Yogurt And Cheese as Primary Models For Microparticulated Whey Protein Application: Systematic Review

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Abstract. This systematic review evaluates the application of microparticulated whey protein (MWP) and their derivatives as fat replacer in yogurt and cheese, based on synthesis of 15 studies. The findings consistently showed that MWP effectively mimics the functional properties of fat, offering promising solution for creating healthier, low-fat dairy products. In both yogurt and cheese models, MWP was found to significantly improve texture and rheology. It enhanced desirable textural attributes by forming a more compact, interconnected protein network. In yogurt, this also led to enhanced water holding capacity and reduced syneresis. The MWP's effectiveness is highly dependent on its specific characteristics, such as particle size and the ratio of native to denatured proteins. The microparticulated form is essential; simple protein isolates do not yield the same textural benefits. MWP also positively impacted sensory attributes. In yogurt, it imparted a smoother, creamier mouthfeel, resulting in higher overall sensory scores. In cheese, MWP generally improved functional properties by softening low-fat cheeses, restoring elasticity, or enhancing spreadability. Studies on petit-suisse, Caciotta, processed cheese, and Cheddar consistently showed better texture, higher moisture retention, and more cohesive microstructures compared to low-fat controls. While not always fully replicating the sensory profile of full-fat products, MWP-fortified low-fat versions consistently outperformed fat-free controls. Overall, MWP serves as a versatile, clean-label fat mimetic that successfully addresses the quality challenges of fat reduction, supporting the development of nutritious and appealing dairy foods.

1 Background

The demand for reduced-fat dairy products has surged globally due to growing health consciousness, yet fat reduction often compromises sensory properties such as creaminess

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and smooth mouthfeel—critical attributes for consumer acceptance. Microparticulated whey protein (MWP) is defined as spherical protein aggregates with particle sizes typically ranging from 0.1 to 10 µm, designed to replicate the structural and sensory properties of fat globules in reduced-fat food systems. Microparticulated Whey Protein (MWP) offers a compelling solution: these micron-sized, spherical whey protein aggregates (typically 0.1–10 µm) emulate the lubrication and texture of fat droplets, enabling calorie reduction while preserving mouthfeel quality [1]. Because MWP is derived from milk proteins and demonstrates its highest compatibility within protein-rich, aqueous matrices, dairy products represent the most suitable model systems for its application. In these products, fat strongly influences structural, rheological, and sensory attributes, making them ideal for evaluating the ability of MWP to replace or replicate fat functionality.

In yogurt, removal of fat leads to weaker casein networks and increased syneresis, resulting in a grainy and watery mouthfeel. Traditional strategies—using stabilizers like hydrocolloids or skim milk powder—bulk the matrix but fail to replicate the sensory profile of fat. MWP compensates by functioning as a tribological fat mimetic: the spherical particles reduce friction between casein-protein aggregates, lowering oral friction ('ball-bearing' effect) and thereby restoring viscosity and creaminess without imparting a starchy or gummy texture [1]. In stirred yogurt, the incorporation of extruded MWP significantly reduced syneresis and increased firmness. These improvements were correlated with particle sizes in the 0.1–10 µm range, as smaller particles more effectively integrated into the casein gel network, thereby strengthening structural integrity and improving water retention [2], [3].

Similarly, in cheese, fat serves structural and textural functions by creating lubrication and creating matrix weaknesses that allow melting. Fat reduction typically yields a firmer, drier texture. In reduced-fat cheese, MWP acts as a filler within the protein matrix, interrupting the dense casein network typically formed when fat is removed. This structural modification enhances meltability, reduces hardness, and improves flowability—parameters strongly associated with consumer perception of texture quality in cheese [3]

The production of MWP generally begins with whey protein concentrates or isolates obtained through membrane separation technologies such as ultrafiltration or microfiltration. These protein solutions are subsequently subjected to a combination of thermal and mechanical processes, most commonly heating to 80–90 °C to induce protein unfolding and aggregation, followed by the application of high shear through homogenization to refine the size and shape of the resulting particles. Spray-drying is commonly used to stabilize MWP into powder form, and parameters such as inlet temperature and drying rate critically determine particle morphology. These morphological features in turn influence dispersibility in dairy matrices and functional outcomes such as viscosity enhancement and water retention [4].

Although numerous studies have explored the functional properties of MWP, the available findings remain fragmented and have not yet been systematically integrated to provide a clear understanding of its performance across different dairy matrices. To fill this gap, the present systematic review focuses specifically on the application of MWP in yogurt and cheese—two dairy products where creaminess and texture are essential—and critically assesses physicochemical, structural, and sensory outcomes. By concentrating on yogurt and cheese as primary model systems, this review aims to clarify the current state of MWP technology, elucidate its sensory advantages, and identify areas requiring further investigation to support wider industrial adoption.

2 Methods

A systematic literature search was conducted using the ScienceDirect database to identify relevant studies investigating the application of microparticulated whey protein (MWP) in yogurt and cheese. Search terms included “microparticulated whey protein” OR “whey protein microparticles” OR “whey protein microgels” OR “protein-based fat replacer” combined with matrix-related terms such as “yogurt” and “cheese”. The initial search yielded 516 records.

Abstracts and full-texts of these studies were then reviewed for eligibility according to the following inclusion criteria: (i) studies written in English, (ii) research articles (not reviews, book chapters, or conference abstracts), and (iii) studies reporting on compositional, structural, textural, sensory, or functional outcomes. Studies focusing on other dairy or non-dairy systems were excluded.

Following this content-based screening, 23 articles were retained. After removing duplicates and studies with insufficient methodological detail, 15 articles were included in the final review. Data were systematically extracted on study design, such as treatments of the studies, dairy product type, analytical approaches, and key outcomes related to texture, microstructure, sensory, and functional properties.

3 Results and Discussion

The application of microparticulated whey proteins (MWPs) consistently improved the physicochemical, rheological, and sensory attributes of reduced- and low-fat dairy products by serving as an effective fat mimetic. While fat provides lubrication and structural integrity through its dispersed globules, MWPs successfully replicate this function by integrating into the protein matrix. This section details the specific effects of MWPs in yogurt and cheese, highlighting the unique mechanisms at play in each product.

3.1 Textural and Rheological Outcomes in Yogurt

Across multiple studies, MWPs consistently enhanced textural and rheological properties in reduced- and low-fat yogurts. The most common improvements were increases in firmness, viscosity, and gel strength, which closely mirrored the structural roles of fat in full-fat controls. For instance, supplementation with WPC in semi-skimmed high-protein yogurts significantly improved firmness, consistency, and apparent viscosity compared with MWP, whereas low-fat stirred yogurts containing high native-to-denatured (N/D) ratio MWPs demonstrated elevated viscosity, yield stress, and elastic modulus (G′) at protein levels of 5% [5]. Similar patterns were observed with liquid extruded MWPs (eMWPs), which formed firmer gels than powdered MWPs in reduced-fat yogurts, and with WPEGM containing milk fat, which generated superior hardness and consistency compared with vegetable oil variants [2]. Notably, particle size showed a negative correlation with viscosity, highlighting the role of submicron particles (<3 μm) as effective fillers. However, excessive WPC addition (>5%) induced lumpiness due to protein aggregation, contrasting with MWPs’ inert filler function that prevented such defects but yielded softer gels [6].

The underlying mechanism can be explained by MWPs’ interactions with casein micelles during acidification, forming denser protein networks through disulfide bonding and hydrophobic interactions. High native protein content supports stronger integration into the casein matrix, increasing gel rigidity, while smaller particle sizes act as active fillers that reduce serum separation and enhance viscoelasticity. These observations align with the “ball model” of yogurt gelation, where MWPs fill structural voids and reinforce the protein matrix.

3.2 Microstructural Outcomes in Yogurt

Microstructural analyses consistently confirmed these rheological trends. Yogurts fortified with MWPs displayed denser, more interconnected protein networks than low-fat controls, as shown by confocal laser scanning microscopy (CLSM) and scanning electron microscopy (SEM). For example, MWP addition produced finer, more uniform pore structures, whereas WPC led to irregular aggregates with weak connectivity [6]. Similarly, high native/soluble protein MWPs (<1 μm) yielded homogeneous networks comparable to full-fat yogurts, while low-native MWPs generated looser matrices. In fat-free yogurts, monodisperse fractal aggregates (MFA) produced denser matrices and smaller pores compared to polydisperse aggregates (PFA) or whey protein isolate (WPI) [7]. Research about whey protein emulsion gel microparticles [8] formed compact voids, in contrast to the branched networks of vegetable oil-based variants. Together, these findings confirm that MWPs promote compact gel structures, thereby mimicking full-fat microstructures.

The consistent formation of denser microstructures is theoretically attributed to MWPs' pre-denatured state, which enhances dispersion and incorporation into the casein gel. Smaller, monodisperse particles promote cohesive, fractal-like networks, consistent with diffusion-limited aggregation theory, whereas polydisperse or larger particles disrupt connectivity and create weak, open structure).

3.3 Sensory Outcomes in Yogurt

Sensory evaluation studies generally indicated improvements in creaminess, body, and overall acceptability following MWP incorporation. Reduced-fat yogurts with eMWPs scored higher for creaminess and smoothness than full-fat references, effectively masking fat-free roughness [2]. High N/D MWPs increased body and delayed meltdown, while MFA-fortified yogurts were perceived as firmer and smoother compared to PFA or WPI controls [7]. Aroma was also positively affected: MWPs enhanced fruity-buttery volatiles (e.g., acetaldehyde, diacetyl), while WPC contributed more ketone- and acid-derived volatile [6]. Divergent findings included slightly sourer notes in high-native MWPs, likely due to flavor binding capacity [5].

These outcomes support the role of MWPs as fat mimetics, where small particles provide lubrication in the oral cavity and mimic fat's creamy perception through tribological effects. Furthermore, pre-denatured proteins reduce protein-flavor binding, improving volatile release, while high-native proteins may exert the opposite effect.

3.4 Functional Outcomes in Yogurt

MWP addition uniformly reduced syneresis and improved storage stability. eMWPs, due to their hydration ability, decreased whey separation more effectively than powdered MWPs [2]. MFA, PFA, and WPI all reduced syneresis at higher inclusion levels, though MFA was most effective due to its monodispersity [7]. WPEGM variants also exhibited enhanced water retention, maintaining stability for up to three weeks [8]. These results can be explained by MWPs' increased water-binding capacity, which stabilizes the gel network against gravitational drainage, as predicted by capillary drainage models.

3.5 Cheese: Texture and Functional Outcomes

From all the data collected, the cheeses analyzed in this study were limited to soft cheese (spread and petit-suisse), semi-hard cheese (Caciotta), hard cheese (Cheddar), and cheese powder. In cheese, MWPs consistently improved rheology, mainly by softening low-fat cheeses and restoring elasticity. In reduced-fat spreads and petit-suisse, MWPs maintained texture similar to full-fat variants even at 40% fat reduction [9]. Low-fat Caciotta fortified with MWPC and exopolysaccharide (EPS)-producing cultures showed softer, springier textures [10]. Whey protein microcoagulate (WPM) addition in processed cheese increased hardness and viscosity in a dose-dependent manner but preserved pseudoplastic behavior [11]. Similarly, Cheddar with microgel WPMs demonstrated reduced hardness and improved fluidity, mimicking the effects of fat [12]. Semihard cheeses with denatured whey protein concentrate (DWPC) showed reinforced networks, acting as active fillers comparable to caseins [13]. These results indicate that MWPs act either as inert fillers (softening) or active fillers (rigidifying), depending on particle state and cheese type.

Functionally, MWPs improved yield, moisture retention, and stability. Low-fat Caciotta with MWPC showed significant increases in yield and moisture, approaching full-fat values [10], [14]. DWPC aggregates enhanced water binding in semihard cheeses [13], while cheese powders with microparticulated proteins displayed better reconstitution and flowability [15]. These functional gains can be explained by MWPs' hydrophilic surfaces, which bind water and improve curd stability, in line with Darcy's law for fluid retention in porous matrices.

3.6 Cheese: Microstructural and Sensory Outcomes

Microstructural studies confirmed that MWPs restored compactness and reduced porosity in reduced-fat cheeses. For example, CLSM analyses revealed that WPM microgels were evenly distributed within Cheddar, loosening dense casein networks [12]. Similarly, petit-suisse with MWPs showed smooth, integrated particles without large aggregates [9]. Sensory analyses aligned with these microstructural improvements: MWPs increased flavor intensity, creaminess, and acceptability, offsetting typical low-fat defects [10], [12], [15]. These findings reflect MWPs' role as fat replacers, providing oral lubrication and flavor enhancement consistent with tribological principles.

Collectively, evidence across yogurt and cheese models demonstrates that MWPs and their derivatives consistently improve textural, structural, sensory, and functional properties in reduced- and low-fat products. The most critical factors are particle size (<3–4 μm) and degree of denaturation (70–90%), which determine whether MWPs act as active or inert fillers. While yogurt studies emphasized improvements in firmness, microstructure, and aroma release, cheese applications highlighted enhanced elasticity, moisture retention, and yield. Divergences—such as lumpiness at high WPC concentrations in yogurt or reduced meltability in some WPM cheeses—reflect matrix-specific interactions. These results collectively support MWPs as versatile, sustainable fat replacers that valorize whey byproducts while meeting consumer demands for healthier dairy products [9], [10], [12], [13], [14], [15].

Conclusion

This systematic review concludes that microparticulated whey proteins (MWPs) effectively function as multifunctional fat replacers and protein fortifiers in yogurt and cheese, consistently enhancing texture, microstructure, sensory quality, and moisture retention while reducing syneresis. Evidence across studies shows that MWP performance is strongly driven by particle size and degree of denaturation, enabling MWPs to reinforce casein networks and mimic structural and tribological roles of fat. These properties make MWPs promising ingredients for developing healthier, lower-fat dairy products without compromising consumer acceptance. Future research should optimize MWP production parameters and explore their application in emerging hybrid dairy-plant systems.

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Table 1. Role of Microparticulated Whey Proteins in Enhancing Quality Attributes of Yogurt Across Production Types

Products	**Treatments**	**Texture Outcomes**	**Microstructures**	**Sensory Outcomes**	**Others**	**Conclusion**
Semi-skim high-protein yogurt [6]	Direct addition of whey protein powders (microparticulated whey protein (MWP) and whey protein concentrate (WPC)) to alter the casein-to-whey ratio.	WPC increased firmness, consistency, and viscosity more than MWP, due to denaturation and casein interaction forming a stronger gel. High WPC levels caused lumpy texture from protein aggregation. MWP acted as an inert filler, yielding a softer product.	WPC yogurts showed large, irregular aggregates with poor connectivity, linking to lumpiness. MWP yogurts had an interconnected network with fine, open pores. Ingredient particle size and morphology influenced the final microstructure.	MWP enhanced acetaldehyde, acetoin, and diacetyl for fruity and buttery notes. WPC increased ketones and acids. MWP improved classic yogurt aroma.	N/A	MWP and WPC differ as protein enhancers due to denaturation levels. WPC boosts firmness but risks lumpiness at high doses. MWP enhances flavors and yields smooth, softer texture.
Yogurt (Reduced-fat, plain-type stirred yogurt) [2]	Addition of MWPs as powdered Simplesse® or liquid extruded MWPs (eMWPs).	eMWPs produced firmer yogurts than powdered MWPs, owing to small particle size aiding gel network integration. Negative correlation between eMWP particle size (0.1–10 µm) and viscosity; smaller particles (<3 µm) enhanced firmness and creaminess.	N/A	Reduced-fat eMWP yogurts scored higher for creaminess, thickness, and smoothness than full-fat controls. Small particles (<3 µm) boosted creaminess perception. All MWP yogurts improved smoothness, masking fat-free roughness. eMWP yogurts were preferred over full-fat and market products due to enhanced texture.	eMWP yogurts had lower syneresis than powdered MWPs, linked to better hydration and particle size/dry matter effects.	Extruded MWPs in suspension outperform powdered forms, reducing syneresis and improving texture. Particle size critically determines instrumental and sensory qualities; smaller eMWPs yield firmer, creamier products.
Low-fat stirred yogurt [16]	Four MWPs with varying compositions and properties added as fat replacers, compared to full-fat (FFY) and low-fat (LFY) yogurts.	N/A	FFY had a compact network with fat globules as links. LFY showed a porous network with serum channels. High native/soluble protein MWPs formed dense,	Fractal dimension quantified network roughness; high native MWPs (M3, MC) matched FFY complexity. PCA grouped high native MWPs with FFY and low		MWP microstructure determines fat replacer efficacy. High native/soluble protein MWPs create dense networks akin to full-fat yogurt. Fractal and

Products	Treatments	Texture Outcomes	Microstructures	Sensory Outcomes	Others	Conclusion
			homogeneous networks like FFY; low native MWPs yielded looser structures like LFY.	native with LFY, validating visual and fractal analyses. High native/soluble proteins and small particles (<1 μm) mimicked full-fat structure via casein interactions.		PCA analyses objectively guide MWP selection for desired low-fat properties.
Low-fat stirred yogurt [5]	Ten MWP powders added to reach 4.25% or 5.0% total protein, compared to full-fat (3.5% fat/protein) and low-fat controls.	All yogurts were shear-thinning. MWP addition, especially at 5.0% protein, improved rheology. High native-to-denatured (N/D) ratio MWPs increased viscosity, yield stress, and elastic modulus for gel-like texture. Denaturation level outweighed initial particle size; high native MWPs integrated better, reducing graininess.	N/A	High N/D MWPs enhanced creaminess, viscosity, body, and slow meltdown, matching full-fat. Low N/D MWPs gave smoother, ropier texture with higher syneresis and sour taste from flavor binding. Strong correlation between rheology and sensory attributes enables predictive testing.	N/A	High native protein MWPs excel as fat replacers, forming networks like full-fat yogurt. Denaturation control is essential; instrumental-sensory correlations aid formulation optimization.
Fat-free set-type yogurt [7]	Pre-formed monodisperse fractal aggregates (MFA) and polydisperse fractal aggregates (PFA) added to skim milk at 0.2–1.5% (w/w), with native whey protein isolate (WPI) as control.	G′, yield stress, and firmness rose with concentration. MFA yogurts were stronger and firmer than PFA, especially at high levels, outperforming WPI. PFA yielded weakest gels due to polydispersity.	CLSM revealed denser MFA networks with smaller pores, explaining firmness. PFA and WPI showed open structures with larger pores, disrupted by larger aggregates.	Triangle tests detected texture differences at ≥0.5% protein; MFA were less firm than WPI. At 1.5%, MFA differed from PFA. Ranking confirmed firmness increased with concentration, with MFA slightly less firm than WPI. Textural differences only, no flavor impacts.	Higher protein reduced syneresis equally for MFA, PFA, and WPI, emphasizing water-holding capacity over gel strength.	Pre-formed whey aggregates control fat-free yogurt texture. Monodispersity yields firmer gels; polydispersity softer ones. They enable protein-enriched yogurts with good syneresis and desirable softness.
Low fat yogurt [8]	Whey protein emulsion gel microparticles (WPEGM) from	V-EG had larger particles, weakening structure. M-EG improved hardness,	SEM showed uniform M-EG networks with small voids; V-EG had branched,	M-EG scored highest, V-EG next, both preferred over skim. V-EG offered	Both improved stability with less whey separation;	WPEGM effectively replace fat, boosting texture and stability.

Products	Treatments	Texture Outcomes	Microstructures	Sensory Outcomes	Others	Conclusion
	vegetable oil (V-EG) or milk fat (M-EG) added as fat replacers, compared to milk/skim powders and native whey/oil.	consistency, and viscosity more, due to stable milk fat cross-linking. Both enhanced texture over skim control.	heterogeneous structures, matching lower water-holding capacity.	creamier color without off-flavors; aroma similar.	V-EG matched M-EG for 14 days, diverging after 21.	Milk fat versions excel in properties, but vegetable oil provides healthier, color-appealing alternatives with short-term equivalence.
Yogurt [17]	Ten MWP types added to low-fat milk at 4.25% or 5.0% protein, compared to full-fat and low-fat controls.	MWP raised viscosity and elasticity, more at higher levels. High native β-lactoglobulin MWPs matched full-fat viscosity; high-denatured MWPs acted as inactive fillers.	Effective MWPs formed compact networks with small aggregates like full-fat; ineffective ones had open, void-filled structures. Microparticulation enabled active filler role, unlike non-microparticulated WPI, via enhanced protein interactions.	N/A	N/A	MWPs improve low-fat yogurt rheology and microstructure. High native β-lactoglobulin content is key for strong networks. Microparticulation makes whey proteins active fillers, surpassing native isolates.
Low fat yogurt [18]	Thermal-denatured whey protein-milk fat emulsion gel microparticles (WPI-EGs) added at 0.5–1.5% fat, compared to separate whey/fat (LF), skim (SMP), and full-fat (WMP).	WPI-EGs boosted firmness, consistency, cohesiveness, and viscosity; 1.5% level was firmest. Frequency sweeps showed higher G' and G'', maintaining $G'>G''$ for gel behavior.	SEM displayed compact WPI-EG networks with small pores; microparticles embedded in casein, avoiding open structures.	WPI-EGs improved viscosity, texture, lubrication, and aroma scores over skim; 1.5% was highest, with heat-treated whey retaining aromas.	N/A	WPI-EGs serve as effective fat replacers, forming dense gels that enhance water-holding, rheology, microstructure, and sensory qualities for consumer-preferred low-fat yogurts.

Table 2. Role of Microparticulated Whey Proteins in Enhancing Quality Attributes of Cheeses Across Production Types

Products	Treatments	Texture Outcomes	Microstructure	Sensory Outcomes	Others	Conclusion
Reduced-fat spread and petit-suisse cheeses [9]	MWP added at varying levels for 5–40% fat reduction.	Spread: MWP minimally impacted 19% reduced-fat viscosity but increased it at higher doses, matching full-fat G' and G" in 10–40% reductions. Petit-Suisse: No changes in hardness, cohesiveness, springiness, chewiness, gumminess, or firmness; acted as inert filler. Adhesiveness rose in 10% reduction via protein interactions.	MWP featured heterogeneous, non-spherical shapes with low aggregation for fat mimetic role.	5% reduced-fat spread matched control in color, aroma, flavor, texture, acceptability. 19% had lower acceptability. 10–40% MWP reductions showed no sensory differences from control.	MWP reduced fat while raising protein for nutrition. Optimal at 90°C/140 bar: >80% denaturation, 1.0–1.5 µm particles.	MWP yields high-quality low-fat cheeses, preserving sensory/textural traits at 5% spread reduction and up to 40% in petit-Suisse.
Caciotta cheese (an Italian semi-hard cheese) [14]	Varied protein-to-fat ratios with 3.0–4.0% MWP in high-, standard-, low-fat milks.	N/A	N/A	N/A	Fat reduction extended coagulation time; MWP had no effect due to low denaturation. Yield fell with fat but MWP improved it, especially 4.0% in low-fat. Low-fat MWP cheeses had higher protein, stable moisture. MWP increased whey protein loss. MWP stabilized low-fat composition/yield, boosting profitability via whey reuse.	MWP replaces fat in Caciotta, optimizing low-fat yield at 4.0% without coagulation issues, despite some protein loss; aids healthier, circular dairy products.

Products	Treatments	Texture Outcomes	Microstructure	Sensory Outcomes	Others	Conclusion
Low-fat Caciotta-type cheese [10]	~0.3% fat milk variants: LFC (low-fat control), LFC-MWPC (0.5% Microparticulated Whey Protein Concentrate), LFC-MWPC-EPS (MWPC + exopolysaccharides (EPS) - producing *Streptococcus t hermophilus* ST446 EPS) , LFC-MWPC-EPS-A (MWPC + EPS + Lactobacillus) vs. full-fat (FFC).	LFC overly firm; MWPC/EPS softened texture, boosted springiness by disrupting casein. Adjuncts preserved texture.	N/A	LFC-MWPC-EPS: uniform color, good taste/texture. Adjuncts cultures (LFC-MWPC-EPS-A) enhanced flavor intensity/acceptability. Full-fat kept "oily taste" and "pleasure at first bite".	MWPC raised moisture (53.0% to 57.5%); EPS to 60.2%. Low-fat yield lower (9–12 kg/100 kg milk) vs. full-fat (15 kg), but MWPC/EPS improved it. Adjuncts increased free amino acids, volatiles (diacetyl, alcohols) for flavor.	The use of EPS-producing cultures and adjunct cultures is crucial for overcoming texture and flavor defects. The EPS helps create a desirable, less firm texture, while the adjunct cultures enhance flavor development.
Cheese powder [15]	Spray-dried: FFCP (full-fat cheese powder), RFCP (60% reduced-fat cheese powder), MPCP (RFCP + Milk Protein (MP)).	N/A	FFCP: smooth particles. RFCP: larger, buckled. Microparticulated Protein (MP) in MPCP: smaller, less wrinkled, like FFCP.	RFCP: lower flavor than FFCP. In potato use, MP increased MPCP flavor/acceptability.	Fat reduction boosted reconstitution (wettability, dispersibility), flowability, reduced caking via low free fat. RFCP solubility lower; MP improved it. RFCP enhanced oxidative stability; MP slightly raised oxidation.	Fat reduction improves powder functionality/stability; Microparticulated Protein mitigates morphological/sensory losses, creating healthier, appealing powders for applications.
Semihard cheese [13]	Denatured whey protein concentrated (DWPC) added to milk, fractionated: sedimentable aggregates, soluble	Moisture-adjusted: DWPC matched caseins in G*. Aggregates as active fillers post-Pressing, raising rigidity via casein links, unlike inert in gels.	DWPC: 3 µm irregular clusters in casein network, yielding Heterogeneous/porous structure.	N/A	DWPC increased yield/moisture via water-binding Aggregates blocking drainage.	DWPC enhances semihard yield via retention, with Aggregates as active fillers boosting

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	proteins, diffusible minerals.				Aggregates drove yield. Protein/fat diluted by moisture, but protein and fat content was stable; pH unchanged.	rigidity; replaces fat/casein effectively.
Cheese [11]	3–8% MWP replaced Anhydrous Milk Fat (AMF) in processed cheese.	Hardness/viscosity rose linearly, max at 7–8%. MWP crosslinked casein via disulfides for strength. Pseudoplastic, G' > G''; peak elasticity at 6–7%.	Higher MWP compacted matrix, mimicking fat by filling space/reducing globules for firmness.	N/A	Meltability good, slightly decreased with MWP. Adhesiveness peaked at 3%, then fell.	MWP replaces fat in processed cheese, raising hardness/viscosity with preserved meltability/compact structure for reduced-fat options.
Cheddar cheese [12]	4 µm MWP (plain/anthocyanin-adsorbed) in reduced-fat Cheddar (RFC) vs. full-fat (FFC).	Lowering hardness/springiness/chewiness like fat, via moisture/loose networks. Increased fluidity/meltability to full-fat levels.	spherical MWP evenly in casein, reducing density/flexibility, mimicking globules.	MWP lightened/yellowed to full-fat; MWP (Ant) added red hue (acceptable). Both improved texture scores; MWP (Ant) best for color. Full-fat superior in flavor/creaminess.	N/A	4 µm MWP substitutes fat in reduced-fat Cheddar, plasticizing for better texture. Anthocyanin version adds color and health benefits.