



## Review

## Melting of natural cheese: A review

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## ABSTRACT

In the past, cheese was produced on a small scale on farms; today, it is produced on a global level, either for consumption as a food on its own or as a food ingredient. In this respect, the characteristics of cheeses at elevated temperatures are significant factors for quality evaluation. Furthermore, the structure of cheese is altered by heating, which affects its functional characteristics. Therefore, the melting of cheese is a major commercial attribute because it is the primary determinant in evaluating quality for specific applications. Thus, the assessment of the melt and flow characteristics of cheese is particularly crucial for the successful use of cheese as an ingredient. This review presents an overview of cheese melting, from the fundamentals of phase transitions to heat-induced changes in cheese. Also, the mechanisms underlying these changes and the current information on melting measurement methods are explained, along with their strengths and limitations.

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## Contents

1. Introduction .....	1
2. Principles of phase transitions .....	2
3. Melting of foods .....	3
4. Melting measurement methods for cheese .....	4
4.1. Empirical methods .....	5
4.2. Objective methods .....	5
5. Melting of cheese .....	7
5.1. Effects of cheese components and environmental factors on melting .....	7
5.2. Effect of cheese ripening on melting .....	10
5.3. Moisture loss, skin formation, and browning reactions during the melting of cheese .....	11
6. Conclusion .....	12
Declaration of competing interest .....	13
Data availability .....	13
References .....	13

## 1. Introduction

Cheese, one of the oldest and most important dairy foods, is manufactured globally in a wide range of varieties and appearances and is recognised as an essential source of protein, fat, and other nutrients (Kindstedt, 1999; Muthukumarappan & Swamy, 2023).

Cheese was traditionally produced as a small-scale farm product, but is currently mainly manufactured on a large industrial scale, either as a standalone food item or as a food ingredient (Everett & Auty, 2008), and the evaluation of quality features of cheese is critical for consumers and the industry (Lei & Sun, 2019). Numerous desirable features of cheese are now widely acknowledged as being primarily determined by its structure. For example, the rheological, mechanical, and cooking characteristics of heated and unheated cheese are determined mainly by the structure (Guinee, 2016; Lucey, Johnson, & Horne, 2003). The heat-induced functionality of

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cheese, which includes melting, softening, flowability, apparent viscosity, browning, and stretchability, is a critical characteristic of its cooking performance (Guinee, 2002). These physical attributes of cheese (melting, texture, etc.) are affected by the gross composition of cheese milk, processing techniques, and ripening conditions. In addition, the state of casein particles in cheese and the degree of proteolysis, which are affected by several environmental factors, are two of the most significant influences on these quality parameters (Lucey et al., 2003).

Meltability is one of the most important functional properties of cheese, primarily when cheese is used as a topping on or ingredient in prepared consumer foods (Wang & Sun, 2002). From a physical standpoint, a material melts when it transforms from a solid-like to a liquid-like condition (Lucey et al., 2003; Walstra & Jenness, 1988). Therefore, the meltability of cheese is typically described as the ease and extent to which it flows when heated. Meltability is a crucial functional characteristic, particularly for cheeses used in foods served hot (Altan, Turhan, & Gunasekaran, 2005; Gunasekaran & Ak, 2002). During heating, cheese undergoes a series of structural changes. In an aqueous environment, the intra- and intermolecular hydrophobic and electrostatic linkages of proteins become stronger as the temperature rises. On the other hand, the quantity and strength of additional connections and interactions, such as hydrogen bonding, reduce with the increment of temperature. This alteration in the equilibrium of forces affects both casein-casein and casein-water interactions. Moreover, fat transformation into a liquid state is another significant structural transformation that occurs during cheese melting. These modifications are significant for the melting characteristics of cheese (Bryant & McClements, 1998; Guinee, Auty, & Mullins, 1999; Lucey et al., 2003; Tunick, 2010).

The determination of cheese meltability is a complicated process because it is determined by the thermal phase transition of solid cheese and the rheology of melted cheese. Also, a sample of melting cheese encounters temperature gradients that are controlled by the thermal characteristics of the cheese, the geometry of the system, and the relative humidity in the analysis environment, which are additional challenges for the evaluation of cheese meltability (Amamcharla & Metzger, 2015; Park, Rosenau, & Peleg, 1984). As a result, studying cheese behaviour at high temperatures has at least two significant challenges: (a) the technological and physicochemical causes are not well understood, and (b) there is no commonly recognised objective procedure for measuring the melting or flowing properties of cheese (Gunasekaran & Ak, 2002).

Therefore, the primary purpose of this review is to present a broad understanding of cheese melting, starting from the fundamentals of phase transitions to current methods of melting evaluation. For this purpose, the review starts with a summary of phase transition principles based on thermodynamic bases. Subsequently, it discusses the melting of foods and addresses a broad understanding of the importance, basic principles, and influencing factors of cheese melting. The final part provides essential knowledge about crucial reactions during cheese melting and current information on melting measurement methods with their advantages and drawbacks.

## 2. Principles of phase transitions

Phase transitions are alterations in the physical structure of a material that have a significant impact on its physical characteristics. The phase transition temperatures of chemically pure substances, such as water and several inorganic and organic chemicals in food materials, are precise. Moreover, there are three fundamental physical states, i.e., liquid, solid, and gaseous. The term

'transition' implies the transformation of the physical condition of a substance that results from a difference in pressure or temperature. Also, heating solid foods are frequently utilised to determine the temperatures at which physical or thermal attributes are altered, such as heat capacity, viscosity, or textural properties (Roos & Drusch, 2016a). The majority of phase transitions in foods include their primary components: proteins, lipids, carbohydrates, and water. The engineering features and physical condition of most foods are determined by the physical condition of their principal constituents, particularly lipids and water (Roos, 2006). According to Ehrenfest (1933), phase transitions are classified into first-order, second-order, and higher-order transitions based on the chemical potential of materials, as shown in Fig. 1. It was defined as a diagram of chemical potential versus pressure or temperature that exhibits a variation in gradient at a phase change pressure or temperature, respectively (Roos, 2006).

Furthermore, at a transition temperature, alterations in Gibbs free energy,  $G$ , and chemical potential,  $\mu$ , constitute the thermodynamic description of a phase transition (Sperling, 2005). At the transition temperature, the first derivatives of  $G$  and  $\mu$ , with respect to temperature, are discontinuous, denoting a first-order transition. At this point, there is a simultaneous shift in entropy, enthalpy, and volume. However, these thermodynamic quantities are the same in second-order transitions, which are the second derivatives of  $G$  and  $\mu$  at the transition temperature (Ehrenfest, 1933; Rao, 2003). Melting, crystallisation, starch gelatinisation, and protein denaturation are considered important first-order transitions in food materials, which include alterations in the physical conditions among gaseous, liquid, and solid states. Even though there are no precisely defined second-order transitions in foods, amorphous, non-crystalline solids show a glass transition in the change between a supercooled liquid and a glassy solid state (Roos, 1998, 2006). On the other hand, the typical transitions that fit second-order transitions occur in various supercritical fluids (such as helium). Furthermore, several anti-ferromagnetic, ferromagnetic spin models and superconductors show third-order transitions (Berlin & Kac, 1952; Cronström & Noga, 2001; Jaeger, 1998; Janke, Johnston, & Kenna, 2006; Wang, Site, & Zhang, 2011).

Long-range order (LRO), which implies simultaneous translational, rotational, and conformational ordering in crystalline particles, is a fundamental concept that permits the distinction between crystalline and amorphous solids. In a crystal lattice, molecular units are expected to repeat in a three-dimensional pattern, but in an amorphous solid, there is no long-range translational orientation symmetry (Petit & Coquerel, 2006; Yu, 2001). The most common and significant condition transition in amorphous systems is the transformation of glass to rubber upon heating over the glass transition temperature,  $T_g$  (Roos, 2006). On the other hand, above the melting temperature,  $T_m$ , a crystalline solid state, undergoes a phase shift into a liquid state (Mei & Lu, 2007). A characteristic thermogram of amorphous sucrose is given in Fig. 2.

Many proteins and carbohydrates are in an amorphous or crystalline solid state at ambient temperature in their chemically pure condition. However, they can appear in semicrystalline, crystalline, partly crystalline, or amorphous states in the absence of water (Karel & Heidelbaugh, 1973). In addition, foods frequently exist in non-equilibrium, metastable, amorphous states with time-dependent characteristics (Roos & Karel, 1991). However, foods are mostly not highly pure components or simple binary mixtures, and their content has an essential effect on phase transition properties and temperatures (Roos & Karel, 1990). Generally, foods contain numerous components; therefore, a transition may occur over a range of temperatures rather than at a single temperature (Rao, 2003). Because foods have heterogeneous and complex systems

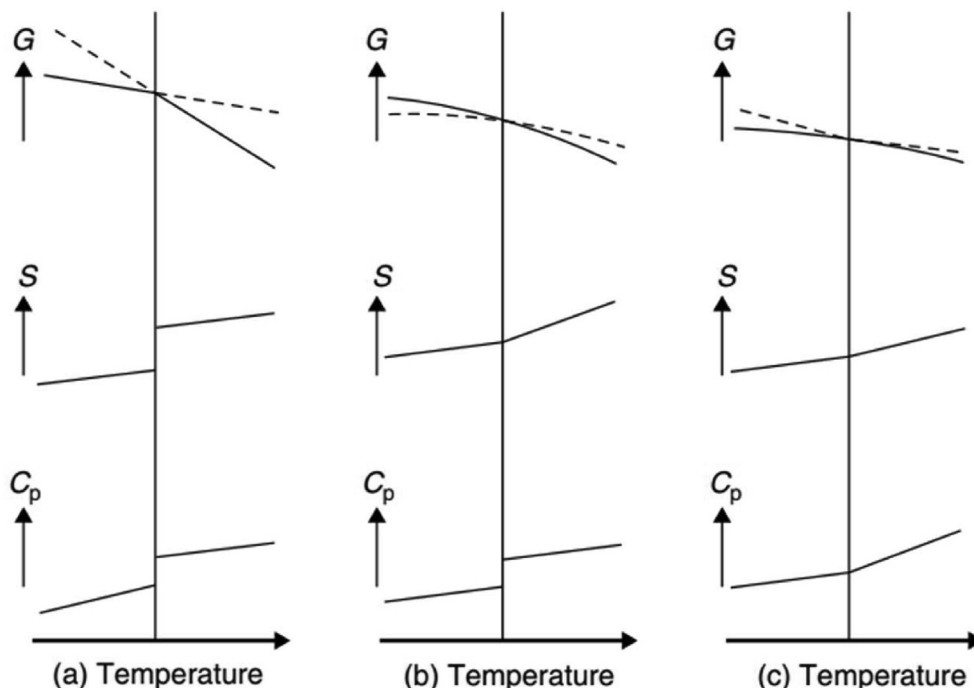


Fig. 1. Categorisation of phase change,  $c_p$ : specific heat,  $S$ : entropy,  $G$ : Gibbs energy. (a): first-order, (b): second-order, (c): third-order transitions. Figure is reproduced with permission from Roos (2006).

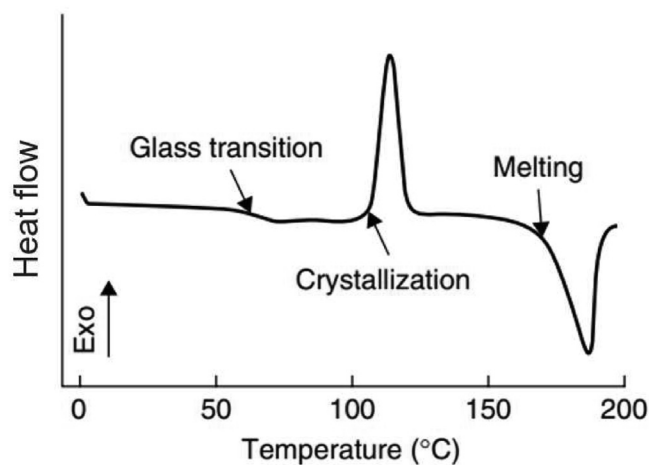


Fig. 2. A characteristic thermogram of a crystallisable, amorphous component demonstrated for sugar as an example. Figure is reproduced with permission from Roos (2006).

with numerous interactions and are also regarded as unstable due to biological, physical, and chemical changes. As a result, the transformation temperatures of food constituents and the structural impacts on phase changes can be utilised in the conception of food items, the arrangement of food manufacturing, and the determination of optimal requirements for storage to ensure shelf-life stability (LeBail et al., 2003).

Furthermore, complex interactions exist between food characteristics and the physical state. The physical state of foods is typically susceptible to temperature, time, and moisture, making them difficult to identify. The primary components of foods may exist in liquid, solid crystalline, or amorphous non-crystalline form. In their chemically pure form, many component chemicals, such as sugars,

fats, and water, crystallise under the equilibrium melting temperature. However, the presence of various chemical components in food solids prevents the creation of such highly organised equilibrium states (Roos & Drusch, 2016b). On the other hand, both unprocessed and processed food components might be in liquid or solid (semicrystalline, amorphous, or crystalline) forms. Depending on the type of applied method, food components undergo phase changes such as amorphisation, crystallisation, or melting throughout processing. In addition, the transitions between liquid and solid phases can occur by eliminating the solvent through freezing, evaporation, or quick cooling under the transformation temperature. However, there is no general theory to clarify the overall process of the motion of inner moisture during drying due to the complex internal mass transfer mechanism (Bhandari & Roos, 2016; Crapiste & Rotstein, 1997).

### 3. Melting of foods

Foods exhibit many phases and state transitions throughout storage and processing. Therefore, these transitions have a substantial impact on the stability of foods through consumption, processing, and storage (Rahman, 2017). The physical states of foods and biopolymers are highly influenced by their content, temperature, and duration of storage. Moreover, changes in physical states, or the phases of the material, have a significant influence on the physical properties of the material (Senapati, Rana, & Maiti, 2017). It is probable that phase transitions of food constituents will modify the physical features of foods, which are complicated systems. However, their macroscopic physical state is frequently determined by the phase transitions of their principal constituents, including lipids, carbohydrates, water, and proteins. Considerably more significant phase and state changes can alter the properties of foods at the supramolecular level, which gives an exciting potential for food science and the engineering of foods.

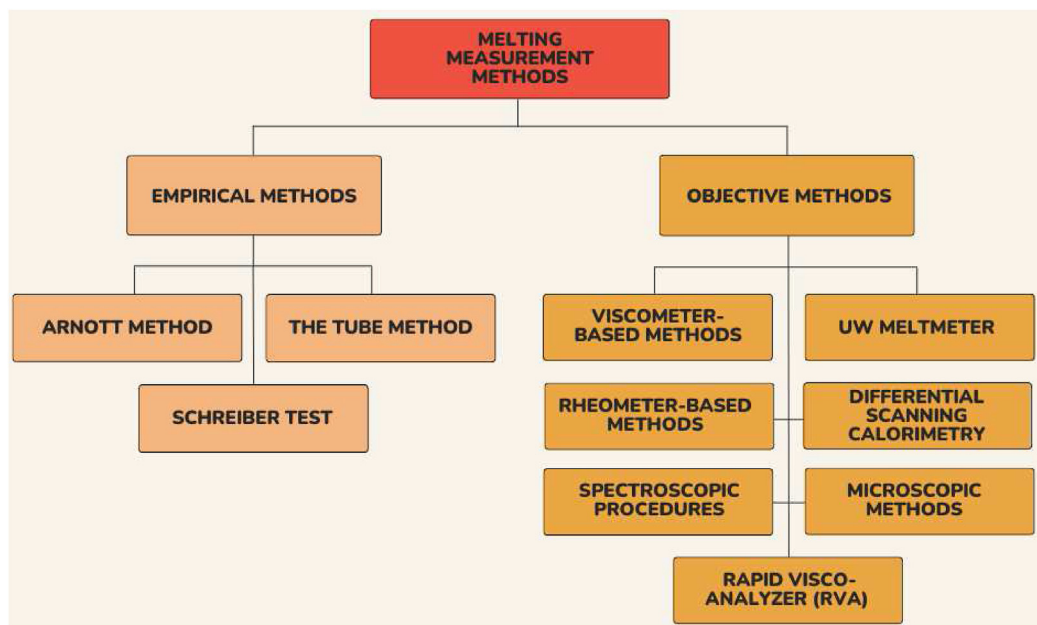


Fig. 3. Empirical and objective approaches for measuring cheese meltability.

Moreover, there are similarities between synthetic polymers and food solids in the behaviour of macroscopic phase transitions (Roos & Drusch, 2016b). Therefore, the food polymer science perspective to analysing the changes in phases, temperature, time, and water connections in foods has generated useful knowledge that may be utilised to simulate food behaviour throughout food storage and processing (Slade, Levine, & Reid, 1991). In addition, several food processing operations require phase transitions. Almost every food processing step involves the phase changes of water among the gaseous, liquid, and solid forms. Thus, water is frequently a crucial constituent that provides evaporative cooling, regulates food temperature during heating, and prevents food from dehydrating. However, processes affected by phase changes of food solids are described by low temperatures, which eliminate water to a different state in the system via the formation of ice, or high temperatures, which extract water by evaporation and cause thermal plasticisation of foods. Therefore, water can present phase transitions between different physical states and can also have an impact on how other food constituents change phases by behaving as a plasticiser or solvent (Roos & Drusch, 2016c; Senapati et al., 2017).

While food solids transition between a glassy and a rubbery state as a result of the removal of a plasticiser and/or cooling, the molecular movement of a food system diminishes. Therefore, the state/phase transitions and physical state of amorphous parts of foods are essential to evaluating molecular durability throughout storage and processing. Moreover, state diagrams represent the physical states throughout phase/state changes in amorphous food constituents as a function of temperature and solid or liquid concentration at fixed pressure for balanced and unbalanced systems (Roos, 1995; Sablani, Syamaladevi, & Swanson, 2010). Furthermore, the changes in the state of frozen, fresh, low- or intermediate-moisture foods can be observed and anticipated using state diagrams (Slade et al., 1991). However, due to the complexity and varied behaviour of food components, changes in the physicochemical properties of food systems may be only moderately explained by state diagrams (Rahman, 2009).

#### 4. Melting measurement methods for cheese

For the food industry, it is crucial to comprehend the process of cheese melting because it is an important commercial characteristic for the profitable usage of cheese as a component (Gunasekaran & Ak, 2002; Vogt et al., 2015). Furthermore, because cheese is heated through processing and culinary application, baking is a frequently used heating method (Paquet & Kalab, 1988). During heating, cheese undergoes a variety of structural changes. These modifications are significant for the melting characteristics of cheese (Lucey et al., 2003).

The fundamental difficulty in objectively determining the characteristics generally referred to as 'meltability' is that they are dependent on the heat transfer and thermal phase transition properties of the solid cheese, as well as the flow or rheological features of the melt (Muthukumarappan, Wang, & Gunasekaran, 1999a). Therefore, a reliable method for measuring the meltability of cheese should take into account both heat transfer and thermal phase transitions of the solid cheese, as well as the rheological flow characteristics of the melt. Furthermore, another challenge for objectively determining melting ability is that there are temperature gradients that are influenced by characteristic thermal features of the cheese and environmental effects such as the geometry used in the study, relative humidity, and temperature distribution in cheese samples (Park et al., 1984). Moreover, for the purpose of understanding the underlying mechanisms of cheese melting, it may also be necessary to isolate certain characteristics.

Therefore, the precise control of cheese meltability needs an accurate and objective assessment of the physical characteristics, which has been a difficulty for a very long time (Guggisberg, Buetikofer, & Albrecht, 2007). As a result, there have been numerous attempts to quantify and control the meltability of cheese. As part of these efforts, a battery of meltability tests, which can be separated into empirical and objective approaches, has been established, as shown in Fig. 3 (Gunasekaran & Ak, 2002). The empirical tests rely on measuring dimensional changes in the sample during melting, such as height, diameter, or circumference (Arnott, Morris, & Combs, 1957; Kosikowski, 1977), whereas the

objective methods depend on evaluating inherent rheological characteristics of the cheese, such as viscoelasticity, viscosity, etc. (Kuo, Wang, & Gunasekaran, 2000; Wang, Kindstedt, Gilmore, & Guo, 1998a).

#### 4.1. Empirical methods

The approach of Arnott et al. (1957) may have been the earliest quantitative method to evaluate cheese meltability. In this method, a standard cheese cylinder is heated at 100 °C for 15 min to test the meltability of the cheese. Then, cylinder height measurements are taken before and after analysis to observe differences. Obviously, the meltability is measured as a relative parameter that is reported as a percentage reduction in cylinder height following a heat treatment (Gunasekaran & Ak, 2002).

Subsequently, two fundamental problems were reported in the usage of the Arnott method, which is the surface layer generation as a result of air exposure during heating and the irregular flow of melted cheese (Olson & Price, 1958). Therefore, Olson and Price (1958) proposed the 'tube method' to determine the melting ability of cheeses. In this method, the sample is kept during the test in a glass tube. Rubber stoppers are used to seal one end of the tube, but a glass tube with a 1-mm diameter serves as the vent. The tube containing the cheese sample (15 g) is heated in an oven while being held horizontally on a rack. The sample is heated in an oven for 6 min at 110 °C after being tempered for 30 min at 4.4 °C. Then, measurements are made of the separation of flow from the reference line. Rewarming the tube in the horizontal position for a further 2 min is followed by another measurement of the flow distance. The 'cheese flow' is the total distance (in mm) that the specimen covers in 6 + 2 min of heating. However, they emphasised that the heating time can be altered to adapt to the evaluated material. Although very empirical, the tube method tackled an essential issue: the production of film and dry surfaces through uncovered heating of cheese in the open air, which affects the melting and flowing behaviour of cheeses (Gunasekaran & Ak, 2002).

However, these aforementioned approaches for determining meltability of cheese did not acquire widespread approval. Therefore, Kosikowski (1977) developed a procedure known as the Schreiber test, which has become the most widely used method to determine the melting features of cheeses in the food industry, due to the simple application procedure. For the application of the Schreiber test, a cylindrical cheese sample, which is centred on a graph with circularly numeric targets (4.8 mm in height and 41 mm in diameter), is heated in an oven set to 232 °C for 5 min, then the longest flow line from the centre to the border of the melt is used to determine the melting features of cheeses (Kosikowski, 1977). While the method offers benefits in terms of simplicity and is widely applied in both academia and industry, disadvantages of this method include uncontrolled and extreme heating, drying, skin formation, and browning, as well as improper flow line monitoring in the event of noncircular melting (Gunasekaran & Ak, 2002; Muthukumarappan, Wang, & Gunasekaran, 1999b).

Numerous studies have explored the impact of heating mode, temperature, surface, sample shape, and dimension, and the method for determining the melting to overcome a number of the fundamental inadequacies of the Schreiber test (Muthukumarappan et al., 1999b; Park et al., 1984; Wang & Sun, 2001, 2002). Furthermore, Altan et al. (2005) investigated the impact of moisture loss during heating in the Schreiber test with (covered) and without a petri dish cover (uncovered). According to the research, the average coefficient of variation was lower for the covered Schreiber test data than for the standard uncovered Schreiber test data, indicating that the covered Schreiber test data

were statistically more reliable. In addition, because the used cover behaved as a barrier to prevent moisture loss, skin formation and browning were not observed (Altan et al., 2005). Numerous studies, and in some instances, the same researchers have utilised different variants of some of the experimental methods mentioned above, and such changes in test procedures limit the application of the test results.

#### 4.2. Objective methods

Researchers have proposed distinct ways of measuring the objective meltability of cheese. These efforts vary from semi-empirical techniques based on basic instruments to fundamental rheological experiments utilising dynamic rheometers (Gunasekaran & Ak, 2002). A summary of objective methods for determining cheese meltability is given in Table 1. Firstly, viscometer-based instrumental measurements were used to determine the melting properties of different cheeses. Lee, Imoto, and Rha (1978) used a Brookfield viscometer with a T-bar spindle, and a distinctive curve of viscometer reading (%) versus temperature was obtained for different tested varieties of cheese. Unfortunately, this test is of limited significance because the geometry and speed of the viscometer are irregular, and the temperature gradient is not uniform. In another study, Kindstedt, Rippe, and Duthie (1989a) used a Brookfield viscometer equipped with a rotating part rather than a cylindrical spindle. It was stated that this method provided useful data. However, the method was altered due to limitations with analyses done on mozzarella cheeses of varying ages and compositions (Kindstedt, Rippe, & Duthie, 1989b). Subsequently, Wang, Muthukumarappan, Ak, and Gunasekaran (1998b) developed an instrument to accurately assess the melt/flow characteristics of cheeses at different temperatures, known as the UW Meltmeter. This device includes a temperature-controlled heater, a linear variable differential transformer, and a computer for the collection of data. The UW Meltmeter can be driven at a constant rate or force, and the index of stress growth was reported as the indicator of the meltability of cheeses (Wang, et al., 1998b). Nonetheless, there are some drawbacks to applying the UW Meltmeter: long test time and clogged parts during analyses. Therefore, even though these changes are essential, they could not lead to an instrument suitable for routine usage in the food industry (Gunasekaran & Ak, 2002).

Rheology is an effective technique that is regularly employed to determine the textural and structural features of cheese (Gunasekaran & Ak, 2002). Smith, Rosenau, and Peleg (1980) reported that capillary rheometry could be used to determine the flowability of melted mozzarella cheese but not Cheddar cheese due to the extreme wall slip of the latter. On the other hand, squeeze flow rheometry is regarded as a proper method to determine the meltability of cheeses (Gunasekaran & Ak, 2002). This method was first used for determining the biaxial extensional behaviour of high-viscosity polymers. Interestingly, the existence of slipping between solid surfaces and the sample is not an issue but rather a necessity for a successful test in the application of squeeze flow rheometry (Campanella, Popplewell, Rosenau, & Peleg, 1987; Chatraei, Macosko, & Winter, 1981). Furthermore, a modified version of the squeeze flow technique and a mechanical model of creep behaviour was used to determine the meltability and viscoelastic behavior of cheese (Kuo et al., 2000). The viscoelasticity index was determined by the instant slope of the creep curve. According to their results, the viscoelasticity index derived from viscoelastic variables can be utilised to estimate the meltability of cheese (Kuo et al., 2000). Dynamic testing techniques provide fast results with minimum chemical and physical alterations (Konstance & Holsinger, 1992). Ustunol, Kawachi, and Steffe (1994)

**Table 1**  
Summary of objective methods for the determination of cheese meltability.

Cheese type	Sample size	Instrument	Measurement	Temperature	Reference
Mozzarella	30 mm diameter cylindrical	UW Meltmeter (squeeze flow)	Biaxial elongational viscosity	40 and 60 °C	(Wang, et al., 1998a)
Cheddar	30 mm diameter cylindrical	UW Meltmeter	Sample height before and after melting	60 °C	(Kuo et al., 2000)
Cheddar	30 mm diameter cylindrical	UW Meltmeter (creep test)	Viscoelasticity index	40 °C	(Kuo et al., 2000)
Cheddar and Mozzarella	30 mm diameter cylindrical	UW Meltmeter	Softening point	From 30 to 65 °C at 5 °C intervals	(Muthukumarappan et al., 1999a)
Cheddar	25 mm diameter cylindrical	Rheometer (SAOS)	Loss and storage modulus crossover	From 25 to 90 °C at 10 °C min <sup>-1</sup>	(Sutheerawattananonda & Bastian, 1998)
German Emmental	Cheese cylinders (d = 25 mm, h = 10 mm)	Squeeze flow test adapted to a rheometer	Sample height was recorded as a function of time and modelled with inverse-Hill function	60 °C	(Hartmann et al., 2015)
Kashar	Cheese cylinders (d = 50 mm, h = 5 mm)	Rheometer (LAOS)	The viscous and elastic stress components of kashar cheese were studied with the Lissajous-Bowditch curves	60, 70, 80, and 90 °C	(Yildirim-Mavis et al., 2022)
Kashar	Cheese cylinders (d = 50 mm, h = 5 mm)	Rheometer (Tack analysis)	Determination of the ability of a sample to adhere to a surface using force measurement	60, 70, 80, and 90 °C	(Yildirim-Mavis et al., 2022)
Process cheese	Cheese cylinders (d = 34 mm, h = 15 mm, 15 g)	Rapid visco analyser	Apparent viscosity data were collected to determine the melting temperature	from 25 to 90 °C, held for 3 min at 90 °C, and cooled from 90 to 25 °C	(Prow & Metzger, 2005)
Tilsit cheese	1 cm × 1 cm cross-section and 4.2 cm length	Fluorescence spectroscopy	Melting temperature was predicted using regression models derived from fluorescence spectral data	25, 30, 35, 40, 45, 50, 55, 60, 65, and 70 °C	(Ozbekova & Kulmyrzaev, 2017)
American Process cheese	–	Dielectric spectroscopy	Dielectric spectroscopy combined with partial least square regression and multilayer perceptron neural network were used to predict melting temperature	–	(Amamcharla & Metzger, 2015)
Cheddar	5 × 5 × 2 mm	Confocal scanning laser microscopy	CLSM images were used to observe melting	from 20 to 80 °C at 3 °C min <sup>-1</sup>	(Auty, Fenelon, Guinee, Mullins, & Mulvihill, 1999)

conducted small amplitude oscillatory shear tests (SAOS) and found a correlation between minimum complex modulus and the meltability of Cheddar cheese. Moreover, Rüegg, Eberhard, Popplewell, and Peleg (1991) reported that  $\tan \delta$  could be used in the prediction of cheese meltability. However, dynamic cheese testing is challenging to carry out at high temperatures due to the risk of sample slippage distorting the results. Using squeeze flow rheometry can be the one approach to counteract the slip and viscoelastic effects when measuring the viscosity of melted cheese (Kuo et al., 2000).

The Rapid-Visco analyser (RVA) is another rotational viscometer that records the viscosity of samples continuously under regulated temperature and shear rate parameters. It is particularly beneficial for examining materials that have complex test procedures and enabling materials to display viscous properties with varying shear rates and temperature values (Gamel, Abdel-Aal, Wood, Ames, & Tosh, 2012). According to Prow (2004) and Prow and Metzger (2005), the RVA melt test evaluates the apparent viscosity of processed cheese continuously throughout a profile of heating, holding, and cooling. As a result, a minimal apparent viscosity is calculated using apparent viscosity versus time curve, known as the hot apparent viscosity, which is an indicator of how well cheese flows at a certain temperature (Kapoor, Metzger, Biswas, & Muthukumarappan, 2007). In the literature, the RVA melt test was generally used to determine the melting properties of processed cheese (Kapoor et al., 2007; Prow & Metzger, 2005) and imitation cheeses (Bi et al., 2016). According to their results, RVA melt test results of these cheeses are correlated to the results of other melt tests, such as the tube test and the dynamic stress rheometry test (Prow & Metzger, 2005). Furthermore, the

Excellence Dropping Point System of Mettler Toledo was used to determine softening point of several cheese samples (Giani, 2023). According to the procedure note, the softening point refers to the temperature at which the sample releases from a specimen holder with an opening and flows vertically down a given distance under defined testing conditions (flow distance). Often, a ball is utilised as a weight to facilitate the passage of the sample, and this elastic retention can be represented as a force of drag with a mathematical model. As a result, the softening point data provides the temperature at which this thermally-induced event happens, whereas the  $\tau_T$  data reveals the rate at which this event occurs (Giani, 2023).

Differential scanning calorimetry (DSC) measures heat, heat flow rates, and a specific temperature of a transition or a reaction (Höhne, McNaughton, Hemminger, Flammersheim, & Flammersheim, 2003). However, analyses pertaining to the application of DSC in relation to the validity of dairy products are limited. On the other hand, the results provided on the adulteration of dairy products indicate that this analytical approach has great importance (Farah, Silva, Cruz, & Calado, 2018). However, Park et al. (1984) compared four methods of cheese meltability determination, and the results of differential scanning calorimetry (DSC) were found unable to reveal any significant patterns that reflect variances among the meltability of different cheese types. Furthermore, they argued persuasively that a well-defined meltability criterion should be based on a full rheological investigation that presents data in terms of time and temperature variables.

Spectroscopic procedures are rapid, relatively inexpensive, and deliver considerable information from a single test (Birlouez-Aragon, Sabat, & Gouti, 2002; Karoui, Bosset, Mazerolles, Kulmyrzaev, & Dufour, 2005). Furthermore, since the melting

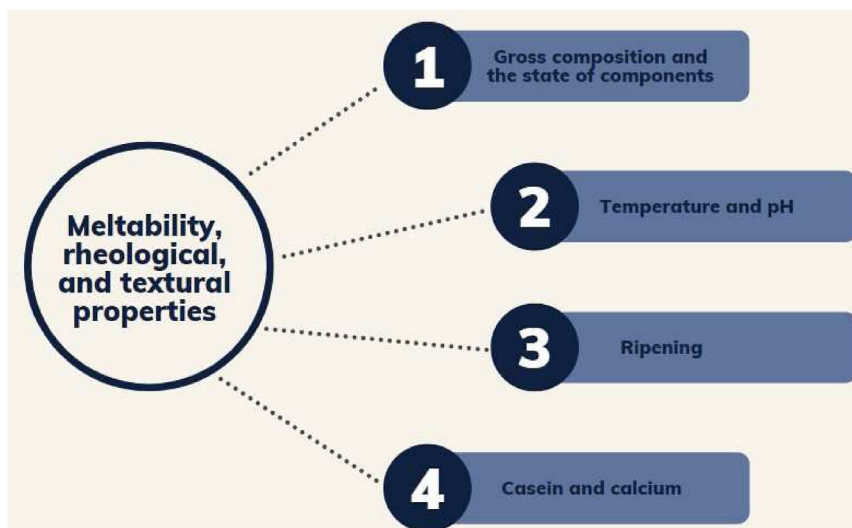


Fig. 4. The factors that affect cheese melting, rheology, and texture.

behaviour and physicochemical properties of cheese originate from interactions at the molecular level, a technology that could offer data on these interactions could also shed light on the impact of processing variables on the functional features of cheese (Karoui, Laguet, & Dufour, 2003). For instance, in the study of Boubellouta and Dufour (2012), the melting temperatures of Comté and raclette cheeses were measured using a rheological method, mid-infrared spectroscopy (1700–1500  $\text{cm}^{-1}$  region), and synchronous fluorescence spectroscopy (at 295 nm, 1634  $\text{cm}^{-1}$  intensity). Interestingly, no significant difference was found between the melting temperature results obtained from the three methods. Moreover, Vogt et al. (2015) reported that the combination of magnetic resonance and rheological analyses ensure a piece of important information about the structural rearrangement of the gel network and dynamic changes of Cheddar and mozzarella cheeses during heating. In another study, front-face fluorescence spectroscopy with chemometric tools was used to measure the melting point of hard and semi-hard cheeses (Karoui, De Baerdemaeker, & Dufour, 2008). According to the results, this non-destructive method can be used to determine the meltability and physicochemical properties of hard and semi-hard cheeses. On the other hand, this preliminary study reported that a considerable amount of additional research, including various cheese types and other dairy products, is necessary before its usefulness can be validated and implemented for routine analysis (Karoui et al., 2008).

## 5. Melting of cheese

The texture of the cheese is a reflection of its molecular and microscopic structure. Moreover, cheese is a complex matrix of minerals, milk proteins, lipids, and other components, such as water, in terms of its structure. The diversity and composition of cheese affect the distribution components, which defines the structural properties to a great extent. At room temperature, it is commonly believed that milk proteins contribute to the hardness of cheese, and milk fats contribute to its smoothness. Due to the fact that the structure determines the functional capabilities of cheese ingredients, the cheese manufacturer must have a thorough understanding of the fundamental steps of cheese structure generation and evolution throughout ripening. These functional qualities are especially crucial for pizza-style cheeses and involve melting,

stretching, expressible moisture, free oil formation, and browning (Everett & Auty, 2008; Lawrence, Gilles, & Creamer, 1983). However, the melting properties of cheese are the critical determinant for its quality for specific product uses (Kuo et al., 2000).

Moreover, the melting of cheese represents a gel-sol transition (Schenkel, Samudrala, & Hinrichs, 2013a). From an empirical analysis point of view, meltability can be described as ‘the ease and extent to which cheese will melt and spread upon heating’. This term combines two characteristics which are the extent of flow and the ease of melting. The heat transport and thermal phase transition features of cheese are most clearly connected to the ease of melting. The degree of flow depends on the rheological qualities of cheese and the force required to induce flow at elevated temperatures (Park et al., 1984). The meltability, rheological parameters, and texture of cheese are influenced by several factors (Fig. 4), such as the concentration of chymosin, moisture and fat content, proteolysis, temperature, pH, sodium chloride concentration, casein-casein, casein-water or casein-fat interactions, and the condition of water and calcium (linked to the matrix of casein or not) (Everett & Auty, 2008; Kuo et al., 2000). These are covered in subsequent sections.

### 5.1. Effects of cheese components and environmental factors on melting

From a structural perspective, cheese is composed of a continuous hydrated protein matrix in which fat globules are distributed (Bryant, Ustunol, & Steffe, 1995). Before and during heating, the two phases (i.e., the fat phase and the hydrated protein) in cheese have distinct rheological characteristics. Milk fat melts at temperatures between 0 and 40 °C, whereas the protein network softens mainly between 30 and 70 °C. Together, the rheological properties of the two phases contribute to the melting characteristics of cheese (Karlsson & Hauert, 2008). However, the only substance in cheese that completely melts is fat (in the regular temperature range) (Lucey et al., 2003).

Furthermore, the fat content has an important influence on the melting characteristics of cheese (Fox, McSweeney, Cogan, & Guinee, 2004; Rügge et al., 1991), but fat concentration is not always precisely proportional to meltability since its effect can be confounded by the ratio of other constituents, such as moisture and protein (Walstra & Vliet, 1982). In the study of Miynek, Oler, Zielińska, Tkaczuk, and Zawadzka (2018), melting time was

recorded with a timer from the time the sample was placed on a plate (80 °C) until a flat shape was formed. Subsequently, melting time was found to be negatively correlated with fat content in cheese milk (-0.293) and in cheese (-0.427). Also, they reported that the high-fat content reduced the force required to cut cheese. As a result, it is reasonable to assume that increasing the fat content of milk can improve the meltability of cheeses (Mitynek et al., 2018). Similarly, researchers mentioned that cheese with a higher fat content melts better, but it can be harder to shred and it generates more free oil, which can be undesirable (Kindstedt & Rippe, 1990; Masi & Addeo, 1986). Moreover, Olson and Bogenrief (1995) reported that changes in fat-in-the-dry-matter (FDM) between 18 and 45% had minimal influence on meltability of mozzarella and Cheddar cheeses. However, FDM levels beyond 45% significantly enhanced meltability. On the other hand, Lefevre, Dewettinck, and Huyghebaert (2000) found a stronger correlation between fat content and cheese meltability results obtained from Arnott test ( $R^2 = 0.90$ ) compared with the relationship between meltability and FDM ( $R^2 = 0.61$ ). The obtained result showed that the moisture content of cheese is also a significant factor influencing cheese meltability as well as fat content. In the study of Emmons, Kalab, Larmond, and Lowrie (1980), the possible changes in functional characteristics of cheeses, as fat level declines, are attributed to the decreased plasticising effect of fat and increased cross-linking within the curd, consequently, in the cheese. Therefore, reduced-fat cheese contains fewer fat globules than full-fat cheese, resulting in a dense structure and a hard, dry cheese that melts poorly (Emmons et al., 1980).

In addition, fat globules in cheese typically serve as filler among protein fibres, which reduces protein-protein interactions inside the matrix. Therefore, when cheese is heated, it takes less energy to melt, and the melting of fat promotes the flow of the cheese (Paulson, McMahon, & Oberg, 1998). It is well-documented that the melting temperature of an oil or fat relies on its chemistry since the melting point for certain fatty acids rises with chain length and decreases, at constant chain length, with the number of double bonds. Moreover, it is also recognised that the composition of fatty acids influences liquid fat viscosity since chain length raises viscosity while double bonds lower it (Mulder & Walstra, 1974; Rohm & Ulberth, 1996; Walstra & Jenness, 1988). However, milk fat consists of many triglycerides, each of which has a distinct melting point. Therefore, some fractions will be liquid at refrigerator temperatures, and others will be solid at ambient temperature, although milk fat is fully liquid above around 40 °C (Walstra & Jenness, 1988). In addition, the morphology of fat globules can

affect the physical features of cheese. For instance, even though Everett and Olson (2003) could not detect a relationship between free-oil generation and fat-globule circularity in Cheddar cheese, Ma, James, Zhang, and Emanuelsson-Patterson (2013) found a positive correlation between the size of fat-globule (Ferret's diameter) in mozzarella cheese and meltability and free oil formation. Also, a previous study has indicated that the content and texture of cheese made from milk with varying milk fat globule (MFG) particle sizes may differ (Logan et al., 2017). For instance, 52-day-aged Emmental cheese made from small MFG size milk (3.3 µm) contained more moisture than cheese manufactured from wide MFG size milk (5.6 µm), resulting in increased cheese yield. This cheese was softer and had lower fracture stress than the cheese made from large MFG milk (Michalski et al., 2004).

Casein and certain serum proteins (found in the serum phase of cheese) are the other main components of cheese. Although proteins do not melt, changes in their interactions can cause the phenomenon known as 'melt' (Lucey et al., 2003). Protein structure is mainly sustained by weak (noncovalent) linkages, such as hydrophobic and disulfide bonds. The system entropy governs hydrophobic forces, and their strength increases with increasing temperature (Joshi, Muthukumarappan, & Dave, 2004). When the curd is cooked, functional properties based on hydrophobic contact become more obvious. When heat is applied to cheese, several proteins undergo conformational changes and migrate past one another, resulting in the deformation and flowing of cheese (Bryant & McClements, 1998; Paulson et al., 1998). At higher temperatures, the rheology, extensibility, and melting properties of cheeses are dictated by the magnitude and quantity of casein-casein interactions, primarily via hydrogen bonds, hydrophobic interactions, calcium-cross linking, and electrostatic forces. In general, the impact of rising temperature on these linkages weakens casein matrix (Park et al., 1984). Even though hydrophobic connections increase as temperature rises, the overall outcome may be a weakening of the gel due to a decline in the contact area of the casein molecules (Zoon, 1988). Similarly, electrostatic repulsion becomes more intense, and hydrogen bonding declines with rising temperature. This implies that the matrix would weaken, and the balance would change in favour of increased repulsion (Bryant & McClements, 1998; Lucey et al., 2003). Moreover, Table 2 illustrates an overview of the potential casein interactions involved in melting as well as samples of how cheese-making circumstances affect these interactions.

According to Everett and Auty (2008), cheese meltability will rise due to all the factors that reduce casein-casein interactions. These include decreasing the pH to 5.2, keeping the ratio of soluble to

**Table 2**  
Summary of how different cheese-producing circumstances alter casein interactions and meltability.<sup>a</sup>

Cheese manufacturing situation	Electrostatic repulsion	Attractive interactions	The effect on the melting of cheese
Production of acid (pH ≥4.9)	Exposure to phosphoserine residues promotes localised repulsion upon the loss of CCP	Diminishes as a result of fewer CCP crosslinks	Increase
Low pH values (pH <4.9)	When caseins approach their isoelectric point, their repulsion lessens	Hydrophobic interactions increase as electrostatic repulsion decreases	Decrease
Proteolysis	Lessening as charged peptides are hydrolysed	Decreases as the overall amount of bonds between proteins decreases	Increase
Solubilisation of CCP	Exposure of phosphoserine residues enhances localised repulsion upon further loss of CCP	Decreases because of fewer crosslinks of CCP	Increase
Concentration of milk	A greater amount of CCP resulted in a decrease	Increases because of more crosslinking of CCP	Decrease
Usage of emulsifying salts	Due to the exposure of phosphoserine residues when CCP is partially chelated, these salts might cause a rise in pH and repulsion	Decreases because of fewer crosslinks of CCP	Increase
Increased amounts of whey protein (native or denatured) incorporated into cheese	—	Increases water-binding or calcium-binding capacity (Lawrence, 1989; Schmidt & Morris, 1984)	Decrease (Mead & Roupas, 2001)

<sup>a</sup> Adapted from Lucey et al. (2003).



insoluble calcium higher, and lowering the overall calcium content of milk through washing the curd, chelation, pre-acidification, or draining the curd at a lower pH. Furthermore, if cheese milk is directly acidified instead of culturing, the amount of bound calcium will decrease at a similar pH (Everett & Auty, 2008). Also, in the study of Kindstedt, Zielinski, and Almena-Aliste (2001), shredded cheese was exposed to acetic acid (glacial acetic acid) or volatile ammonia (concentrated ammonium hydroxide, 28–30%) to determine the effect of cheese pH on melting properties. They reported that mozzarella cheese melts inadequately below pH 5 due to insufficient casein aggregate fusion (Kindstedt et al., 2001). Because reducing the cheese pH to 4.7 increases the robust casein-casein connections as the casein reaches its isoelectric point, and has a negative effect on the flow, melt, and stretch features of cheese. Although meltability is known to be affected by pH, this may be due to a change in the ratio of bound to soluble calcium. The level of casein-bound, rather than total calcium, is likely more crucial in determining melting properties (Lucey et al., 2003; Pastorino, Hansen, & McMahon, 2003). The percentage of calcium linked with casein (micellar calcium) is greater at higher pH values (5.4) than at low pH (Choi, Horne, Johnson, & Lucey, 2008; McAuliffe, Kilcawley, Sheehan, & McSweeney, 2016). Furthermore, during cheese production, the pH at the time of whey draining has a significant impact on the functional durability of the curd as well as the functional characteristics of cheese (Keller, Olson, & Richardson, 1974; Kindstedt, 1985). Also, the greater concentrations of micellar calcium enhance casein-casein interactions inside the cheese matrix. Strong casein-casein connections are recognised to improve the structural stiffness of the cheese matrix; as a result, cheeses are prone to be firmer and more elastic, and they have less tendency to melt (McMahon, Paulson, & Oberg, 2005). At a moderate pH (5.1), casein-casein associations diminish when negatively charged portions of the casein are exposed because of the limited solvation of micellar calcium, resulting in a cheese with a soft structure and high meltability (Lucey et al., 2003). Furthermore, Monteiro, Tavares, Kindstedt, and Gigante (2009) reported that with rising pH from about pH 4.2 to 6.8, the microstructure of cheese seemed more consistent or inflated, showing that the casein became more hydrated; also, the hardness of cheese reduced, while its meltability improved.

Water, the most prevalent component of the majority of cheeses, appears as a continuous phase distributed across a porous casein matrix (Guo & Kindstedt, 1995). Furthermore, in cheese, there are three primary phases of water: bulk water in the serum channels, trapped water nearby the casein matrix, and bound water firmly attached to the caseins and unsuitable as a solvent (Kuo, Anderson, & Gunasekaran, 2003). In general, cheese gets softer as moisture levels rise. The texture-softening impact of moisture has been attributed to two primary causes: (1) water in the cheese matrix acts as a lubricant, and (2) raising the levels of moisture leads to a proportional decline in the level of casein, the primary structural component. Nevertheless, the influence of water on the melting properties of cheese is quite complicated. Increasing the overall moisture level of cheese does not necessarily result in an improvement in its meltability. In contrast, casein-water interactions (which are heavily impacted by ionic strength, pH, and colloidal calcium phosphate) are claimed to have a greater influence on the melting qualities of cheese than overall moisture levels (Lamichhane, Kelly, & Sheehan, 2018; Marshall, 1990; McMahon et al., 2005; McMahon, Fife, & Oberg, 1999; Pastorino, Ricks, Hansen, & McMahon, 2003). However, a higher amount of bound water offers a reserve against the loss of moisture during baking and lowers protein-protein interactions, which would otherwise limit protein flow when cheese is heated (Joshi, Muthukumarappan, & Dave, 2003a,b).

Salt has a significant impact on the entire quality of cheese, particularly its textural characteristics and cooking ability (Guinee, 2004). Moreover, due to the addition of salt during the cheese-making process, cheese has a comparatively high level of sodium compared with other dairy products (El-Bakry, 2012). Thus, determining the impact of NaCl reduction or substitution on the melting properties of cheeses becomes essential. Moreover, McCarthy, Wilkinson, Kelly, and Guinee (2016) reported a substantial influence of salt reduction on meltability, with lowered-salt cheeses displaying much greater meltability than full-salt Cheddar cheeses. Interestingly, contradicting results have also been recorded about the impact of salt concentration on cheese meltability. For example, rising salt levels (~2%) lowered the meltability property of mozzarella cheese (Olson, 1982) but enhanced the meltability features of nonfat mozzarella cheese (Rowney, Roupas, Hickey, & Everett, 2004). The observed difference could be attributed to the different methods used for meltability measurements. A summary of the parameters that have effects on the melting of cheese is presented in Table 3.

The heat treatment of cheese milk also has an effect on the rheological and textural characteristics of cheeses (Lucey et al., 2003). For example, it has been demonstrated that the stretching and melting properties of mozzarella cheeses manufactured from high-temperature heated milk (30 min, 71 °C) were mediocre compared with those made from pasteurised (30 min, 63 °C) or raw milk (Ghosh & Singh, 1990). This finding was confirmed by the study of Rynne, Beresford, Kelly, and Guinee (2004), who reported that the mean flowability of half-fat Cheddar cheese decreased with the increasing milk pasteurisation temperature (from 72 °C 87 °C for 26 s) during 360 days of ripening. On the other hand, these results differ from those of Schafer and Olson (1975), who stated that the increasing pasteurisation temperature (from 80 to 130 °C, for 2 s) did not have any effect on melting and flowing properties of mozzarella cheeses. As a result, the alterations in cooking and rheological characteristics related to the high pasteurisation temperature of milk can be attributed to the concurrent modifications in composition, the decrease in free oil, and an increment in protein hydration (Rynne et al., 2004).

The variation in the heating temperature and time significantly alters the cooking conditions of cheeses. Subsequently, several sample shapes are also employed to observe cheese melting, ranging from the most popular cylindrical cheese discs to cube-shaped samples (Lelievre, Shaker, & Taylor, 1990). From a practical point of view, the role of usage heating apparatus also has a very significant effect on the melting behaviour of cheese. For instance, convective heating by forced-air ovens, is known to significantly dehydrate the surface of cheeses (Rudan & Barbanò, 1998; Wadhvani, McManus, & McMahon, 2011). Moreover, Apostolopoulos, Bines, and Marshall (1994), did not observe any significant difference in the melting results (spread of the specimen) of mozzarella cheeses between conventional heating and microwave oven at the maximum power. However, Gulzar et al. (2020) reported the heating methods to have a significant effect on the melting properties of pizza cheese produced from mozzarella and Cheddar cheeses. According to their results, meltability and oiliness were found to be greater in the microwave-heated pizza cheese, whereas surface breakage was lower than in pizza cheese heated in the conventional oven. Furthermore, despite traditional oven-heated pizza cheese, microwave-heated samples exhibited less browning around the edges (Gulzar et al., 2020). Subsequently, Gulzar et al. (2020) reported that this might be owing to the fact that a microwave does not reach the ideal temperature that induces browning (Chaffe, 1939). On the other hand, the temperature history of the product throughout heating may also alter the melting characteristics of cheeses; Kuo, Wang,

**Table 3**  
Summary of the parameters that have effects on the melting of cheese.

Cheese type	Parameter	Effects on melting	Reference
Mozzarella	Reducing calcium concentration	Fast melting, increased meltability	(Joshi, Muthukumarappan, & Dave, 2003a,b)
Cheddar	Low level of Ca, P, residual lactose, and S/M content	High meltability	(Chevanan & Muthukumarappan, 2007)
Mozzarella	Pressure treatment (High pressure, 200 MPa for 60 min)	Increased meltability	(Johnston & Darcy, 2000)
Low-fat mozzarella	The size of electron-dense areas between casein substructural units	Increases during ripening and can result in increased melting	(Cooke, Tunick, Malin, Smith, & Holsinger, 1995)
Low-fat mozzarella	Milk pre-acidification	Increasing level of milk pre-acidification had a negative influence on the post-melt chewiness	(Metzger, Barbano, & Kindstedt, 2001)
Full-fat and low-fat mozzarella	Konjac glucomannan usage as a fat replacer	Higher meltability than control mozzarella cheeses	(Dai et al., 2019)
Mozzarella	Various starter cultures	Mozzarella produced with very heat-sensitive starter cultures showed a higher meltability ratio	(Ma et al., 2013a)
Low-moisture, part-skim mozzarella	Coagulants; bovine calf chymosin (BCC) and camel chymosin (CC)	Higher melting temperature for cheeses made with CC	(Moynihan et al., 2014)
Shredded cheeses (various types)	Use of excessive anticaking agents (cellulose, starches)	Decreases due to absorption of moisture and melting milk fat	(Lucey, 2008; Meals, Harwood, & Drake, 2021)
Low-moisture mozzarella cheese	Ripening temperature	Increasing storage temperature from 0 °C to 15 °C resulted in a decrease in the melt time	(Guinee, Feeney, & Fox, 2001)
Mozzarella and Cheddar	Smaller physical size of cheese pieces during melt analysis	The increasing side length (from 25 to 70 mm) and thickness (from 2 to 4 mm) of square cheese slices resulted in increased meltability	(Wang & Sun, 2002)
Fat-reduced Gouda	Microparticulated whey protein (Simplese®) addition	Meltability increased with the addition of whey protein	(Schenkel, Samudrala, & Hinrichs, 2013b)
Mozzarella and Cheddar	Holding time at specific temperature before melting	The increased holding time had a negative effect on the meltability of ripened cheese, whereas the melting property of fresh cheese minimally affected	(Kuo et al., 2001)
Processed cheese spread a mixture of Cheddar cheese (25% ripened and 75% young)	Different levels of phytosterols incorporated into the cheese	Phytosterol-added cheese spread samples (3% and 4%) had higher cheese melting viscosity than the control	(Giri, Kanawjia, & Rajoria, 2014)
Mozzarella	Water activity	Higher water activity was associated with easier melting of cheese	(Ma et al., 2013b)

Gunasekaran, and Olson (2001) reported that increased holding time at 60 °C had a negative effect on the meltability of ripened cheese samples.

The basic ingredients of a pizza are mozzarella cheese, pizza sauce, and dough base, and their composition varies considerably. Consequently, the mass transfer of components across ingredients can lead to alterations in the composition, which can have an effect on the meltability of cheeses (Wang, et al., 1998a). According to the results of them, treatment with pizza sauce drastically reduced pH, Ca, and NaCl level, while increasing the moisture content of part-skim mozzarella cheese. Subsequently, the meltability of mozzarella cheeses treated with pizza sauce decreased significantly compared with control cheese samples after 12 d of storage. On the other hand, it has been demonstrated that there is a high correlation between rheological data of mozzarella cheese and sensory results of mozzarella cheese baked with pizza sauce. Also, they reported that the results of the Multiple Stress Creep Recovery test could be a suitable option for predicting baked-cheese properties (Banville, Power, Pouliot, & Britten, 2015). Furthermore, Zisu and Shah (2007) showed that the addition of exopolysaccharide-producing cultures improved the pizza bake features of low-fat mozzarella cheese, in terms of meltability, after 45 days of storage.

### 5.2. Effect of cheese ripening on melting

Proteolysis, glycolysis, and lipolysis, as well as the delayed solubilisation of part of the remaining micellar colloidal Ca phosphate, are a few of the biochemical processes during ripening that

transform curd from a rubbery, tasteless product to a ripened cheese with a distinctive flavour and texture. Proteolysis is the most significant metabolic process during ripening in the majority of cheese types (Fox, Lucey, & Cogan, 1990). Cheese aging has a considerable influence on structure and texture. Fat globules in mozzarella cheese form a collection from separate parts and coalesce over time, forming greater anisotropic fat particles that may contribute to the creation of free oil. Larger fat globules require a lower Laplace pressure to rupture; hence they probably contribute to the formation of free oil, which may behave as a lubricant and positively contribute to the melting of cheese (Everett & Auty, 2008; O'Mahony, Lucey, & McSweeney, 2005). In general, the melting characteristics of cheese are modified during ripening (Bähler, Back, & Hinrichs, 2015; Lawrence, Creamer, & Gilles, 1987). Furthermore, according to the study of Miynek et al. (2018), the hardness and meltability of cheese are associated with the fat content of milk and cheese, as well as the lipid transformations that occur during ripening and influence the chemical quality of fats. Moreover, it has been suggested that an increase in fat content during ripening led to substantial reduction in the average melt time and apparent viscosity and a major increment in the mean flowability (Guinee, Auty, & Fenelon, 2000). For example, in general, mozzarella cheeses with a lower fat concentration have become less meltable. As fat acts as a lubricant between protein domains in mozzarella cheese, its absence can impede the flow of protein matrices and slow cheese motion throughout heating, which explains why fat reduction decreased meltability (McMahon, Alleyne, Fife, & Oberg, 1996; Sahan, Yasar, Hayaloglu, Karaca, & Kaya, 2007).

Changes in cheese structure resulting from protein hydrolysis significantly impact the storage-related increase in cheese melting. Casein proteolysis causes fat globules, originally distributed within the protein matrix, to coalesce when cheese is heated, enhancing its meltability. Alterations in the state of water and protein in cheese can account for the rise in its meltability that occurs with storage (Joshi et al., 2004; Kiely et al., 1993; Tunick, Cooke, Malin, Smith, & Holsinger, 1997). Furthermore, excessive proteolysis of casein in cheeses with high moisture or high-fat content results in a softer structure and flows at significantly low-temperature values (Lucey et al., 2003). The calcium equilibrium is recognised to have a major impact on the hardness of cheese. Calcium attached to the casein matrix solubilises with time, diminishing inter-casein molecular connections (Everett & Auty, 2008; O'Mahony et al., 2005). Furthermore, the softening of cheese is caused by proteolysis from residual chymosin and native milk enzymes, as well as proteases from starter cultures and other microorganisms. Casein hydration takes place over time, notably in pasta filata cheese variants, resulting in enhanced cheese melting properties and reduced serum expressibility (O'Mahony et al., 2005). Several studies indicate that the particular hydrolysis patterns of casein and the subsequent peptide profiles may have an influence on the melting and stretching properties of cheeses (Lamichhane et al., 2018). According to the study of Kindstedt, Kiely, Yun, and Barbano (1991), the type of coagulant did not influence the cheese composition, whereas coagulant considerably impacted the kinetics and sensitivity of proteolysis during ripening, as well as differences in meltability, free oil generation, and viscosity. For instance, the kind of milk coagulant has no effect on the textural hardness of Mozzarella cheese throughout ripening; however, the meltability of the samples prepared with the proteinase from *Cryphonectria parasitica* is found to be much greater than that of cheese samples produced with calf rennet (Yun, Kiely, Kindstedt, & Barbano, 1993).

### 5.3. Moisture loss, skin formation, and browning reactions during the melting of cheese

The temperature-induced functionality changes in cheese, which includes softening, melting, stretchability, flowability, browning, and apparent viscosity, is a crucial feature of its cooking performance. According to Guinee (2002), some of the most important functional features of heated cheeses can be rheological adjustments, which involve the movement of matrix layers in response to applied stresses caused by physicochemical changes throughout heating, such as fat coalescence and interactions between casein particles. The degree of displacement during heating relies on the casein hydration level, the percentage of calcium-to-casein, fat content, pH, and emulsification of the fat in the non-heated cheese. Also, the proportion of matrix fluidity or elasticity is determined by the level of casein hydration (Guinee, 2002). Additionally, it is documented that the water-holding capacity of casein micelles diminishes with increasing temperature (Nöbel, Weidendorfer, & Hinrichs, 2012). A previous study demonstrated that cheese samples had roughly 15% moisture loss of their weight during melting. However, fresh cheeses were found to be more susceptible to evaporative moisture loss than aged cheeses (Banville et al., 2015). Furthermore, the effect of fat content on moisture loss was evaluated in the study of Kim, Lim, and Gunasekaran (2011), who reported that the reduced-fat cheese exhibited greater moisture loss, while the full-fat cheese showed a higher fat loss, due to the fat expulsion during heating. The reason for the observed results can be the better meltability of full-fat cheese than reduced-fat cheese because full-fat cheese provides a comparatively greater surface area for the loss of moisture throughout heating, while it expands more than its lower-fat

cheese counterparts (Altan et al., 2005). Moreover, the higher moisture loss of reduced-fat cheese samples is linked to the significant fat amount that separates from full-fat cheese as free oil, which prevents the loss of moisture by coating the surface of melted cheese (Rudan & Barbano, 1998). The protein content of cheeses rises with the increased fat and moisture loss during melting. As a result of this tendency, low-fat cheese can have greater protein-to-moisture and protein-to-fat percentages than full-fat cheese. Consequently, moisture and fat losses during the heating of reduced-fat cheese reduce their accessibility to perform as a surface barrier layer to limit the development of dry skin (Altan et al., 2005).

As caseins include a considerable number of hydrophobic regions, protein aggregation through hydrophobic interactions is one of the most significant alterations in cheese upon heating (Kinsella & Morr, 1984). Similarly, Kim et al. (2011) measured the protein interactions in reduced-fat and full-fat Cheddar cheeses using several dissociating substances, and the greater degree of protein-protein interactions that arise from hydrophobic interactions and disulfide bonds, as well as relatively ionic bonds with calcium are thought to be responsible for skin formation in reduced-fat cheeses. On the other hand, a model study on mozzarella cheese showed that a hydrophobic coating on cheese prevented water evaporation and presented better meltability (Rudan & Barbano, 1998). In addition, according to the results of Rudan and Barbano (1998), using a hydrophobic surface coating to prevent water evaporation from the cheese surface ensures comparable results for fat-free or low-fat cheeses with full-fat cheeses in terms of skin formation, melting, and browning characteristics. Similarly, Joshi et al. (2004) applied a thin vegetable oil layer on the surface of cheeses. According to the results, compared with normal cheeses, oiled cheeses showed a more extensive melt area; however, due to the considerable variety in findings, no apparent impact of oil utilisation on the melting of low-calcium cheese could be determined. Therefore, they assumed that the variations in test conditions, cheese compositions, and the physical form of cheeses could be the reason for the difference between the results of studies.

In general, during melting and baking, cheeses need to completely melt and shred without being too soupy, and there should be some free oil (FO) released to give the surface a glossy appearance without creating pools of oil. Blistering and browning must also occur, but not to the point where it looks burned (Kindstedt, 1991). The inconsistent colour distribution of final products is caused by the browning and blistering of cheese during heating (Ma, Balaban, Zhang, Emanuelsson-Patterson, & James, 2014). Blisters are pockets of trapped vapour and warm air that expand and do not release through the cheese surface and cause dry, tougher patches of melted cheese. According to a previous study, cheese meltability influences the occurrence of cheese blistering (Hong, Yun, Barbano, Larose, & Kindstedt, 1998). Moreover, browning is a feature of cheese that results in dark patches on the surface of the cheese during baking (Alvarez, 1986). Cheese browning is mainly generated by the Maillard reaction, a heat-induced reaction involving free amino groups in proteins and reducing sugars.

Galactose content is believed to be connected to cheese browning during baking, and free oil modulates the dehydration of cheese to influence browning qualities (Johnson & Olson, 1985; Richoux et al., 2008; Thomas, 1969). Furthermore, cheese browning begins during manufacturing and slow cooking following processing and has been noticed in cheese preserved in temperate environments (Bley, Johnson, & Olson, 1985; Thomas, 1969). Therefore, researchers have examined the effect of various starter cultures on the residual sugars in cheese and, by extension, cheese browning. A substantial correlation was discovered between the

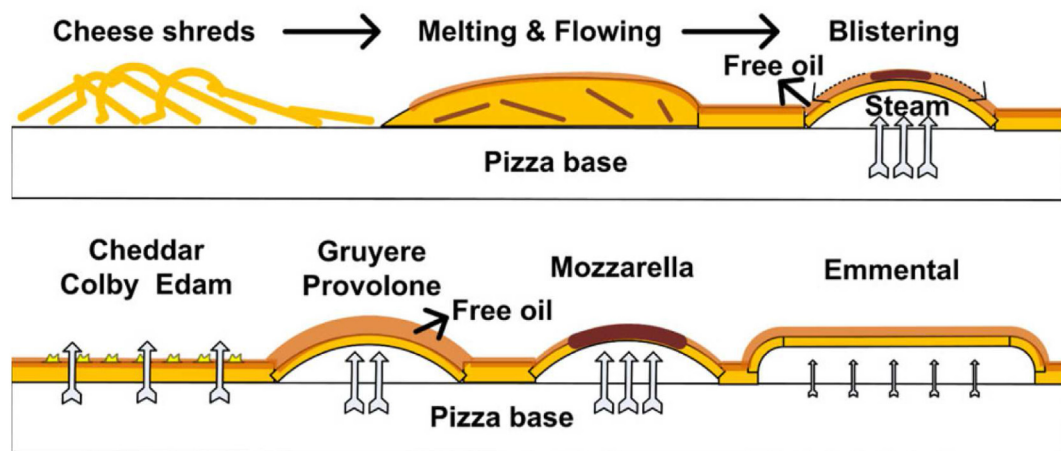


Fig. 5. Illustrative diagrams of blister formation and heating performance of various kinds of cheese. Figure is reproduced with permission from Ma et al. (2014).

colour of processed cheese and its galactose content (Bley et al., 1985). In a recent study, mozzarella cheese was produced with more and less heat-sensitive strains to compare the blistering and browning properties of samples (Ma, James, Balaban, Zhang, & Emanuelsson-Patterson, 2013a). According to their results, the galactose content of cheeses produced with low heat-sensitive starter cultures was found to be more than 25 times greater than that of cheeses manufactured with a more heat-sensitive starter culture. Therefore, the mozzarella prepared with high heat-sensitive starter cultures exhibited the least significant browning and a few blisters (Ma et al., 2013a). The observed difference in the galactose content of cheeses could be attributed to the different galactose-fermenting abilities of selected starter strains (Law & Tamime, 2011).

In another significant study, the browning and blistering properties of mozzarella cheeses, which had various salt and moisture contents, were studied (Ma, James, Balaban, Zhang, & Emanuelsson-Patterson, 2013b). As a result, all mozzarella samples had the same browning properties, due to their similar galactose concentrations. On the other hand, mozzarella cheeses with a greater salt content had substantially smaller fat globules and reduced water activity, resulting in a phase change temperature, elastic and stretching resistances, and smaller blisters (Ma et al., 2013b). A study of the role of fat release on the melting and browning features of mozzarella cheeses was carried out by Rudan and Barbano (1998), and they reported that the critical point is the released fat amount from cheese during melting rather than the overall fat content. Based on the model of the melting and browning dynamics proposed by them, moisture, fat, and protein constituents have an effect on the browning and melting properties of cheeses. Interestingly, Dai, Jiang, Shah, and Corke (2019) reported that the usage of a fat replacer (konjac glucomannan, KGM) in Mozzarella cheese showed less browning on the surface of cheeses than in the samples without KGM due to the water-holding capacity of KGM, which can cause lower moisture loss from the cheese during heating. In addition to its better bake performance, cheeses with KGM had a whiter appearance after the heating process. Based on previous studies, the increased whiteness of cheeses with KGM can be attributed to the induced aggregation of peptides and casein in colloidal suspension by KGM. As a result, the amount of reflected light from cheese increases during heating (Metzger, Barbano, Rudan, Kindstedt, & Guo, 2000). Also, the white colour of KGM can be another reason for the increased whiteness of KGM-added cheeses (Dai, Corke, & Shah, 2016).

Furthermore, for the difference in the blistering and browning features between Cheddar, Edam, Colby, provolone, Gruyere, and mozzarella cheese samples, Ma et al. (2014) constructed a diagram including baking performance and blister formation of cheeses, as shown in Fig. 5. These researchers reported that Cheddar, Colby, and Edam did not develop blisters due to their comparatively low elasticity. As depicted in Fig. 5, the gas bubbles of these cheeses burst at an early stage of blister formation, presumably because their inadequate elastic responses are unable to withstand the steam forces. On the other hand, for provolone and Gruyere, a considerable amount of free oil covers the bubbles, preventing the moisture loss from cheese and resulting in less intense browning. However, mozzarella has far less free oil covering the bubbles, so the moisture in the cheese evaporates more readily, leaving a scorched surface on each blister (Ma et al., 2014).

During heating and melting, another critical parameter is the whiteness of cheeses, which has been linked to the protein and fat matrix, as well as the heating-induced restriction of the serum phase within the protein matrix (Imm et al., 2003; Rudan, Barbano, Joseph Yun, & Kindstedt, 1999). According to Metzger et al. (2000), the reversibility of the apparent whiteness alteration during heating and chilling suggested that cheese undergoes a reversible, heat-induced interaction. Based on the results of the study, they proposed a model to explain the impacts of serum, fat, and serum-casein matrix interactions during heating and cooling. This model proposes that the L-value, which is the indicator of whiteness, of mozzarella cheese throughout heating and chilling is affected by both the state (i.e., particle size) and amount of fat in mozzarella cheese, as well as the state (i.e., protein concentration) and amount of serum phase. During heating, some of the protein in the serum phase interacts to generate gel particles, which reflect light and enable the cheese to appear whiter (Metzger et al., 2000). In addition, they found that the whiteness values of low-fat Mozzarella cheeses increase throughout heating from 7 to 60 °C. Similarly, Joshi et al. (2003a,b) observed a significant increase in the whiteness values of Mozzarella cheeses, which are fat-free and have different calcium contents, during heating from 5 to 60 °C.

## 6. Conclusion

Cheese is one of the oldest and most fundamental dairy foods, and the functionality of cheese is essential since it is used as an ingredient in the food industry. Moreover, melting is a crucial functional characteristic, particularly for cheeses used in foods

served after heating. This review presents current knowledge on the melting properties of cheese. A basic understanding of how phase change influences the numerous heat-induced functionality of cheese is demonstrated. Such knowledge is especially valuable for understanding the characteristics of cheese during heating for both consumers and the food industry. As a result, a proper measurement of the cheese melting with controlled parameters has great importance. However, it is a complicated process due to the thermal phase transition of solid cheese and the rheology of melted cheese. Overall, comprehensive knowledge about the accurate measurement methods of melting and heat-induced changes in cheese is key to determining the specific functionalities of cheese.

## Declaration of competing interest

None.

## Data availability

No data was used for the research described in the article.

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