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REVIEW

Improving Quality Characteristics of Whipped Cream Based on Novel Additives: A Review of Current Status, Challenges, and Strategies

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Abstract
Whipped cream is popular among consumers due to its smooth texture and delectable taste. In recent years, it has also attracted increasing attention from producers and researchers and has been widely developed in the food industry. However, whipped cream systems are complex and unstable, and additives are applied to the system to obtain a more stable and excellent whipped cream product. Additionally, the high-fat content in whipped cream has a potential health risk to consumers, so the concept of low-fat whipped cream has been gradually developed as a strategy. However, the sensory and whipping properties of low-fat whipped cream need to be improved. This paper systematically discusses the effects of five types of additives (hydrocolloids, proteins, emulsifiers, carbohydrates, and lipid compounds) applied to improve the whipping, rheological, electrostatic, sensory, and nutritional properties of whipped cream. There are limited studies about nutritional properties, which should be the focus of future work, and the strategy of functional whipped cream is also a new direction. Further, this paper provides information on standards and regulations for additives, aiming to avoid the risks associated with the inappropriate application of additives by researchers and traders. The ultimate objective is to provide a healthy whipped cream with exceptional sensory properties and heightened nutritional value.

Keywords Whipped cream · Novel additives · Improving quality characteristics · Nutritional properties

Introduction

Whipped cream is widely used in desserts and cakes as surface decoration, decoration, and filling. Whipped cream is popular with consumers due to its unique aroma and smooth taste, which has an excellent trade market. According to Data Bridge Market Research, the whipped cream market was valued at $819.1 million in 2021 and is expected to reach $1268.5 million by 2029, growing at a compound annual growth rate of 5.62% during the forecast period from 2022 to 2029 (Research, 2022). Numerous researchers have conducted studies on whipped cream, with a focus on exploring its formation mechanism as well as enhancing its quality characteristics (Blankart et al., 2020a; Long et al., 2012).

Whipped cream is a whipped aerated system, mainly composed of sugars, emulsifiers, proteins, and fats, which forms a complex foam by whipping semi-crystalline oil/water emulsions containing the above substances (Zeng et al., 2021). Whipped cream differs from conventional emulsion systems in that it needs to remain static and relatively stable before whipping, and a destabilizing effect occurs during whipping and aerating, promoting partial coalescence of fat to form a foam structure composed of protein-stabilized emulsion and partially coalesced fat stabilized bubbles (Singh & Gallier, 2017). Emulsion stability is a crucial factor in producing high-quality whipped cream. If too stable, it is difficult to have partial coalescence during the whipping process and form a stable foam structure; on the contrary, flocculation, emulsion precipitation, aggregation, and phase transformation will occur (Elaine et al., 2024; McClements & Gumus, 2016). As a critical substance in whipping emulsion, fats have a major contribution to the stability of the foam structure formed by the system.

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Therefore, prior studies have been focused on the fat state and mechanism in whipped cream.

In early studies, partial coalescence of fat has been the main research content of whipped cream, as it is critical for the formation of a stable foam structure of whipped aerated emulsion system. Partial coalescence of whipped cream refers to the formation of incomplete aggregates in droplets containing solid particles (generally fat crystals) during diffusion, which can be divided into surface-mediated and shear-induced partial coalescence according to the difference coalescence mechanisms of fat globules during the whipping process (Jiang et al., 2018; Strieder et al., 2023). In recent years, based on the previous development of whipped cream, researchers have gradually increased their interest in studying the quality characteristics of whipped cream, in terms of whipping, physical, texture, and rheological properties. Whipped cream as a commodity, consumers demand an attractive appearance, high-quality nutrition, healthy ingredients, and excellent organoleptic qualities (taste, flavor). At the same time, traders need better storage and whipping properties to reduce production costs and increase commercial value.

Excellent whipping properties are the basis for producing high-quality whipped cream, which requires high whipping foaming rates, quick and easy whipping, and a stable foam structure. Many studies have reported improvement in the quality characteristics of whipped cream by using additives, for example, locust bean gum/λ-carrageenan (Rezvani et al., 2020), xanthan gum (Zhao et al., 2009b), milk fat globule membrane (MFGM) (Phan et al., 2014), sucrose ester S1570 (Zeng et al., 2022a), and medium chain length saturated monoacylglycerol (me-sMAG) (Blankart et al., 2022).

As a vital part of the modern food industry, additives can improve the quality characteristics of foods, improve processing conditions, and extend the storage period (Barzegar et al., 2023). Additives are also widely used in whipped cream to improve quality properties, which is pivotal in enhancing its whipping properties, sensory properties, texture properties, rheological properties, and even nutritional properties. As shown in Table 1, the additives applied to whipped cream can be mainly divided into hydrocolloids, proteins, lipid compounds, carbohydrates, and emulsifiers. These additives are applied to whipped cream and have advantages and disadvantages on its quality characteristics (including whipping, rheology, sensory). Additionally, even the same additive applied to different systems can have multiple effects, which should be related to the constituent substances of the system. Food additives are essential for extending shelf life, enhancing food safety, and improving food quality properties, and most may be beneficial to health (Shen et al., 2024). However, food additives still have worrying aspects when used, such as the specification of food additives and the maximum authorized amount (Chen et al., 2022). Countries worldwide attach great importance to safely managing the quality and use of additive products. Still, different regions and countries may have different standards for food additives, and researchers and business practitioners in the food field need to understand the different standards. Table 2 shows the standards for the use of cream and cream-like food additives issued by four major countries or organizations, including “GENERAL STANDARD FOR FOOD ADDITIVES CODEX STAN 192–1995” (Nations and Organization 2016) jointly formulated by the World Health Organization-Food and Agriculture Organization of the United Nations, “REGULATION (EC) No.1333/2008” (Union, 2008) by the European Union, “National Standard of the People’s Republic of China GB/2760–2014” (China 2014) by China, and “Code of Federal Regulations Title 21” (Administration, 2008) by the USA. To the clearly defined additives listed in Table 2, there are many natural substances utilized to improve the quality characteristics of whipped cream, such as sunflower oil (Mitsou et al., 2016). Although earlier studies have improved the quality characteristics of whipped cream in different aspects, the improvement of the quality characteristics by novel additives has not been reported comprehensively and systematically. Based on the broad and positive market prospect, it is essential and meaningful to develop whipped creams with better textural, rheological, whipping properties, and sensory properties. Besides these properties, the nutritional properties of whipped cream are also noteworthy. Developing low-fat, healthy, or nutritional whipped cream is the key to further expanding the market and developing functional whipped cream products. This article will introduce the improvement and application of whipped cream quality characteristics (whipping, texture, rheological, sensory, and nutritional properties) from hydrocolloids, proteins, lipid compounds, carbohydrates, and emulsifiers.

Improved Whipped Cream Whipping Properties by Additives

The Formation Mechanism of Whipped Cream

Whipping inflation is crucial in transforming whipped cream from oil-in-water emulsion to water-in-oil foam system. As shown in Fig. 1, whipping inflation can be divided into three stages (Han et al., 2018; Wu et al., 2016). (1) In the first stage (protein bubble formation stage), large bubbles are filled into the system during the whipping process, and the proteins will be quickly adsorbed to the surface of the bubbles. During this phase, fat globules collide with each other, mainly due to shear-induced partial coalescence (Fig. 1b). (2) In the second stage (intermediate stage), as more gas is whipped into the system, the large

Table 1 Research progress on additives being applied to whipped cream

Types	Additives	Advantages and disadvantages	References
Hydrocolloid	λ-Carrageenan and locust bean gum	✓ The strong interaction of λ-carrageenan with protein increased the viscosity ✓ Locust bean gum improved the shear stability of the emulsion ✓ Increases viscosity and thixotropic behavior, significantly improving the stability of the whipped foam × High percentage of locust bean gum causes reduced viscosity due to hydrocolloid antagonism	Camacho et al. (2005); Kováčová et al. (2010)
	Hydroxypropyl methylcellulose	✓ Improved firmness, cohesiveness, consistency, and viscosity × Have a dose-dependent effect, greater than 0.025% had no significant effect	Zhao et al. (2009a)
	Xanthan gum	✓ Partial coalescence of fat is increased, and the content is positively correlated with firmness, cohesiveness, or viscosity × Content greater than 0.100% has a disadvantages effect on consistency	Zhao et al. (2009b)
	Basil seed gum and Cress seed gum and Quince seed gum	✓ Increased viscosity, firmness, and overrun ✓ The effect of CSG on firmness and adhesion is significantly weaker than BSG ✓ The improvement effect of QSG on G' and G'' was weaker than that of BSG × Increased concentration reduces the foam stability of whipped cream	Farahmandfar et al. (2017)
	Carboxymethyl cellulose and locust bean gum	✓ Improved the physical and sensory properties (including apparent viscosity, firmness, mean particle size and overrun, and drainage) of the low-fat cream ✓ Reduced fat content by replacing 20% fat as a partial fat replacer × Increased levels will result in increased overruns	Rezvani et al. (2020)
	Sage (*Salvia macrosiphon*) seed gum Balangu (*Lallemantia royleana*) seed gum	✓ Improved apparent viscosity, yield stress, and shear-thinning properties ✓ Improved foaming properties and flow behavior of low-fat whipped cream × The foam capacity decreased with increased the gum concentration	Farahmandfar et al. (2019)
	Pectin	✓ Increased elastic modulus and yield strain provide foam firmness close to whipped cream × Significant differences in large-deformation rheology	Allen et al. (2008a)

Table 1 (continued)

Types	Additives	Advantages and disadvantages	References
Lipid compound	Sunflower oil	✓ Partial replacement of palm kernel oil reduces the content of dietary hydrogenated fats and trans fatty acids and improves nutritional value ✓ Improves the stability, and bubble uniformity of whipped cream ✕ Increased consistency and hardness of the whipped product and decreased density	Mitsou et al. (2016)
	Refined vegetable oils and hydrogenated palm kernel oil and hydrogenated palm kernel oil and refined vegetable oils and transesterification oil	✓ Rich in lauric acid and myristic acid, it facilitates the formation of small crystals and dense crystal networks ✓ Contains a high content of stearic acid, which will form large spherical crystals, improves the firmness, firmness, and stability of whipped cream ✕ Rich in palmitic acid and oleic acid, resulting in the formation of a weak crystal network, prolonging the whipping time, and reducing the overrun and firmness	Liu et al. (2021)
	Milk fat globule membrane	✓ Improved whipping properties, increased overrun and firmness, and reduced serum loss ✕ Highly influenced by the source, additives obtained from buttermilk result in lower density and hardness, high overrun, and serum loss	Phan et al. (2014)
	Monoacylglycerol (unsaturated and saturated)	✓ Unsaturated monoacylglycerol reduces whipping time, reduces overrun and serum loss, and increases whipped cream firmness ✕ Saturated monoacylglycerol has the opposite effect	Fredrick et al. (2013)
	Shea butter	✓ Partial replacement of fat, reduction of unsaturated fatty acid content, and overrun are not significantly different from hydrogenated palm kernel oil whipped cream ✕ Results in a lower average overrun of the whipped cream	Shin et al. (2021)

Table 1 (continued)

Types	Additives	Advantages and disadvantages	References
Emulsifier	Sorbitan monostearate	✓ Improve the overrun, apparent viscosity, and sensory properties ✗ High concentration caused an increase in both the partial aggregation of fat and the particle size of the fat droplets, with a decrease in texture and a dull color	Zhao et al. (2013)
	Triglycerol monostearate	✓ Increased viscosity, ζ-potential and overrun, reduced serum loss, and whipping time ✗ As concentration increased to 0.5%, overrun and serum loss increased, hardness decreased	Li et al. (2020a)
	Monoacylglyceride and diacylglyceride	✓ Saturated monoglycerides improve emulsion and foam stability ✗ Unsaturated monomeric glycerides reduce emulsion stability and prevent the foaming of the model system ✗ High concentrations increase displacement and destroy foam stability	Blankart et al. (2020a); Blankart et al. (2020b)
	Medium chain saturated monoacylglyceride	✓ Improved stability during emulsion homogenization in model aerosol whipped cream ✗ Decreased foaming ability	Blankart et al. (2021)
	Sucrose esters S1570	✓ High concentration increases partial coalescence caused by shear forces, delays surface-mediated partial coalescence, improves overrun, and shortens whipping time ✗ Low concentration delays partial coalescence during the beating process, prolongs the whipping time, and reduces the firmness and stability	Zeng et al. (2022a)
	Sucrose ester S370	✓ 0.05 wt% concentration improves crystal network homogeneity, firmness, and bubble stability ✗ Low concentrations increased crystal size and inhomogeneity, leading to reduced hardness and bubble stability	Zeng et al. (2021)

Table 1 (continued)

Types	Additives	Advantages and disadvantages	References
Carbohydrate	Cellulose nanofiber	✓ Blended with soy protein isolate as a fat substitute instead of 10% cream achieves the goals of fat reduction, low calorie, anti-melting and texture-like taste, and enhancing nutritional properties × Excessive levels can damage the fat globule network and affect the texture of the final product	Sun et al. (2015)
	Electrohydrodynamic modified cellulose	✓ Increased whipped cream viscosity, firmness, overrun, and hysteresis stability ✓ Has better stability, texture and color properties and reduced fat content × High concentrations provide excessive viscosity and hardness	Athari et al. (2021)
	Micronized cornstarch	✓ Partial substitution of fat, with increasing substitution rate the apparent viscosity increased × Decreased partial aggregation rate, overrun rate, and textural properties	Wang et al. (2013)
	Raw starches	✓ Improved foaming and foam stability, increased viscosity × Decreased stability	Iftikhar and Dutta (2020)
	Physically modified rice starches	✓ Improved foaming and foam stability, resulting in a cream texture that replaces some fats closest to commercial cream standards, reduced glycemic index, calories, and price, and enhances the nutritional properties of whipped cream × Have a negative effect on the color of the whipped cream	

Table 1 (continued)

Types	Additives	Advantages and disadvantages	References
Protein	Soy protein isolate	✓ Partial replacement of the milk fat, enhances nutritional properties, avoids drainage and coagulation, and improves foam stability and firmness ✗ Significantly increased the flocculation of fat droplets	Ghribi et al. (2021)
	Casein	✓ Micellar/ Calcium/ Sodium casein concentrate increases viscosity at 2.5% ✗ Calcium caseinate reduces stability at concentrations of 2.5% ✗ Sodium caseinate has a negative effect on whipping properties at concentrations of 2.5%	Li et al. (2020b)
	Modified whey protein concentrate	✓ Improved viscosity, firmness, and stability at lower pH and longer heat treatment times, and also better stability at lower fat content compared to other processes ✗ Higher contents result in increased the syneresis of the whipped cream	Sajedi et al. (2014)
	Zein	✓ Making zein colloidal particles for whipped cream increased the overrun, improved foam stability, and exhibited the desired hardness and shape ✗ Decreased partial aggregation of fat globules	Cao et al. (2020)
	Whey protein concentrate	✓ Increased whipping time and apparent viscosity, reduced maximum overrun, foam drainage ✓ Improved the stability of the foaming, providing a more compact microstructure ✗ Decreased overrun rate and hardness	Long et al. (2016); Emam-djome et al. (2008)
	Rice bran protein	✓ Replaces fat to improve the foam structure of whipped cream, improves the elasticity of whipped cream, and enhances the foam structure ✗ Decreased the apparent viscosity	Ghorbani-HasanSaraei et al. (2019)
	SPI and its hydrolysates	✓ Compared to SPI and soybean protein isolate hydrolyzed by papain (SPHPa), soybean proteins isolate hydrolyzed by pepsin (SPHPe) has better foaming stability, suitable for forming high-quality recombinant soy-based cream ✗ SPHPa has the worst whipping stability ✗ SPHPe has weaker overruns and whipping times than SPHPa	Fu et al. (2020)

Table 1 (continued)

Types	Additives	Advantages and disadvantages	References
Other	NaCl, KCl, and $CaCl_2$	✓ Increasing ionic strength can reduce whipping time, where $CaCl_2$ has the greatest effect ✗ Excessive addition can have adverse effects	Börjesson et al. (2015)
	Potent GPR120 agonist	✓ Improved the strength of the mouth wrap, the thickness and density of the taste, and reduced the rate of melting in the mouth, comparable to the sensory score of full-fat whipped cream ✗ Effects on textural properties, including more likely negative effects, cannot be controlled	Iwasaki et al. (2022)

*Where "✓" and "✗" indicates that advantages and disadvantages

bubble bursts into small bubbles, and the specific surface area of the bubbles increases (Fig. 1c). Fat globules are adsorbed to the gas/liquid interface at this stage, where mainly surface-mediated partial coalescence. (3) In the third stage (fat network structure formation stage), the last stage of whipping, a fat coalescence network structure is formed around the bubbles, and the aqueous phase is fixed inside (Fig. 1d).

Effect of Additives on the Whipping Properties of Whipped Cream

The unique smooth taste of whipped cream is the main reason for its popularity among consumers, owing to the combined effect of the bubbles in whipped cream and the human mouth. Therefore, the size, quantity, and stability of bubbles are of great significance to whipped cream. Overrun is an important indicator of the whipping characteristics, and it can effectively reflect the percentage of gas in whipped cream, which is a key factor affecting the texture (Jakubczyk & Niranjan, 2006). The foam system is thermodynamically more unstable than emulsions, with decreasing stability under the influence of gravity drainage, merging, gas diffusion, and Ostwald aging, resulting in rougher foams (Du et al., 2021). The size of the foam bubbles in whipped cream is also significant in determining its appearance. Smaller bubbles result in a whiter color, a more delicate appearance, and a better overall form. In addition, the bubble particle size also affects the stability of the foam system (Fig. 2). To improve these properties, hydrocolloids, proteins, emulsifiers, carbohydrates, and lipid compounds are applied to whipped cream; part of the mechanism is shown in Fig. 3.

Hydrocolloids

Hydrocolloids are polymers with a three-dimensional grid structure that can expand and absorb water, and are used as thickeners, stabilizers, and water retention agents in different food systems (Imeson, 2011; Williams & Phillips, 2021). Hydrocolloids are generally used in emulsion systems to increase the apparent viscosity and form a gel network structure. In whipped aerated systems, hydrocolloids can interact with fat globules to affect the performance, as shown in Fig. 3a. It affects stability through three mechanisms, including repulsive flocculation of fat globules due to hydrocolloids and proteins, gel network structure formed by hydrocolloids, and interaction of active surface molecules adsorbed on fat globules (Cai et al., 2018; Moschakis et al., 2005). (1) Hydrocolloid repulsive flocculation: the hydrocolloid molecules in the system are repelled by proteins, and an exclusion zone of hydrocolloid molecules will be formed around the fat globules. When the fat globules approach

Table 2 Current standards for the use of additives in major countries/organizations

Additives	Functional class	Food category	Max level			
			GSFA	(EC) No 1333/2008	GB 2760–2014	FDA
Hydroxypropyl methylcellulose	Stabilizer, thickener	Pasteurized cream	GMP	Quantum satis	Use inappropriate amounts according to production needs	Add-on needed must comply with GMP
Raw starches	Stabilizer, thickener	Fermented milk, not heat-treated/heat-treated after fermentation				
λ-carrageenan	Stabilizer, thickener	Sterilized and UHT creams, whipping and whipped creams, and reduced fat creams				
Xanthan gum	Foaming agent, thickener					
Carboxymethyl cellulose	Stabilizer, thickener					
Locust bean gum	Stabilizer, thickener					0.5%
Pectin	Stabilizer, thickener					GMP
Electrohydrodynamic modified cellulose	Classified as powdered cellulose					-
NaCl, KCl, and $CaCl_2$	Stabilizer, thickener					0.3%
Cellulose nanofiber	Stabilizer, thickener					-
Sorbitan monostearate	Emulsifier, stabilizer		1000 mg/kg	-	1.0 g/kg	Not more than 0.4% alone; can exceed 0.4% in combination with polysorbate 60
Triglycerol monostearate	Emulsifier, stabilizer		1000 mg/kg	-	1.0 g/kg	Not more than 0.5%
Mono- and diacylglyceride	Emulsifier, stabilizer		GMP	Quantum satis	10.0 g/kg	GMP
Medium chain saturated monoacylglyceride	Emulsifier, stabilizer		GMP	-	10.0 g/kg	-
Sucrose esters S1570	Foaming agent, stabilizer		5000 mg/kg	5000 mg/kg	10.0 g/kg	Not more than 2.0%
Sucrose ester S370	Foaming agent, stabilizer		5000 mg/kg	5000 mg/kg	10.0 g/kg	Not more than 2.0%
β-Cyclodextrin	Stabilizer, thickener	Water-based flavored drinks, including "sport," "energy," or "electrolyte" drinks, and particulated drinks	500 mg/kg	-	0.5 g/kg	-

*Where "Functional class" and "Food category" are provided by the GSFA; "GMP" is good manufacturing practices; "Max Level" = Quantum satis, this means that no maximum numerical level is specified and substances shall be used by good manufacturing practice; "-" indicates that the additive is not retrieved in the cream and cream-like food regulations and information

each other, the repulsion zones will overlap, which generates an osmotic pressure, resulting in the solvent between the fat globules flowing out of the repulsion zone, and ultimately causing the repulsion flocculation. (2) Gel network structure formed by hydrocolloids: The gel network structure formed by hydrocolloids can fix fat globules and prevent the agglomeration and coalescence of fat globules. (3) Interaction with surface-active molecules: hydrocolloid molecules may interact with surface-active molecules adsorbed on fat globules.

Hydrocolloids can help foam hold more water and maintain its shape, which helps create a better foam texture and improve the ability of whipped cream. Camacho et al. (2005) optimized the composite addition of locust bean gum (LBG) and λ-carrageenan, and the results showed that when LBG was relatively low, their mixture could improve the stability of whipped cream. The intrinsic viscosity of LBG is greater than λ-carrageenan and should have higher viscosity when the mixture has a higher proportion of LBG, but the actual result is the opposite, which indicates that there may be

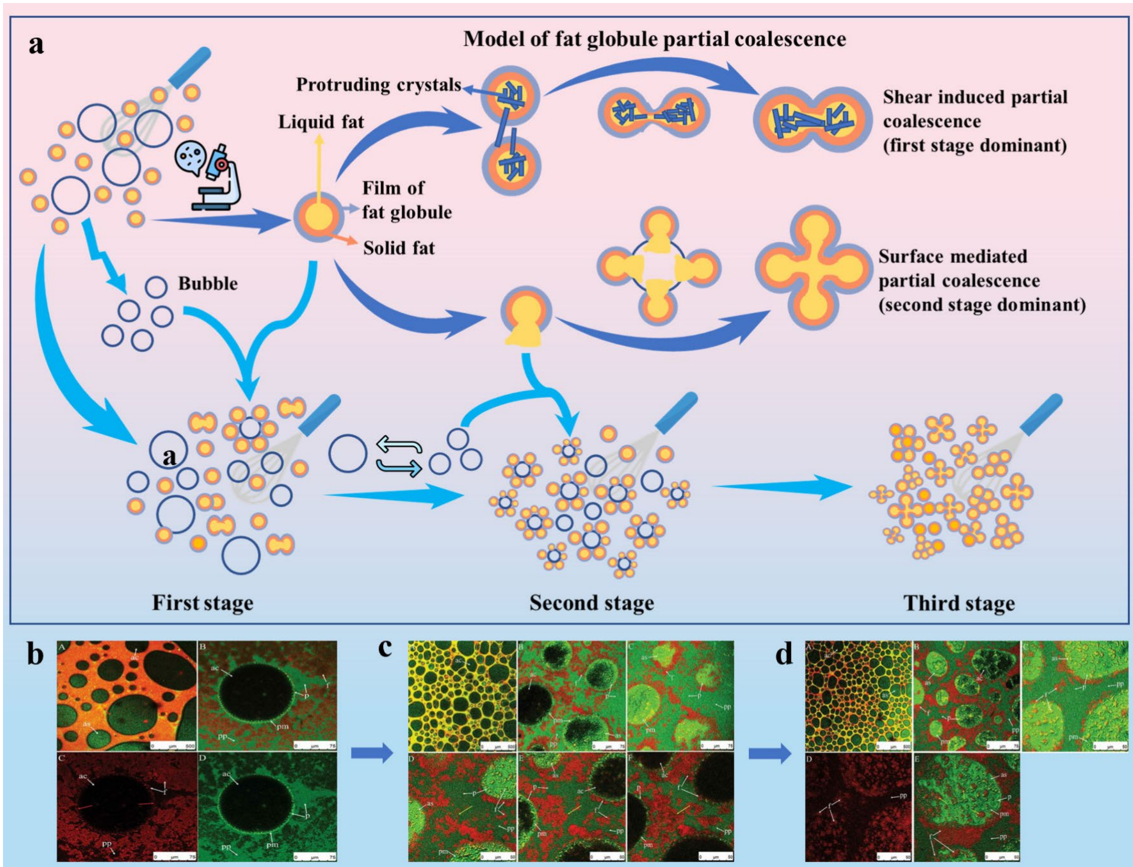

Fig. 1 Mechanism of coalescence and whipping inflation of fat globules of whipped cream (**a**); microstructural evolution in whipping process observed by confocal laser scanning microscopy (**b**, **c**, **d**) (Han et al., 2018)

hydrocolloid antagonism between LBG and λ-carrageenan, and they are not suitable for simultaneous addition or need to be added in particularly precise amounts. Rezvani et al. (2020) indicated that LBG and carboxymethyl cellulose (CMC) were able to reduce the surface tension of fat globule films in low-fat whipped cream, thereby increasing the mean particle size and foam stability. Liszka-Skoczylas et al. (2014) also proved that high content of λ-carrageenan would provide higher firmness foam for whipped cream and improve stability. This was attributed to λ-carrageenan reducing the increased viscosity of the air cell network in the whipped cream and the leakage of the serum phase (Ghribi et al., 2021).

Xanthan gum is widely used in food systems due to its excellent emulsion stability, temperature/acid/alkali stability, and water solubility (Fitzpatrick et al., 2013). Zhao et al. (2009b) studied the effect of xanthan gum on the preparation of whipped cream and showed that the average particle size and partial coalescence of fat also tended to increase at the 0.025–0.125% level, and the 0.025% level was sufficient to provide the desired stability. Due to the thickening property of xanthan gum, it will promote more air to enter the bubble, and it is difficult to flow out when a large amount of air contained by the system will show stronger binding force, thus improving the stability of the already formed bubble (Allen et al., 2006). The increase in the average particle size of the whipped cream is because xanthan gum increases the viscosity and reduces the water fluidity, thus affecting the emulsification process (Regand & Goff, 2003). Hydroxypropyl methylcellulose (HPMC) also could improve the partial coalescence, average particle size, and overrun of whipped cream (Zhao et al., 2009a). The enhancement of fat partial coalescence is related to the competitive adsorption of HPMC with sodium casein and casein formed at the interface and bubble surface during the whipping (Zhao et al., 2009a). Further, partially coalesced fat droplets form a three-dimensional network that connects to the fat blocks in the system and droplets on the bubble surface, enhancing the structural integrity of the foam, and thereby increasing the mean particle size (Dickinson, 2015).

Farahmandfar et al. (2017) investigated the effects of basil seed gum (BSG), cress seed gum (CSG), and quince seed gum (QSG) on the stability of whipped cream; at low

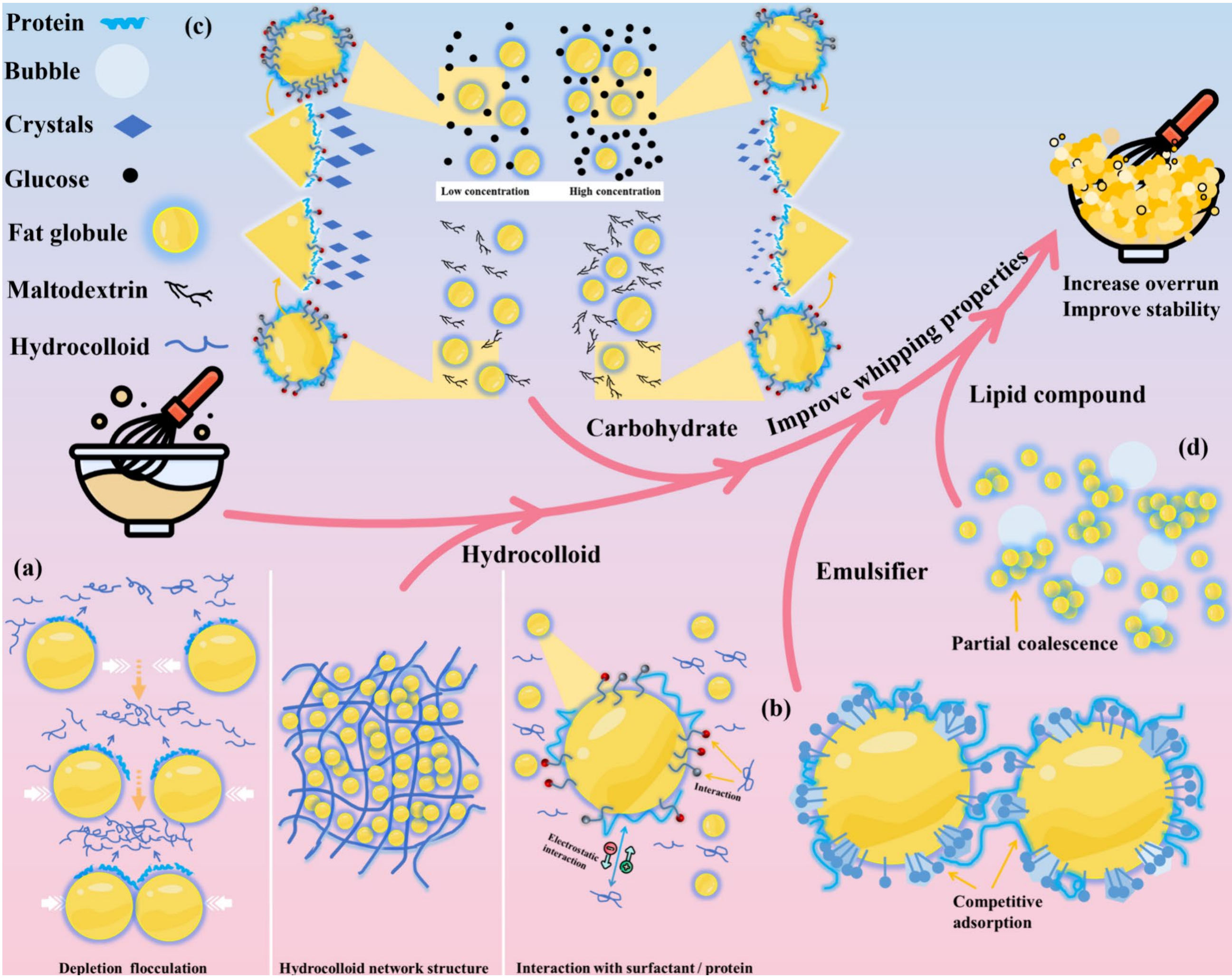

Fig. 2 Partial mechanism to improve the whipping characteristics of whipped cream by different additives (**a**) hydrocolloid; (**b**) emulsifiers; (**c**) carbohydrates; (**d**) lipid compounds

concentrations, they were not significantly different; at increasing concentrations, only the stability of QSG whipped cream increased, BSG and CSG showed the opposite pattern, and 0.3% BSG whipped cream had the lowest stability. Generally, the stability will enhance with the increase of hydrocolloid concentration and will be more stable at high viscosity, because hydrocolloid increases the viscosity of the liquid phase, which will form a network structure in the system and enhance the interfacial wall, but the anomalies of BSG and CSG have not been reported yet (Schramm, 2014). Numerous previous studies have demonstrated that hydrocolloids can improve whipping properties, partial coalescence of fat, average particle size, and overrun, and foam stability of whipped cream. However, the amount of hydrocolloid added is critical to the effect and antagonism that may occur between hydrocolloids, and their dosage and interactions need to be considered when used.

Proteins

Proteins are of great interest for emulsification properties due to the combination of hydrophilic and hydrophobic groups and good film-forming ability (Foegeding & Davis 2011; Phillips & Williams, 2011). Once the protein reaches the interface, it forms a viscoelastic film that resists mechanical stress, provides spatial stability, and electrostatic forces, but is affected by solvent conditions and protein species (Elaine et al., 2024). Proteins are extensively applied in dairy products, such as whey protein (WP), and their modified proteins are also often used in whipped cream and dairy foam. WP will form surface gels at the air–water interface and can also stabilize the system by thermally induced gelation (Li et al., 2023). Zhao et al. (2008) evaluated the effect of WP on the whipping properties of whipped cream, with particle size and $d_{4,3}$ decreasing with increasing WP

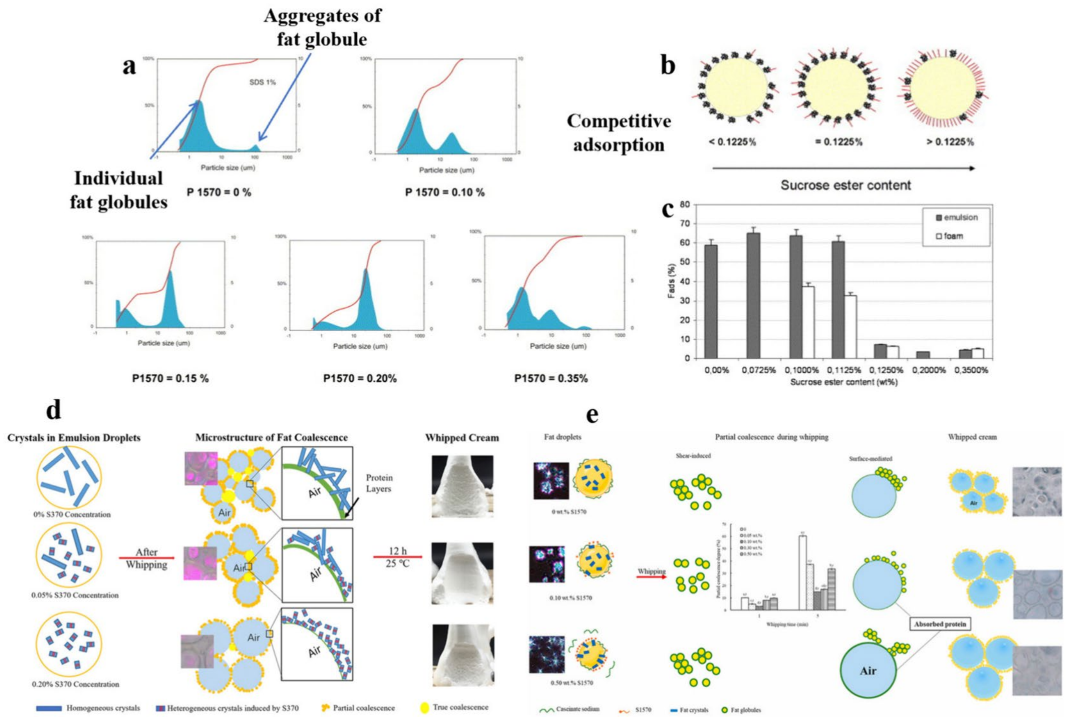

Fig. 3 The mechanism and effect of emulsifier sucrose ester on the whipping process of whipped cream. The effect of sucrose ester on the fat droplet size of the emulsion (**a**); competitive adsorption mechanism (**b**); effect on whipped cream foam formation (**c**) (Tual et al., 2006). Effect of sucrose esters (S370) on the fat crystal network and quality of whipped cream (**d**) (Zeng et al., 2021). Effect of sucrose ester (S1570) on partial aggregation and whipping properties (**e**) (Zeng et al., 2022a)

addition, improving the stability. Furthermore, the addition of WP also significantly improved the partial coalescence of whipped cream, which is beneficial for its stability. Modified or concentrated WP also has the effect of improving foam stability. For example, whey protein concentrate (WPC) provides a more compact microstructure for whipped cream and improves foam stability (Emam-djome et al., 2008); whey protein isolate (WPI) provides the desired overrun and foam with 2% concentration (Narchi et al., 2009).

Most proteins stabilize emulsions and foams by adsorbing strongly at the air–water interface, forming a viscoelastic adsorption layer, which results in a high viscosity protein network (Rullier et al., 2010). Rice bran protein (RBP) is an excellent plant protein with good foaming and emulsifying properties, and it has also been used to improve quality properties in whipped cream (Esmaeili et al., 2016). Peng et al. (2018) found that adding 1% milk fat globule membrane protein (MFGMP) significantly increased the $d_{3,2}$ of whipped cream. But with the continuous increase in the concentration of milk fat globule membrane protein, there was a decrease in $d_{3,2}$, even if it was not obvious. The increase in $d_{3,2}$ is due to the formation of a partially coalesced droplet network structure in the whipped cream, which can connect bulk cellulite and adsorb on the surface of the bubble, thereby increasing the integrity of the foam (Peng et al., 2018). The reduction in $d_{3,2}$ should be due to the competitive adsorption of MFGMP molecules on the surface of fat droplets resulting in a change in surface tension, thereby reducing the particle size. Sodium caseinate (CN) is a popular protein derivative that is widely used in dairy products due to its high nutritional value and specific functionalities such as emulsification, foaming, gel formation, and texture improvement properties (Sadeghi et al., 2018). Zhao et al. (2008) reported the positive effect of sodium caseinate on whipped cream overruns and found that the maximum overrun rate was achieved by adding 0.7% CN when almost all bubbles were wrapped in coalesced fat globules at the interface. The increased overrun was attributed to the good emulsifying properties of CN, which is easily absorbed into the interfacial space and forms a viscoelastic layer near the bubbles, thereby improving the stability of the foam (Rezvani et al., 2020). It is necessary to note that although CN will increase the overrun of whipped cream, it can also have negative effects if the level of addition is too high. Zhao et al. (2008) showed that adding 0.9% CN led to a decrease in expansion, and Rezvani et al. (2020) also found that a CN above 0.5% led to a reduction in overrun. This may be due to the high concentration of CN forming an excessively thick viscoelastic layer around the fat globules, reducing the sensitivity of the emulsion to partial coalescence, which leads to partial rupture of the foam and reduces the expansion rate (McClements, 2007; McClements & Jafari, 2018).

Among a variety of proteins, soy protein isolate (SPI) is widely used in the food industry due to its mild flavor and a variety of functional and nutritional properties, but reports of its application in aerated emulsions are still limited (Huang et al., 2023). In recent years, the use of SPI in aerated emulsions has also gained more attention. Fu et al. (2020) investigated the effect of SPI and its hydrolysate on the stability of recombinant plant-based whipped cream (RSWC), and results showed that RSWC overrun containing soybean proteins isolate hydrolyzed by pepsin (SPHPe) was only lower than soybean protein isolate hydrolyzed by papain (SPHPa), but the best stability and was most suitable for the preparation of high-quality RSWC. Ghribi et al. (2021) also found that SPI can enhance the overrun and stability of low-fat whipped cream due to SPI being quickly adsorbed to the interface during whipping, thereby reducing surface tension and enhancing air binding.

Emulsifiers

Emulsifier is considered to have an important influence on the quality of whipped cream, as shown in Fig. 3b, where it can reduce the interfacial tension of fat globules and increase stability by competing with proteins adsorbed at the interface during whipping. It also promotes the partial coalescence of fat globules, which contributes to the formation of foam structures.

Since sucrose esters can affect interfacial properties and fat crystallization, sucrose esters of different compositions have been widely used in food systems and industry (Nelen et al., 2014). Sucrose esters have attracted attention in the study of emulsions or whipping aerated systems due to their environmental compatibility and extensive hydrophilic-hydrophobic balance, and will also become the focus of future attention (HLB) values (Jiang et al., 2018; Teng et al., 2021). Sucrose esters affect shear-induced partial coalescence and surface-mediated partial coalescence (Fig. 1a) during whipping by synergistic and competitive adsorption at the oil/water interface, and the different mechanisms are shown in Fig. 3e. Tual et al. (2006) studied the effect of sucrose ester content (0–0.35 wt%) on whipping dairy products and found that sucrose esters below 0.1 wt% could not produce foam, and about 0.1 wt% had the strongest and most stable foam structure (Fig. 3b and c). Figure 3a shows that the second peak representing the fat globule aggregates became larger with increased sucrose ester content, indicating an increased degree of aggregation. Under 0.1 wt% sucrose ester conditions, fat globule adsorption and partial coalescence around the bubbles during whipping and inflation form a network structure composed of partial coalescence fat globules, which provides firmness and stability for the foam. The competitive adsorption mechanism of sucrose esters and proteins at different concentrations is shown in Fig. 3b; when the sugar ester content exceeds 0.1225 wt%, an excessive amount of free surfactant will compete with the existing surfactant–protein complex, resulting in a decrease in the protein adsorbed around the droplet. However, in the presence of more sucrose esters (0.35 wt%), it will compete with the surfactant–protein complex and reduce the protein on the droplet surface, which will lead to complete a coalesce of the droplets during foaming, although bubbles will also form at this time, but with less stability and hardness (Teng et al., 2021). Zeng et al. (2021) found that low concentrations of sucrose ester S370 (<0.05 wt%) resulted in reduced whipped cream overrun, and high concentrations (>0.05 wt%) were the opposite. The mechanism of different concentrations of sucrose ester S370 on fat crystals and the effects of whipped cream are shown in Fig. 3d. At low concentrations, due to the lack of S370 as an induction template and high nucleation energy, the presence of large fat crystals in the droplets will cause a high degree of fat coalescence, resulting in reduced whipped cream overrun (Cheng et al., 2016). At high concentrations, S370 reduced nucleation energy, promoted fat microcrystal formation in droplets, caused fat binding, and reduced interfacial protein concentration, thus increasing the overrun of whipped cream (Chen et al., 2015; Jiang et al., 2019). Similarly, whipped cream at high levels (0.1–0.5 wt%) sucrose ester S1570 not only had richer overrun but also higher stability than low levels (Zeng et al., 2022a). It was possible that the combined effect of surface-mediated partial coalescence delay and shear-induced increase in partial coalescence caused by S1570 increases the degree of partial coalescence and promotes the formation of stronger structures (Fig. 3e).

In addition to the widely concerned sucrose esters, there are also a variety of emulsifiers used in whipped cream to improve its whipping properties. Allen et al. (2008b) compared the effects of lactic acid esters of monoglycerides (LACTEM), glycerol monooleate (GMO), and diacetyltartaric esters of monoglycerides (DATEM) on quality properties of acidified caseinate-stable whipped cream models. The results showed that the addition of 0.5 wt% GMO, lecithin, and DATEM resulted in 40–50%, 50%, and 60% overrun, respectively, which was lower than that of the system containing LACTEM or ordinary whipped cream. Their low foaming properties are caused by the synergistic adsorption of emulsifiers and proteins on the surface of fat globules, which enhances the elasticity and consistency of the surface film, thus inhibiting shear-induced partial coalescence (Krog & Sparso, 2004). Span 60 is also used to improve the whipping properties, which promotes partial coalescence of fat with the increase in concentration, reduces the average particle size, and increases overrun (Zhao et al., 2013). These studies suggest that although sucrose esters have a positive effect on the properties of whipped aerated dairy products, it requires an optimal level; otherwise, this effect can also be negative.

Carbohydrates

As shown in Fig. 3(c), carbohydrates affect the size and morphology of the crystals in the system, and can also affect the whipping properties by adsorption and gelation affecting the functional properties of the protein at the oil/water interface. Wang et al. (2013) investigated the effect of micronized cornstarch as a partial fat substitute on the whipping properties of whipped cream, and the results showed that with the increase of fat replacement rate, the viscosity increased, while the partial coalescence and overrun decreased, but at a fat replacement rate of 15%, low-fat whipped cream had similar whipping characteristics as full-fat whipped cream. Iftikhar and Dutta (2020) found that the addition of raw and modified rice starch as a partial fat substitute to whipped cream significantly improved the foaming stability, increased overrun by up to 44%, and its water retention and structural stability also improved. The enhanced phenomenon of rice starch on overrun may be because starch increased the viscosity and improved the ability to trap air, thus increasing the air holding rate (Rybak, 2016). Zeng et al. (2022b) evaluated the effects of glucose and corn syrup on whipping properties and found that increased glucose concentration improved the fat coalescence rate and foam stability of whipped cream. Corn syrup could also improve the whipping properties, but behaves slightly weaker than glucose because the maltodextrin in corn syrup hinders the formation of a continuous network structure during whipping.

Lipid Compounds

Fat is the key substance in whipped cream, and during the whipping process, fat globules partially coalesce to form a three-dimensional network structure (Fig. 4d), which provides stronger stability and firmness for whipped cream. Additionally, the fat is gradually distributed on the surface of the protein-covered bubbles, enhancing the stability of the foam. Crystallization of lipids also has an essential role in whipped cream; the number and type of crystals affect the texture; moreover, at least 40% of fat crystals are needed to promote partial coalescence (Truong et al., 2014). Among the three crystal forms (α, β, and β') of fat, the β' crystal is the most desirable, as it is relatively small in size and can also combine with a large amount of liquid fat in the crystal network, which is positive for the stability of the whipped cream (Domingues et al., 2018; Sun et al., 2022). Che Man

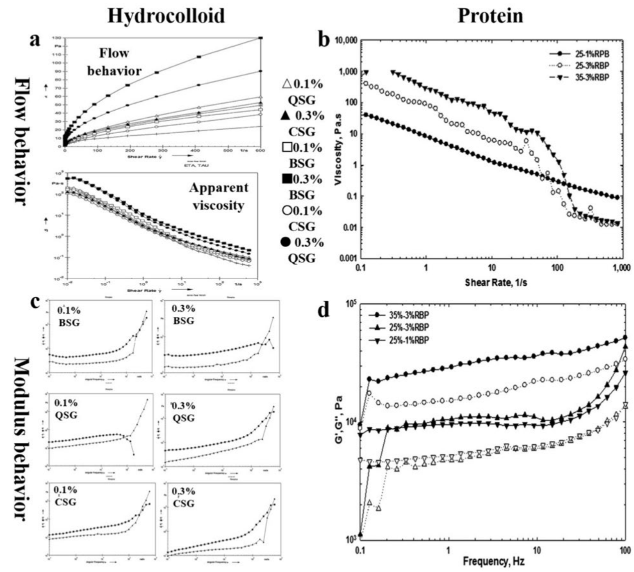

Fig. 4 Effect of hydrocolloids and proteins on the rheological properties of whipped cream. Effect of multiple/different contents of hydrocolloids on flow behaviour (**a**) and modulus behaviour (**c**) (Farahmandfar et al., 2017); effect of different levels of protein on flow behaviour (**b**) and modulus behaviour (**d**) (Ghorbani-HasanSaraei et al., 2019)

et al. (2003) studied the crystal structure of palm oil-based whipped cream and showed that the mixture of refined, bleached, and deodorized palm oil (RBDPO) and palm kernel oil (RBDPKO) had a stable and glossy β' crystal at 25 °C, meaning they were able to maintain the stability of palm oil-based whipped cream foam. In early studies, RBDPO and RBDPKO mixtures proved to have a positive effect on the foam stability of whipped cream, which remains stable even at temperatures of 40 °C after whipping (Shamsi et al., 2002). The advantage of RBDPO and RBDPKO when applied to whipped cream is attributed to the abundance of β' crystals in the mixture, which grow together to form a network structure that retains the liquid oils and droplets, also providing more small bubbles and greater volume.

The choice of lipid compounds plays an important role in the whipping foaming and consistency of whipped cream. For instance, Fredrick (2011) showed that a mixture of oleic acid-rich monoacylglycerol and stearic acid-rich monoacylglycerol improved the whipping properties of recombinant cream. Phan et al. (2014) found that MFGM from different sources (reconstituted buttermilk (BM) and buttermilk whey (whey)) had different effects on the whipping properties of reconstituted whipped cream. Whey-MFGM improves the stability of recombinant cream, similar to natural cream, but it has a lower overrun, BM-MFGM significantly increases the overrun, and their mixture has high stability and overrun, comparable to the whipping properties of natural cream. Crystalline fat can have a marked effect on the functional properties of the whipped aerated emulsion. Therefore, it is wise to use the different properties of lipid compounds to improve the whipping properties of whipped cream to prepare high-quality whipped cream.

Enhancement of Rheological Properties of Whipped Cream Based on Additives

There is a strong link between food and rheological properties, and the apparent viscosity, viscoelasticity, yield stress, and modulus of the food are highly correlated with the taste in the sensory properties, in addition to affecting the unit operating parameters of food processing. Whipped cream introduces air during the whipping process, constantly forming a more rigid structure, and these structural and rheological properties are the main reasons for affecting the texture properties (Ghorbani-HasanSaraei et al., 2019).

Improvement of Whipped Cream Flow Behavior

The development of gas–liquid films and the viscosity of the liquid phase are important for the foam structure and stability of whipped cream systems (Truong et al., 2014). Studies have shown that the whipping time, whipping foaming rate, and foam diameter of whipped cream are all related to liquid viscosity, and there is also a significant correlation between liquid viscosity and strain firmness (Ihara et al., 2010). The whipped cream system is usually interpreted as a non-Newtonian fluid with shear-thinning properties, and its rheological behavior is basically in line with the Herschel-Bulkley model (Doublier & Durand, 2008).

In whipped cream with an ideal foamy texture, the viscosity should be at the optimal level to maintain the structure of the cream, promote partial coalescence of the fat, and trap maximum air (Rezvani et al., 2020). If the viscosity is too high, it may prevent air into the system, reducing the movement and partial coalescence of the fat globules, and conversely, the resistance to air bubbles and fat globules is too low, which can cause the small air bubbles and fat globules already formed to merge and make their film collapse during whipping process (Indrawati et al., 2008; Zhao et al., 2009a). Farahmandfar et al. (2017) found that the addition of BSG, CSG, and QSG increased the apparent viscosity of whipped cream, but the rheological behavior remained consistent with the Herschel-Bulkley model, and BSG had a stronger effect at the same level (0.3%) (Fig. 4a). The increase in apparent viscosity caused by hydrocolloids is due to the binding of hydrocolloid molecules in the system with water, which increases the flow resistance of the sample and thus leads to a decrease in fluidity (Gyawali & Ibrahim, 2016). LBG and λ-carrageenan also increase the viscosity of whipped cream, and λ-carrageenan has a more outstanding effect, probably due to the interaction of proteoglycans (Kováčová et al., 2010). Rezvani et al. (2020) also evaluated the effects of LBG and CMC on the rheology of low-fat whipped cream, which significantly increases the viscosity of whipped cream. The CMC is a water-soluble anionic polymer with water absorption, and the polymer chains will unfold/twist in the aqueous solution, strengthening the resistance to shear force, and thus increasing the system viscosity (Gómez et al., 2007).

Protein bridging may also affect the viscosity of whipped cream (McClements, 2007). Emam-djome et al. (2008) observed that the viscosity of whipped cream increased with WPC addition, but uniquely, the viscosity of whipped cream containing 2.1 wt% WPC was lower than 1.4 wt%, which may be explained by the higher WPC concentration leading to gel formation. Similarly, as illustrated in Fig. 4b, Ghorbani-HasanSaraei et al. (2019) investigated the effect of RBP concentration on the rheological properties of commercial whipped creams with different fat contents (25% and 35%) and showed that at the same shear rate, the apparent viscosity ranged from large to small: 35% fat + 3% RBP, 25% fat + 3% RBP, and 35% fat + 1% RBP. This indicates that the fat content in the whipped cream significantly affects its apparent viscosity, but this effect can be compensated by the addition of RBP. Added MFGMP to whipped cream also increases its viscosity, but they were not dose-dependent and the effect was not significant at the 1% and 5% levels; the viscosity increase should be caused by the ability of MFGMP to bind water (Peng et al., 2018). Fu et al. (2020) found that various proteins had different effects on the viscosity of RSWC, with RSWC containing SPI having the highest viscosity, followed by hydrolyzed proteins 7S and 11S, and SPHPe and SPHPa having the lowest viscosity, which may be caused by protein structure, composition, molecular weight, and interaction with other proteins. Ghribi et al. (2021) also reported the improving effect of SPI on the viscosity of low-fat whipped cream and the addition of SPI increased the viscosity, which they attributed to the water trapping function of SPI.

Enhancement of Whipped Cream *Modulus* Behavior

Due to the high sensitivity of the results of oscillation experiments to the physical structure and chemical composition of the subject, it is often used to analyze the viscoelastic behavior of food systems (Rao, 2010). Jakubczyk and Niranjan (2006) found that the storage modulus (G') of all creams is greater than the loss modulus (G'') during whipping, showing elastic advantage behavior. In addition, at low frequencies, there was no significant difference between G' and G'', but G' was gradually larger than G'' when the frequency was greater than 3 Hz, suggesting that the G' of whipped cream plays an important role in shaping mechanical behavior. Farahmandfar et al. (2017) found that higher concentrations of BSG, CSG, and QSG increased the G' and G'' of whipped cream with 0.1–100 Hz, and G' always greater than G'', indicating that they promoted the formation of macromolecular networks, made whipped cream have stronger rigidity, and its viscoelasticity has always been in an elastic dominant state (Fig. 4c). With the increase of hydrocolloid concentration, G' and G'' also showed a slow increase trend, suggesting that there is a dependence between the increase of whipped cream modulus and hydrocolloid concentration, and at the same concentration, BSG whipped cream G' and G'' are higher than CSG and QSG, suggesting that BSG can provide more solid-like structures for the sample (Farahmandfar et al., 2017).

Ghorbani-HasanSaraei et al. (2019) conducted a dynamic oscillation test on whipped cream with different fat and RBP content, and the results (Fig. 4d) showed that all whipped cream samples had G' values greater than G'' values, were in a state of elastic dominance, and had solid-like properties, which were consistent with other studies. Both fat and RBP content in whipped cream affect its G' and G'' values, and whipped cream containing 35% fat and 3% RBP has the highest G' and G'' values, which indicates that the modulus of whipped cream can be improved by adding RBP. The improvement of whipped cream RBP modulus by RBP should be due to the adsorption of proteins to the oil–water interface, forming a pseudo gel network that shows higher G' and G'' values (Speroni et al., 2009). Homogenization is an important process in the processing of whipped cream, but some studies have found that it has a detrimental effect on the protein structure, causing a decrease in the G' value and impairing the elasticity of the foam. Emam-djome et al. (2008) demonstrated that this unfavorable effect of homogenization can be compensated by the addition of WPC, owing to its ability to cause gelation in shear. Sun et al. (2015) investigated the rheological properties of SPI and cellulose nanofiber (CNF) as partial cream substitutes and found that G' and G'' values decreased with increasing SPI levels in SPI-CNF mixtures, which may be related to large-scale crosslinking of SPI at high concentrations. Peng et al. (2018) also found that the G' and G'' values of whipped cream increased with the increase of MFGMP level, and the G' value was always greater than the G'' value, indicating that MFGMP had the effect of enhancing the rigidity of whipped cream, but did not change its initial solid-like state. Fu et al. (2020) also showed that the G' and G'' values of whipped cream with SPHPe and SPHPa were consistently greater than others, which due to SPHPe and SPHPa improved the emulsification and gel properties of RSWC and promoted the formation of stronger molecular protein network structure in RSWC.

Study on Improving the Electrostatic Properties of Whipped Cream

In the whipped aerated emulsion system, the size of the fat droplets, the characteristics of the interfacial membrane, and the viscosity of the external phase are the main reasons that affect the stability of the emulsion. Proteins, carbohydrates, lipid compounds, and emulsifiers all affect the stability of the emulsion system through different electrostatic effects (Evans et al., 2013; Fitzpatrick et al., 2013). In emulsion systems with large areas of fat interfaces, there are usually large protein micelles distributed between the droplets, which stabilize the system by electrostatic interaction between charges. Because electrostatic repulsion prevents the aggregation of protein-coated oil droplets and thus improves emulsion stability (Lam & Nickerson, 2013). For emulsifiers, it will stabilize the emulsion by forming an electrically charged interfacial layer, different molecular properties and the external environment of the emulsion (including pH, ionic species/strength, and charge properties) lead to different effects and ways of action, but they can both improve the stability of the system by strong electrostatic repulsion (Cai et al., 2023; Zhu et al., 2019). Some carbohydrates also have the effect of enhancing emulsion stability. It has been reported that in protein emulsions with added polysaccharides, coacervates are formed by electrostatically binding to proteins, thereby improving emulsion stability (Liu et al., 2009). However, different polysaccharides (type and size) and solvent conditions (pH, ionic species, ionic strength) can greatly affect the stability of the emulsion (Nor Hayati et al., 2009). Hydrocolloids with electric charges may also interact with adsorbed proteins with opposite charges. In addition, the electrostatic repulsion between fat globules also plays a very important role in preventing fat globules from approaching each other.

Allen et al. (2006) compared the overrun and stability of the acidified sodium caseinate (ACE) system containing liquid oil droplets with whipped cream foam. It found that ACE system with glucono-δ-lactone (GDL) produced a higher spill (> 600%) than whipped cream (approximately 120%), but the stability of ACE foam is strongly dependent on the pH and the concentration of added calcium ions. ACE causes GDL to be hydrolyzed, producing free protons that neutralize the net negative charge carried by casein molecules in the neutral pH, and the degree of acidification will also increase the ionic strength. The electrostatic repulsion between molecules promotes mutual attraction between nonionic proteins and proteins, which is conducive to the formation of gelation. Regand and Goff (2003) found that xanthan gum, as an anionic polysaccharide, excludes casein under the repulsion of electric charge. Narchi et al. (2009) also showed that in the whipped cream model containing xanthan gum and WPI, electrostatic and spatial interactions enhance the formation of the xanthan gum network structure. In addition, they also showed that in the whipped foaming simulation system of pectin-glucose syrup, the cation released from the caseinate matrix could shield the electrostatic repulsion between protein and polysaccharide, thus affecting the enhancement of the interaction between glucose syrup and pectin by protein. Wu et al. (2016) reported that the foaming stability of recombinant low-fat cream containing glycerol monostearate (GMS) was highly dependent on ζ-potential, which may be related to the electrostatic repulsion caused by the change of ζ-potential. Jourdain et al. (2008) also proved that the electrostatic repulsion and interaction repulsion between droplets have the effect of enhancing stability. Rezvani et al. (2020) also suggest that LBG and CMC play an important role in the whipping inflation process with CN through electrostatic, hydrogen, and covalent bonding at the air/serum interface. However, there are still few reports on the electrostatic characteristics of whipped cream, and there is no more in-depth and systematic study, which may need to be filled in the following work.

Improvement of Sensory Properties of Whipped Cream by Additives

Acceptance and preference for the sensory properties of food are also one of the most important criteria for determining food choices. For food to be recognized and accepted by consumers, it should have outstanding sensory properties, including the color, texture, and taste of the food.

Texture Property Enhancement

When evaluating the acceptability of food, texture is an important sensory attribute that can objectively reflect the sensory properties of food. Having outstanding texture properties is a key factor in the popularity of food consumers, such as firmness, cohesiveness, and consistency. Firmness is the force required to deform the product to a certain degree, cohesiveness represents the strength of the internal bond, and consistency is the degree to which the product can be deformed before it breaks (Chen et al., 2021; Li et al., 2023).

The proper consistency is very important for whipped cream, and it can have a huge impact on the sensory quality and acceptance. Much research has been focused on improving the texture of whipped cream by additives, including firmness, consistency, cohesiveness, and viscosity (Table 3). As a consequence of the increasing consumer demand for healthier foods and the modern trend towards healthier low-fat diets, hydrocolloids are increasingly being used in food products to improve the texture and quality of products (Williams & Phillips, 2003). Zhao et al. (2009b) found that the concentration of xanthan gum and the firmness and cohesiveness of whipped cream were highly correlated. High-fat whipped cream (55% fat) had a higher firmness than low-fat whipped cream (30% fat), and the addition of BSG, CSG, and QSG as fat substitutes increased the firmness to achieve textural properties similar to high-fat whipping cream, with BSG having a more significant effect on firmness (Farahmandfar et al., 2017). During the foaming process of whipped cream, the fat globules will form a three-dimensional network structure through partial coalescence, providing a stable and firm structure for whipped cream, and when the fat content is reduced, the stability and solidity of the structure will be weakened, which is manifested as a decrease in firmness (Emam-djome et al., 2008). Hydrocolloids added to whipped cream can effectively prevent the merging of bubbles and reduce the formation of unstable large bubbles, thereby enhancing the firmness of whipped cream as a partial fat substitute (Lal et al., 2006). Similarly, Zhao et al. (2009a) found that HPMC can improve the firmness, cohesiveness, and consistency of whipped cream and that the difference in firmness and cohesiveness is not significant at lower levels (0.025–0.075%), and significantly increased at higher levels (0.075–0.125%). It is attributed to the hydrophilic and thickening effect of HPMC, which binds the water in the system, reduces the water flow in the matrix, and also increases cohesiveness. In addition, the competing adsorption of HPMC with caseinates at the interface and bubble surface will also whip the cream to provide a more ideal structure (Lal et al., 2006). Rezvani et al. (2020) also demonstrated the feasibility of compensating for the decrease in whipped cream firmness due to low-fat content by adding LBG and CMC.

Aside from the fact that hydrocolloids can be applied to improve the textural properties of whipped cream, a variety of proteins have similar functions. Zhao et al. (2008) reported that WP and CN increased the firmness, consistency, and cohesiveness of whipped cream, and CN had a stronger cohesiveness value and stronger resistance to vandalism and deformation. Sun et al. (2015) replaced partial cream with a mixture of SPI and CNF, which had little to no difference in elasticity and cohesiveness from the cream. Ghribi et al. (2021) found that the addition of SPI and λ-carrageenan, which improves the firmness and elasticity of low-fat whipped cream, also promotes rigid film formation, making the product more rigid. Peng et al. (2018) reported the effect of MFGMP on the firmness and consistency of whipped cream during storage, which increased with increasing levels of MFGMP addition. Fu et al. (2020) found that whipped cream with 7S added had higher consistency, cohesiveness, and firmness.

Table 3 Effect of different additives on the sensory properties of whipped cream

	Additives	Effects on whipped cream				References
Textural		**Firmness**	**Consistency**	**Cohesiveness**	**Viscosity**	
	Xanthan gum (0.025–0.125%)	Increased at 0.050–0.125% level	< 0.100%, increased with higher levels; > 0.100%, decreased	Increased with dose-dependent	Improved with dose-dependent	Zhao et al. (2009b)
	HPMC (0.025–0.125%)	Increased, > 0.075% dose-dependent	Increased with dose-dependent	Increased with dose-dependent	Improved with dose-dependent	Zhao et al. (2009a)
	BSG and CSG and QSG (0.1% and 0.3%)	Both increase the hardness, and the effect of BSG is significantly greater than QSG and CSG	-	-	Improved, BSG had the best effect, and CSG and QSG were dose-dependent	Farahmandfar et al. (2017)
	WP and CN (0.3–0.9%)	Both increased firmness, with CN having a greater effect than WP	Both increased in consistency and CN was better	Increased, dose-dependent, CN better than WP	Both have improved viscosity and CN has better effects	Zhao et al. (2008)
	SPI	Decreased with increasing content	Decreased with increasing content	Decreased with increasing content (slight change)	Decreased with increasing content (significant change)	Sun et al. (2015)
	SPI and 7S and 11S and SPHPe and SPHPa (4%)	All increased firmness, with 7S as best	Except for 11S all were significantly increased, with 7S as best	Except for 11S all were significantly increased, with 7S as best	Except for 11S all were significantly improved, with 7S as best	Fu et al. (2020)
Color		**Lightness (L^* value)**	**Redness (a^* value)**	**Yellowness (b^* value)**		
	WPC (0.7–2.1 wt%)	The L^* value was decreased with increasing concentration	-	The b^* value is increased with increasing concentration		Emam-djome et al. (2008)
	CMC and LBG	CMC increased the L^* value	LBG decreased the a^* value	Both CMC and LBG increased the b^* value		Rezvani et al. (2020)
	Raw and physically modified rice starches	Added starch increased the L^* value and no significant difference was observed for different types starch	No significant changes	Added starch decreased the b^* value and no significant difference was observed for different types starch		Iftikhar and Dutta (2020)
Sensory		**Color**	**Taste**	**Texture**	**Overall acceptance**	
	CMC and LBG	No significant difference	No significant difference	Significantly improved	Significantly improved	Rezvani et al. (2020)
	SPI and λ-carrageenan	No significant difference from reference (full fat cream)	No significant difference from reference	Although improved, it still differs from the reference and can be reduced by adjusting the content or ratio	Improved overall acceptance of low-fat cream to be close to the reference	Ghribi et al. (2021)
	Palm oil	Decreased with increasing content	-	Improved with increasing content	Decreased with increasing content	Shim et al. (2004)
	Span 60	Enhanced gloss, but high levels (0.8%) had the opposite effect	Improved mouthfeel and reduced roughness and greasiness, but high levels had the opposite effect	Significantly improved texture in the range of 0–0.6%	With increasing levels (0–0.6%) overall acceptability increases, but decreases as the level continues to increase	Zhao et al. (2013)

*Where "-" indicates that not detected

The Color Change Improvement

Although the color of food is secondary in sensory characteristics, it still has an essential function in food selection by influencing sweetness perception, pleasure, food preference, and acceptability (Pathare et al., 2013). In whipped cream, as shown in Table 3, the additives used also affect its color (L^*, a^*, and b^* value). For example, Emam-djome et al. (2008) found that the b^* value of whipped cream was significantly increased, but the L^* value decreased significantly, which should be the result of the combined effect of whipping, homogenization, and WPC concentration. The homogenization treatment enhances the light scattering, thereby increasing its L^* value and increasing its brightness, but the addition of WPC will reduce the lightness (the L^* value decreases) of the foam and increase its yellowness (the b^* value decreases). Rezvani et al. (2020) found that CMC and LBG in low-fat cream interacted with CN on color parameters, CMC-CN increased the L^* and b^* values of whipped cream, LBG-CN reduced the a^* value but increased the b^* value, and CMC-LBG reduced the a^* value. The decrease in a^* value may be due to the combination of yellow fat and blue protein in whipped cream, and the particle size and surface properties of whipped cream also change the L^* and b^* values by affecting light scattering (Emam-djome et al., 2008; Nair et al., 2000). Iftikhar and Dutta (2020) observed that whipped cream with rice starch had slightly higher L^* values and lower b^* values compared with commercial cream, but whipped cream containing different types (raw and modified) starches did not differ significantly in L^*, a^*, and b^* values. The change in the color difference in whipped cream after adding starch may be due to starch partially replacing the fat (Gaonkar and McPherson 2016).

The Improvement of Sensory Evaluation

Sensory evaluation is evaluated by trained professionals/untrained consumers, who can most intuitively assess the sensory advantages of food. Color, flavor, texture, and overall acceptability are often used to evaluate the sensory properties of whipped cream. As indicated in Table 3, hydrocolloids, proteins, lipid compounds, and emulsifiers were applied to whipped cream to improve its sensory properties. Hydrocolloids and proteins were applied to whipped cream, not only improved other quality characteristics but also the desired sensory properties appeared. Rezvani et al. (2020) conducted a sensory evaluation of low-fat whipped cream containing protein and hydrocolloids and found no changes in the color and taste of whipped cream at optimal addition levels (0.35% CN, 0.15% CMC, and 0.15% LBG), but their improvement in texture properties was perceptible. SPI and λ-carrageenan were able to compensate for the sensory loss of partial-fat substitute whipped cream, and there was no significant difference between partial-fat substitute and full-fat whipped cream in terms of texture and taste, and the stability was higher at the proportions of SPI, water, and λ-carrageenan of 46.4%, 44.5%, and 9%, respectively (Ghribi et al., 2021). Lipid compounds and emulsifiers also have similar sensory improvement effects as other additives and have been used in several studies. Shim et al. (2004) found that the taste value of compound cream increased with the increase of palm oil added, but had a negative effect on flavor and overall acceptability, but this effect was not significant within 2 weeks of storage, and the negative effect after 2 weeks may be caused by fat oxidation. Zhao et al. (2013) demonstrated that Span 60 significantly improved the sensory score of whipped cream and that whipped cream without Span 60 had a higher coalescence rate and a larger average particle size, resulting in a rough whipped cream taste, poor gloss, and high oil content, and the addition of Span 60 (0.6%) solved these problems and obtained the highest sensory evaluation score.

Enhanced Nutritional Properties of Whipped Cream Based on Additives

With the continuous development of the economy and society, consumer awareness and concern about the relationship between food and health have been increasing, and their requirements for food are gradually increasing, and they expect/demand food that can make them physically and mentally healthy (Domínguez Díaz et al., 2020b). Whipped cream is widely used in the food industry as a dessert or topping, and is popular with a huge number of consumers, including children, teenagers, and even the elderly. However, whipped cream can also present some potential health risks to consumers due to excess fat. In addition, for children or adolescent, it can also become a more "functional" food, which can solve the problem of "malnutrition" that children may experience by enhancing its nutritional or functional properties. In particular, "malnutrition" here refers not only to undernutrition but also to imbalances in nutrient intake. Figure 5 illustrates the nutritional challenges faced by whipped cream and the strategies to address problem, which can improve its nutritional attributes by optimizing composition and enhancing functional properties.

Low-Fat Whipped Cream with Partial Fat Substitute

Rezvani et al. (2020) claim that whipped cream with a fat content of 30–40% has pleasant sensory properties, and the foam formed during whipping aerated also exhibits outstanding stability during storage, making it one of the most popular dairy products. In fact, as shown in Fig. 5, natural whipped cream generally contains more than 40%

fat, so while enjoying delicious whipped cream, also needs to bear the negative effects of intake of too much fat, such as potential obesity, diabetes, and cardiovascular disease (Krystyjan et al., 2015). In this case, the partial substitute of fat in whipped cream is a healthy and resourceful choice, yet it also faces daunting challenges. Fat partially substituted whipped cream needs to meet the requirements of producers and consumers; it needs to have better whipping and physical properties. Also, it should be stable and repeatable whipping in a modern factory environment, and require an economic assessment and lower cost of replacing milk fat, rather than a higher (Smith et al., 2000). Additionally, consumers will also be concerned about its product functionality, sensory properties, and safety, and need a fat part that is better or similar to whipped cream and can ensure food safety to replace whipped cream products.

As shown in Fig. 5, it is possible to optimize the composition of whipped cream by adding hydrocolloids and proteins to partially substitute the fat. Allen et al. (2006) obtained a stable, highly spilled foam by whipping and inflating gradually acidified ACE. Although it is not necessarily a direct substitute for whipped cream, it can be considered a partial substitute for other low-fat and hydrocolloid whipped aerated dairy products. Inspired by this simulation system, more researchers are also turning their attention to the development of healthy whipped cream products. Narchi et al. (2009) found that there was almost no difference in rheological properties and foaming capacity between the mixture of WPI and guar gum and the glucose syrup containing WPI (Fig. 5a), indicating that the WPI-guar gum mixture can be used as a substitute for glucose syrup in foamed foods, thereby reducing sugar and energy intake. Farahmandfar et al. (2017) found that the firmness of low-fat whipped cream with 0.3% CSG was not significantly different from that of high-fat whipped cream. However, both CSG and QSG decreased cohesiveness, and only BSG increased cohesiveness. Therefore, as long as BSG is contained in low-fat whipped cream, its cohesiveness is not significantly different from high-fat whipped cream. This shows that the substitution of some fats can be achieved through the combined effects of different levels and types of hydrocolloids to produce whipped cream products with similar or even the same texture characteristics as high-fat whipped cream.

As illustrated in Fig. 5b, Wang et al. (2013) used micronized cornstarch to partially substitute the fat in whipped cream, and when the fat replacement rate was 15%, low-fat whipped cream had good foaming and stability. Iftikhar and Dutta (2020) investigated the feasibility of rice starch as a fat substitute in whipped cream and found that the partial substitute of fat in whipped cream by modified waxy starch can obtain the closest texture properties to commercial whipped cream. Whipped cream prepared from modified waxy starch has a fat content reduction of more than 62% compared to commercial whipped cream, providing a low glycemic index, low calorie, and low-cost alternative to commercial full-fat cream. Ghorbani-HasanSaraei et al. (2019) found that commercial whipped creams with different fat content (25% and 35%) had different apparent viscosities (25% < 35%) under the same shear conditions, and the addition of RBP could compensate for the viscosity drop due

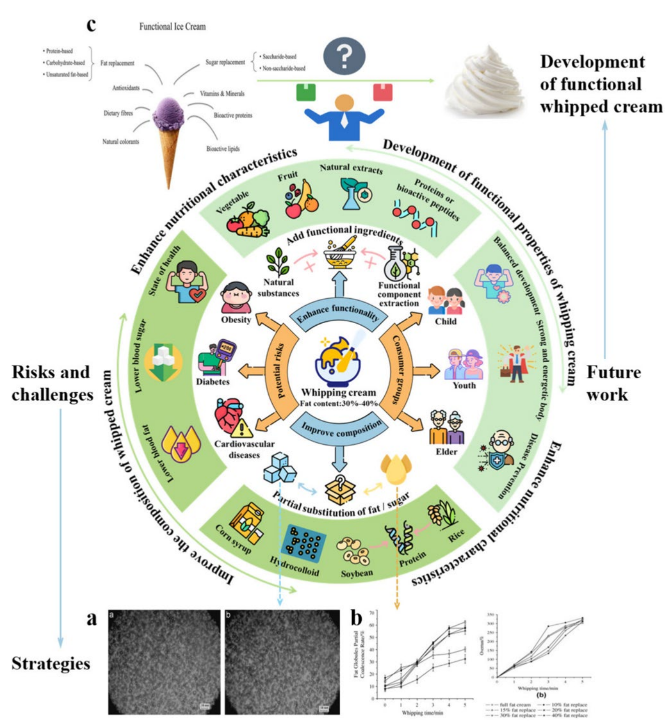

Fig. 5 Challenges and strategies for the nutritional properties of whipped cream. Effect of partial substitution of sugar on bubble distribution in foams (**a**) (Narchi et al., 2009); effect of partially substituted fat on the partial aggregation rate of fat globules and overrun of whipped cream (**b**) (Wang et al., 2013); functional ice cream health benefits (**c**) (Genovese et al., 2022)

to reduced fat content. Based on the compensatory effect of RBP on the reduction of fat content, it can be applied to the production of whipped cream with similar rheological properties but lower fat content, which can not only develop whipped cream with lower costs but also reduce health problems caused by excessive fat intake by consumers. Rezvani et al. (2020) found that CN, LBG, and CMC were added at 0.15%, 0.15%, and 0.35%, respectively, and had the most ideal sensory properties, reducing whipped cream fat to 20%. Sun et al. (2015) also reported that CNF-SPI (1:7) mixtures have the closest texture properties to cream, and can be used to replace 10% of cream, thereby reducing fat and calories. Fu et al. (2020) showed that the significant improvement effect of SPHPe on the whipping properties of RSWC provides a new avenue for the development of high-quality recombinant vegetable cream. Ghribi et al. (2021) replaced the fat in whipped cream with a mixture containing water (44.5%), λ-carrageenan (9%), and SPI (46.4%), reducing the energy value of full-fat whipped cream from 235.88 to 161.63 kcal, providing a lower energy product solution.

The fat in whipped cream has been partially replaced to make it a healthier food and reduce the potential risk of excessive fat intake. However, the negative effect of fat reduction on the quality characteristics of whipped cream (including whipping properties, sensory properties) is not expected, so it is a wise choice to use additives to improve its quality characteristics, which can provide consumers with a product that is not only healthy but also has excellent quality.

Whipped Cream Development with Enhanced Functionality

Consumers' increased awareness of the close relationship between diet and health has led to a greater tendency to choose functional foods because they are designed to improve quality of life by preventing nutrition-related diseases (Domínguez Díaz et al., 2020a, b). There is no single definition of functional food, but it should have healthier properties/functional effects/possible ability to reduce disease. From Fig. 5, it can be seen that in the strategy of developing functional whipped cream, besides the fat substitution, it is also possible to substitute sugars, develop functional proteins, or add proven active ingredients (Hossain et al., 2020; Samakradhamrongthai et al., 2021). However, except for some of the fat substitutions mentioned above in whipped cream, other strategy-related studies have rarely been reported, only occasionally in ice cream products. For example, Mehditabar et al. (2020) developed an ice cream rich in pumpkin puree that significantly increased the total phenolic, fiber, and free radical scavenging activity of the ice cream. Because in addition to being rich in nutrients such as dietary fiber, carotenoids, and minerals, pumpkin has also been shown to play a role in the prevention and treatment of a variety of diseases such as diabetes, cardiovascular disease, intestinal parasites, tumor growth, and cancer (Carvalho et al., 2012; Jacobo-Valenzuela et al., 2011). The development of "functional" ice cream has been the attention of many researchers, and Genovese et al. (2022) have described it in detail in the review (Fig. 5c). Unfortunately, research on whipped cream in the meaning of "functional" is rare; only a few researchers have paid attention to the development of functional whipped cream. Such as Zeng et al. (2022b) used 25–35 wt% corn syrup to replace the sugar in the whipped cream, and the resulting low-sugar whipped cream still has excellent whipping properties and stability, which proves the feasibility of corn syrup or maltodextrin to partially replace the sugar in whipped cream, and provides a new direction for the development of low-sugar whipped cream.

Even though the development of functional whipped cream may still receive little attention, this work is important and meaningful. Developing whipped cream with a certain function can be achieved by adding some food supplements (additives or natural ingredients) with specific functions (Fig. 5). The information or "claims" on the labels of functional foods are important to help or guide consumers in identifying the specific health benefits of these foods (Hieke et al., 2016). Therefore, the management of functional food labels is also strict, and the USA, Japan, and Europe have issued relevant regulatory statements or regulations, which the USA is also considered to be an important part of global functional food regulation (De Boer & Bast, 2015). Health-related food claims approved by the US Code of Federal Regulations include three categories: nutrient content claims, structure/function claims, and health claims. And the health claims are the most relevant to functional foods, which are statements that express the relationship between food ingredients or food supplement ingredients and disease or health-related conditions (Domínguez Díaz et al., 2020b). Further, health claims that are to be recognized by the FDA need to meet the Significant Scientific Agreement (SSA health claims) and FDMA health claims recognized by the US government or the National Academy of Sciences (FDA, 2019). Bagchi (2014) also showed that SSA standards are the most appropriate health claims to appear on food and food supplement labels. As a new product developer, it is crucial to stay on top of the latest regulations and declarations that determine whether the new product being developed can appear on the market. Based on the SSA health claims and FDMA health claims list, Table 4 lists some health claims that may be applied to whipped cream to inform researchers developing functional creams (FDA, 2013, 2022). This information provides some functional natural substances/ingredients that have the potential to be used in whipped cream. They can be used to supplement the nutritional elements required by different consumer groups, so as to prevent/eliminate some diseases caused by malnutrition and

Table 4 List of SSA and FDMA health claims

Component	Disease/health condition	Model claim statement(s)
Calcium, vitamin D	Osteoporosis	Adequate calcium and vitamin D as part of a balanced diet, along with physical activity, may reduce the risk of osteoporosis
Dietary fats	Cancer	A diet low in total fat may reduce the risk of certain cancers
Fibrous cereal products		A low-fat diet rich in fiber-rich grain products, fruits, and vegetables may reduce the risk of certain types of cancer
Fruits and vegetables		A low-fat diet rich in fruits and vegetables (foods that are low in fat and may contain dietary fiber, vitamin A, or vitamin C) may reduce the risk of certain types of cancer
Dietary supplements with selenium		Selenium intake may reduce the risk of specific types of cancer
Dietary supplements containing vitamin E and/or vitamin C		Intake of antioxidant vitamins has the potential to reduce specific types of cancer
Dietary saturated fat and cholesterol	Coronary heart disease	A diet low in saturated fat and cholesterol may reduce the risk of developing this disease
Fruits, vegetables, and grain products that contain fiber, especially soluble fiber		Diets low in saturated fat and cholesterol and rich in fruits, vegetables, and grain products containing certain types of dietary fiber (especially soluble fiber) may reduce the risk of heart disease
Soy protein		A diet low in saturated fat and cholesterol, including 25 g of soy protein per day, may reduce the risk of heart disease
Monounsaturated fatty acids in olive oil		Since olive oil contains monounsaturated fats, consuming about (23 g) of olive oil per day may reduce the risk of coronary heart disease
Unsaturated fatty acids in canola oil		Because of the unsaturated fats in canola oil, consuming approximately (19 g) of canola oil per day has the potential to reduce the risk of coronary heart disease
ω-3 fatty acids		Consumption of EPA and DHA ω-3 fatty acids may reduce the risk of coronary heart disease
Saturated fats, cholesterol, and trans fats	Heart disease	A diet low in saturated fat and cholesterol and as low as possible in trans fats can reduce the risk of heart disease
Replace saturated fats in the diet with unsaturated fatty acids		Replacing saturated fats with a similar amount of unsaturated fats may reduce the risk of heart disease
Corn oil and products containing corn oil		Since corn oil contains unsaturated fats, consuming about 16 g of corn oil per day may reduce the risk of heart disease
Plant sterol/stanol esters		A total intake of at least 1.3 g as part of a diet low in saturated fat and cholesterol may reduce the risk of heart disease
Folic acid	Neural tube defects	A healthy diet with enough folic acid can reduce a woman's risk of having a child with a brain or spinal cord defect
Dietary supplements containing vitamins B6, B12, and/or folic acid	Vascular disease	As part of a balanced diet low in saturated fat and cholesterol, folic acid, vitamin B6, and vitamin B12 may reduce the risk of vascular disease
Dietary supplement containing soybean-derived phosphatidylserine	Cognitive dysfunction and dementia	Intake of phosphatidylserine may reduce the risk of dementia and cognitive dysfunction
Chromium picolinate	Diabetes	Chromium picolinate has the potential to reduce insulin resistance and therefore the risk of both types of diabetes

provide more accurate nutritional supplements. Moreover, besides developing precise nutritional compensation products for groups, there is even possible to develop "exclusive" functional whipped creams based on the health status of each consumer, which may be crazy but exciting.

Challenges and Future Prospects

While whipped cream is getting more and more attention from consumers and its market share is rising, the same challenges are also increasing. Whipped cream contains relatively large amounts of fat, which contributes to the high intake of these nutrients and therefore increases the risk of obesity and cardiovascular disease (Genovese et al., 2022; Rezvani et al., 2020). According to Krystyjan et al. (2015), obesity is increasing, especially among children and adolescents in developed countries, who are unfortunately also lovers of whipped cream. In addition, even though children and adolescents are the main consumers of whipped cream, middle-aged and elderly people also enjoy whipped cream, which increases the risk of cardiovascular disease. Data indicating that the global burden of cardiovascular disease, including the number of disability-adjusted life years and the number of deaths, is steadily increasing. Total cardiovascular disease cases have increased from 271 million in 1990 to 523 million in 2019, and the number of deaths has steadily increased from 12.1 million in 1990 to reach 18.6 million in 2019 (Roth et al., 2020). In this environment, the development of healthy, nutritionally enhanced whipping cream is a new challenge to be faced. From the current research, the partial substitution of fat and sugar in whipped cream are gradually being focused by some researchers, but most of the research still focuses on the whipping process. Additionally, there is still a gap in the development of functional whipped creams, and whipped creams with health enhancements are far superior to just minimizing the negative effects of health. Therefore, the development of low-fat, low-sugar and functional whipped creams is the priority of future work and needs more attention. It should be noted that consumers are always looking for more "natural" foods that do not contain synthetic additives (e.g., dyes, flavors, etc.) (Durmaz et al., 2020). This suggests that even if the nutritional properties of whipped cream are enhanced by additives, the health and naturalness of the additives need to be considered. In summary, the development of enhanced nutritional properties and functional whipped cream are both opportunities and challenges. Firstly, as consumer awareness increases, they tend to choose healthier and safer foods, especially safety, which puts forward higher requirements for additives used in whipped cream. Further, functional food labelling is strictly regulated worldwide and the "functional" whipped cream developed should comply with these regulations or regulatory claims.

Conclusion

Whipped cream has a wide range of consumer groups and broad market prospects, but the development of society has also prompted consumers to choose healthier products with better quality characteristics. This paper systematically summarizes the current application of additives in whipped cream and discusses the improvement effect and mechanism of five types of additives, hydrocolloid, protein, emulsifier, carbohydrate, and lipid compounds, on the quality characteristics (whipping characteristics, rheological properties, electrostatic properties, sensory properties, and nutritional properties). However, compared to other properties, research on the electrostatic and nutritional properties of whipped cream has rarely been reported, providing opportunities for more challenging researchers. In particular, the enhanced nutritional properties of whipped cream are critical based on the consumer's propensity for healthier food choices. Apart from the low-fat and low-sugar whipped creams that are currently of interest to researchers, enhancing the functional properties is an interesting and challenging strategy. In future work, whipped cream products with some functional characteristics may be able to further promote the development of research and market. After all, a whipped cream with the potential to improve consumer health or even eliminate some diseases caused by malnutrition is exciting.

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

Declarations

Competing Interests The authors state that they have no conflict of interest.

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