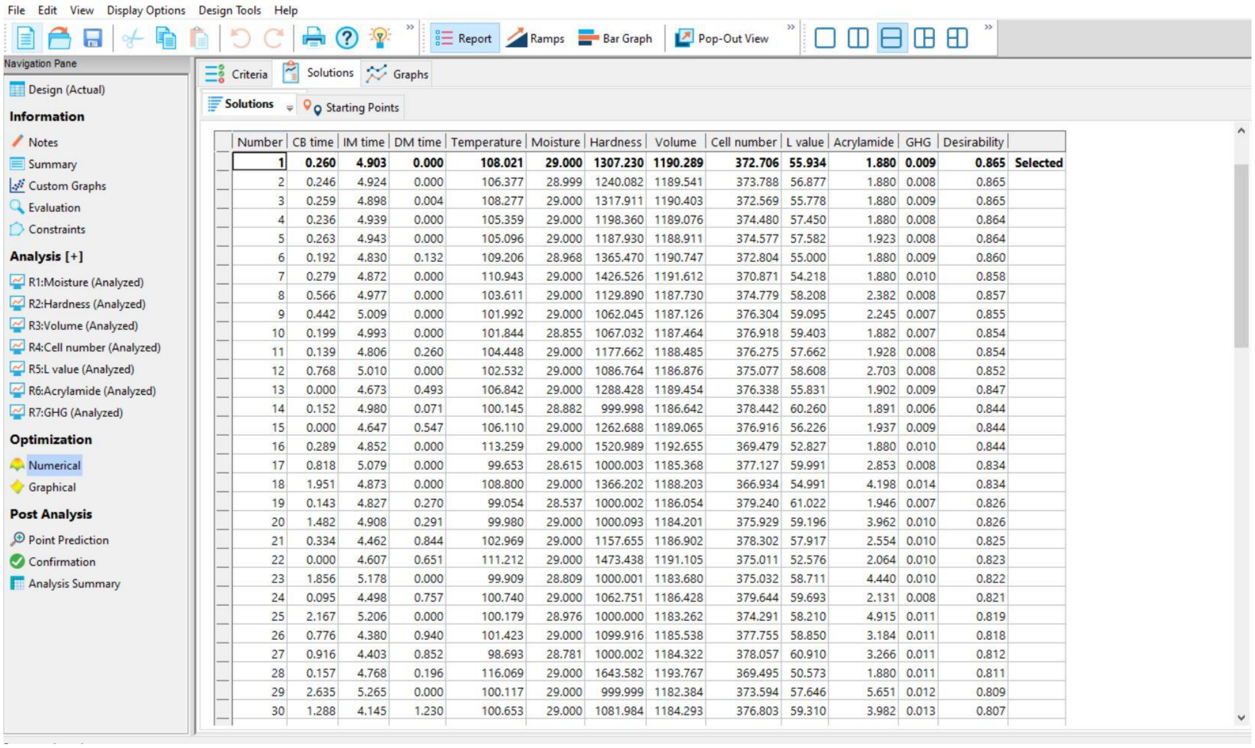
Analysis: GHG

Goal: target → 0.006

	Lower	Upper
Limits:	0.006	0.089
Weights:	1	1

Importance: +++++

This Figure below displays the predicted responses generated from the numerical optimisation process. For each solution, software calculates predicted values for moisture, hardness, volume, cell number, L value, acrylamide, and GHG emissions. The final column provides an overall desirability score, which reflects how well each solution meets the optimisation criteria defined for all responses. The solution with the highest desirability value is automatically marked as Selected, indicating it offers the best compromise among all targeted goals.



Number	CB time	IM time	DM time	Temperature	Moisture	Hardness	Volume	Cell number	L value	Acrylamide	GHG	Desirability	
1	**0.260**	**4.903**	**0.000**	**108.021**	**29.000**	**1307.230**	**1190.289**	**372.706**	**55.934**	**1.880**	**0.009**	**0.865**	**Selected**
2	0.246	4.924	0.000	106.377	28.999	1240.082	1189.541	373.788	56.877	1.880	0.008	0.865	
3	0.259	4.898	0.004	108.277	29.000	1317.911	1190.403	372.569	55.778	1.880	0.009	0.865	
4	0.236	4.939	0.000	105.359	29.000	1198.360	1189.076	374.480	57.450	1.880	0.008	0.864	
5	0.263	4.943	0.000	105.096	29.000	1187.930	1188.911	374.577	57.582	1.923	0.008	0.864	
6	0.192	4.830	0.132	109.206	28.968	1365.470	1190.747	372.804	55.000	1.880	0.009	0.860	
7	0.279	4.872	0.000	110.943	29.000	1426.526	1191.612	370.871	54.218	1.880	0.010	0.858	
8	0.566	4.977	0.000	103.611	29.000	1129.890	1187.730	374.779	58.208	2.382	0.008	0.857	
9	0.442	5.009	0.000	101.992	29.000	1062.045	1187.126	376.304	59.095	2.245	0.007	0.855	
10	0.199	4.993	0.000	101.844	28.855	1067.032	1187.464	376.918	59.403	1.882	0.007	0.854	
11	0.139	4.806	0.260	104.448	29.000	1177.662	1188.485	376.275	57.662	1.928	0.008	0.854	
12	0.768	5.010	0.000	102.532	29.000	1086.764	1186.876	375.077	58.608	2.703	0.008	0.852	
13	0.000	4.673	0.493	106.842	29.000	1288.428	1189.454	376.338	55.831	1.902	0.009	0.847	
14	0.152	4.980	0.071	100.145	28.882	999.998	1186.642	378.442	60.260	1.891	0.006	0.844	
15	0.000	4.647	0.547	106.110	29.000	1262.688	1189.065	376.916	56.226	1.937	0.009	0.844	
16	0.289	4.852	0.000	113.259	29.000	1520.989	1192.655	369.479	52.827	1.880	0.010	0.844	
17	0.818	5.079	0.000	99.653	28.615	1000.003	1185.368	377.127	59.991	2.853	0.008	0.834	
18	1.951	4.873	0.000	108.800	29.000	1366.202	1188.203	366.934	54.991	4.198	0.014	0.834	
19	0.143	4.827	0.270	99.054	28.537	1000.002	1186.054	379.240	61.022	1.946	0.007	0.826	
20	1.482	4.908	0.291	99.980	29.000	1000.093	1184.201	375.929	59.196	3.962	0.010	0.826	
21	0.334	4.462	0.844	102.969	29.000	1157.655	1186.902	378.302	57.917	2.554	0.010	0.825	
22	0.000	4.607	0.651	111.212	29.000	1473.438	1191.105	375.011	52.576	2.064	0.010	0.823	
23	1.856	5.178	0.000	99.909	28.809	1000.001	1183.680	375.032	58.711	4.440	0.010	0.822	
24	0.095	4.498	0.757	100.740	29.000	1062.751	1186.428	379.644	59.693	2.131	0.008	0.821	
25	2.167	5.206	0.000	100.179	28.976	1000.000	1183.262	374.291	58.210	4.915	0.011	0.819	
26	0.776	4.380	0.940	101.423	29.000	1099.916	1185.538	377.755	58.850	3.184	0.011	0.818	
27	0.916	4.403	0.852	98.693	28.781	1000.002	1184.322	378.057	60.910	3.266	0.011	0.812	
28	0.157	4.768	0.196	116.069	29.000	1643.582	1193.767	369.495	50.573	1.880	0.011	0.811	
29	2.635	5.265	0.000	100.117	29.000	999.999	1182.384	373.594	57.646	5.651	0.012	0.809	
30	1.288	4.145	1.230	100.653	29.000	1081.984	1184.293	376.803	59.310	3.982	0.013	0.807	