

REVIEW PAPER

# Baking a Complex Thermal Process and its Application in Food Processing—A review

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## ABSTRACT

Baking is one of the oldest and complex thermal process of food industry widely used in the manufacture of cereal-based foods such as bread, biscuits, cakes, rusks, etc. The baking process involves complex physical, chemical, and biochemical changes which collectively determined the product quality. This review paper presents a comprehensive overview of the baking process with emphasis on its fundamental mechanisms, including heat transfer, moisture migration, dough expansion, starch gelatinization, protein denaturation, crust formation, and browning reactions such as the Maillard reaction and caramelization. The role of raw ingredients and their functionality is also reviewed. The influence of critical process parameters such as baking temperature and baking time is also discussed. In addition, recent trends and developments in baking technology are highlighted.

**Keywords:** Biochemical changes, product quality, Maillard, baking technology, manufacture

The concept of baking food or baking as an industry is as old as human civilization. Baking is a thermal process that is carried out under high temperatures. Baking is the key unit operation in a bakery (Manohar, 2014). Baking of bakery products can be defined as the process which transforms dough into a product with unique sensorial features. A dough, basically made of flour, water and other ingredients such as sugars, fat, egg, leavening agent, and other additives will depend on each specific product (Purlis, 2010). Baking has historically been seen as a fusion of tradition, taste, and creativity. However, there is a complicated interaction between physics, chemistry, and food science that goes beyond aroma and aesthetic. Baking is more than simply producing a delicious loaf of bread in the modern food industry; it's also about managing transfer of heat, moisture

migration, and biochemical reactions in order to develop reliable, secure, and shelf-stable products.

Baking is the one of the oldest and most widely practiced methods of food preparation, playing central role in the global food industry. This article focuses on the science and engineering principles behind baking. It also aims fundamental concepts, techniques and technologies involved in baking process. It highlights how raw ingredients are transformed into baked products with desired textures, flavours and self-life while ensuring the safety, efficiency, and consistency in large-scale production. Baked products are considered as a staple food worldwide.

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They are essential for human nutrition as they are an important source of carbohydrates, protein, dietary fiber, vitamins, micronutrients, and antioxidants (Cappelli *et al.* 2021).

In bread making, baking is a crucial step where raw dough is converted into a light, porous, easily digestible, and flavourful product through the application of heat. To achieve the desired quality attributes, the baking process must be carefully controlled. A typical bread-baking process can be described in three stages. During the initial stage, which accounts for about one-fourth of the total baking time of 26 minutes. The outer crumb temperature gradually increases to around 60 °C. It enhances enzyme activity and yeast fermentation, resulting in oven spring. The volume increases by one-third of the original while the surface begins to lose elasticity and show browning. In the second stage, the crumb temperature rises rapidly at a rate of 5.4 °C per minute to approximately 98–99 °C. At this stabilized temperature, all reactions are maximised, including moisture evaporation, starch gelatinisation, and protein coagulation. It leads to the formation of a stable crumb structure as heat penetrates from the outer to inner regions. Simultaneous crust development and browning become evident as surface temperatures reach 150–205 °C. The final stage, occupying the remaining one-fourth of the baking time, is characterized by the volatilization of organic compounds, commonly referred to as bake-out loss, which contributes to flavour development and final moisture reduction in the bread (Therdthai *et al.* 2002).

### **Market potential and production status of bakery products**

Bakery products are popular food among all age groups. Baked goods are an essential part of human daily life (Olakanmi *et al.* 2024). India is the second-largest food producer in the world after China. The bakery industry is an important part of India's processed food sector. Because of busy lifestyles, changing food habits, and Western influence, people are buying more bakery products. According to

IMARC Group, the Indian bakery market is expected to grow at a moderate rate between 2020 and 2025 (Deshmukh and Soans 2019). The growing population is resulting in the increasing demand for bakery food products in India. Besides this, bakery products offer convenience and affordability to consumers, thereby gaining immense popularity across India.

According to the International Market Analysis Research and Consulting Group (IMARC) bakery market analysis report: (1)The global bakery products market size reached USD 532.6 Billion in 2024. Looking forward, IMARC Group expects the market to reach USD 701.1 Billion by 2033, exhibiting a growth rate CAGR of 3.1% during 2025-2033. Europe currently dominates the market, holding a market share of 36.3% in 2024.(2) The Indian bakery market size reached USD 13.8 Billion in 2024. It is expected to grow to USD 31.5 billion by 2033, growing at a rate of 9.12% per year from 2025 to 2033. This growth is mainly due to increasing urbanization, higher income levels, and rising demand for ready-to-eat and convenient food products. The fast growth of organized retail stores and changing consumer preferences for healthier and premium bakery products are also supporting market growth.

### **Ingredients and its Functionality in Formulations**

Each ingredient in a baked product serves more than just taste.

#### **1. Flour**

Flour, typically derived from wheat, rye, corn and rice which provides the structural framework to bread and baked goods. Flour supplies the structural framework through gluten. Among the cereal flours, wheat flour is special because, when combined with water in the right amounts, the protein will create an elastic dough that can hold gas and will set to a spongy structure when baked (Lauterbach *et al.* 1994). Several factors influence the baking performance of wheat flour. Flour quality, which depends on the characteristics of the grain used for milling, is affected by the wheat genotype (cultivar) as well as the growing environment and agronomic practices

during cultivation. The baking value of flour is also influenced by post-harvest conditions, including grain storage, milling methods, and flour storage. Among agronomic factors, nitrogen fertilization is particularly important because it affects both the quantity and quality of wheat proteins, especially gluten proteins, as reported in numerous studies (Wysocka *et al.* 2024). Wheat flour is the primary ingredient in bread making. During bread making, wheat flour is mixed with water to form dough, noticeable macroscopic changes occur. The dry flour particles hydrate to form a sticky and seemingly uniform paste. With continued mixing or kneading, this paste gradually incorporates the remaining flour particles and develops into a cohesive, elastic, rubber-like dough. These transformations typically occur within a few minutes of mixing, usually around five minutes (Schiraldi, A. and Fessas, D. 2012).

## 2. Water

Water plays different roles in the process of manufacturing of bakery products. A sufficient amount of water must be absorbed by gluten proteins before gluten is formed. Water affects the rheology of the dough and plays a crucial role in the production of gluten. Bakery products have a various amount of water, depending of their specific. The main roles of water in bakery production imply conservation and shelf life of products (Tulbure *et al.* 2013).

Water is a major ingredient in bread making and, by weight, is the second most important constituent after starch in many bakery products. After baking, water plays a crucial role in determining product shelf life, as it strongly influences texture, microbial stability, and overall quality during storage (Tulbure *et al.* 2013). Water plays a critical role in the major transformations that occur during dough baking, including starch gelatinization, protein denaturation, yeast and enzyme inactivation, and flavour and colour development. Both the water content and its distribution strongly influence the shelf life of bread, affecting microbial stability, crumb softness, crust crispness, crumb firming, crumbliness, and other changes associated with staling and reduced

consumer acceptance. Additionally, water functions as a universal solvent, dissolving salt, sugar, and other ingredients and providing the medium in which fermentation reactions take place. Yeast cells require water to metabolize sugars and produce carbon dioxide, which is responsible for dough expansion. Likewise, enzymes naturally present in flour depend on water for their activity, hydrolysing starch into simpler sugars that support yeast fermentation. Water accounts for approximately 40% of standard bread dough and more than 35% of baked bread. Water absorption and dough development are further influenced by the ingredients used in bread making; for instance, increasing salt (sodium chloride) concentration raises water absorption and dough development time, likely due to reduced protein water-holding capacity, whereas fats lower the hydration capacity of dough (Czuchajowska *et al.* 1989).

## 3. Leavening agents

Leavening is an important step in the bread production process. A leavening agent is defined as a substance that causes the expansion of batter or dough, resulting in baked products with larger volume and a porous texture, primarily through the production of gases such as air, steam, and carbon dioxide. Traditionally, *Saccharomyces cerevisiae* has been used as the primary biological leavening agent, converting sugars into carbon dioxide and alcohol through fermentation. Native yeast fermentation is relatively slow, typically requiring around 8 hours, whereas engineered yeast strains, developed using DNA technology, significantly reduce fermentation time to approximately 0.5–1.0 hour. In addition to biological leavening, baking powder has been used as a chemical leavening agent for over a century. It is composed mainly of sodium bicarbonate, potassium bitartrate, and cornstarch, and upon the addition of water, sodium bicarbonate reacts with potassium bitartrate to release carbon dioxide gas, contributing to dough aeration (Garcia-Hernandez *et al.* 2022).

Leavening agents are responsible for expansion of dough and batter by release of gases within the

food mixture during baking. It will help to create porous structure and texture to the baked product. In conclusion the leavening agents are used to achieve a light and crunchy texture and to increase the volume and porosity of baked foods like cakes, breads and cookies. They include air, steam, yeast, baking powder, baking soda, etc (Neeharika *et al.* 2020).

#### 4. Sugars

Sugar not only enhances sweetness but also influences color, moisture retention, and shelf life. On addition of small amount of sugar help yeast to raised dough. Sugar plays a critical role in bread fermentation by serving as an energy source for yeast. The commonly used baking yeast, *Saccharomyces cerevisiae*, metabolizes sugars to produce carbon dioxide and alcohol through fermentation. While moderate sugar levels can accelerate fermentation, excessive sugar concentrations may inhibit yeast activity due to osmotic effects, where water is drawn out of yeast cells. Conversely, insufficient sugar slows fermentation, resulting in denser bread with reduced volume. Therefore, understanding the influence of sugar concentration on yeast activity is essential for optimizing bread texture, flavour, and loaf expansion (Gardner, 2025).

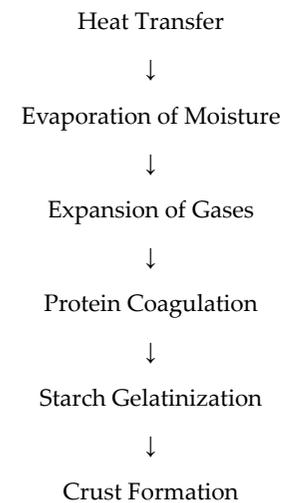
#### 5. Fat

Fat has significant roles in baking, including shortening, creaming, imparting taste, and creating an emulsion with other ingredients baked (Lauterbach *et al.* 1994). Fats act as shortening agents in dough, where the term *shortening* refers to their ability to lubricate and weaken the structural network of food components, thereby improving texture. In baked products, fats play a vital role in imparting desirable textural characteristics by interacting with other ingredients to influence dough structure, mouthfeel, and overall lubricity. These interactions contribute significantly to the softness, tenderness, and sensory quality of the final product (Mamat and Hill, 2014). Fats and oils are important components in bread formulation, added primarily to improve loaf quality. Their inclusion enhances loaf volume

and delays the onset of staling, thereby contributing to improved freshness and extended shelf life (Smith and Johansson., 2004).

#### Changes occurred in baking products during baking process

During baking, dough undergoes many physical and chemical changes, including: evaporation of water; dough-crumb transition; formation of crumb and crust structures; volume expansion; protein denaturation; and starch gelatinization (Yin & Walker, 1995). Fig. 1 shows the changes taking place during the baking process.



**Fig. 1:** Changes taking place during the baking process

These changes are responsible for the development of the final texture, structure, flavour, and colour of bakery products.

#### Heat Transfer

During baking, heat penetrates from the surface to center of the product. Transformation of batters and doughs into baked goods occurs with the interaction of heat during baking, which results in the formation of firm dry crust and softer center. The effect of heat on raw dough leads to light, porous, and flavourful bakery products. Common baked foods such as bread, cakes, and cookies are produced through this transformation of semi-fluid dough or batter during baking. Various properties of the product like specific

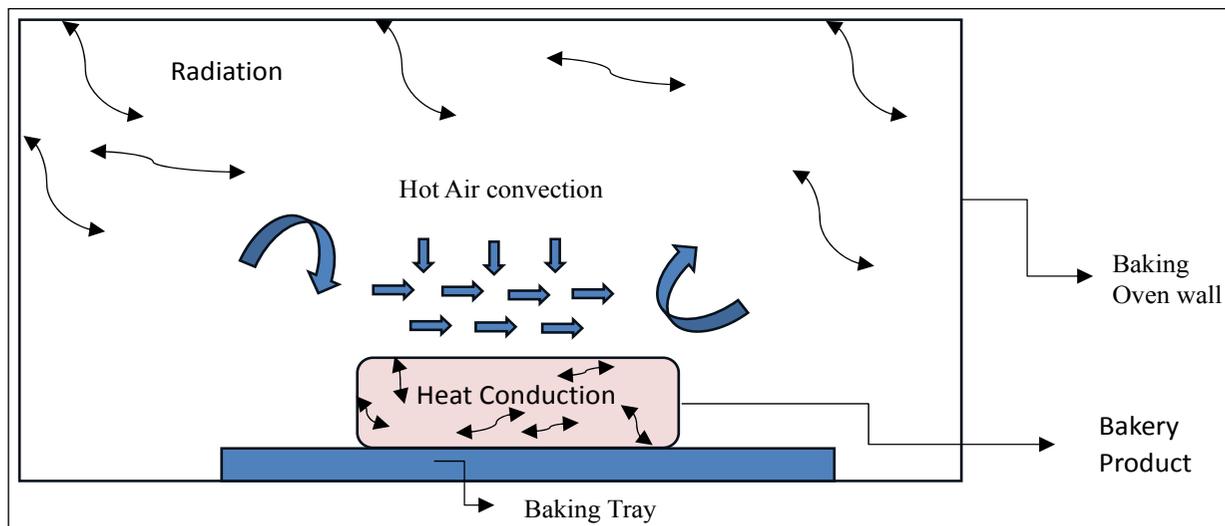
heat, thermal conductivity, thermal diffusivity and moisture diffusivity, influence temperature and moisture simulation of the product during baking (Chakraborty and Dash, 2023).

Using heat in food preparation allowed humans to unlock helpful nutrients and kill harmful bacteria. As soon as product kept in the oven moisture evaporates and baking started. An oven used for baking is a heated enclosure that cooks food evenly. Industrial baking oven conditions are usually generated using the three modes of heat transfer: radiation, convection and conduction. During baking, heat is transferred

mainly by convection from the heating media, and by radiation from oven walls to the product surface followed by conduction to the geometric center (Sablani *et al.* 2002). Table 1 shows the various mechanisms for the modes of heat transfer. Baking is governed by simultaneous heat and mass transfer processes occurring within the product and between the product and the oven environment. Heat is transferred to the product through multiple mechanisms acting concurrently. Fig. 2 shows the Mechanism of heat transfer during baking process inside the baking oven.

**Table 1:** Mechanism of heat transfer

Mode of Heat Transfer	Source	Role
Radiation	Emission of thermal energy through oven walls, heating elements, and surrounding hot surfaces.	Heat is transferred by thermal radiation from hot oven walls and heating elements to the product surface. This mechanism dominates at high temperatures and contributes significantly to rapid surface heating and crust formation.
Convection	Circulation of hot, humid air within the oven chamber.	Heat transfer occurs through the movement of hot air around the product. Regulates heat exchange at the product surface, controls moisture evaporation, and ensures uniform temperature distribution for uniform baking.
Conduction	(i) Direct contact between the product and the carrier medium (baking tray, mould, or conveyor band) (ii) Heat transfer within the product matrix from the surface toward the core	Heat is transferred through direct contact between the product and heated carrier surfaces and further conducted internally within the product



**Fig. 2:** Mechanism of heat transfer during baking process inside the baking oven

The relative contribution of each heat transfer mechanism depends on the product characteristics and oven configuration. These mechanisms can be used to regulate moisture loss and achieve the desired quality attributes in the final baked product (Marcotte, 2007).

The major factors associated with the heat distribution in the oven chamber include the air flow, the heat supply, the humidity, the oven load and the baking time. Product quality depends on the amount of heat absorbed by the product during baking. The rate of heat absorption varies significantly during baking operation. In beginning product is at room temperature leading to rapid absorption of heat as it suddenly exposed to the high temperature of oven. The heat absorbed by the product in the initial phase will initiate a number of mechanisms and will lead to the temperature rise in the product which determines the quality of the finished product. As baking continues, the temperature difference between the product and the oven decreases, resulting in a lower rate of heat absorption during the later stages of baking (Boulet *et al.* 2010).

During baking, bread undergoes a series of distinct physical transitions, in which the dough turns into crumb and then into crust. These transformations are driven by simultaneous heat and mass transfer processes occurring within the product (Nicolas *et al.* 2014).

### Evaporation of Moisture

Along with heat transfer, moisture moves out of the product (Marcotte M. 2007). The mass transfer phenomena are also significant and involve evaporation, condensation and diffusion (Boulet *et al.* 2010). Moisture phase change (MPC), a key process in bread baking, significantly impacts heat and mass transfer (Zhang *et al.* 2025). As baked goods are heated, the moisture content within the dough or batter begins to evaporate, creating steam (Xue & Walker, 2003). Many studies have shown that, during baking, heat and mass transfer occur at the same time. As the product is heated, moisture and other liquid components move from the inner core toward the

surface (Suchintita *et al.* 2023). This happens mainly because water at the surface evaporates, creating a moisture difference between the inside and the surrounding air. Moisture moves inside the product by diffusion, while at the surface it is removed by convective mass transfer to the hot air. Both internal diffusion and external convection strongly influence product quality. Therefore, accurate knowledge of mass transfer parameters is essential for optimizing the baking process and producing bakery products with better texture, moisture content, and overall quality. During baking, the moisture distribution within baked products is influenced by both baking time and temperature and is strongly governed by mass transfer mechanisms. To optimize the baking process and achieve uniform moisture distribution, it is essential to understand the mass transfer parameters and how they change with baking time and temperature (Demirkol *et al.* 2006).

During baking, heat moves toward the centre of the product and causes water to move inside it, leading to changes in moisture distribution. Water moves in two directions at the same time: one part moves toward the centre due to heat penetration, while another part moves toward the surface where moisture is lost. As soon as the product enters the oven, water at the surface starts to evaporate because of the high temperature. At the surface, rapid evaporation takes place due to high temperature, leading to drying of the outer layers. Beneath this region, water vapour diffuses through the porous structure toward the surface, while liquid water migrates from the core due to moisture gradients. Because internal moisture diffusion is slower than surface evaporation, a drying zone develops and increases in thickness over time, resulting in crust formation (Wagner *et al.* 2007).

### Expansion of Gases

Dough expansion is caused due to water evaporation as well as production and thermal expansion of gases. Expansion is an important event in texture formation. It is determined by the rheological properties of batter, which depend on the behaviour and interactions of its components and the solubility

of gas in the continuous phase (Chevallier *et al.* 2002). Leavening agents are responsible for the expansion of doughs and batters by releasing gases inside the food product. It causes formation of a porous structure in baked products. These agents help develop the desired structure and texture by causing gas expansion, either through chemical reactions or by providing sites where gas bubbles can form. Leavening can occur in different ways, such as through yeast fermentation, mechanical incorporation of air during mixing or creaming, the formation of water vapour during baking, and the release of gases like carbon dioxide or ammonia from chemical leavening agents (Neeharika *et al.* 2020). At the initial stages of baking, the dough undergoes rapid expansion due to a sudden increase in internal pressure. As the temperature rises, yeast activity reaches its maximum, producing carbon dioxide; additional carbon dioxide may also be generated from chemical leavening agents. With further heating, yeast activity gradually decreases and the yeast becomes inactive at around 55 °C. At the same time, carbon dioxide dissolved in the liquid phase of the dough is released into the surrounding gas cells. The gases trapped within these cells, including air and carbon dioxide formed during mixing, shaping, and proofing, expand due to the increasing temperature, contributing to overall dough expansion (Suchintita *et al.* 2023).

During baking, the rise in temperature increases the release of carbon dioxide from the dough, causing it to move from the liquid phase into the gas phase. Existing air bubbles in the dough act as nucleation sites, where carbon dioxide accumulates and gradually enlarges the bubbles. As baking continues, these gas bubbles grow, merge with one another, and become fewer in number but more varied in size. Toward the later stages of baking, when the temperature of the outer regions of the dough reaches the boiling point of water, water vapour is generated. The pressure of this vapour provides an additional driving force for further dough expansion until the crumb structure begins to set. Increasing temperature raises internal gas pressure, which further promotes

bubble expansion. However, once the cell walls open and the crumb structure starts to set, gas escapes rapidly, leading to a reduction in internal pressure and the end of dough expansion (Miś *et al.* 2016).

### Protein Coagulation

Protein coagulation refers to the irreversible transformation of proteins from a fluid or flexible state into a solid, set structure. This process begins as temperature rises, typically starting at about 38 °C, and is largely completed between 71 °C and 82 °C. During baking, heat induces permanent changes in protein structure through a combination of physical, chemical, and biochemical interactions. These heat-driven transformations cause proteins to denature and aggregate, leading to coagulation that contributes to the setting of the product structure and the development of final texture. Wheat flour mainly contains two storage proteins, glutenin and gliadin, which are also present in smaller amounts in other cereals. When flour is mixed with water, these proteins interact to form gluten, a viscoelastic network that gives dough its stretchability. During baking, heat causes the gluten proteins to coagulate, leading to firming and hardening of the gluten network. This heat-induced coagulation results in the solidification of the protein structure, which helps set the dough and contributes to the formation of a stable crumb structure in baked products (Hong *et al.* 2025).

During baking, the heat causes the protein molecules in bakery products to vibrate, and this movement disrupts the bonds that maintain the protein's three-dimensional structure. As a result, the protein molecules unfold and lose their shape, which can affect the texture, flavour, and appearance of the product. The extent of denaturation depends on several factors, such as the type of protein, the baking temperature, and the baking time. At 74 °C the gluten starts to coagulate, and the chains of protein begin to solidify. This process is called gluten coagulation. Gluten matrix surrounding the individual cells is transformed into a semi-rigid film structure (Das *et al.* 2023).

The glutenin polymer structure, size distribution, subunit composition and the gliadin/glutenin ratio are major factors in determining dough quality and, hence, the breadmaking potential of wheat flour (Wang *et al.* 2017).

### Starch gelatinization

Starch gelatinization refers to a series of changes that occur in starch granules when they are heated in the presence of water. Initially, the granules absorb water and begin to swell. As heating continues, they expand to several times their original size, and finally, starch components are released from the granules, leading to the formation of a viscous and structured matrix (Sakiyan *et al.* 2011). The formation of a viscous solution or a gel during starch gelatinization mainly depends on the starch-to-water ratio. However, it is also influenced by processing conditions such as temperature, heating rate, and the mechanical stresses applied during processing (Sakonidou *et al.* 2003). The gelatinization behaviour of starch is extremely important in baked products because it strongly influences product setting and texture. The temperature at which starch gelatinizes and the extent of gelatinization determine how the structure of the product develops during baking. Both sufficient water and heat are required for starch gelatinization to occur. Small solutes such as sugar and salt reduce water availability in the system, which raises the temperature needed for starch gelatinization. In addition, sugars can interact directly with starch molecules in the amorphous regions of the granules, further contributing to an increase in gelatinization temperature (Ghiasi *et al.* 1983). The gelatinization temperature of starch, therefore, depends on the crystal stability (van Rooyen *et al.* 2023). Baking temperature and time significantly affect the degree of starch gelatinization. Since starch gelatinization involves the absorption of water, higher baking temperatures and longer baking times promote a greater extent of gelatinization, leading to increased moisture retention in bread (Faridi and Rubenthaler, 1984).

Starch is the major component of the flour. Hence it plays important role in textural quality of freshly baked products. The main factors controlling the extent of starch gelatinization were baking absorption, temperature and time (Lineback *et al.* 1980). Watson and Johnson (1965) found that susceptibility of starch to  $\beta$ -amylase after 30 min of baking indicated that the starch had undergone maximum gelatinization at the temperature attained and with the moisture available in the bread.

### Crust Formation

The crust refers to the outer region of the bread, close to the surface, where the structure is denser and firmer than the inner crumb. The texture of baked bread and the processes that control it are key concerns for bread manufacturers (Jefferson *et al.* 2006). Although the crust and crumb originate from the same dough, they develop different final characteristics because they experience different heat and moisture conditions during baking. When the dough is placed in the oven, water evaporates rapidly from the surface layers, leading to a much lower moisture content at the surface (below 20% on a wet basis) compared to the inner core (Vanin *et al.* 2009). Bread crust is formed due to drying of bread surface and the consequent heat-induced chemical reactions, especially Maillard reaction (Vanin *et al.* 2009). When the product is placed in the oven, water near the surface starts to evaporate due to heat, absorbing energy and causing the outer layers to dry. Below this drying layer, water vapor moves through small connected pores toward the surface because of differences in vapor concentration. At the same time, liquid water moves from the center of the dough toward the surface. Since water evaporates at the surface faster than liquid water can move from the center, a dry layer gradually forms and becomes thicker, leading to crust formation.

The formation of the crust limits dough expansion during baking. As a result, crust thickness influences bread volume, crumb structure, and the size of air bubbles, which are key factors in determining bread quality. Crust formation is closely related to moisture

loss during baking, and greater moisture loss leads to a thicker crust, which further affects how much water can evaporate from the dough. (Soleimani Pour-Damanab *et al.* 2014).

### Role of Temperature and Time in Baking Process

Bread baking is a complex process involving numerous physical, chemical, and biochemical interactions. Baking fundamentally involves the conversion of raw ingredients into a palatable and visually appealing final product through a series of complex physical and chemical processes. Temperature plays a critical role at every stage of this transformation, from the initial mixing of ingredients to the final stages of baking in the oven (Dcosta, 2024). The optimum baking conditions, such as time and temperature, vary depending on the type of product and its specific formulation. The oven is therefore rightly regarded as the “heart of the bakery”, as it brings about the final transformation of raw dough into bread through the application of heat. Achieving baked products with the desired quality attributes thus requires a carefully controlled baking process (Yin and Walker., 1995). In an industrial bread making, bread is usually baked in an oven set at a constant temperature. The vital influence on final product quality includes the rate and amount of heat application, the humidity level in the baking chamber and baking time. However, because of the oven design, the bread actually passes through four main temperature zones during baking. The temperature in each zone plays a key role in different baking processes such as starch gelatinization, enzyme activity, and browning reactions. These temperature-dependent changes together determine the final quality of the bread (Therdthai *et al.* 2002). Surface colour development during baking, resulting from Maillard reactions and sugar caramelisation, is strongly governed by the time–temperature profile at the crust. In contrast, the time–temperature profile at the slowest heating point (core) controls the transformation of dough into crumb, primarily through the kinetics of starch gelatinisation. Time–temperature profiles have also been widely applied

to develop kinetic models for evaluating thermal inactivation of enzymes and probiotics, as well as the thermal degradation of anthocyanins during bread baking. Similarly, the formation of process-induced contaminants, such as acrylamide and 5-hydroxymethylfurfural (HMF), depends largely on the product’s thermal history, among other factors. Since these temperature-dependent changes directly influence the sensory and nutritional quality of baked products, time–temperature profiles are essential tools for the design, control, and optimisation of the baking process (Purlis, 2023).

Baking temperature and time are two key factors that determine the final quality of baked products. They strongly influence product characteristics such as crust colour and thickness, loaf volume, crumb cell structure, moisture content, firmness, and shelf life. In the bakery industry, product colour is an important marketing attribute, as it directly affects consumer purchasing decisions. Increasing baking temperature and time generally leads to darker crust colour and reduced colour saturation, along with an increase in crust thickness. Higher baking temperatures tend to result in greater initial moisture retention, whereas longer baking times reduce the initial moisture content of bread. Crumb firmness shows a positive correlation with both baking temperature and time, increasing as these parameters rise. The use of higher baking temperatures can be advantageous, as breads with higher initial moisture content exhibit slower moisture loss during storage, thereby improving shelf life. Overall, results from baking studies indicate that baking temperature has a greater impact on bread properties than baking time (Jusoh, 2008). Breads baked at higher temperatures for shorter durations generally exhibited better overall quality than those baked at lower temperatures for longer times, although separation of the upper and lower crusts occurred under all baking conditions. These observations suggest that pocket formation is influenced more by dough moisture content than by oven temperature. In contrast, longer baking times at lower temperatures produced drier breads with rough, dry crumb structures and failed to

develop desirable crust characteristics (Faridi and Rubenthaler, 1984).

Apart from baking temperature and time, air flow plays a crucial role in ensuring uniform temperature distribution, which significantly influences the quality of the finished product. Adequate air flow enhances convective heat transfer, shortens baking time, and improves overall oven performance. Different types of baking ovens such as tunnel ovens, pilot plant ovens, microwave-combination ovens, and electric ovens operate with varying air-flow rates, leading to differences in temperature distribution within the oven chamber and, consequently, product quality (Azmi *et al.* 2019). The overall quality of bakery products is strongly influenced by changes in moisture content, which vary as a function of key process parameters such as time and temperature. Consequently, moisture content is a critical factor governing the quality of baked products (Šarić *et al.* 2014).

#### **Browning in bakery products**

Colour development in bakery products during baking, commonly referred to as browning, is one of the most important quality attributes perceived by consumers. The external appearance of baked goods is often the first indicator of quality and plays a decisive role in consumer acceptance or rejection. Surface colour formation during baking is a desirable characteristic and primarily results from non-enzymatic browning reactions, namely Maillard reactions and sugar caramelisation. The characteristic brown colour arises from the formation of melanoidins, which are insoluble brown pigments, and caramel compounds. However, these reactions may also lead to the formation of undesirable compounds with potential health concerns, such as acrylamide, hydroxymethylfurfural (HMF), and furfural, along with a reduction in nutritional value. Changes in surface colour are therefore widely used as a key indicator of baking completion. As browning strongly influences overall product quality, it affects both sensory attributes and nutritional properties, including protein and amino acid bioavailability,

formation of process-induced contaminants, and the generation of compounds with antioxidant activity. During the baking of bakery products, crust formation occurs alongside progressive colour development. The initial change in crust colour begins with the appearance of light yellow dextrins when the surface temperature reaches approximately 110–120 °C. As the temperature continues to rise, Maillard reactions and caramelisation take place, leading to the formation of melanoidins and caramel compounds, while excessive heating may result in product combustion and the development of a black, porous mass. The rate of surface colour development is primarily governed by baking temperature and time; however, it is also significantly affected by other factors such as moisture content, water activity, pH, and the concentration of reducing sugars (Lukinac *et al.* 2022).

The Maillard reaction is associated with a reduction in digestibility and the possible formation of toxic and mutagenic compounds, while also contributing to the generation of antioxidant compounds. Caramelisation refers to a complex set of reactions resulting from the direct heating of carbohydrates, particularly sucrose and reducing sugars. In food systems such as bread, which contain both reducing sugars and amino groups, Maillard reactions and caramelisation can occur simultaneously during heating. Both reactions are strongly influenced by temperature, water activity, and pH (Purlis and Salvadori, 2009 and Purlis, E. 2010).

#### **Storage of bakery Products**

The shelf-life of bakery product can be short as a few hours as well as long as a year. It depends on the type of product, storage and packaging condition. The shelf life of bakery products is limited by physiochemical and microbial factors and is highly dependent on their moisture content (Giannou *et al.* 2014). According to (Smith *et al.* 2004) Spoilage in bakery products can be classified into three main types:

1. Physical spoilage, which includes moisture loss and staling of the product.

2. Chemical spoilage, mainly caused by rancidity of fats.
3. Microbiological spoilage, which occurs due to the growth of yeast, molds, and bacteria.

The type of spoilage that occurs most depends on several inter-related factors. These include storage temperature, relative humidity, the amount of preservatives used, pH of the product, type of packaging material, and the gaseous environment around the product. Among all these factors, moisture content plays the most important role.

#### **Recent development in bakery**

The industrial baking sector is rapidly transforming with innovations in automation, artificial intelligence, and sustainability.

#### **Artificial Intelligence and Smart Manufacturing**

According to Magazine BBM (2025), the industrial bakery sector is undergoing major technological changes. Artificial Intelligence (AI) is a fast-growing technology that is affecting many sectors of daily life. Thus, utilizing AI in food industry is not an exception. Artificial intelligence (AI) had a important role in the evolution and development of industrial bakeries. Smart sensors help monitor dough mixing, fermentation, and baking conditions, ensuring accuracy and consistency during production. AI-powered image recognition systems are used to check baked products for defects such as cracks, uneven baking, or contamination. This helps ensure that only good-quality products reach consumers and allows quick corrective action when problems occur. In addition, AI-based production scheduling helps optimize the use of resources, reduce waste, and improve overall production efficiency.

Various automated systems, such as food quality sensors, are widely used in the bakery industry. These sensors convert food properties into electrical signals, which are then used to measure different quality parameters. Smart ovens are also used in modern bakeries to control temperature, humidity, and baking time accurately. Due to advancements

and use of artificial intelligence in bakery technology, baking operations have become easier and less time-consuming. Intelligent control systems help maintain optimal baking conditions, improve process efficiency, and enhance overall product quality.

#### **3D Printing in Baking**

3D food printing technology is revolutionizing the bakery industry by enabling the creation of intricate and customized designs. Bakery products with interesting colour, shape and texture have been created using 3D food printing. Zhang *et al.* 2022 studied about new formulations and the optimization of the printing and post-printing treatment processes. It is helpful to obtain high-quality 3D-printed bakery products. Several technologies have been developed for 3D food printing such as extrusion-based 3D printing technique, binder jetting, selective sintering printing (SLS) and inkjet printing. This 3D printing technologies that have been used to fabricate bakery products. Table 2 shows the 3D printing used in the baked products.

#### **New trends in bakery**

When it comes to bakery products, consumers are increasingly looking for newer and healthier options. To meet this growing demand, the bakery industry has started fortifying products to suit the needs of health-conscious Indian consumers. As a result, many healthier bakery products have been introduced in the market. (Ishrat *et al.* 2014).

#### **Vegan Bakery products**

Vegan bakery products are baked goods that are free from animal products such as eggs, dairy, and honey. They use plant-based ingredients. The increasing demand for health-promoting, plant-based bakery products causes many new innovations in ingredients and product development. The development of plant-based bakery products reflects a transformative shift toward healthier, more sustainable food options. By using nutrient-rich ingredients such as legume flours, pseudocereals, fruit and vegetable by-products, and plant-based proteins, bakery products can be made

**Table 2:** Different 3D food printing methods used in baked products

Printing methods	Mechanism and applications	Reference
Extrusion-based 3D printing technique	Extrusion-based printers are the most commercially available and used in the food industry. In this method, food inks through a nozzle deposited layer by layer to create a three-dimensional shape. The material is extruded using a screw, a piston, or a pneumatic system (compressed air).	Outrequin, <i>et al.</i> 2023
Binder jetting	In this method, an edible liquid binder is lightly sprayed over a powdered food ingredient to bind the particles together after the powder is spread on a surface. Binder-jetting 3D food printers are used to produce powder-based food products. It is often used to produce crunchy, porous textures, commonly found in baked goods. Additionally, dry ingredient printing enables the creation of complex, multi-layered structures in a single print.	Thejasvi <i>et al.</i> 2024
Selective sintering printing (SLS)	In this method, powdered material is fused using heat from a laser that scans the surface according to a 3D digital design provided by the software. After the first layer is scanned, a new layer of powder is spread on top. The powder bed then moves down by one layer thickness, and this process is repeated to build a three-dimensional object.	Mudau <i>et al.</i> 2024
Inkjet printing	Inkjet printing works by spraying tiny droplets of food material onto specific areas of a food surface to create designs or surface fillings on products such as cookies, cakes, and pizzas. This process uses either thermal or piezoelectric print heads. In thermal inkjet printing, the print head is electrically heated to create pressure pulses that force droplets out through the nozzle.  Inkjet printers usually work with low-viscosity materials, so they are mainly used for decorating food surfaces rather than for building complex three-dimensional food structures.	Pitayachaval <i>et al.</i> 2018

more nutritious. These ingredients help increase fiber, antioxidants, and important micronutrients, while also meeting the dietary needs of people following plant-based and vegan diets (Mohammadi, Zoha & MB, Anusha. 2025).

#### Gluten-Free products

Some individuals suffer from a gluten-related autoimmune disorder known as celiac disease. The treatment consists of dietary and total exclusion of gluten from the diet. With the increasing prevalence of celiac disease and gluten sensitivity, the demand for gluten-free bakery products has grown rapidly. Gluten-free products can be developed using flours such as rice, corn, and quinoa. The addition of hydrocolloids, such as xanthan gum, helps improve dough rheology and enhances the texture and overall sensory quality of gluten-free bakery products (Preichardt, Leidi & Gularte, 2014).

#### CONCLUSION

Baking is a critical unit operation in cereal processing and represents a complex thermal process involving simultaneous heat and mass transfer coupled with significant physicochemical transformations. These changes play a decisive role in determining the quality attributes of bakery products. A thorough understanding of heat transfer mechanisms—namely conduction, convection, and radiation—during baking is essential for effective control of product characteristics such as volume, texture, crust colour, moisture content, and shelf-life. Precise regulation of baking conditions, appropriate oven design, and optimized ingredient formulation are vital for achieving desirable sensory properties, product stability, and extended shelf life. Recent advancements in baking technology, formulation optimization, and process modelling present substantial opportunities to improve energy efficiency, product uniformity, and

nutritional quality. Overall, a deeper understanding of the scientific principles underlying baking will enhance the efficient utilization of agricultural raw materials and strengthen the role of bakery processing as an important avenue for post-harvest value addition.

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