International Journal of Gastronomy and Food Science 44 (2026) 101476

Contents lists available at ScienceDirect

International Journal of Gastronomy and Food Science

journal homepage: www.elsevier.com/locate/ijgfs

Functional and sensory evaluation of commercial plant-based mozzarella analogues

Irene Fenga, Marcello Alinovi *, Emma Chiavaro, Maria Paciulli

Food and Drug Department, University of Parma, Parco Area delle Scienze Pad. 33 (Tecnopolo), Parma, Italy

ARTICLE INFO

Keywords:
Plant-based alternatives
Cheese analogues
Sensory analysis
Rheology
Cooking behavior
Stretchability

ABSTRACT

The growing demand for plant-based alternatives to animal-derived foods has led to an increased availability of plant-based cheese analogues, particularly those mimicking mozzarella. However, these products often fail to replicate the functional and sensory properties of cheeses. This study evaluates the physical, structural, functional, and sensory characteristics of three commercial plant-based mozzarella analogues in comparison with two dairy references. Physicochemical and structural analyses included moisture content, pH, color, oscillatory rheology, differential scanning calorimetry (DSC), low-field ^{1}H NMR, and texture profile analysis. Meltability, browning, oiling-off, and stretchability tests were also conducted to assess functionality during cooking. Sensory acceptability and Just-About-Right (JAR) tests were combined to identify penalizing attributes of the samples melted on pizza. The structures of the plant-based samples showed inability to replicate the texture and the cooking properties of dairy products. Rheological and DSC data revealed different melting behaviors. Sensory data confirmed a lack of consumer acceptance for plant-based samples, mainly due to texture and flavor limitations. Stretchability was identified as a key penalizing attribute. The findings underline structural challenges in replicating casein functionality with plant ingredients and provide insights to guide formulation strategies for future development of plant-based mozzarella analogues.

1. Introduction

In recent years, an increasing portion of consumers have shown interest in plant-based dietary patterns. These diets mostly or totally exclude animal-origin foods and can include different types of diets such as vegetarian and flexitarian ones (Hargreaves et al., 2023). This dietary shift is largely driven by concerns related to health, animal welfare, and sustainability (Fresán et al., 2020; Landry and Ward, 2024). These issues are further amplified by debates about the ability of the current food system to satisfy the nutritional needs of a growing global population.

As a result, the plant-based market has significantly expanded its size and offering, introducing new categories of plant-based foods designed to replicate the characteristics of the animal-origin ones (e.g., meat, dairy products, eggs, and seafoods) (McClements, 2024). A report by the Good Food institute highlighted a 34% increase in global retail sales of plant-based substitutes for animal products (excluding plant-based eggs) between 2019 and 2023, reaching a total of $29 billion (The Good Food Institute, 2023). The target of the plant-based analogues' market doesn't include only vegans but also consumers that are interested in reducing their animal-based food consumption (Waehrens et al., 2023).

Despite growth in emerging plant-based markets, some challenges are rising in more mature markets such as the U.S. where plant-based sales decreased in 2023 compared to the previous year (The Good Food Institute, 2023). A major barrier is the lack of consumer appreciation for the organoleptic properties of plant-based alternative, which often fail to replicate the sensory characteristics of their animal-based counterparts (Abe-Inge et al., 2024). Since taste, flavor, appearance, and texture are key drivers in plant-based products choice, improvement of these characteristics can help the marketers to enhance their appeal (Venter De Villiers et al., 2024).

In Italy, from 2021 to 2023, the sales value of all plant-based food categories increased with plant-based cheese having the highest growth rate, reaching a +79.6% increase in market value (GFI Europe, 2024). Cheese analogues have attracted increased popularity leading to significant efforts in research and development aimed at the improvement of their organoleptic properties to meet consumers' expectations (Grossmann and McClements, 2021). Various types of plant-based cheese analogues have been developed to provide an offer able to

* Corresponding author.
E-mail addresses: irene.fenga@unipr.it (I. Fenga), marcello.alinovi@unipr.it (M. Alinovi), emma.chiavaro@unipr.it (E. Chiavaro), maria.paciulli@unipr.it (M. Paciulli).

https://doi.org/10.1016/j.ijgfs.2026.101476
Received 3 December 2025; Received in revised form 17 February 2026; Accepted 8 March 2026
Available online 9 March 2026
1878-450X/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

align with the wide range of cheese categories available on the market, including different textures (e.g., hard, soft, spreadable), shapes (eg., blocks, wheels, sliced, shredded), and flavors (Bresciani et al., 2025; Craig et al., 2022; Grasso et al., 2021; Mefleh et al., 2022; Nicolás Saraco and Blaxland, 2020).

One of the most popular plant-based cheese analogue categories on the Italian market is the one aiming at replicate mozzarella cheese (Bresciani et al., 2025). Mozzarella is a pasta filata cheese highly appreciated for its sensory attributes when consumed raw and for its distinctive behavior upon heating, making it a versatile ingredient in various culinary applications. Especially when designed to be used as pizza topping, mozzarella cheese analogue is expected to exhibit specific techno-functional properties such as meltability, stretchability, oiling-off, and browning (Ah and Tagalpallewar, 2017). These target characteristics make the development of plant-based mozzarella analogues particularly difficult due to the inability of plant-proteins to replicate caseins' functionality. The melting of cheese is indeed partially caused by the melting of fat (completely liquid at 40 °C) but also and most importantly by changes in the interactions between proteins that cause softening and loss of elasticity of the matrix, resulting in a liquid-like behavior if the viscous modulus became greater than the elastic (Lucey et al., 2003).

For these reasons, the market for plant-based cheese analogues is characterized by a wide variety and combination of different ingredients that involve various strategies aiming to achieve similar characteristics compared to conventional cheeses. Vegetable fats and oil, protein isolates, starches, and hydrocolloids are often used with or without the inclusion of whole plant materials (e.g., pulses, nuts, grains) (Grossmann and McClements, 2021).

Among protein isolates, promising results have been reported with zein in terms of melting and stretching properties; however, its high cost and limited exploration in commercial applications remain a barrier (Mattice and Marangoni, 2020). Currently, most commercially available plant-based mozzarella analogues rely on other ingredients trying to achieve the desired melting effect, often using saturated vegetable oils (e.g., coconut oil), or ingredients able to form thermo-reversible gels such as starches (e.g., waxy, modified starches) and/or other hydrocolloids (e.g., carrageenan, agar) (Dobson and Marangoni, 2023; Lyu et al., 2023; Ścieszka and Klewicka, 2019).

Previous studies (Braitmaier et al., 2024; Grasso et al., 2021; Mattice and Marangoni, 2020; Nicolás Saraco and Blaxland, 2020) have identified limitations in the techno functional performances of plant-based cheese analogues available on the market, particularly in terms of melting and stretching properties of cheddar-like cheese analogues.

Other studies have instead focused on the sensory perception of plant-based cheese analogues. Falkeisen et al. (2022), for instance, have revealed low consumer acceptance of plant-based cheddar analogues both as raw and melted when heated on tortilla. Similarly, a study conducted on different plant-based analogues highlighted that, in the case of plant-based hard cheese analogues, the products on the market need extensive improvements; consumers would like the analogues to mimic more closely the sensory attributes of cheeses in terms of flavor, texture, and appearance (Waehrens et al., 2023).

However, there is limited knowledge on how commercially available products behave under realistic cooking conditions and how their thermal transitions relate to consumer perception.

In the specific case of mozzarella cheese analogues, techno-functional properties critical for pizza topping applications, including meltability, stretchability, browning, and oiling-off, remain either insufficiently investigated or completely unexplored. While, as reported, meltability and stretchability have received some attention in cheddar-like plant-based cheese analogues, these properties have been little studied in mozzarella-like analogues, and pizza-specific attributes such as browning and oiling-off are missing from the literature. Furthermore, no studies have combined comprehensive techno-functional characterization with sensory evaluation in specific consumption contexts such as pizza. This gap is particularly relevant for culinary applications, where cheese analogue success depends not only on room-temperature characteristics but also on cooking performance and final sensory quality.

Based on the current state of research, the techno-functional properties of plant-based mozzarella cheese analogues may differ substantially from traditional dairy products, influencing consumer perception. The objective of this study was therefore to perform a complete techno-functional analysis of these products, comparing them to dairy references, and, on the same products, to couple sensory analysis to identify which measurable functional properties negatively impact consumer acceptability, with a particular focus on their cooking behavior, to identify the major weaknesses of the currently available products and produce useful information to guide the improvements in the future market offering.

2. Material and methods

2.1. Materials

For this study five samples have been selected: two mozzarella cheeses (D1 and D2) manufactured with cow milk and three cheese analogues derived from plant-based ingredients (PB1, PB2, and PB3). Details regarding the list of ingredients and the nutritional composition of these products are presented in Table 1. Products were selected among those marketed as mozzarella or as plant-based alternatives to mozzarella and intended for pizza preparation. Additional selection criteria included consistent availability from local retailers or producers and variability in formulation to encompass the market great variability, were considered as selection criteria.

2.2. Composition, moisture content and pH

The samples composition was evaluated by analyzing nutritional values and ingredient list reported on the samples' labels (Table 1).

The determination of the moisture content (g water/100 g sample) was conducted on the raw samples in triplicate by gravimetric method through oven drying (NSV 9035, ISCO, Milan, Italy) at 105 °C until constant weight (AOAC, 1990).

The samples' pH was measured in triplicate using a portable pH meter (Portamess 913, Knick, Berlin, Germany) equipped with equipped with a Double Pore F electrode (Hamilton Company, Reno, Nevada, USA).

2.3. Low field ^1H NMR analyses

NMR analyses were conducted on raw samples using a low-resolution ^1H NMR spectrometer (the Minispec mq20, Bruker, Massachusetts, USA) with a frequency of 20 MHz and a magnetic field strength of 0.47 T. During the analysis, the temperature was controlled at 25 °C using an external thermostatic bath (Julabo F30, Julabo Labortechnik GmbH, Seelbach, Germany). Cylinders (10-mm-height, 8-mm-diameter) were portioned from each sample and transferred into NMR tubes (10-mm outer diameter); each tube was sealed with laboratory film to prevent moisture loss during analysis.

The ^1H T_2 spin-spin relaxation curves were measured and analyzed according to Alinovi et al. (2020) with modification. A Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence was applied by performing 16 scans with a RD of 10s (>5 ^1H T_1); the acquisition parameters, i.e. number of data points and interpulse spacing (τ), were optimized for each sample basing on preliminary tests (D1 and D2: data points = 15,000, τ = 0.05 s; PB1: data points = 7,500, τ = 0.04 s; PB2 and PB3: data points = 8,500, τ = 0.05 s). The ^1H T_2 curves were analyzed as quasi-continuous distributions of relaxation times using UPENWin software (Alma Mater Studiorum, Bologna, Italy, Borgia, Brown and Fantazzini, 1998; 2000), all the default parameters were used as UPEN settings except for the LoXtrap parameter that was set to 1

Table 1
Ingredients and nutritional composition of the selected dairy and plant-based samples. D1 and D2 were commercial mozzarella cheese; PB1, PB2, and PB3 were commercial plant-based mozzarella analogues.

	Ingredients	Nutritional values (per 100 g)					
		Energy (kJ/kcal)	Total Fat (Saturated Fat) (g)	Total Carbohydrate (Total Sugars) (g)	Fiber (g)	Protein (g)	Salt (g)
D1	Milk, salt, rennet, acidity corrector: citric acid	1107/266	20 (14)	1.6 (1.6)	0.0	20.0	0.90
D2	Milk, salt, acidity corrector: citric acid	1080/260	19 (13)	2.2 (1.6)	00.0	20.0	0.90
PB1	Bio SuRice® 46% preparation (water, sprouted brown rice 20.8%, salt, apple cider vinegar), water, cold-pressed coconut oil, sunflower oil with oregano infusion, lemon juice. Thickeners: agar-agar, gum arabic, xanthan gum, locust bean gum.	766/185	16 (13.6)	8.5 (0.3)	2.2	0.7	1.50
PB2	Chickpea milk (water, chickpeas 10%) 51.5%, tapioca starch, waxy corn starch, high oleic sunflower oil, rice protein, salt, natural flavors, onion, thickener: Carrageenan	1073/259	22 (20)	13 (2.0)	2.9	1.4	1.70
PB3	Water, fresh cashew, and almond cream (cashews 12.5%, water, peeled almonds 2%), coconut oil, psyllium husk powder, extra virgin olive oil, sea salt, starter cultures.	1214/290	30 (18.5)	4.9 (1.0)	3.6	3.4	1.00

and the window width D of the T_2 Filter that was set to 0.15 for the sample PB3 due to its high Noise/Signal ratio. All NMR analyses were conducted at least in triplicate.

2.4. Differential scanning calorimetry

Thermal analysis was conducted on raw samples in triplicate using a DSC Q200 instrument (TA Instruments, New Castle, DE, USA) calibrated with indium (melting temperature 429.75 K, $\Delta Hf = 28.45$ J g^{-1}) and mercury (melting temperature 234.35 K, $\Delta Hf = 11.4$ J g^{-1}). Samples (16-27 mg) were directly weighed in stainless steel pans (PerkinElmer, Waltham, MA, USA). Pans with sample were hermetically sealed and pre-equilibrated at +4 °C. The analysis was carried out by performing a heating ramp from +4 to +200 °C with a heating rate of 5 °C min^{-1}. An empty pan was used as reference. The thermograms obtained were processed using Universal Analysis software (Version 4.5 A, TA Instruments).

2.5. Rheological properties

Visco-elastic properties were analyzed, according to Fenga et al. (2025), by oscillatory rheology with a MCR 102 rheometer (Anton Paar, Graz, Austria) equipped with a 25-mm-diameter cross-hatched parallel-plate probe and an ARES solvent trap cover (TA instruments New Castle, DE, USA), to prevent moisture loss during the analyses. A Peltier convection system (CTD 180, Anton Paar, Graz, Austria) was used to control the temperature. Temperature sweep, amplitude sweep, and frequency sweep tests were carried out on the samples according to the temperature conditions described below. Samples were portioned using a borer and a hand slicer in 25-mm-diameter disks (thickness ~5 mm). Between the plates a 5 mm gap was set for raw samples, it was adjusted at 4 mm for samples subjected to heating and cooling.

Temperature sweep test was conducted at a temperature ramp from 25 to at a rate of 0.5 °C/min, using a strain of 0.05% and an angular frequency of 10 rad/s.

Frequency sweep test was performed on the raw samples at 25 °C, on the sample heated at 80 °C at the end of the temperature ramp, and again on the same sample cooled back to 25 °C. The test was conducted with a strain of 0.05% and in a frequency range from 0.1 to 100 rad/s. The dependence of the elastic and viscous moduli (G′ and G″) within the evaluated frequency range was described by power law equations (Eq. (1) and (2)):

$$G' = k'(f)^{n'} \quad (1)$$

$$G'' = k''(f)^{n''} \quad (2)$$

where k′ and k″ (Pa) represent the magnitude of the corresponding modulus at a frequency of 1 rad/s while n′ and n″ indicate the frequency-dependence of the moduli. All tests were performed at least in triplicate.

The Amplitude sweep test was performed at 25 °C on both the samples before and after the temperature ramp to ensure the other test to be conducted in the linear viscoelastic region. Amplitude Sweep test was conducted at a frequency of 10 rad/s and in a strain range from 0.01 to 100%.

2.6. Color and browning measurement

Color analysis was conducted in triplicate both on raw and cooked samples using a Minolta Colorimeter (CM2600d, Minolta Co., Osaka, Japan) equipped with a standard D65 illuminant and a standard observer position of 10°. The cooked samples were prepared in accordance with Rudan and Barbano (1998) with some modification as follows: 20 g of products were shredded by using a cheese grater with 5 mm diameter holes and transferred into aluminum cups of 8.6 cm diameter before being oven-cooked using a domestic oven (Whirlpool, Michigan, USA) for 5 min at 250 °C in forced air conditions. The results were expressed in accordance with the CIELAB color space by considering the values of L^* (lightness), a*(-green; +red), and b*(-blue; +yellow).

Browning was expressed as total color difference between the cooked and raw sample (ΔE) (Eq. (3)) (Tarapata et al., 2025):

$$\Delta E = \sqrt{\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b^* - b_0^*\right)^2} \quad (3)$$

Where L_0^*, a_0^* and b_0^* refer to the color coordinates of the raw product.

2.7. Texture profile analysis

According to Alinovi et al. (2020) a double compression Texture Profile Analysis (TPA) test was performed at room temperature on the raw samples using a Texture Analyzer TA. XT plus (Stable Micro System, Godalming, U.K.) equipped with a 25 kg load cell and a 35 mm cylindrical probe (P/35). All the analyses were performed by setting a deformation of 60%, a pre-test speed of 2 mm/s, a test speed of 1.5 m/s, a return speed of 3 mm/s, return distance of 35 mm, and a 0.05 N trigger force. At least seven cubes (1.5 cm^3) of each sample were tested. Results were expressed in terms of Hardness (force peak during the first compression, N), cohesiveness (ratio between the area of the second over the first compression), springiness (ratio between the time distance

of the second over the first compression), and gumminess (hardness x cohesiveness, N).

2.8. Oiling-off, meltability, and stretchability

Oiling-off of the samples was tested on at least four replicates according to Wang and Sun (2004) through the following method: sample portions (5 mm height, 17 mm diameter) were positioned in the middle of laboratory filter papers (11-cm diameter) and placed on a tray. The tray was covered with an aluminum foil and placed in a forced air oven (Whirlpool, Michigan, USA) at 110 °C for 5 min. After cooking the perimeter of the halo generated by the released oil was traced on the surface of the filter paper. The filter paper was then scanned (Epson Perfection V550 Photo) and the halo area measured trough image analysis (ImageJ, v. 1.53, National Institutes of Health, Maryland, USA). Oiling-off was expressed in terms of percentage of released oil's area over the sample's area.

The melting behavior of the samples was evaluated using Schreiber's meltability test as described by previous authors (Grasso et al., 2021) with slight modifications. Samples (5 mm height, 41 mm diameter) were placed in an aluminum container and cooked at 235 °C for 5 min in a forced air oven (Whirlpool, Michigan, USA). The samples were then cooled at room temperature for 30 min. Pictures of the samples before and after cooking were acquired with a scanner (Epson Perfection V550 Photo) and the areas of the samples were analyzed by image analysis (ImageJ, v. 1.53, National Institutes of Health, Maryland, USA). Meltability has been expressed in terms of percentage increase in area relative to the initial area. At least five replicates for each sample were tested.

Extensibility test of melted samples was conducted using a TA. XT plus texture analyzer (Stable Micro System, Godalming, U.K.) equipped with sandpaper-coated tensile grips (A/TS) probes following a method by Mattice and Marangoni (2020) with some modifications. A vertical uniaxial extension was applied with a test speed of 2.5 mm/s and maximum extension distance of 150 mm. Samples (40 × 30 × 5 mm) were previously melted by placing them in hermetically closed plastic containers and heated to a 65 °C core temperature using a 90 °C water bath. The melted samples were then immediately clamped between grips, aligned parallel to the direction of extension. Stretchability has been expressed as the maximum extensibility distance reached before breakage (mm). At least seven replicates were performed for each sample.

2.9. Sensory analysis

A panel of 63 untrained tasters was recruited using flyers distributed at university venues, excluding individuals with food allergies or intolerances. Due to the involvement of human participants, the sensory evaluation protocol was reviewed and approved by the University of Parma Institutional Review Board. Written informed consent was obtained from all participants, who also had the opportunity to ask questions to the researchers prior to participation. All procedures involving human subjects were reviewed and approved by the REB- Research Ethics Board of the University of Parma (Protocol ID: 0305003 December 6, 2023).

Sensory testing was conducted through a blind questionnaire evaluating melted samples on pizza, with panelists unaware of the nature of the samples to prevent bias. Sample preparation has been conducted following the method of Moynihan et al. (2014) with some modifications. Ready-to-cook pizza dough and tomato puree were purchased from a local supermarket. The pizza dough (size 25 × 25 cm) was dressed with 30 g of tomato puree and baked for 10 min at 200 °C in an air-forced oven (Whirlpool, Michigan, USA). The pizza was then divided into 5 × 5 cm sections, and each section was covered in a randomized order with 12 g of shredded dairy or plant-based sample shredded with a cheese grater with holes of about 5 mm. The sections were then baked for an additional 10 min at 200 °C. All five samples, identified by a three-digit code, were presented to each taster in randomized order immediately after cooking. Participants were instructed to drink water between the tasting of different samples. The questionnaire also included a demographic profiling about age, gender, education level, frequency of pizza consumption, and dietary preferences. The sensory test section asked participants to rate the acceptability and JAR (Just About Right) levels of the samples. Acceptability was evaluated by asking to rate on a 9-point hedonic (1 = extremely disliked; 5 = neither liked nor disliked; 9 = extremely liked) the levels of overall acceptability, flavor, appearance, and texture of the samples. JAR levels were rated on a 5-point scale (1 = too much low, 2 = slightly too low, 3 = just about right, 4 = slightly too much, 5 = too much) on different attributes: appearance (level of melting, greasiness, browning, and liquid release), texture (stretchability, chewiness, and adhesiveness), and flavor (sourness, saltiness, sweetness, milky flavor). Participants were also given the opportunity to provide additional comments. The JAR results were collapsed from 5-point JAR scale into 3 categories (too little, JAR, and too much) and analyzed by penalty analysis (PA) to calculate the mean drop related to non-JAR levels of the attributes for each sample (Zhi et al., 2016). The attributes' non-JAR levels selected by at least 20% of the participants and with a mean drop of 1.0 or more were described as penalizing for the product (Marcano et al., 2015).

2.10. Statistical analysis

Results of physico-chemical analyses and sensory acceptability tests were expressed as means and standard deviations of the replicates, that were performed on different sampling units of the same cheese for each cheese type.

Following verification of assumptions of normality (Shapiro-Wilk test) and homogeneity of variance (Levene test), analysis of variance (one-way ANOVA), or Welch test in case of homogeneity of variance not verified, were conducted with SPSS v.29 (SPSS Inc., Chicago, USA). To detect significant differences ($p < 0.05$) among samples by Tukey's HSD test or Games-Howell test, in case that the assumption of homogeneity of variance was not verified, were conducted. Penalty analysis was conducted by XLSTAT extension for Microsoft Excel.

3. Results and discussion

3.1. Composition, moisture content, and pH

The nutritional values and ingredient list of the five selected samples are reported in Table 1. Compared to the dairy references, plant-based products showed substantially lower protein contents and higher levels of carbohydrate and NaCl, highlighting the need to adjust their composition to obtain products that can reach closer equivalence with cheese not only by an organoleptic point of view but also by a nutritional one.

The ingredients lists of plant-based products (Table 1) were markedly heterogeneous and, as expected, longer compared to the dairy references, reflecting the complexity of mimic the target structural properties without using animal-derived ingredients. The formulations of plant-based products included oil and fats from plant sources (e.g., coconut, sunflower, olive) and PB1 and PB2 were characterized by an extensive use of added hydrocolloids and polysaccharides (e.g., agar-agar, gum arabic, xanthan gum, locust bean gum, tapioca starch, waxy corn starch and carrageenan) that have the function to enhance and stabilize the structure and potentially confer functional properties such us melting (Saha and Bhattacharya, 2010). In contrast the plant-based products, PB3, mainly based on nuts, was characterized by the shortest list of ingredients and the absence of ingredients such as starches, hydrocolloids, or additives, except for psyllium husk powder, a soluble-fiber rich ingredient with acknowledged water absorption, emulsion stabilization, and gelling properties (Belorio and Gómez, 2022;

Fu et al., 2022; Guo et al., 2009). Notably, PB3 also showed the highest protein content among the analyzed plant-based samples, in agreement with the previously reported higher average protein content in cashew-based products (Craig et al., 2022; Grossmann and McClements, 2021). Finally, PB3 is the only one that exhibits the presence of microbial starters in the formulation probably used to obtain specific characteristics of structure and flavor driven by fermentation.

Moisture content (Table 2) varies among products. The highest water content was observed in PB1, likely influenced by the use of ingredients (e.g., agar-agar, gum arabic, xanthan gum, locust bean gum) able to absorb a significant amount of water.

The pH (Table 2) of D1 and D2 resulted to be around 5.58-5.80. The pH of plant-based analogues showed variability among different samples (4.37-6.67). The pH of PB2 is higher than the others, consistently with the absence of acidulants and fermentation step in the process.

3.2. Low field ^1H NMR analyses

Low-field NMR analyses revealed distinct protons' populations in dairy (D) and plant-based (PB) samples, highlighting differences in structural organization and mobility of water molecules (Fig. 1).

Both dairy samples (D1 and D2) exhibited comparable ^1H T_2 relaxation profiles characterized by four partly overlapped, protonic populations confirming what previously found in other studies on mozzarella-type cheeses that reported the presence of four different protonic populations, the first attributed to "junction zone water" the second and the third to entrapped water and fat, and the last one to expressible serum water (Alinovi et al., 2020; Gianferri et al., 2007; Tidona et al., 2021).

In contrast, the ^1H T_2 distributions in plant-based samples appeared more homogeneous, involving fewer and narrower proton population, and showed greater variability among the samples which may arise from the presence of starch and soluble fibers, which form hydrogen-bond networks that restrict water mobility at different degrees.

For instance, the case population T_{2A} is distinguishable exclusively in the plant-based samples PB2 at a relaxation time of approximately 2ms, (3.9% abundance), suggesting the presence of some water tightly bound to biopolymers (e.g., polysaccharides and/or proteins) (Luo et al., 2020).

The peaks related to T_{2B}, $T_{2C,}$ and T_{2D} are observable in all the three PB samples but they differ notably in terms of relative abundances and relaxation times compared to each other and to the dairy samples. The relaxation times of T_{2C} and $T_{2D,}$ result compatible with different types and fractions of vegetable edible oils (Okay, 2023). However, T_{2C} may also include immobilized water bound to biopolymers, while T_{2D} could indicate the protons belonging to loosely bound water fraction (Cai et al., 2022). The sample PB3 is generally characterized by higher proton mobility as indicated by its longer relaxation times (~30 ms, ~90 ms, and ~250 ms) and the dominant population (66.59% relative abundance) at higher relaxation time. Moreover, PB3 is the plant-based sample that shows T_{2D} peak at the highest relaxation time (>200ms) possibly suggesting the higher presence of free or weakly bound water (Luo et al., 2020). The sample PB1 exhibited the majority (69.14%) of the protons in the population T_{2C} with peak around 40ms, that probably represents the immobilized water molecules bonded to the monolayer (Luo et al., 2020). Notably, PB1 also showed the highest water content among the plant-based samples (Table 2) and its protonic distribution suggests a high ability of its ingredients of binding water.

These findings highlight clear structural differences between dairy and plant-based samples. Dairy samples exhibited greater complexity and heterogeneity in protons' relaxation behavior, while plant-based samples mainly contained immobilized water and lacked clear populations of strongly bound or free water, more strongly entrapped within a compact biopolymeric network, which may restrict mobility and, consequently, influence mechanical properties such as elasticity and firmness. Some exception were observed such as the presence of T_{2A} in PB2 and T_{2D} at higher relaxation times in PB3. Moreover, plant-based samples showed greater variability in relaxation mechanisms across the different formulations.

Table 2
Moisture content and pH of the samples. D1 and D2 were commercial mozzarella cheese; PB1, PB2, and PB3 were commercial plant-based mozzarella analogues.

Sample	Moisture (%)	pH
D1	54.39 ± 0.25 d	5.80 ± 0.03 b
D2	60.47 ± 0.21 b	5.58 ± 0.02 c
PB1	69.43 ± 0.11 a	5.27 ± 0.06 d
PB2	53.29 ± 0.15 e	6.67 ± 0.02 a
PB3	57.62 ± 0.57 c	4.37 ± 0.03 e

a-e Different letters indicate significant differences among samples ($p < 0.05$).

3.3. Differential scanning calorimetry

Representative DSC thermograms of the different samples are illustrated in Fig. 2. The dairy samples presented comparable profiles characterized by an endothermic transition (a) composed of multiple peaks. The thermal behavior of D1 and D2 is consistent with the melting of different milk fat fractions, with DSC patterns similar to those previously observed in milk fat (Smiddy et al., 2012; Ten Grotenhuis et al., 1999; Tunick et al., 1989). The endothermic transition related to fat crystals melting (a) was also present in samples PB1 and PB3 but in these samples the peak resolves at lower temperature and is characterized by one single clearly distinguishable peak (26-29 °C) with one/two slight shoulders at lower temperature. Samples PB1 and PB2 contain coconut oil, which has already been reported to melt in a similar range of temperatures (Tan and Che Man, 2002). Other lipid sources are present in PB1 (sunflower oil) and PB3 (olive oil, cashew, and almond) that can contribute to the lipid composition, but their melting was not clearly distinguishable probably because outside of the investigated temperature range (e.g., almond, sunflower oil) or overlapped with other phenomena (e.g., olive oil) (Fasina et al., 2008). In contrast, fat melting peak is not visible in PB2 because the high oleic sunflower oil, used in this formulation, has a melting temperature below 0 °C, outside the range of analysis used in the current study (Chiavaro et al., 2009).

Distinct endothermic transitions were also observed in PB1 and PB2, associated with the melting or gelatinization of polysaccharide-based components. Specifically, PB1 exhibited a second endothermic phenomenon (c) at around 80 °C which could be attributed to agar-based gel melting, as previously comprising at least two partially overlapping peaks can be distinguished at around 60 and 64 °C that could be related to the starch (waxy corn starch and/or tapioca starch) contained in this sample. This phenomenon could be explained by gelatinization of native crystal starch or, alternatively, melting of retrograded starch crystals, previously gelatinized during the production process (Durrani and Donald, 1995; Jane et al., 1999; H. Liu et al., 2010).

An exothermic phenomenon with a peak at temperatures above 150 °C had been also identified for all the samples that can be related to different phenomena such as Maillard reaction, caramelization, sugar crystallization or protein/carbohydrates decomposition (Conceição et al., 2024; Pugliese et al., 2016). This phenomenon appeared to start at higher temperatures (>180 °C) for PB1, possibly because of the different composition, including higher water content that may modify the reaction kinetics involved in the exothermic transition (Q. Liu et al., 2002).

3.4. Rheological properties

All the samples showed differences in their rheological behaviors in both their raw and heated states, reflecting their compositional and structural diversity. At 25 °C before heating, differences among samples in k' and k'' values were observed. The dairy samples (D1 and D2)

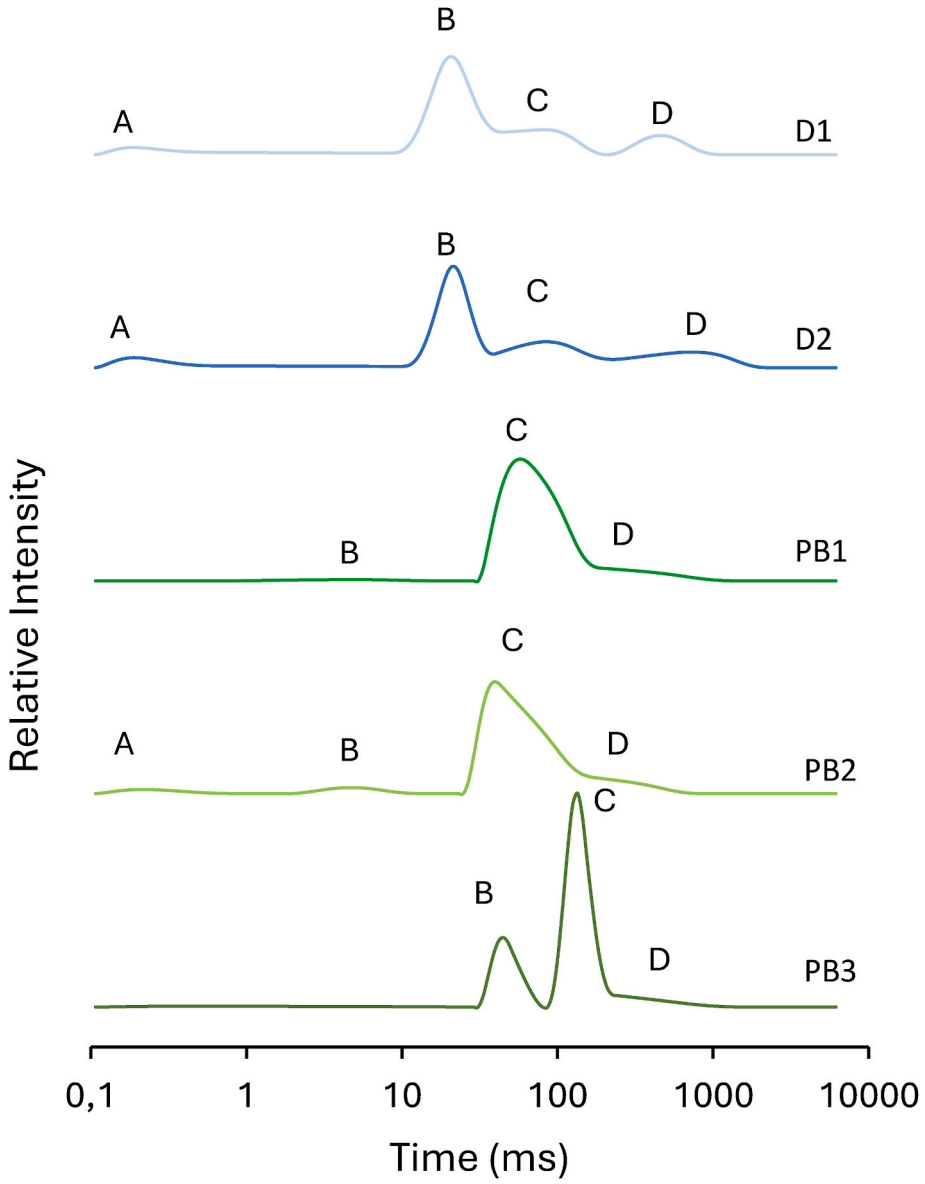


Fig. 1. ^{1}H T_2 NMR representative relaxation curves for the different samples. D1 and D2 were commercial mozzarella cheese; PB1, PB2 and PB3 were commercial plant-based mozzarella analogues.

differed from each other with D1 showing higher k″ than D2, indicative of higher viscous behavior. This may be associated with differences in moisture content, which can influence the viscous dissipation of the system. Among all samples, PB2 showed the highest values of k′ and k″ at 25 °C before heating, suggesting a stiffer structure and the presence of a firm gel network compared to the other samples. In contrast, PB3 was the sample with the lowest k′ and k″, indicating a weaker, softer structure.

The values of n′ at 25 °C before heating were greater than zero for all samples, indicating a relatively low frequency dependence typical of a gel having a well-organized network structure, as opposed to visco-elastic fluids that are highly frequency dependent and usually report a crossover between the moduli (Hundschell and Wagemans, 2019). The n′ coefficient was higher in dairy products than in plant-based ones, suggesting that casein networks are less rigid compared to the networks formed by the structural components (i.e. starches, hydrocolloids) present in the plant-based alternatives. Among the plant-based samples, PB3 was the one with similar n′ values compared to dairy products, which suggests a level of molecular organization closer to that of D1 and D2. The higher protein, fat, and fiber content of PB3 combined with its lower carbohydrate content likely contributed to this behavior since other authors demonstrated higher frequency dependence in gels where the protein structural contribution is relevant, compared to starch-based systems (Joshi et al., 2014). Moreover, it may suggest the presence of a paste-like structure where the structure is conferred by the concentration of the solid particles more than by an actual continuous biopolymer network (Braitmaier et al., 2024). In contrast, PB1 and PB2, rich in starches and/or hydrocolloids, exhibited values closer to 0, indicating a stronger and more crosslinked gel structure compared to the other samples.

At the end of the heating phase at 80 °C, a general drop was observed in k′ and k″ values for most of the samples, except for PB1, which maintained similar values of k′ and an increase in the value of k″, possibly indicating a heat-resistant structure in which the increase in temperature up to 80 °C does not destabilize the bonds responsible for the network stability and in which the components are able to absorb water when heated increasing their viscous contribution.

To better describe the behavior of samples upon heating, the trend of tanδ as a function of temperature is shown in Fig. 3 Tanδ represents the ratio of G″ to G′. A tanδ lower than 1 is typical of a material in which the

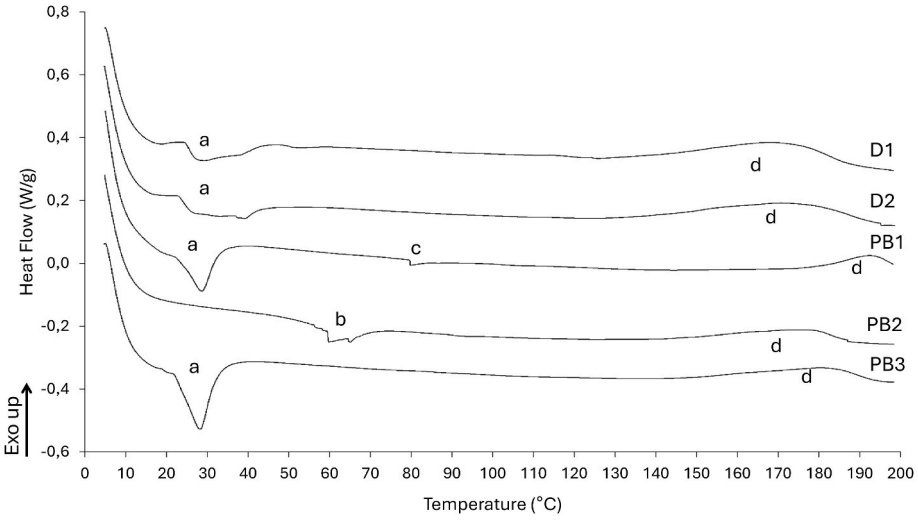


Fig. 2. Representative differential scanning calorimetry (DSC) thermograms of the samples. D1 and D2 were commercial mozzarella cheese; PB1, PB2 and PB3 were commercial plant-based mozzarella analogues.

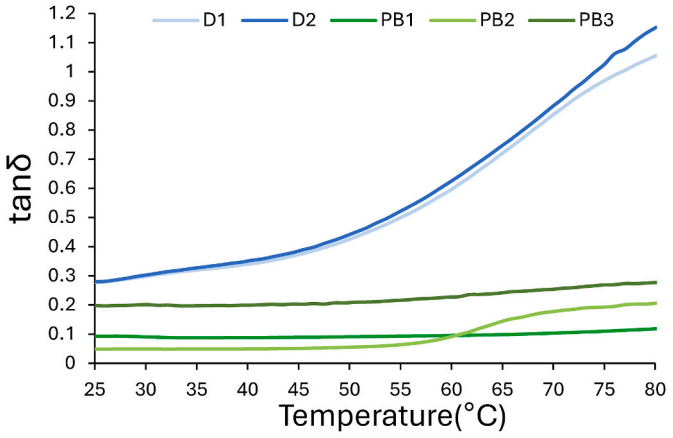


Fig. 3. Temperature dependance of tanδ for the different samples. D1 and D2 were commercial mozzarella cheese; PB1, PB2 and PB3 were commercial plant-based mozzarella analogues.

elastic behavior is predominant (i.e. solid-like behavior); when greater than 1, viscous behavior prevails (i.e. fluid-like behavior). The crossover between the two moduli ($G' = G''$; $\tan\delta = 1$) corresponds to the transition from one behavior to the other one. At 25 °C, a predominantly elastic ($\tan\delta<1$) behavior was found for all samples (Fig. 3). As the temperature increases, a rise in the value of tanδ was observed, with varying intensity depending on the sample. D1 and D2 showed a sharp tanδ increase, with crossovers at 76.7 °C and 74.2 °C, respectively, related to the melting phenomena within the structure. The tanδ increase is indicative of a reduction in elastic dominance and weakening of the structure. In cheese this phenomenon commonly denotes milk fat melting (below 40 °C) and changes in casein-casein hydrophobic interactions that cause a contraction of the casein network leading to a decrease in contact area and weakening of the matrix (Lucey et al., 2003). In PB1, PB2, and PB3, the increase in tanδ was less pronounced and the crossover was not observable ($\tan\delta<1$ throughout the observed temperature range), highlighting a lower sensitivity of the plant-based matrices to temperature increase, in accordance with what has been previously reported for other plant-based products (Grasso et al., 2021; Mattice and Marangoni, 2020). The difference in tanδ before and after heating ($\Delta\tan\delta_{80°C\text{-}25°C}$), in PB2 is higher (0.158 ± 0.027) than in PB1 (0.026 ± 0.002) and PB3 (0.079 ± 0.003) and occurred mainly between 60 °C and 80 °C (Fig. 3) suggesting temperature-related physical changes in PB2 at this range. This behavior of PB2 upon heating may be associated, as previously observed, with the melting of retrograded amylopectin crystals (Yuan and Thompson, 1998), belonging to the waxy corn starch and/or tapioca starch used in this formulation. In the product at 25 °C, the starch amylopectin contributes to the predominance of the elastic behavior over the viscous one, but, when melted, it partially loses its ability to confer structure. This hypothesis is consistent with the results of DSC analysis, which showed an endothermic peak (b) during heating (Fig. 2), probably associated with the same phenomenon. Moreover, after heating, the frequency dependence (n', n''') of the moduli (Table 3) generally increased, especially for dairy samples indicating a decrease in molecular interactions. Among plant-based samples, only PB3 did not show a statistically significant increase in n' values when passing from 25 °C to 80 °C highlighting that even if the level of organization at 25 °C is closer to the one of dairy samples (i.e. similar n' and n'' at 25 °C), the type of network has a different nature, less impacted by temperature increase probably caused by the inability of most plant-protein networks to weaken by heating (Mattice and Marangoni, 2020a).

After cooling back to 25 °C a general stiffening of the structure was observed for almost all the samples, as indicated by the higher values of k' and k'' in comparison to those at 80 °C, and in some cases even higher than the initial values (i.e. raw samples at 25 °C). The higher k' and k'' values after heating and further cooling, compared to the initial values, could be caused by partial dehydration of the sample matrix or the formation of new irreversible bonds favored by the heating process that are then stabilized during the cooling phase. An exception was observed for PB2, where the coefficients k' and k'' (Table 3) maintained low values even after cooling. After losing its structure, amylopectin, of which both waxy corn and tapioca starch are rich, requires longer time to return to the crystalline state, in comparison to amylose which retrogrades faster, leading to a weak structure and hysteretic behavior in PB2 (Pongsawatmanit et al., 2013; Yuan and Thompson, 1998). In PB3, containing no starch but psyllium husk powder, the low rheological modification upon heating and cooling agrees with what has been previously observed for psyllium husk gels, for which the decline of the moduli is slow and steady, but much sharper above 80 °C, and does not show hysteresis upon cooling (Guo et al., 2009). The n' and n'' values (Table 3) tended to decrease again after cooling in dairy samples and PB3 supporting the hypothesis of a thermo-reversible nature of their bonds; in PB1 and PB2, n' and n'' did not decrease after cooling and, especially in the case of PB2, they showed higher frequency dependence than in the raw products. In PB2 this supports the hypothesis of an

Table 3
Power law fitting parameters of frequency sweep test. D1 and D2 were commercial mozzarella cheese; PB1, PB2, and PB3 were commercial plant-based mozzarella analogues.

	25 °C Pre-heating	80 °C	25 °C Post cooling	25 °C Pre-heating	80 °C	25 °C Post cooling
	k′ (Pa)			n′ (−)		
D1	18587 ± 2230 bA	938 ± 537 cB	23007 ± 556 aA	0.171 ± 0.005 aC	0.550 ± 0.128 aA	0.192 ± 0.004 aB
D2	10527 ± 407 cA	149 ± 26 dB	10174 ± 1357 bA	0.174 ± 0.002 aB	0.687 ± 0.021 aA	0.182 ± 0.005 aB
PB1	16951 ± 992 bB	16881 ± 970 aB	21755 ± 1240 aA	0.055 ± 0.005 bB	0.081 ± 0.001 cA	0.092 ± 0.008 bA
PB2	164878 ± 14400 aA	4150 ± 1019 bB	4199 ± 695 cB	0.032 ± 0.002 cC	0.156 ± 0.015 bB	0.223 ± 0.019 aA
PB3	1173 ± 105 dA	541 ± 113 cB	1688 ± 230 dA	0.141 ± 0.035 abcAB	0.222 ± 0.036 bcA	0.116 ± 0.038 abB
	k″ (Pa)			**n″ (−)**		
D1	5207 ± 590 bB	1229 ± 355 bC	9041 ± 145 aA	0.180 ± 0.005 aB	0.431 ± 0.072 bA	0.175 ± 0.011 bB
D2	2964 ± 121 cB	272 ± 39 cC	4178 ± 495 bA	0.1822 ± 0.0004 aB	0.564 ± 0.012 aA	0.147 ± 0.005 cC
PB1	1321 ± 63 dB	2428 ± 162 aA	2840 ± 250 cA	0.136 ± 0.005 bB	0.108 ± 0.002 dC	0.170 ± 0.005 bA
PB2	6968 ± 478 aA	941 ± 224 bB	1123 ± 159 dB	0.093 ± 0.004 dC	0.219 ± 0.022 cB	0.338 ± 0.010 aA
PB3	252 ± 24 eA	181 ± 33 cB	328 ± 34 eA	0.117 ± 0.007 cA	0.124 ± 0.012 dA	0.114 ± 0.003 dA

a-e Different lowercase letters in the same column indicate significant differences among samples ($p < 0.05$). A-C Different uppercase letters in the same row indicate significant differences among different points of the temperature ramp within the same sample ($p < 0.05$). The statistical analysis of k' and k'' values was conducted on log-scale normalized data.

irreversible structural loss after heating within the timescale observed during the experiment.

Overall, the rheological results highlight clear differences in the structural nature of the matrices. Dairy samples showed a dynamic, thermos-reversible network typical of casein systems, while plant-based samples exhibited more rigid and formulation-dependent structures with limited flexibility and temperature responsiveness.

3.5. Texture profile analysis

Results from the texture profile analysis (TPA) are reported in Table 4. Significant differences among samples were found for all textural parameters. The dairy samples showed significantly different hardness values, with D1 harder than D2; this difference may be influenced by the differences in moisture and pH (Table 2) as previously reported for mozzarella-type cheeses (Guinee et al., 2002; McMahon et al., 2005).

Table 4
Texture profile analysis parameters of the samples. D1 and D2 were commercial mozzarella cheese; PB1, PB2, and PB3 were commercial plant-based mozzarella analogues.

Sample	Hardness (N)	Cohesiveness (−)	Springiness (%)	Gumminess (N)
D1	25.59 ± 2.98 b	0.53 ± 0.04 a	78.45 ± 8.95 a	13.64 ± 1.87 a
D2	11.10 ± 1.61 c	0.52 ± 0.03 a	74.77 ± 5.75 a	5.78 ± 0.85 b
PB1	5.97 ± 0.22 e	0.20 ± 0.02 b	41.67 ± 5.46 bc	1.18 ± 0.14 e
PB2	30.36 ± 3.63 a	0.11 ± 0.03 c	51.70 ± 11.97 b	3.41 ± 0.98 c
PB3	7.47 ± 0.62 d	0.24 ± 0.01 b	28.52 ± 2.39 c	1.76 ± 0.10 d

a-e Different letters indicate significant differences among samples ($p < 0.05$).

Among the plant-based samples the hardness' differences also appeared to be partially related to moisture content (Table 2) with PB2 (Moisture content ~53%) resulted to be the hardest sample. However, this relationship was not monotonic across the entire dataset since PB3 (Moisture content ~58%) is softer than D2 (Moisture content ~60%). This suggests, as expected, that in these relevantly different systems, moisture alone is not sufficient to explain hardness' variations among plant-based samples and that other structural factors likely play a relevant role.

In D1 and D2, the structure is provided by a continuous protein network formed by caseins, which confers a cohesive structure that exhibits solid but flexible behavior, capable of a partial recovery once strain is removed. Cohesiveness, springiness, and gumminess of dairy samples were higher than that of plant-based samples confirming the limited ability of the latter to replicate the textural properties of mozzarella.

In plant-based samples, the lower cohesiveness suggests that, although their structures showed high level of organization and rigidity at low deformations (Table 3), they also showed pronounced fragility and fracturability. This characteristic was also confirmed, in PB1 and PB2, by the presence of a fracture peak during the first compression (data not shown), confirming what has been previously observed on some plant-based cheese analogues (Braitmaier et al., 2024). Among the plant-based samples, PB2 exhibited the lowest cohesiveness indicating a highly fragile structure.

Regarding springiness, the lowest value was found in PB3 probably reflecting its structure in which protein and fats play a more relevant role compared to the polysaccharide based of PB1 and PB2; as previously hypothesized for a commercial nut-based cheese analogues, they create a paste-like rather than an elastic and well organized network, with liquids filling the pores between the particles (Braitmaier et al., 2024). This interpretation is consistent with the presence of the longer relaxation time of the population T_{2D} in NMR results (Fig. 1), and with the higher frequency dependance and tanδ before heating observed in rheological analyses compared with the other PB samples (Fig. 3) that suggest the presence of a weak network with high mobility and high tendency to energy dissipation when deformed.

Overall, the TPA results highlight that the textural differences between dairy and plant-based samples mainly derive from the latter's composition, which promotes rigidity or brittleness and limits their ability to mimic the elasticity of dairy networks.

3.6. Color and browning

Dairy products before baking showed a lighter, more yellow and slightly greenish color in comparison to the plant-based ones as indicated by higher L* and b* values and lower a* (Table 5). Plant-based products, instead, exhibited a darker, less yellowish, and more reddish appearance with positive a* values and noticeable color differences of all the PB samples compared to both the animal-based ones, with the minimum color difference ΔE between PB3 and D2 (ΔE 4.3) and the maximum between PB2 and D1 (ΔE = 12.7), highlighting substantial color differences that can be perceived by consumers and potentially influence their product liking (Limbo and Piergiovanni, 2006).

After baking, all samples showed a decrease in lightness (L*), an increase in yellowness (b*), and a shift in color towards either greenish (D1 and D2) or reddish (PB1, PB2, and PB3) values. This darkening and intensification of the color can mainly be attributed to the effect of Maillard reaction between amino acids and reducing sugars that causes the formation of pigmented molecules (Ah and Tagalpallewar, 2017; Dai et al., 2019). The total color difference caused by baking is expressed by the ΔE value. The dairy samples had a different ΔE value, with D1

Table 5
CIELAB Color parameters before (L^*_r, a^*_r, and b^*_r) and after browning test (L^*_b, a^*_b, and b^*_b). Color difference before and after cooking (ΔEb-r). D1 and D2 were commercial mozzarella cheese; PB1, PB2, and PB3 were commercial plant-based mozzarella analogues.

Sample	L^*_r	a^*_r	b^*_r	L^*_b	a^*_b	b^*_b	$\Delta E_{b\text{-}r}$
D1	89.96 ± 0.10 b	−0.02 ± 0.04 d	17.44 ± 0.30 a	64.57 ± 2.74 c	−1.59 ± 0.32 c	23.90 ± 3.59 a	26.45 ± 3.00 a
D2	90.56 ± 0.03 a	−0.44 ± 0.02 e	14.91 ± 0.07 b	74.95 ± 3.01 a	−2.09 ± 0.82 c	16.52 ± 1.90 c	15.90 ± 3.05 c
PB1	78.71 ± 0.14 d	0.58 ± 0.03 a	12.02 ± 0.10 c	71.86 ± 0.70 b	1.05 ± 0.13 b	18.17 ± 0.56 b	9.24 ± 0.69 d
PB2	78.88 ± 0.83 d	0.19 ± 0.04 c	11.21 ± 0.33 d	57.81 ± 1.56 d	5.50 ± 1.63 a	15.87 ± 1.75 c	22.31 ± 2.01 b
PB3	88.72 ± 0.21 c	0.40 ± 0.02 b	11.16 ± 0.17 d	73.34 ± 6.17 ab	2.67 ± 3.30 ab	16.54 ± 6.07 bc	17.00 ± 8.15 bc

a-e Different letters indicate significant differences among samples ($p < 0.05$).

showing a higher color variation than D2, possibly because of their differences in pH and moisture (Table 2). As previously reported, the higher pH in cheese can cause faster browning (Thomas, 1969). Moreover, it is possible that the higher oiling-off (Table 6) of D1 may have limited the dehydration of the sample, thereby slowing its browning (Feng et al., 2021).

Differences in browning intensity are also observed among the plant-based samples with PB1 having the least browning, probably due to its low level of proteins and sugars, which are necessary for the Maillard reaction. Notably, PB1 also exhibited the highest temperature for the exothermic transition (attributed to reactions including Maillard reaction, caramelization, sugar crystallization, or protein/carbohydrates decomposition), observed in the DSC thermograms (Fig. 2) suggesting a possibly reduced propensity for the Maillard reaction in this sample. The plant-based sample with the highest color change after browning was found to be PB2 possibly because of its higher sugar content (Table 1) and higher pH (Table 2) as previously mentioned.

3.7. Oiling-off, meltability, and stretchability

Functional characteristics during baking (i.e. oiling-off, meltability, stretchability) are reported in Table 6.

The highest oiling-off was found for PB3 followed by the dairy products D2 and D1, and then by PB2 and PB1. In plant-based products, composition and formulation can play a major role in the differences between the samples. The higher oiling-off observed in PB3 for example can be related to the higher fat content of this sample in comparison to the others (Table 1), but also to the different ability of the ingredients to bind oil and form structures possibly able to obstacle oil loss during cooking, as an example some hydrocolloids such as xanthan gum can decrease the oiling-off by increasing matrix stability (Dularia et al., 2025).

The results of meltability (Table 6) showed the lowest meltability values were observed for PB2 and D2, while D1 showed intermediate meltability and was not significantly different from these samples according to the statistical analysis. The highest meltability was observed for PB1 followed by PB3. These results appear to be inconsistent when compared with the temperature-dependent rheological profile (Fig. 3) in which plant-based products, especially PB1 and PB3, showed a low tendency to melt and flow. This discrepancy could be due to the different experimental conditions used in the two methods: maximum temperature (80 °C vs. 235 °C), cooking time, heating rate, and heat transfer modes (conduction vs. convection) that can affect the results even through phenomena such as drying, crust formation, and browning (Altan et al., 2005). Furthermore, the increased tendency to flow, as indicated by rheological analyses, may have favored a more rapid expansion of the sample surface, leading to dehydration that limited further expansion. This suggests that meltability, as evaluated under baking conditions, is not only governed by network breakdown but also by surface phenomena such as water loss and crust formation. Moreover, the possible melting of components above 80 °C (i.e., the maximum temperature reached during rheological analysis) possibly influenced the melting and should be considered. The sample PB1, which showed the highest meltability, was the most stable during the thermo-rheological analyses, however, it contains agar-agar, which is used as a gelling agent, and can form thermo-reversible gels capable of melting at temperatures higher than 80 °C, depending on the interaction with the other ingredients (Khoobbakht et al., 2024). Similarly, gels containing psyllium powder, which is included in PB3, have shown in previous studies a greater softening tendency at temperature higher than 80 °C (Guo et al., 2009).

Table 6
Oiling-off, meltability, and stretchability of the samples. D1 and D2 were commercial mozzarella cheese; PB1, PB2, and PB3 were commercial plant-based mozzarella analogues.

Sample	Oiling-off (%)	Meltability (%)	Stretchability (mm)
D1	181.68 ± 27.21 c	190.45 ± 10.02 bc	148.82 ± 1.00 a
D2	254.57 ± 22.63 b	167.26 ± 23.35 c	148.68 ± 1.84 a
PB1	0.06 ± 0.05 d	252.41 ± 14.65 a	7.71 ± 1.21 c
PB2	32.15 ± 12.23 d	154.13 ± 11.54 c	67.24 ± 10.39 b
PB3	459.71 ± 43.42 a	224.53 ± 31.86 ab	74.52 ± 21.42 b

a-d Different letters indicate significant differences among samples ($p < 0.05$).

Stretchability, i.e. the maximum extension that can be reached by subjecting the sample to unilateral extension, also showed significant differences among the samples. For the dairy samples, the stretchability value was equal to the maximum extension allowed by the instrument, indeed in the measurement range the sample breakage was not observed. In dairy products, the ability to stretch upon heating is due to the ability of the continuous caseins network to weaken without losing bonds between the caseins' molecules, allowing deformation and extension without breaking (Lucey et al., 2003). Plant-based samples showed stretchability values lower than the dairy ones, with PB1 being less extensible than PB2 and PB3. Notably, the differences between stretchability of the samples follows similar trends of the differences between the frequency dependences of the rheological moduli at 80 °C (Table 3), with an increase in stretchability as the frequency dependance increases. This relation can suggest that a weaker level of molecular organization of the heated matrix can increase the flexibility of the samples and their ability to stretch without breaking. The significant difference between dairy and plant-based samples' stretchability reveals the structural differences between the two products and the inability of the continuous polysaccharides and/or protein matrix to replicate the properties imparted by the casein network, as also previously reported on cheddar plant-based alternative (Mattice and Marangoni, 2020).

3.8. Sensory analysis

The results of the acceptability test (Fig. 4) showed a clear preference for dairy samples with higher overall liking scores (≈6.9) than plant-based samples (<5.0), which were generally not appreciated in their melted form according to what previously observed on "cheddar style" plant-based cheese analogues (Falkeisen et al., 2022). Among the plant-based samples the one with the highest overall acceptability score was found to be PB3, with a score of ≈5 ("neither like nor disliked").

In addition to overall acceptability, liking was evaluated in terms of appearance, texture, and flavor (Fig. 4). For all the attributes, D1 and D2 showed statistically significant higher scores (6.40-6.95). In terms of

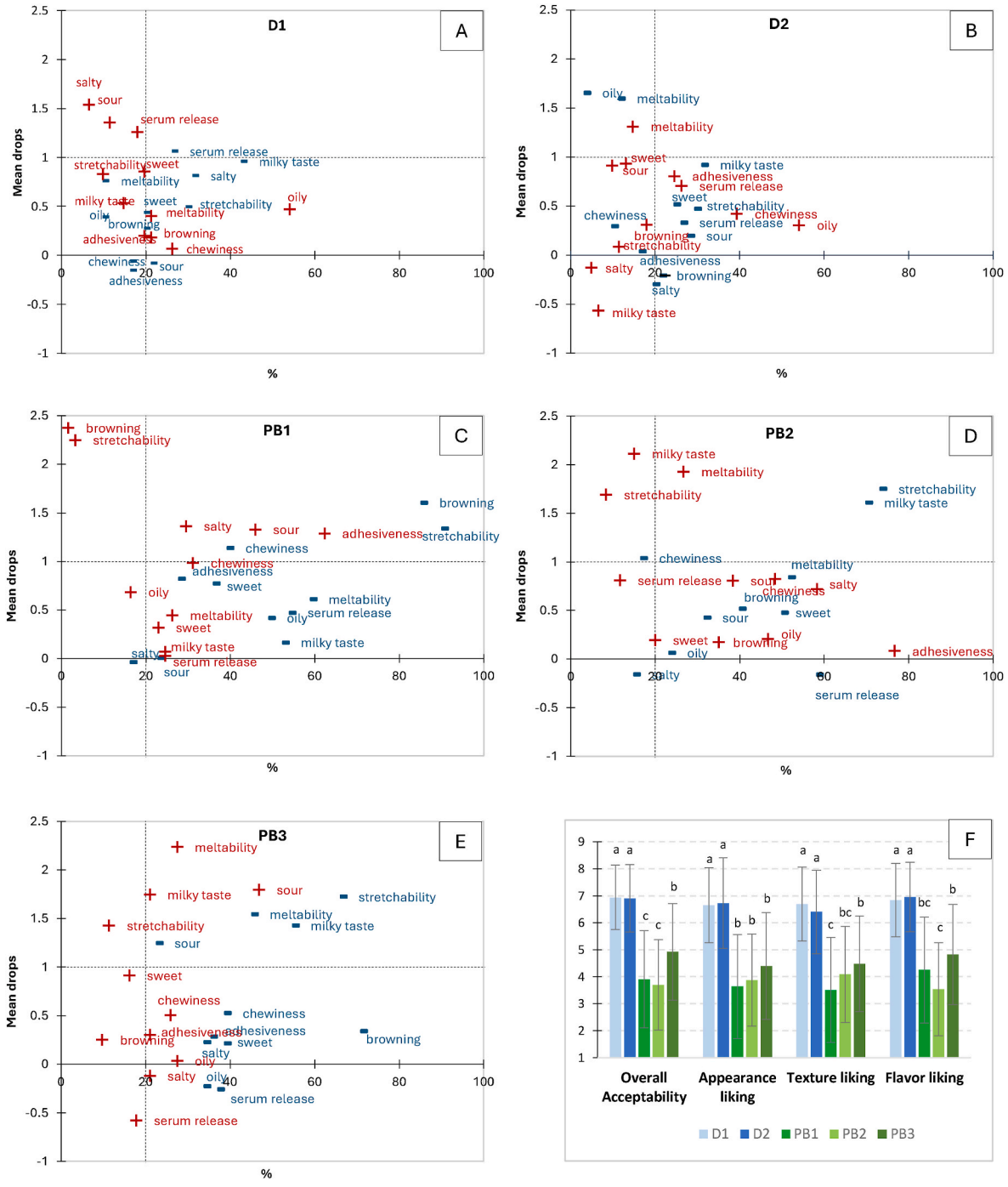


Fig. 4. Mean drops plot for the five samples (A-E) represented as mean drop plotted vs the percentage of consumer selecting that non JAR attribute. Acceptability on hedonic scales (1-9) of the samples (F). D1 and D2 were commercial mozzarella cheese; PB1, PB2 and PB3 were commercial plant-based mozzarella analogues.

appearance, no significant differences were found between plant-based samples with values of about 4. Sample PB3 was the most liked among the plant-based samples in terms of both flavor and texture. The least appreciated texture was found for PB1 which was described by consumers as a kind of spreadable cheese, with a creamy texture, or a processed cheese-like product. Overall, none of the plant-based products reached an acceptable level of texture liking with PB2 described as "sticky" and "gummy" and PB3 described as "gummy" and "too soft". The product PB2 was the least appreciated in terms of flavor, probably because of the presence of an unpleasant note (onion), as indicated by some of the comments reported by the consumers and probably originating from flavoring agents' inclusion. These findings partially confirm that previously observed in plant-based cheddar cheese analogues were descriptors like "mouthcoating", "rubbery", and "presence of off-flavors" attributes were found to negatively influence consumers' liking (Falkeisen et al., 2022).

The evaluation of sensory attributes on JAR scales was combined with the results of the overall acceptability test by Penalty Analysis to better investigate the penalizing attributes for product acceptability. Mean drop values caused by non-JAR levels selection of the attributes were plotted as a function of the percentage of panelists that selected the non-JAR levels (Fig. 4). Attributes rated with a non-JAR level by at least 20% of the panelists and responsible for a mean drop of at least 1 point were identified as penalizing for the sample.

For D1 and D2, non-JAR levels of attributes were selected by fewer panelists than for plant-based products, with a predominance of "non-JAR" attributes' levels; only for sample D1 it was possible to identify a penalizing attribute (too low serum release), while none of the sensory attributes were found to be penalizing for the sensory acceptance of D2. For plant-based samples more attributes were reported on non-JAR levels with many identified as penalizing.

All plant-based samples were found to be penalized by a too low level of perceived stretchability; this result was in accordance with the instrumental stretchability results that highlighted low values for plant-based products (Table 6). In particular, PB1 was perceived as not enough stretchable by more than 80% of the panelists and was also the one with the lowest measured stretchability.

A perceived low meltability was also indicated for all plant-based samples by at least 40% of participants and resulted to be a penalizing attribute for PB3. In contrast, a too high perceived meltability was indicated by at least 20% of the participants in all the plant-based samples and resulted to be penalizing for PB2 and PB3, possibly indicating a segmentation in consumers preferences or difficulties in the evaluation of this aspect by non-trained consumers, that resulted in differences in its perception.

A too high sour flavor was found to be penalizing for PB1 and PB3 consistently with their lower pH (Table 2). Other penalizing attributes were more specific for the different products as for the "too low browning" that was selected by at least 40% of the consumers for all the plant-based samples but resulted penalizing only in the case of PB1, that notably showed the lowest value in the browning test (Table 5). The sample PB1 resulted also penalized by "too much salty". Moreover, "too low milky taste" was selected by many consumers for all the plant-based products and resulted penalizing for PB2 and PB3, accordingly with previous studies that indicated, in the case of plant-based semi-hard cheese, that the consumers' ideal version have more cheesy and less artificial flavor compared to the products currently available on the market (Waehrens et al., 2023).

Overall, sensory results supported instrumental evidence with dairy products characterized by balanced texture and flavor attributes, whereas plant-based samples were penalized by low stretchability, limited meltability, and off-flavors, reflecting their structural and compositional limitations.

4. Conclusions

The results of this study highlighted peculiar and different characteristics of plant-based cheese analogues compared to Mozzarella cheeses. Plant-based matrices, mainly structured through interactions among lipids, starch and hydrocolloids, were not able to reproduce the dynamic flexibility of casein systems, showing rigid or fragile structures, limited thermal responsiveness and reduced stretchability, with high variability depending on formulation. Both instrumental and sensory results indicates that current plant-based mozzarella analogues remain functionally limited in pizza applications. Poor melting performance and stretching ability, inadequate browning and an undesirable texture after heating emerged as major obstacles to consumer acceptance, leaving room for formulation improvement, as emerged from penalty analysis. Flavor also played a central role, with excessive sourness and saltiness negatively affecting overall liking.

However, given the compositional heterogeneity of commercial products and the lack of detailed compositional and microstructural characterization, structure-function relationships remain hypothetical. Future research should integrate compositional profiling and microstructural analyses to enable a mechanistic understanding of how formulation and microscale organization determine performance. Moreover, sensory studies including trained panels and quantitative descriptive analysis would strengthen the link between instrumental measurements and sensory perception.

Expanding the investigation to a broader and more geographically diverse product range will be essential to validate these trends on more mature markets and support the development of plant based mozzarella analogues with improved gastronomic performance and stronger consumer acceptance.

5. Implications for gastronomy

This study provides chefs, culinary researchers, and food professionals with evidence-based insights into the performance of commercially available plant-based mozzarella alternatives in realistic cooking conditions. Products were evaluated under pizza-baking scenarios using both laboratory trials and sensory analysis, revealing specific functional limitations that currently compromise their culinary performance. These include poor meltability, limited stretch, insufficient browning, rubbery textures, and flavor notes that are unappealing or insufficiently dairy-like, all of which reduce overall acceptability.

By bridging laboratory analysis and real-world cooking performance, this work offers a scientific foundation to guide the improvement of commercial plant-based cheeses and their more effective application in contemporary gastronomy.

CRediT authorship contribution statement

Irene Fenga: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Marcello Alinovi:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Emma Chiavaro:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Maria Paciulli:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Ethical statement

All procedures involving human subjects were reviewed and approved by ***[Details omitted for double-anonymized reviewing]***.

Funding statement

This study was funded by the IPSUS (https://ipsus.org) project supported by the Joint call ERA-NETs SUSFOOD2 and FOSC. These projects have received funding from the European Union's Horizon 2020 research and Innovation program under grant agreement No. 727473 and No. 862555, respectively.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors also acknowledge Rondina's Food s. r.l.s. and PARMA FOOD LAB s. r.l. for providing some of the samples analyzed in this research. The authors thank Gianluca Accurso Tagano, Marika De Flaviis, and Ilaria Fusi for their contribution in data collection.

Data availability

Data will be made available on request.

References

Abe-Inge, V., Aidoo, R., Moncada de la Fuente, M., Kwofie, E.M., 2024. Plant-based dietary shift: current trends, barriers, and carriers. Trends Food Sci. Technol. 143, 104292. https://doi.org/10.1016/J.TIFS.2023.104292.

Ah, J., Tagalpallewar, G.P., 2017. Functional properties of Mozzarella cheese for its end use application. J. Food Sci. Technol. 54 (12), 3766–3778. https://doi.org/10.1007/s13197-017-2886-z.

Alinovi, M., Corredig, M., Mucchetti, G., Carini, E., 2020. Water status and dynamics of high-moisture Mozzarella cheese as affected by frozen and refrigerated storage. Food Res. Int. 137, 109415. https://doi.org/10.1016/J.FOODRES.2020.109415.

Altan, A., Turhan, M., Gunasekaran, S., 2005. Short communication: Comparison of covered and uncovered schreiber Test for cheese meltability evaluation. J. Dairy Sci. 88 (3), 857–861. https://doi.org/10.3168/JDS.S0022-0302(05)72751-X.

AOAC, 1990. Official Methods of Analysis of the AOAC, fifteenth ed. vol. 2. Association of Official Analytical Chemists, Inc., Washington,DC, USA.

Belorio, M., Gómez, M., 2022. Psyllium: a useful functional ingredient in food systems. Crit. Rev. Food Sci. Nutr. 62 (2), 527–538. https://doi.org/10.1080/10408398.2020.1822276.

Braitmaier, H., Wahl, A.L., Hinrichs, J., Atamer, Z., 2024. Can plant-based cheese alternatives be characterized by methods for dairy cheese? Extending dairy cheese methods to characterize plant-based cheese alternatives. Int. Dairy J. 159, 106056. https://doi.org/10.1016/J.IDAIRYJ.2024.106056.

Bresciani, A., Biscotti, P., Angelino, D., Del Bo', C., Pellegrini, N., Riso, P., Marti, A., Martini, D., 2025. Formulation and nutritional quality of plant-based cheese sold in Italy. Applied Food Research 5 (1), 100816. https://doi.org/10.1016/J.AFRES.2025.100816.

Cai, Q., Zhong, Y., Xu, M., Huang, Q., Lu, X., 2022. 3D printed high oil custard cream: effects of whey protein isolate, hydroxypropylated starch and carrageenan on physicochemical properties and printing performance. Lebensm. Wiss. Technol. 156, 113039. https://doi.org/10.1016/J.LWT.2021.113039.

Chiavaro, E., Vittadini, E., Rodriguez-Estrada, M.T., Cerretani, L., Capelli, L., Bendini, A., 2009. Differential scanning calorimetry detection of high oleic sunflower oil as an adulterant in extra-virgin olive oil. J. Food Lipids 16, 227–244. https://doi.org/10.1111/j.1745-4522.2009.01143.x.

Conceição, D.G., Reis, L.C.C., da Silva Virgens, E., de Jesus, J.C., Bauer, L.C., Chaves, M. A., Bonomo, R.C.F., Santos, L.S., Ferrão, S.P.B., 2024. Thermal, structural and spectroscopic properties of powder sheep milk obtained by different drying methods. Int. Dairy J. 150. https://doi.org/10.1016/j.idairyj.2023.105845.

Craig, W.J., Mangels, A.R., Brothers, C.J., 2022. Nutritional profiles of non-dairy plant-based cheese alternatives. Nutrients 14, 1247. https://doi.org/10.3390/nu14061247.

Dai, S., Jiang, F., Shah, N.P., Corke, H., 2019. Functional and pizza bake properties of Mozzarella cheese made with konjac glucomannan as a fat replacer. Food Hydrocoll. 92, 125–134. https://doi.org/10.1016/J.FOODHYD.2019.01.045.

Dobson, S., Marangoni, A.G., 2023. Methodology and development of a high-protein plant-based cheese alternative. Curr. Res. Food Sci. 7, 100632. https://doi.org/10.1016/J.CRFS.2023.100632.

Dularia, C., Meena, G.S., Hossain, S., Khetra, Y., Singh, A.K., Arora, S., 2025. Hydrocolloids induced changes of processed cheese product matrix from milk protein concentrate 80 (MPC80). Int. J. Dairy Technol. 78 (3), e70029. https://doi.org/10.1111/1471-0307.70029.

Durrani, C.M., Donald, A.M., 1995. Physical characterisation of amylopectin gels. Polym. Gels Netw. 3 (1), 1–27. https://doi.org/10.1016/0966-7822(94)00005-R.

Falkeisen, A., Gorman, M., Knowles, S., Barker, S., Moss, R., McSweeney, M.B., 2022. Consumer perception and emotional responses to plant-based cheeses. Food Res. Int. 158, 111513. https://doi.org/10.1016/J.FOODRES.2022.111513.

Fasina, O.O., Craig-Schmidt, M., Colley, Z., Hallman, H., 2008. Predicting melting characteristics of vegetable oils from fatty acid composition. Lebensm. Wiss. Technol. 41 (8), 1501–1505. https://doi.org/10.1016/j.lwt.2007.09.012.

Feng, R., Barjon, S., van den Berg, F.W.J., Lillevang, S.K., Ahrné, L., 2021. Effect of residence time in the cooker-stretcher on mozzarella cheese composition, structure and functionality. J. Food Eng. 309, 110690. https://doi.org/10.1016/J.JFOODENG.2021.110690.

Fenga, I., Alinovi, M., Paciulli, M., Mucchetti, G., Chiavaro, E., 2025. Structural and Physico-Chemical Changes of Mozzarella di Bufala Campana Cheese Influenced by Covering Liquid Composition. Foods 14 (9), 1506. https://doi.org/10.3390/foods14091506.

Fresán, U., Errendal, S., Craig, W.J., 2020. Influence of the Socio-Cultural environment and external factors in following plant-based diets. Sustainability 12 (21), 9093. https://doi.org/10.3390/su12219093.

Fu, Q. quan, Liu, R., Zhou, L., Zhang, J. wen, Zhang, W. gang, Wang, R. rong, 2022. Effects of psyllium husk powder on the emulsifying stability, rheological properties, microstructure, and oxidative stability of oil-in-water emulsions. Food Control 134, 108716. https://doi.org/10.1016/J.FOODCONT.2021.108716.

GFI Europe, 2024. Italy Plant-based Food Retail Market Insights (2021-2023). https://gfieurope.org/wp-content/uploads/2024/10/EN-Italy-plant-based-food-retail-market-insights-October-2024.pdf. (Accessed 3 July 2025).

Gianferri, R., Maioli, M., Delfini, M., Brosio, E., 2007. A low-resolution and high-resolution nuclear magnetic resonance integrated approach to investigate the physical structure and metabolic profile of Mozzarella di Bufala Campana cheese. Int. Dairy J. 17 (2), 167–176. https://doi.org/10.1016/J.IDAIRYJ.2006.02.006.

Grasso, N., Roos, Y.H., Crowley, S.V., Arendt, E.K., O'Mahony, J.A., 2021. Composition and physicochemical properties of commercial plant-based block-style products as alternatives to cheese. Future Foods 4, 100048. https://doi.org/10.1016/j.fufo.2021.100048.

Grossmann, L., McClements, D.J., 2021. The science of plant-based foods: approaches to create nutritious and sustainable plant-based cheese analogs. Trends Food Sci. Technol. 118, 207–229. https://doi.org/10.1016/J.TIFS.2021.10.004.

Guinee, T.P., Feeney, E.P., Auty, M.A.E., Fox, P.F., 2002. Effect of pH and calcium concentration on some textural and functional properties of Mozzarella cheese. J. Dairy Sci. 85 (7), 1655–1669. https://doi.org/10.3168/JDS.S0022-0302(02)74238-0.

Guo, Q., Cui, S.W., Wang, Q., Goff, H.D., Smith, A., 2009. Microstructure and rheological properties of psyllium polysaccharide gel. Food Hydrocoll. 23 (6), 1542–1547. https://doi.org/10.1016/J.FOODHYD.2008.10.012.

Hargreaves, S.M., Rosenfeld, D.L., Moreira, A.V.B., Zandonadi, R.P., 2023. Plant-based and vegetarian diets: an overview and definition of these dietary patterns. Eur. J. Nutr. 62, 1109–1121. https://doi.org/10.1007/s00394-023-03086-z.

Hundschell, C.S., Wagemans, A.M., 2019. Rheology of common uncharged exopolysaccharides for food applications. Curr. Opin. Food Sci. 27, 1–7. https://doi.org/10.1016/J.COFS.2019.02.011.

Jane, J., Chen, Y.Y., Lee, L.F., Mcpherson, A.E., Wong, K.S., Radosavljevic, M., Kasemsuwan, T., 1999. Effects of amylopectin branch chain length and amylose content on the gelatinization and pasting properties of starch, 76(5), 629. https://doi.org/10.1094/CCHEM.1999.76.5.629.

Joshi, M., Aldred, P., Panozzo, J.F., Kasapis, S., Adhikari, B., 2014. Rheological and microstructural characteristics of lentil starch–lentil protein composite pastes and gels. Food Hydrocoll. 35, 226–237. https://doi.org/10.1016/J.FOODHYD.2013.05.016.

Khoobbakht, F., Khorshidi, S., Bahmanyar, F., Hosseini, S.M., Aminikhah, N., Farhoodi, M., Mirmoghtadaie, L., 2024. Modification of mechanical, rheological and structural properties of agar hydrogel using xanthan and locust bean gum. Food Hydrocoll. 147, 109411. https://doi.org/10.1016/J.FOODHYD.2023.109411.

Landry, M.J., Ward, C.P., 2024. Health benefits of a plant-based dietary pattern and implementation in healthcare and clinical practice. Am. J. Lifestyle Med. 18 (5), 657–665. https://doi.org/10.1177/15598276241237766.

Limbo, S., Piergiovanni, L., 2006. Shelf life of minimally processed potatoes: part 1. Effects of high oxygen partial pressures in combination with ascorbic and citric acids on enzymatic browning. Postharvest Biol. Technol. 39 (3), 254–264.

Liu, H., Yu, L., Tong, Z., Chen, L., 2010. Retrogradation of waxy cornstarch studied by DSC. Starch Staerke 62 (10), 524–529. https://doi.org/10.1002/star.201000017.

Liu, Q., Yada, R., Arul, J., 2002. Characterization of thermal properties op Potato dry matter-water and starch-water System. J. Food Sci. 67 (2), 560–566. https://doi.org/10.1111/j.1365-2621.2002.tb10638.x.

Lucey, J.A., Johnson, M.E., Horne, D.S., 2003. Invited review: perspectives on the basis of the rheology and texture properties of cheese. J. Dairy Sci. 86 (9), 2725–2743. https://doi.org/10.3168/JDS.S0022-0302(03)73869-7.

Luo, H., Guo, C., Lin, L., Si, Y., Gao, X., Xu, D., Jia, R., Yang, W., 2020. Combined use of rheology, LF-NMR, and MRI for characterizing the gel properties of Hairtail Surimi with Potato starch. Food Bioprocess Technol. 13, 637–647. https://doi.org/10.1007/s11947-020-02423-y.

Lyu, Z., Sala, G., Scholten, E., 2023. Melting properties of vegan cheese: effect of emulsion and protein addition on the thermal behaviour of starch gels. Food Hydrocoll. 144, 108917. https://doi.org/10.1016/J.FOODHYD.2023.108917.

Marcano, J., Varela, P., Cunha, L.M., Fiszman, S., 2015. Relating dynamic perception of reformulated cheese pies to consumers' expectations of satiating ability. Food Res. Int. 78, 369–377. https://doi.org/10.1016/J.FOODRES.2015.09.005.

Mattice, K.D., Marangoni, A.G., 2020. Physical properties of plant-based cheese products produced with zein. Food Hydrocoll. 105, 105746. https://doi.org/10.1016/j.foodhyd.2020.105746.

Mcclements, D.J., 2024. Novel animal product substitutes: a new category of plant-based alternatives to meat, seafood, egg, and dairy products. Compr. Rev. Food Sci. Food Saf. 23, e313330. https://doi.org/10.1111/1541-4337.13330.

McMahon, D.J., Paulson, B., Oberg, C.J., 2005. Influence of calcium, pH, and moisture on protein matrix structure and functionality in direct-acidified nonfat mozzarella cheese. J. Dairy Sci. 88 (11), 3754–3763. https://doi.org/10.3168/JDS.S0022-0302(05)73061-7.

Mefleh, M., Pasqualone, A., Caponio, F., De Angelis, D., Natrella, G., Summo, C., Faccia, M., 2022. Spreadable plant-based cheese analogue with dry-fractioned pea protein and inulin-olive oil emulsion-filled gel. J. Sci. Food Agric. 102 (12), 5478–5487. https://doi.org/10.1002/jsfa.11902.

Moynihan, A.C., Govindasamy-Lucey, S., Jaeggi, J.J., Johnson, M.E., Lucey, J.A., McSweeney, P.L.H., 2014. Effect of camel chymosin on the texture, functionality, and sensory properties of low-moisture, part-skim Mozzarella cheese. J. Dairy Sci. 97 (1), 85–96. https://doi.org/10.3168/JDS.2013-7081.

Nicolás Saraco, M., Blaxland, J., 2020. Dairy-free imitation cheese: is further development required? Br. Food J. 122 (12), 3727–3740. https://doi.org/10.1108/BFJ-11-2019-0825.

Okay, C., 2023. Classification of edible oils by using time domain NMR (TD-NMR) technique and microwave (MW) dielectric spectroscopy. Food Anal. Methods 16, 1529–1536. https://doi.org/10.1007/s12161-023-02520-6.

Pongsawatmanit, R., Chantaro, P., Nishinari, K., 2013. Thermal and rheological properties of tapioca starch gels with and without xanthan gum under cold storage. J. Food Eng. 117 (3), 333–341. https://doi.org/10.1016/J.JFOODENG.2013.03.010.

Pugliese, A., Paciulli, M., Chiavaro, E., Mucchetti, G., 2016. Characterization of commercial dried milk and some of its derivatives by differential scanning calorimetry. J. Therm. Anal. Calorimetry 123, 2583–2590. https://doi.org/10.1007/s10973-016-5243-y.

Rudan, M.A., Barbano, D.M., 1998. A model of Mozzarella cheese melting and browning during pizza baking. J. Dairy Sci. 81 (8), 2312–2319. https://doi.org/10.3168/jds.S0022-0302(98)75812-6.

Saha, D., Bhattacharya, S., 2010. Hydrocolloids as thickening and gelling agents in food: a critical review. J. Food Sci. Technol. 47 (6), 587–597. https://doi.org/10.1007/s13197-010-0162-6.

Ścieszka, S., Klewicka, E., 2019. Algae in food: a general review. Crit. Rev. Food Sci. Nutr. 59 (21). https://doi.org/10.1080/10408398.2018.1496319, 3538–3447.

Smiddy, M.A., Huppertz, T., van Ruth, S.M., 2012. Triacylglycerol and melting profiles of milk fat from several species. Int. Dairy J. 24 (2), 64–69. https://doi.org/10.1016/J.IDAIRYJ.2011.07.001.

Tan, C.P., Che Man, Y.B., 2002. Differential scanning calorimetric analysis of palm oil, palm oil based products and coconut oil: effects of scanning rate variation. Food Chem. 76 (1), 89–102. https://doi.org/10.1016/S0308-8146(01)00241-2.

Tarapata, J., Szymá Nska, E., Van Der Meulen, L., Miltenburg, J., Huppertz, T., 2025. Moisture loss from cheese during baking: influence of cheese type, cheese mass, and temperature. Foods 14, 165. https://doi.org/10.3390/foods14020165.

Ten Grotenhuis, E., Van Aken, G.A., Van Malssen, K.F., Schenk, H., 1999. Polymorphism of Milk Fat Studied by Differential Scanning Calorimetry and Real-Time X-ray Powder Diffraction 76 (9), 1031–1039. https://doi.org/10.1007/s11746-999-0201-5.

The Good Food Institute, 2023. State of the Industry Report: Plant-Based Meat, Seafood, Eggs, and Dairy.

Thomas, M.A., 1969. Browning reaction in cheddar cheese. Aust. J. Dairy Technol. 24 (4), 185–189.

Tidona, F., Alinovi, M., Francolino, S., Brusa, G., Ghiglietti, R., Locci, F., Mucchetti, G., Giraffa, G., 2021. Partial substitution of 40 g/100 g fresh milk with reconstituted low heat skim milk powder in high-moisture mozzarella cheese production: rheological and water-related properties. Lebensm. Wiss. Technol. 137. https://doi.org/10.1016/j.lwt.2020.110391.

Tunick, M.H., Basch, J.J., Maleeff, B.E., Flanagan, J.F., Holsinger, V.H., 1989. Characterization of natural and imitation Mozzarella cheeses by differential scanning calorimetry. J. Dairy Sci. 72 (8), 1976–1980. https://doi.org/10.3168/JDS.S0022-0302(89)79320-6.

Venter De Villiers, M., Cheng, J., Truter, L., 2024. The shift towards plant-based lifestyles: factors driving young consumers' decisions to choose plant-based food products. Sustainability 16, 9022. https://doi.org/10.3390/su16209022.

Waehrens, S.S., Faber, I., Gunn, L., Buldo, P., Bom Frøst, M., Perez-Cueto, F.J.A., 2023. Consumers' sensory-based cognitions of currently available and ideal plant-based food alternatives: a survey in Western, Central and Northern Europe. Food Qual. Prefer. 108, 104875. https://doi.org/10.1016/J.FOODQUAL.2023.104875.

Wang, H.H., Sun, D.W., 2004. Evaluation of the oiling off property of cheese with computer vision: correlation with fat ring test. J. Food Eng. 61 (1), 47–55. https://doi.org/10.1016/S0260-8774(03)00181-X.

Yuan, R.C., Thompson, D.B., 1998. Rheological and thermal properties of aged starch pastes from three waxy maize genotypes; rheological and thermal properties of aged starch pastes from three waxy maize genotypes, 75(1), 117. https://doi.org/10.1094/CCHEM.1998.75.1.117.

Zhi, R., Zhao, L., Shi, J., 2016. Improving the sensory quality of flavored liquid milk by engaging sensory analysis and consumer preference. J. Dairy Sci. 99 (7), 5305–5317. https://doi.org/10.3168/JDS.2015-10612.