Quantification of Pizza Baking Properties of Different Cheeses, and Their Correlation with Cheese Functionality

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Abstract: The aim of this study is to quantify the pizza baking properties and performance of different cheeses, including the browning and blistering, and to investigate the correlation to cheese properties (rheology, free oil, transition temperature, and water activity). The color, and color uniformity, of different cheeses (Mozzarella, Cheddar, Colby, Edam, Emmental, Gruyere, and Provolone) were quantified, using a machine vision system and image analysis techniques. The correlations between cheese appearance and attributes were also evaluated, to find that cheese properties including elasticity, free oil, and transition temperature influence the color uniformity of cheeses.

Keywords: color uniformity, machine vision, pizza baking, principal component analysis

Practical Application: Different cheeses can be employed on "gourmet" style pizzas in combination with Mozzarella. Based on the findings, cheeses with some attributes can be used to cook pizzas to meet the specific preferences of consumers.

Introduction

Image analysis techniques based on machine vision have been applied increasingly in the food and agricultural industry, offering rapid, objective and consistent assessment. More specifically in applications to pizzas, various techniques have been used to evaluate the shape and size of the pizza base (Du and Sun 2004), the sauce spread (Sun and Brosnan 2003; Du and Sun 2005), and the pizza toppings (Sun and Brosnan 2003; Du and Sun 2005). However, the appearance of pizzas baked with cheese is commonly evaluated by sensory method (Rudan and Barbano 1998) and colorimeter (Aydemir and Dervisoglu 2010), and only Mozzarella cheese (which browns and blisters) has been investigated using machine vision (Ma and others 2013a, 2013b).

The blistering and browning of cheese during baking result in a nonhomogeneous color distribution on pizzas, which increases the evaluation difficulty. An image analysis method based on machine vision has been developed to quantify the color and color uniformity of nonhomogeneously colored agricultural materials, which has been applied to rabbit meat and banana samples (Balaban 2008). However, this image analysis method has not been applied to baked cheese. Browning is the overall color evaluation of the cheese after pizza baking, and excessive browning of cheese is a defect (Matzdorf and others 1994; Wang and Sun 2003). The moisture content of low fat Mozzarella has usually been increased to prevent undesirable scorching or browning (Fife and others 1996; McMahon and others 1999; Broadbent and others 2001), and free oil is involved in browning by modulating the dehydration of cheese (Richoux and others 2008). Blisters are trapped pockets of heated air and steam that may be preferentially scorched upon baking, and blistering has been suggested to be affected by cheese melt properties (Hong and others 1998). However, scientific studies on cheese blistering and browning have mainly focused on Mozzarella cheese (Ma and others 2013a, 2013b), even though other cheeses are frequently employed on "gourmet" style pizzas in combination with Mozzarella. The aim of the current study was to develop improved methods for quantifying and differentiating the appearances of different pizzas after baking (by quantifying browning and blistering behavior). To achieve this aim, first, cheeses including Mozzarella, Cheddar, Colby, Edam, Emmental, Gruyere, and Provolone were baked on pizzas and their images were captured using machine vision, and the color, color uniformity, and browning areas of cheeses were evaluated. Then, to further understand the pizza baking performance of cheeses, some cheese attributes (moisture, free oil, and so on) were evaluated. Finally, different cheeses were classified by their pizza baking performance.

The majority of pizza cheese is Mozzarella and the aim of using the alternative cheeses in this study was to exacerbate differences in browning and blistering behavior in order to optimize the quantification tool. To further understand the pizza baking properties of different cheeses, their correlation to other properties including the rheology, free oil, transition temperature, and water activity of cheeses were also studied. Aging and proteolysis also have a strong influence on the functionality of cheese (McMahon and others 1999), as well as the residual sugar content (Johnson and Olson 1985), but they were not included in the current study, since the main aim was to develop a reliable machine vision system for grading browning and blistering performance. This in

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doi: 10.1111/1750-3841.12540

Journal of Food Science A Publication of the Institute of Food Technologists

turn influences the choice of cheeses, since they were expected to give very different behavior during baking.

Materials and Methods

Cheese preparation and pizza baking test

Mozzarella, Cheddar, Colby, Edam, Emmental, and Gruyere were bought from a local supermarket and Provolone was bought from a local delicatessen in Auckland, New Zealand.

Cheeses were stored at 4 °C for a month, and each type of cheese was shredded separately using a food processor (BFP400, Kitchen Wizz, Sydney, Australia) before the pizza baking test. Pizza bases (approximately 23 cm diameter and about 1 cm thickness, Leaning Tower^{TM} Thin) were stored in a freezer and thawed for 3 h at room temperature before the tests. A metal ring (21 cm in diameter, 5 cm high) was placed on each pizza base, and 125 g cheese shreds were spread evenly in the circular area, leaving about 1 cm edge uncovered. The shreds were deeper than a single layer on the pizza base, and were evenly spread, so that the shred distribution would not influence the color distribution of the pizza after baking. Each pizza was baked in a convection oven (Turbofan E32D4, MOFFAT, Christchurch, New Zealand) at 232 °C for 5 min (Rudan and Barbano 1998). The pizza was immediately removed from the oven, and placed in a light box system. Images of the pizzas were obtained with a digital video camera, under controlled illumination conditions, as described below.

Image acquisition

Most image analysis methods are sensitive to noise, and illumination would contribute to noise, so the images were taken in a light box, with constant and known illumination. Furthermore, the images were color-corrected to a known color standard, to account for small variations in illumination. Details for image acquisition were as previously described (Luzuriaga and others 1997). In summary, the system was composed of a digital video camera (DFK 31 BF03, Imaging Source, Charlotte, N.C., U.S.A.) attached to a laptop computer by a IEEE1394 cable, a lens (Tamron 12VM612) with a circular polarizing filter (35.5 mm B+W filter, Bad Kreuznach, Germany), and a light box. The light box used 2 fluorescent light bulbs (Lumichrome F15W1XX, color temperature = 6500 °K, color retention index = 98, Lumiram, Larchmont, N.Y., U.S.A.) emulating D65 illumination (natural daylight at noon). Diffuse light inside the box was obtained by using a Polycast acrylic #2447 plastic sheet (Faulkner Plastics, Gainesville, Fla., U.S.A.) between the fluorescent bulbs and the sample space.

Color evaluation

Color analysis was conducted using the software LensEye (Gainesville, Fla., U.S.A.) to capture images and analyze their color attributes. To represent colors, the $L^*a^*b^*$ model was applied: L^* (from 0 to 100: black to white), a^* (from −120 to 120: green to red), and b^*(from −120 to 120: blue to yellow).

In the software, a circular region of interest (ROI) was used with each image to select equal areas. The ROI can be moved on the image so that it can be centered on the pizza. The circular ROI on the pizza images were selected to be the size of cheese spread on the base, to avoid measuring the color of the pizza base.

The color of the each pizza was evaluated by measuring the average L^*, a^*, and b^* of the area selected by this circular ROI, by averaging the values of every pixel in the ROI.

Color uniformity

The dark spots scattered on pizzas as a result of cheese browning and blistering during baking are not easily quantified, so they are usually qualitatively described by subjective terms, or even neglected, which may lead to misleading conclusions (Yam and Papadakis 2004). This is relevant to the color uniformity: the pizza with fewer dark spots has more uniform color distribution. We quantified the color nonuniformity of pizzas using color primitives, in order to quantitatively analyze the pizza appearance with respect to the dark spots.

A color primitive is defined as a continuous area, in which the color intensity of any pixel is within a given threshold value range. The color intensity difference (ΔI) between 2 pixels (Balaban 2008) is defined as:

$$\Delta I = \sqrt{(R_i - R_j)^2 + (G_i - G_j)^2 + (B_i - B_j)^2} \qquad (1)$$

where subscripts i and j represent 2 pixels being compared, and R, G, and B represent the red, green, and blue components of a pixel color. To obtain the color primitives of an image, LensEye calculated the color intensity differences between a pixel and its immediate neighbors, and continued with the immediate neighbors of these neighbors until ΔI exceeded the given threshold. Then a new primitive was started, and the process was repeated until all pixels were processed, and all color primitives were determined. Meanwhile, equivalent circles having the same area (in pixels) as the color primitives were calculated, and were drawn centered at the center of gravity of the primitive (Balaban 2008).

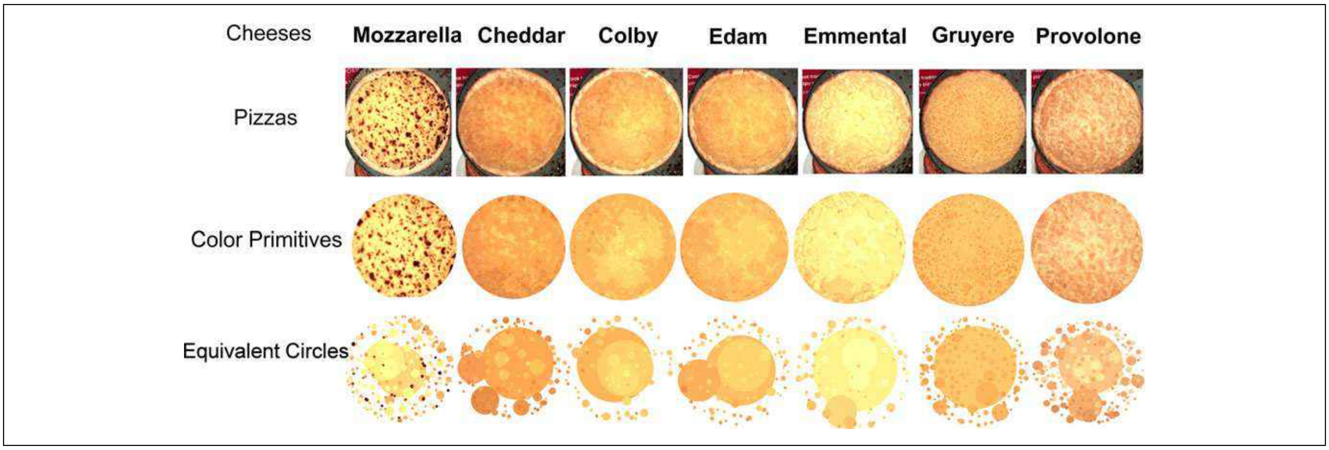

Figure 1–Color primitives analysis on pizzas with different cheeses.

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Color primitives are contiguous regions in the image where the difference of color intensity of every pixel in the region is less than a specified threshold value compared to the anchor pixel (Balaban 2008), that is, the colors in a primitive are very similar to each other. Separating the image into primitives effectively segments it into areas where color is relatively uniform. This is useful in quantifying the color nonuniformity of the image.

To evaluate the color nonuniformity, the number of color primitives (#Primitives) and the color change index (CCI) were calculated by LensEye. CCI is defined by Balaban (2008):

$$CCI = \frac{\sum \Delta I \, for \;\; neighboring \;\; primitives}{\sum distance \;\; between \;\; each \;\; primitive} \times \frac{number \;\; of \;\; neighbors}{object \;\; area} \times 100 \qquad (2)$$

The color intensity difference (ΔI) between neighboring color primitives was calculated by Eq. 1. A high CCI value indicates more "changes" in the color of an object—less uniformity (Balaban 2008).

Browning area analysis

Some parts of cheese on each pizza have darker colors than their neighbors, that is, they have lower L^* values. Pizzas made with different cheeses may have different overall colors, and thus need different threshold values to distinguish darker pixels from the rest of each pizza. To address this issue, 95% of the average L^* value of each pizza was chosen as the threshold by trial and error, and pixels with lower L^* than this threshold were highlighted as surface browning. The area% of browning was also measured.

Cheese attributes evaluation

The cheeses were assessed for moisture content, water activity, transition temperature, and temperature profiles. Rheological properties and free oil formation were also evaluated. All tests were done in triplicate.

Moisture and water activity. Each cheese was assessed for the water activity and moisture content. Samples of 3 g of shredded cheese were analyzed for water activity at 25 °C (Novasina LabMaster, Novasina AG, Neuheimstrasse, Lachen, Switzerland). Moisture content of each cheese was achieved by atmospheric oven method in accordance with AOAC method (Helrich 1990).

Rheology. Specimen (3 mm thick) was sliced from each cheese block (a similar sampling pattern was used on each of 3 occasions) and cut into a disk (40 mm in diameter). A serrated parallel plate (40 mm in diameter) attached to the rheometer (AG-2R, TA Instruments, New Castle, Del., U.S.A.) was used. Temperature sweeps from 15 to 90 °C, with a temperature step gap of 5 °C and a holding time of 1.5 min at each step were performed. Constant strain of 0.05% and frequency of 0.8 Hz were used to ensure a linear viscoelastic range. Elastic Modulus (G') and Viscous Modulus (G'') curves were plotted to evaluate cheese viscoelasticity (Ma and others 2013c).

Transition temperatures and temperature profiles. The transition temperature of each cheese was measured as the temperature at which G' and G'' cross each other during the temperature sweep, and it indicates the temperature at which cheese became more viscous than elastic (Sutheerawattananonda and Bastian 1998). It also refers to the softening point during heating, which indicates the ease of melting (Gunasekaran and Ak 2003).

Temperatures of each cheese, during baking on pizza bases, were measured using a thermocouple (K type, Q1437, Dick Smith™) with a wire probe inserted among cheese shreds near the center of pizza, and the oven door was then closed with the long wire of probe going through the door. A temperature profile curve was drawn by recording temperature at every minute during pizza baking for 5 min.

Free oil. A cheese disk (approximately 2 mm thick and 17 mm diameter) sliced and cut from each cheese block was weighed, placed on a filter paper in a glass Petri dish and then heated in an oven at 200 °C for 1 h. After heating, photographs were taken using the machine vision system described in Section "Image acquisition." The area of free oil was measured using Image Pro plus 6.0 software (Media Cybernetics Inc., Bethesda, Md., U.S.A). The ratio between the free oil area on the filter paper and the weight of sample was used to evaluate the free oil release (Ma and others 2013a).

Statistical analysis

One-way analysis of variance (ANOVA) was performed to investigate the significant difference between cheese samples. Correlation between all cheese properties was studied using principal component analysis (PCA) (Ma and others 2013c).

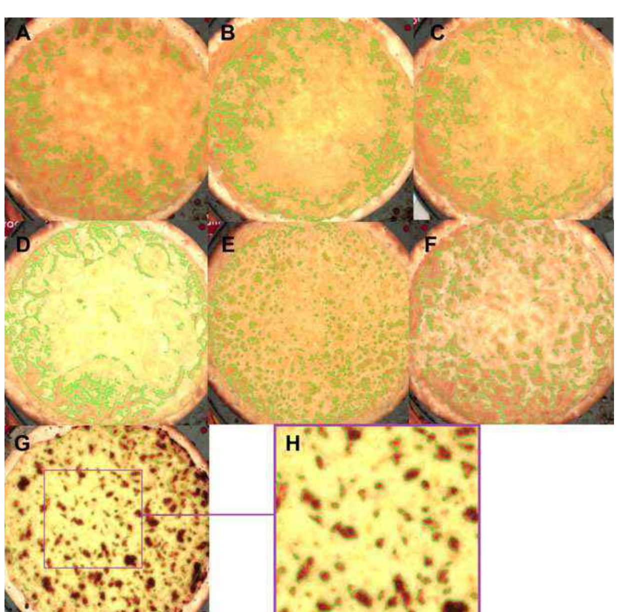

Figure 2–Browning of pizzas: (A) Cheddar, (B) Colby, (C) Edam, (D) Emmental, (E) Gruyere, (F) Provolone, (G) and (H) Mozzarella (brown areas were outlined).

Results and Discussion

Color of cheeses

From the average L^*, a^*, and b^* values, the colors of pizzas baked with different cheeses had different color descriptions under the ISCC-NBS color system (Kelly and Judd 1976): Mozzarella, Colby, Edam, and Gruyere were described as moderate orange yellow; Cheddar was strong orange; Emmental was light yellow; Provolone was light orange. Table 1 indicates that Emmental with the highest L^* and lowest a^* and Cheddar with the lowest L^* and highest a^* are distinguished from the other cheeses ($P < 0.05$).

Table 1–Parameters evaluating appearances of cheeses after pizza baking.

	Cheese types						
Parameters	Mozzarella	Cheddar	Colby	Edam	Emmental	Gruyere	Provolone
L^*	78.87^b	72.62^a	80.72^b	80.61^b	92.74^c	79.48^b	78.95^b
a^*	10.04^b	26.28^d	14.26^c	14.21^c	-6.18^a	16.07^c	17.08^c
b^*	53.03^b	58.02^c	59.16^c	59.15^c	52.03^b	56.49^{bc}	44.69^a
No. Primitives	9758^c	2905^{ab}	2685^a	3413^b	2492^a	2697^a	3299^b
CCI	3.62^e	0.18^c	0.10^a	0.15^b	0.15^b	0.19^c	0.30^d
L^* of browning area	52.79^a	64.52^b	73.10^c	72.30^c	83.33^d	71.37^c	69.24^{bc}
Browning area (%)	28.41^c	27.74^c	20.78^b	18.03^a	20.23^b	17.47^a	29.57^c

Parameters with different superscript letters in a row have significant differences ($P < 0.05$).

Provolone had the lowest b^*, and Mozzarella had significantly different a^* from other cheeses ($P < 0.05$). On the other hand, Colby, Edam, and Gruyere could not be distinguished from each other based on their average L^*, a^*, or b^* colors.

Color uniformity

Figure 1 shows the original photos of pizzas, calculated color primitives, and resulting color primitive equivalent circles of different cheeses. As shown in Table 1, Colby with the lowest #Primitives and CCI had the highest color uniformity. Mozzarella was easily distinguished from the other cheeses by its extremely nonuniform color—more than 3 times more #Primitives and an order of magnitude higher CCI than the other cheeses.

Browning

Figure 2 highlights pixels with $L^* < 0.95 \times L^*_{average}$ for each cheese, and the browning area (shown in Table 1), as the area% of the outlined pixels, quantifies the overall darkening of the cheese upon baking. Edam and Gruyere had the smallest browning area% ($P < 0.05$), followed by Colby and Emmental. Moreover, Mozzarella, Cheddar, and Provolone had significantly higher browning areas ($P < 0.05$). Mozzarella, Gruyere, and Provolone had relatively even distribution of browning spots, while the other cheeses mostly browned around the edge. It is noted in Figure 2 that Emmental had big bubbles with only slight browning, while Mozzarella had extremely high browning.

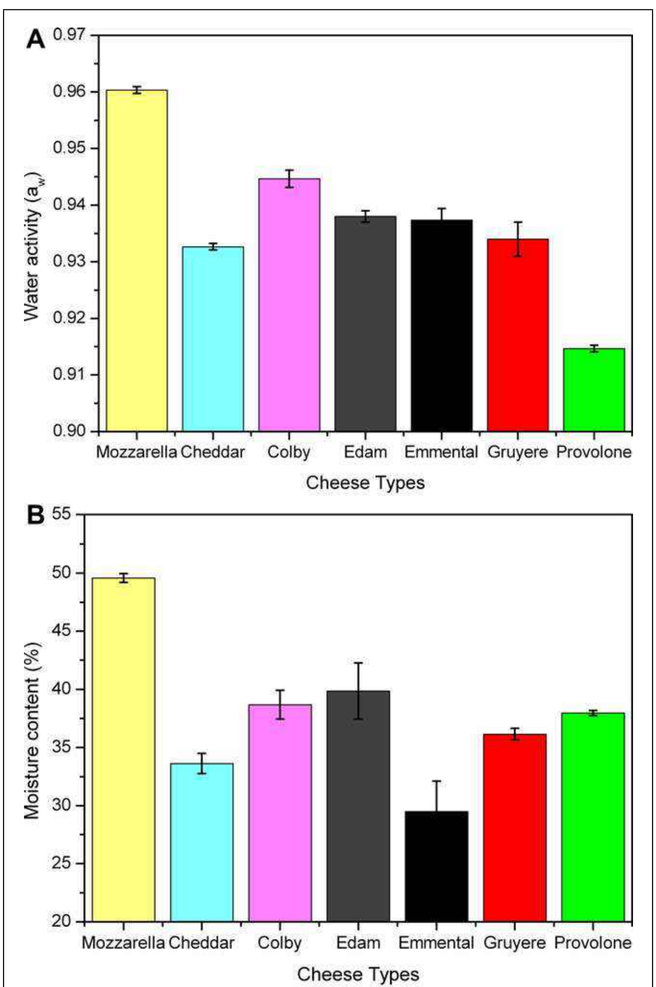

Figure 3–(A) Water activity. (B) Moisture content of cheeses.

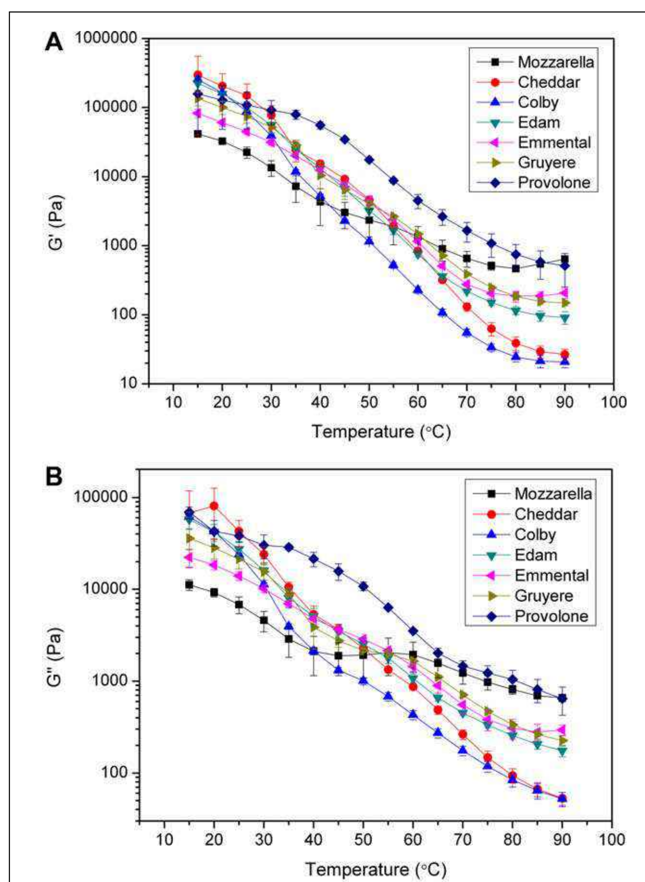

Figure 4–Rheological parameters of cheeses: (A) Elastic modulus: G'. (B) Viscous modulus: G''.

Cheese attributes and their effects on pizza appearance

As shown in Figure 3, Mozzarella had the highest water activity (0.961, $P < 0.05$), and Provolone had the lowest (0.915, $P < 0.05$); Mozzarella also had the highest moisture content (49.6%, $P < 0.05$), whereas Emmental had the lowest (29.5%, $P < 0.05$). Gruyere and Provolone, with similar pizza baking performance, had similar moisture contents (36.2% and 37.9%, respectively). The other cheeses (Cheddar, Colby, and Edam) with relatively high color uniformity had a wide range of moisture contents (33.6% to 39.9%).

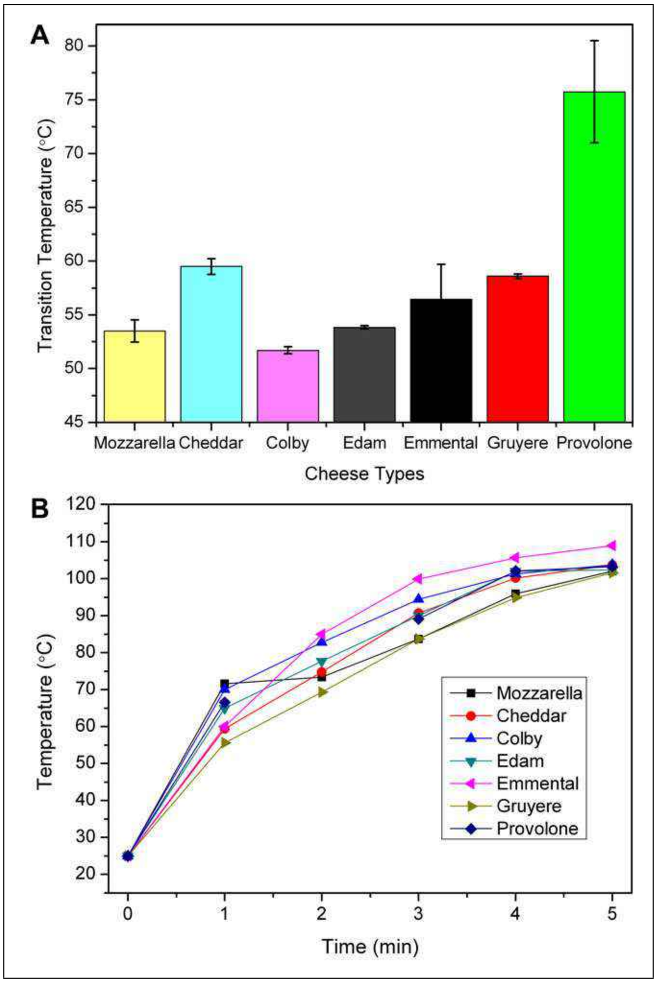

Figure 5–(A) Transition temperatures. Temperature profiles of cheeses.

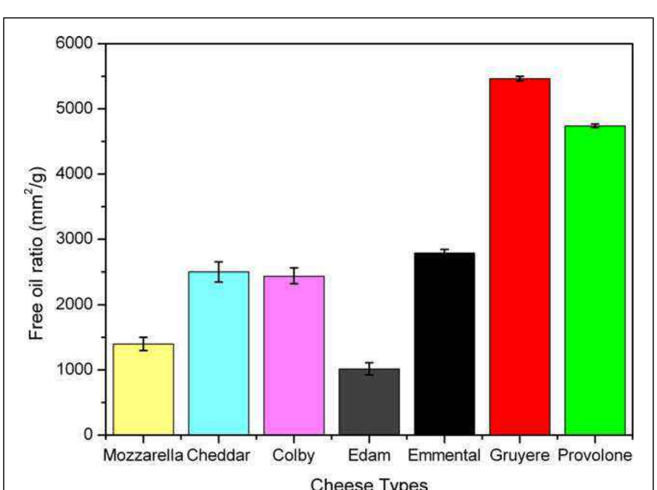

Figure 6–Free oil released by cheeses.

Figure 4 shows that G' and G'' of cheeses deceased with an increasing temperature, and Mozzarella had the lowest decreasing rates. Provolone had the highest G' and G'' from 35 to 85 °C, and Cheddar and Colby had lower G' and G'' from 65 to 90 °C ($P < 0.05$).

Comparing the transition temperatures and temperature profiles between cheeses in Figure 5, we found that after 2 min of baking, all cheeses had temperatures higher than 65 °C, which were higher than their transition temperatures except Provolone; cheeses except Provolone behaved more like viscous liquid than elastic solid for the majority of the baking time. However, the conversion of moisture present in cheese to steam would occur only in the last minute of baking, when the temperature of cheese reached 100 °C.

The water activity was found to negatively correlate with transition temperature, which is in accordance with previous research (Duggan and others 2008). The correlation is linear if Mozzarella is excluded ($R^2 = 0.977$). Moreover, there is a significant positive impact of transition temperature on color uniformity as quantified by CCI ($R^2 = 0.948$). It is indicated that higher water activity means less energy is needed for the moisture in cheese to escape from the bonds of protein, and thus the cheese melts easier (reflected by lower transition temperature). Moreover, the better melting of cheese can produce more evenly distributed melted cheese on pizza during baking, and thus more uniform color distribution. Mozzarella is an exception, because of its unique blistering and browning behavior. The aging and proteolysis of cheeses is also expected to influence pizza baking properties, as will the starter culture used in production (Ma and others, 2013a), however as stated previously these aspects were not the focus of this study.

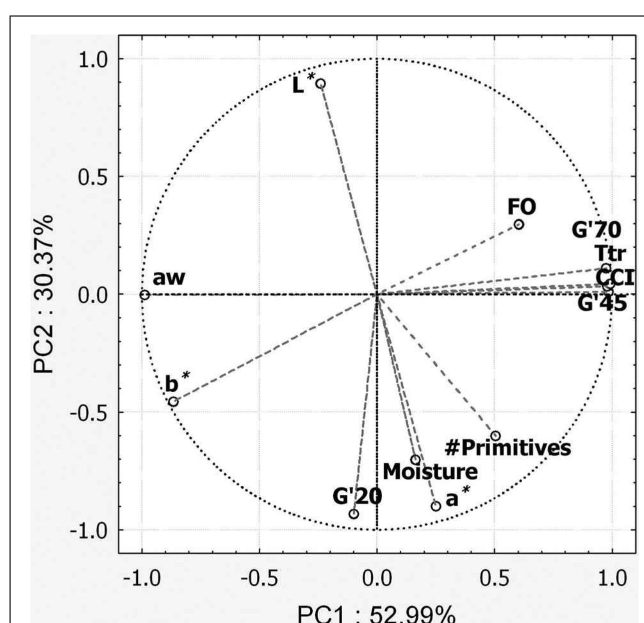

Figure 7–Loadings of variables of cheese samples for principal components: PC1 and PC2 (FO, free oil; Ttr, transition temperature; aw, water activity; G'45: G' at 45 °C; G'70: G' at 70 °C).

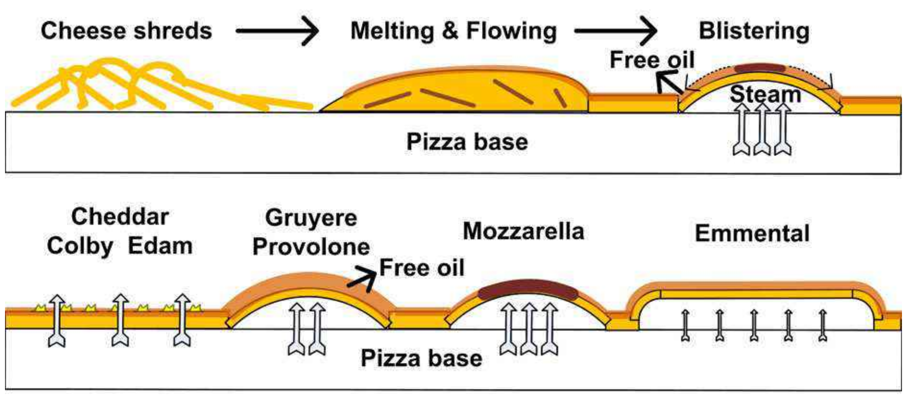

Figure 8–Schematic diagrams of blister formation and pizza baking performance of different cheeses (the number of arrows reflects the amount of moisture).

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In Figure 6, we found that the free oil of Edam was the lowest (1017 mm^2/g), Mozzarella was approximately 40% higher, and Cheddar, Colby, and Emmental were 150% to 180% higher than Edam. Gruyere and Provolone had the highest free oil amounts—4.5 to 5.5 times of Edam.

Correlation between pizza baking and other cheese properties

Mozzarella was found to have extremely different pizza baking performance from the other cheeses, reflected by its lowest color uniformity. To better detect the minor variance between the other types of cheeses, PCA was applied to their pizza baking properties and other cheese properties.

As reflected by Figure 7, the 2 principal components (PCs) account for 81.8% of the total variance of these parameters. PC1 represents the color uniformity, and PC2 reflects the color parameters. It is indicated by Figure 7 that there is a strong positive correlation between transition temperature and color uniformity (quantified by the negative of CCI), which both negatively correlate to water activity (a_w). The better melting of cheese can produce more evenly distributed melted cheese on pizza during baking, and thus more uniform color distribution.

As indicted by PCA, Figure 7, the moisture content, free oil, and elasticity (reflected by G' at 45 and 70 °C) also affect the color uniformity of cheese. Elasticity is defined as the ease and extent to which cheese returns to its original shape after the deformation stress is removed (Gunasekaran and Ak 2003). G' is the mathematical description of the tendency to be deformed elastically when a force is applied to it. G' is normally used to evaluate the elasticity of cheese, and for cheese melt, G' at high temperatures shall be used to reflect its elasticity. The differences between these parameters of different cheeses may result in their different pizza baking performance, by influencing blistering and browning (Ma and others 2013a, 2013b). For Cheddar, Colby, and Edam, blisters were not formed because of their relatively small elasticity. As shown in the schematic diagram (Figure 8), gas bubbles of these cheeses burst at an early stage of the formation of blisters, possibly because their limited elastic responses cannot resist the steam forces.

For Gruyere and Provolone, sufficient amount of free oil covers bubbles, which prevents moisture evaporating from cheese, hence less intensive browning occurs. In contrast, Mozzarella has much less free oil covering the bubbles, from which the moisture in cheese evaporates more easily, leaving a burnt surface of each blister.

It is indicated that the steam force is related to moisture content, so Mozzarella generates the most steam, followed by Gruyere and Provolone, and Emmental has the least steam. For Emmental, the steam force is only enough to hold fewer bubbles, and each bubble is produced by the moisture of a larger area of cheese. The resulting bubble has a larger area than other cheeses, with lower height; hence free oil may not flow from the top of each bubble. Consequently, moisture is difficult to evaporate from bubbles, and browning is hardly seen on the bubbles of Emmental.

It is noted that the residual sugar content was reported to be a major determinant of browning (Johnson and Olson 1985). The starter cultures used in cheese manufacture metabolize lactose, and produce galactose in cheese (McSweeney and Fox 2004). Some starter cultures can ferment galactose, while the others cannot, which accumulate galactose in cheese, resulting in excessive browning (Ma and others 2013a). While, the galactose contents of most studied cheeses were not significantly different (<51 mg/kg) (Van Calcar and others 2014), and thus no intensive browning was observed. Because of the main objectives of this study, residual sugar contents were not investigated.

Mozzarella is widely used in making pizzas, and a mixture with other cheeses is often adopted to satisfy different preferences of customers. In addition, cheese would be less burnt with more free oil, and higher color uniformity can also be achieved by adding other cheeses with high water activity.

Conclusions

Pizza baking performance of different cheeses was evaluated in this study, including the blistering and browning. The color and color uniformity of cheeses after baking on pizzas were quantified, as well as the cheese properties. The elasticity, free oil, moisture, water activity, and transition temperature were found to influence the color uniformity of cheeses.

For Cheddar, Colby, and Edam, blisters were not formed because of their small elasticity. Sufficient amount of free oil prevents moisture evaporation, and thus less intensive browning occurs on Gruyere and Provolone. Browning is hardly seen on the Emmental mainly because of its weak steam force.

Mozzarella has high water activity and elasticity, but mostly importantly, it has unique stretchability, which makes it commonly used as a pizza topping. Different cheeses can be employed on "gourmet" pizzas in combination with Mozzarella. Gruyere and Provolone can be added to obtain less burnt appearance by producing more free oil, and the color would be more uniform by adding cheeses with low elasticity, such as Colby.

In order to develop a sophisticated evaluation technique of pizza baking, comparisons of this technique and the evaluation of experienced graders are recommended for future study.

Acknowledgments

The project funding was jointly supported by Fonterra Co-operative Group Limited and Chinese Scholarship Council. We appreciate the technical assistance Dr. Zayde Alçiçek at the Univ. of Auckland.

Author Contributions

B. James designed the study. X. Ma collected the data and drafted the manuscript. M. Balaban technically assisted the study. L. Zhang and E. Emanuelsson-Patterson gave valuable suggestions.

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