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Review

A narrative review investigating the potential effect of lubrication as a mitigation strategy for whey protein-associated mouthdrying

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ABSTRACT

Whey is consumed by active adults to aid muscle recovery and growth, the general population as a nutritious convenient food, and by older adults to prevent sarcopenia due to its high leucine content. However, whey protein has poor consumer acceptance in this latter demographic, partially due to mouthdrying. This is thought to result from electrostatic interactions between whey and salivary proteins, mucoadhesion to the oral mucosa, and the inherent astringency of acidity. Previous unsuccessful mitigation strategies include viscosity, sweetness and fat manipulation. This literature review reveals support for increasing lubrication to reduce mouthdrying. However, of the 50 papers reviewed, none have proposed a method by which whey protein could be modified as an ingredient to reduce mouthdrying in whey-fortified products. This review recommends the use of modern technologies to increase lubrication as a novel mitigation strategy to reduce mouthdrying, with the potential to increase consumer acceptance.

1. The need for protein supplementation to combat sarcopenia development

Sufficient protein intake, in combination with exercise, is necessary to increase and maintain a high level of muscle mass and strength. To maximise their muscle gain in response to exercise, an increasing proportion of active younger adults are looking to supplement their protein intake. It was estimated that 66% of American college students regularly take dietary supplements, 16% of which consume protein supplements at least once per week (Lieberman et al., 2015). The most common reasons given for this were to improve general health, to increase energy levels, to increase muscle strength and to enhance performance. Increased supplement consumption may also reflect an increasingly busy lifestyle with reduced time spent cooking and preparing meals, meaning the ability to consume protein on the go is an appealing option to many adults. Protein supplements are also consumed by middle aged adults to maintain muscle mass and delay the typical changes seen during ageing.

Ageing is associated with numerous changes to the musculoskeletal system including a loss of skeletal muscle mass (Mitchell et al., 2012), impacting strength and physical function of older adults. This term commonly refers to adults over the age of 65, a classification which will be continued in this review. Clinically these age-associated changes are classified as sarcopenia: sarcopenia significantly affects quality of life (Beaudart et al., 2018) and is associated with an increased risk of falls (Lim & Kong, 2022), frailty (Woo, Leung, & Morley, 2015), morbidity and mortality (Sobestiansky, Michaelsson, & Cederholm, 2019). Whilst some age-associated changes are typical, sarcopenia is partially preventable through adequate nutrition in combination with exercise. Epidemiological evidence supports a positive correlation between protein intake and muscle mass for older adults (Nunes et al., 2022, Hanach, McCullough, & Avery, 2019, Geirsdottir, Arnarson, Ramel, Jonsson, & Thorsdottir, 2013) suggesting that elevated protein consumption may be beneficial in combatting sarcopenia; however, Hanach et al. (2019) recognised the need for more high quality research in this area. Increased protein intake in middle aged adults also has the potential to delay these age-associated changes; this highlights the importance of adequate protein intake in all demographics. Specifically for older

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adults, protein requirements are thought to increase despite reductions in physical activity (Suryadinata, Wirjatmadi, Adriani, & Lorensia, 2020) and a decrease in resting metabolic rate (Fukagawa, Bandini, & Young, 1990), due to anabolic resistance to postprandial muscle protein synthesis and increased inflammation, driving skeletal muscle catabolism (Aragon, Tipton, & Schoenfeld, 2023). This is compounded by decreased muscle perfusion, reduced insulin sensitivity and increased incidence of illness and bed rest, all of which promote muscle atrophy. Based on this, the European Society for Clinical Nutrition and Metabolism recommend 1.0–1.2 g/kg/day of protein for older adults (Deutz et al., 2014). However, the proportion meeting this target is sub-optimal: it was estimated that 29.2% of older adults currently meet the higher recommendation of 1.2 g/kg/day (Hengeveld et al., 2020). In addition, 21.5% of community-dwelling older adults are thought to consume less than 0.8 g/kg/day of protein (Hengeveld et al., 2020). Older adults are at an increased risk of malnutrition, highlighting the need for protein supplementation to prevent the development of chronic conditions including sarcopenia. Whilst supplementation may not be appropriate for older adults with chronic kidney disease, where high protein diets are known to negatively impact renal function, for healthy older adults' supplementation can have many clinical benefits. Supplementation in younger adults is only promoted for active muscle gain and to aid muscle recovery after strenuous exercise.

Numerous studies have demonstrated the benefits of whey protein supplementation for older adults, summarised in Table 1. A systematic review reported that oral nutritional supplement (ONS) consumption was linked to significant reductions in surgical complications, including wound healing, pressure ulcers and infection rates (Cawood, Stratton, & Elia, 2011). Hospital readmission rates were reduced by 30% with ONS supplementation which may be reflective of the increased strength and improvements in daily physical function seen in this group (Cawood et al., 2011). Protein fortification has been shown to successfully increase protein intake in older adults (Beelen, de Roos, & de Groot, 2017, Morilla-Herrera et al., 2016). No studies have been able to correlate fortification with improvements in physical function but, as highlighted by Morilla-Herrera et al. (2016), the studies are of poor quality and have too small sample sizes for reliable conclusions to be drawn. Whilst more robust research is needed to conclude the effects of protein fortification, the positive results seen with ONS consumption and whey protein supplementation suggests that methods to increase protein intake in older adults is an important avenue for future research. When considering that the United Kingdom has an ageing population, it is anticipated that sarcopenia and frailty will increase in prevalence, highlighting the need for research into this area.

Table 1
The effect of whey protein supplementation in older adults. 8 articles selected based on relevance from Scopus search for whey protein AND supplementation AND older adults.

Study	Type of study	Effects
(Colonetti et al., 2023)	Double-blind randomised trial	Whey protein and vitamin D supplementation combined with resistance training significantly improved lean and total mass in institutionalised older adults.
(Hernández-Lepe, Miranda-Gil, Valbuena-Gregorio, & Olivas-Aguirre, 2023)	Systematic review	Synergistic effect of whey protein supplementation with resistance exercise improves skeletal muscle mass, total lean mass, strength, speed, stability and quality of life in sarcopenic older adults.
(Kamińska et al., 2023)	Meta-analysis	Whey protein supplementation combined with exercise improved muscle mass and lower limb function in older adults with sarcopenia, but caused no change in healthy older adults.
(Nasimi et al., 2023)	Meta-analysis	Whey protein supplementation significantly improved physical function, gait speed and lean mass of frail older adults. No effect seen in healthy older adults.
(Prokopidis et al., 2023)	Meta-analysis	Whey protein supplementation significantly reduced circulating IL-6 levels in individuals with sarcopenia and pre-frailty.
(Spoelder et al., 2023)	Randomised controlled trial	Whey protein led to attenuation of exercise induced-muscle damage 24 h post-exercise. No differences in muscle strength, soreness or skeletal muscle mass were observed.
(Kuo, Chang, Huang, & Liu, 2022)	Meta-analysis	With resistance training, whey protein supplementation had a significant effect on bicep curl strength and lower limb lean mass of post-menopausal women. No significant effects seen with supplementation alone.
(Kang et al., 2019)	Randomised controlled trial	Whey protein supplementation with exercise led to significant improvements in handgrip, gait speed and chair-stand time compared to improvements from resistance exercise alone.

2. Whey protein as a protein source for supplementation

Whey protein is often used as the protein source for supplements and fortified foods due to its high proportion of branched chain amino acids, particularly leucine (Etzel, 2004)). Consumption of foods high in leucine leads to increased protein synthesis; in older adults (n = 14, mean age = 72) blood concentration of essential amino acids and leucine was significantly higher after whey protein consumption compared with casein consumption (Burd et al., 2012). This pattern was echoed in a larger older adult study (n = 48, mean age = 74) where whey protein stimulated postprandial muscle protein synthesis more effectively than casein (Pennings et al., 2011). Protein bioavailability is a key requirement to achieve the clinical benefits of supplementation, so supports the use of whey protein in these avenues. In addition to high leucine levels, whey protein behaves advantageously in the digestive system: whey protein forms more soluble aggregates during the gastric phase, leading to faster gastric emptying, intestinal hydrolysis and leucine absorption compared with casein (Mulet-Cabero et al., 2020).

Despite its positive bioavailability, whey protein is associated with negative characteristics which limit consumer acceptance. Fortification with whey protein is linked to undesirable taste attributes, off-notes in aroma and negative mouthfeel properties, summarised in Table 2. One is these attributes is mouthdrying. In the literature this term is sometimes used interchangeably with astringency: a puckering sensation caused by the binding of polyphenols, such as tannins, to salivary proteins. However, due to the absence of tannins in whey protein, this paper will use the term mouthdrying to refer to a drying sensation in the mouth experienced during or after consumption. The sensory profile of whey proteins includes the taste and flavour attributes sweet, musty, cooked, milky, doughy, fatty, cabbage, brothy, cardboard, wet dog, pasta water, soapy, feacal, bitter and catty (Norton, Lignou, Bull, Gosney, & Methven, 2020). Mouthfeel attributes associated with whey protein include grainy, astringent, chalky, thick, mouthdrying and mouthcoating (Norton et al., 2020, Bull et al., 2017). Several negative attributes were highlighted by Norton et al. (2020) in their comparisons of fortified and unfortified cupcakes: fortification led to significantly increased mouthdrying, hardness and perception of "off" flavours and odours, such as rancid, sulphurous or eggy, whilst significantly reducing the melting rate, moistness and liking (Norton et al., 2020). These negative attributes are of clinical consequence as low consumer acceptability reduces compliance and consumption. Providing un-utilised supplements compounds the socioeconomic burden of sarcopenia. A cost-analysis showed that ONS, when used correctly, are cost effective due to subsequent

Table 2
Summary of the sensory profile associated with whey protein for taste and mouthfeel attributes.

Study	Comparison	Taste attributes associated with whey protein	Mouthfeel attributes associated with whey protein
(Bull et al., 2017)	Whey protein concentrate beverages heated for different durations	Biscuit, cooked milk, sweet, cooked butter, sour	Body, chalky, drying, furring, mouthcoating
(Childs & Drake, 2010)	Whey protein isolate of various strengths and different citric acid levels	Cardboard, cabbage, fruity, sweet, sour	Astringent
(Norton et al., 2020)	Whey protein concentrate fortified scone and unfortified scone	Rancid, off-flavours, sulphate off-note, fatty, eggy, bitter, metallic	Firmness, chewy, crumbliness, mouthdrying, salivating
(Norton, Lignou, & Methven, 2021b)	Whey protein concentrate beverage and whey protein permeate beverage	Sour, sweet, vanilla	Body, chalky, mouthdrying, easiness to swallow, easiness to drink

reductions in healthcare costs and hospitalisation rates (Elia, Parsons, Cawood, Smith, & Stratton, 2018). However, this does not stand true when compliance rates are considered: Hubbard *et al.* (2012) reported a mean compliance of 78% for ONS, a figure which fell to 67% in a hospital setting. Jobse, Bartram, Delantonio, Uter, Stehle, Sieber, and Inken Volkert (2015) reported that only 35.7% of nursing home residents consumed more than 80% of a given ONS during an intervention trial, and a further 28.6% consumed less than 30% (Jobse, 2015), highlighting issues with compliance within this demographic. Consumer acceptance is important for fortification to equate to real-world benefits.

3. Aims and scope of literature review

Whey protein consumption is advantageous to older adults in the prevention of sarcopenia and for younger adults in maximising muscle mass. Addressing the sensory issues associated with whey protein is of public health importance to increase protein consumption in older adults and subsequently increase muscle strength. No recent review has comprehensively investigated the potential mechanisms causing whey protein derived mouthdrying, nor combined it with research into potential mitigation strategies. This review assesses current proposed mechanisms of mouthdrying in whey protein, typically examined in isolation but considered here simultaneously. The review subsequently compares outcomes of mitigation strategies in current literature; novel mitigation strategies are proposed based on these findings.

The key research questions that this narrative review aimed to address were: what causes whey protein-associated mouthdrying? What methods have been tested previously to address this and how successful have they been? Can lubrication be used to mitigate whey protein-derived mouthdrying? Using these research questions and their key words (below), the authors interrogated WebofScience for relevant peer-reviewed journal articles. Articles were screened for relevance based on their abstract and then categorised based on the research questions. Search terms were varied to maximise the number of relevant articles found; for example, search terms used for the first theme included "whey (protein) + mouthdrying", "whey (protein) + astringency", "whey (protein) + sensory", "whey (protein) + drying", "whey (protein) + thirst". Articles were also identified in an investigative way by following relevant references in articles found with the search terms. To maximise the number of articles found, "ONS" was also used in place of "whey" and then abstracts were screened to ensure the ONS used contained whey protein. Using these techniques, 50 papers were found to be of relevance and included in the narrative review.

4. Mechanisms of whey protein-derived mouthdrying and potential mitigation methods

4.1. Proposed mechanisms of mouthdrying with whey protein

Astringency is defined as a complex sensation involving the perceived roughness of oral surfaces with the perception of tightening, drawing in, or puckering of the oral mucosa and muscles around the mouth as a result of exposure to alums or tannins (Lawless, Horne, & Giasi, 1996). This is well-defined for beverages with a high tannin content such as wine and tea. However, whey proteins exhibit a sensation similar to astringency termed "mouthdrying". Whey proteins do not contain alums or tannins, meaning the mechanism responsible for this sensation is likely to be different. There are three main theories for whey protein-associated mouthdrying (Table 3): acid astringency (acidity alone and changes caused by low pH levels), electrostatic interactions between whey proteins and salivary proteins, and the binding of whey proteins to the oral mucosa. Each of these theories have their own limitations and there is considerable overlap between them. These have been considered in isolation in Table 3, reflective of current literature trends, but it is likely that mouthdrying is a result of multiple theories working simultaneously, as highlighted in Fig. 1. With respect to tannin-based astringency, Bajec and Pickering (2008) speculated that both taste and tactile mechanisms may combine to produce the sensation of astringency (Bajec & Pickering, 2008), supporting the hypothesis of multiple theories causing mouthdrying.

The acidity theory suggests that the inherent astringency of acidity is responsible for mouthdrying rather than a contribution from whey proteins. Decreasing the pH of whey protein beverages leads to increased mouthdrying (Beecher, Drake, Luck, & Foegeding, 2008, Withers, Cook, Methven, Gosney, & Khutoryanskiy, 2013). However, mouthdrying can also result from neutral whey protein beverages (Vardhanabhuti, Kelly, Luck, Drake, & Foegeding, 2010), which is unexplained by this theory. In addition, lowering the pH of solutions whilst maintaining acid concentration increases astringency (Sowalsky & Noble, 1998), suggesting that whey protein does contribute to this sensory perception. An alternative explanation for the increase in mouthdrying seen in acidic beverages, may be an increase in mucoadhesion or electrostatic attractions in this reduced pH environment.

The electrostatic attraction theory attributes mouthdrying to electrostatic attractions between negatively charged whey proteins and positively charged salivary proteins (Beecher et al., 2008). This net electrostatic attraction leads to aggregation between whey and salivary proteins, creating oral friction and reducing lubrication. Supporting this theory are studies manipulating the charge on whey proteins by varying the pH: at a pH of 7.0 isolated lactoferrin is more astringent than whey protein isolate (WPI), which contains a range of protein fractions including lactoferrin. This could be because lactoferrin remains positively charged so can interact with negatively charged salivary proteins, but overall WPI is negatively charged at this pH so it cannot (Vardhanabhuti et al., 2010). Ye, Streicher, and Singh (2011) demonstrated that there was no complexation between whey proteins and human saliva at pH 5.0 as both are negatively charged, but that complexation increased in acidic conditions. This provides a potential explanation for the mouthdrying seen in acidic beverages where whey proteins would be more highly charged, increasing their propensity to interact with salivary proteins. However, evidence against the electrostatic attraction theory can be seen at very low pH levels where the charge on saliva is negligible but there is still a further increase in turbidity and particle size when decreasing pH from 2.5 to 2.0 (Ye et al., 2011).

It is possible that whey proteins do not only bind with salivary proteins but also with the oral mucosa. The mucoadhesion theory hypothesises that the binding of whey proteins to the oral mucosa

Table 3
Proposed theories for whey protein isolate (WPI)-associated mouthdrying and evidence for or against them.

Theory	Specific theory	Summary	Evidence supporting this theory	Evidence contradicting this theory
Acidity	**Acid**	Inherent astringency of acidity from ionic interactions with salivary proteins is responsible for mouthdrying in acidic whey-fortified beverage[a]	• Acids cause astringency. pH levels negatively correlated with astringency and mouthdrying [b] • Acidic whey protein beverages are astringent [c, d] • Decreasing pH of whey protein increases mouthdrying [e] • Addition of whey protein to acidic solution does not increase astringency [a]	• Lowering pH of solutions whilst maintaining acid concentration increases astringency [f] • Diluted phosphoric acid (pH 3.4) was less astringent than WPI solutions at the same pH [a] • Astringency with whey proteins seen at neutral pH [g] • Whey protein concentrate with different heating times had similar pH yet differ in mouthdrying [i-h]
	Isoelectric	Saliva (pH 7.0) mixed with acidic whey protein creates intermediate solution (pH 5.0), matching the isoelectric point of whey protein [d]	• Maximum turbidity of whey protein seen at pH 4.6-5.2, near the isoelectric point of whey proteins [i] • Whey protein aggregates create oral friction in the mouth, decreasing lubrication	• Astringency with whey proteins seen at a neutral pH [g]
	Sulphur bonding	Acidic beverages lead to exposure of sulphur bonding groups. Highly sulphated whey proteins form covalent disulphide bonds with salivary proteins leading to increased particle size, turbidity and mouthdrying	• Acidification increases concentration of dimethyl disulphide leading to increased sulphur bonding [j] • Heating exposes hydrophobic and thiol groups and increased mucoadhesion (linked to increased mouthdrying) [k]	• Mouthdrying found from whey proteins with low sulphate groups • Astringency with whey proteins seen at neutral pH [g]
Muco-adhesion	**Wetting**	Whey protein swells when in contact with wet mucosal surfaces. Materials with higher affinity to spread results in stronger adhesion to the oral mucosa.	• Mucin has higher adhesive potential for binding, so mucins in saliva likely to react with dry powdered whey [l] • WPI forms impermeable layer between powder and water [m]. Increases time powder remains on surface and prolongs rehydration.	• WPI exhibits poor wettability and has low water penetration rate [n]. WPI will be slow to interact with water present in saliva so unlikely to be primary cause for mouthdrying • Does not account for increased mouthdrying with heating or acidity
	Dehydration	The movement of water from saliva or oral mucosa to whey protein reaches an equilibrium and forms an adhesive joint.	• Polyacrylic acid and mucin shown by spectroscopy to interact through chain interpenetration and form adhesive interface [o] • WPI components known to interact with oral mucosal cells [e] so capable of forming adhesive joint	• WPI has low rate of water penetration [n] so will be slow to form adhesive joint with saliva • Does not account for the increased mouthdrying with acid or heating
	Mechanical	Binding of whey proteins to oral mucosa directly decreases lubrication in the mouth and increases oral friction.	• B-lactoglobulin and lactoferrin bind to human oral mucosal cells [e, p] • Heating increases mucoadhesion and exposes hydrophobic and thiol groups [k] • At low pH proteins present on oral epithelial cell membranes undergo conformational changes, exposing more binding sites [p] • Increased saliva flow seen after whey protein consumption	• Gel electrophoresis studies identified interactions between whey and salivary proteins [g] which are not accounted for
Electrostatic attraction	**Electrostatic attraction**	Mouthdrying is a result of interactions between positively charged whey proteins and negatively charged salivary proteins [c]. Causes net electrostatic attraction leading to aggregation.	• Lactoferrin more astringent than WPI at pH 7.0 as remains positively charged, and interacts with negative salivary proteins (WPI is negatively charged at pH 7.0 so does not interact) [g] • Astringency and turbidity most intense at pH 3.4 [q], which correlates to highest charge • Whey protein more drying than buffer solutions at same pH [g] • No complexation found between whey and human saliva at pH 5.0 as both negatively charged. Lower pH levels increase particle size representing complexation [q] • Binding of b-LG increases with reduced pH reflecting increased charge interactions [p] • Whey protein-mucin interactions increase at pH 3.5 compared to pH 1.2, due to a difference in charge [r]	• Whey protein concentrate with different heating times had similar z-potentials so cannot explain changes to mouthdrying with heating [h] • Turbidity and particle size increased from pH 2.5 to pH 2.0. This is not explained as saliva has low charge at this pH (zeta potential near zero) [q] • Whey proteins astringent at low pH when charge is negligible (leading to decreased interactions between whey and saliva) [q] • Astringency increased from pH 2.4 to 2.0 which cannot be explained by charge [q]

[a] (Lee & Vickers, 2008); [b] (Lawless et al., 1996); [c] (Beecher et al., 2008); [d] (Sano, Egashira, Kinekawa, & Kitabatake, 2005); [e] (Withers et al., 2013); [f] (Sowalsky & Noble, 1998); [g] (Vardhanabhuti et al., 2010); [h] (Bull et al., 2017); [i] (Liu, Shim, Shen, Wang, & Reaney, 2017); [j] (White et al., 2013); [k] (Bull et al., 2022); [l] (Alhalaweh, Vilinska, Gavini, Rassu, & Velaga, 2011); [m] (Ji, Fitzpatrick, Cronin, Crean, & Miao, 2016); [n] (Ji et al., 2017); [o] (Jabbari, Wisniewski, & Peppas, 1993); [p] (Aiqian et al., 2012); [q] (Ye et al., 2011); [r] (Hsein, Garrait, Beyssac, & Hoffart, 2015).

directly decreases lubrication in the mouth and increases oral friction leading to mouthdrying. Supporting this is the observation that beta-lactoglobulin and lactoferrin, components of whey protein, bind to human oral mucosal cells (Withers et al., 2013). This theory may explain the mouthdrying in acidic beverages, as at low pH levels oral epithelial cell membranes undergo conformational changes, exposing additional binding sites (Aiqian, Tao, Ye, & Harjinder, 2012). However, gel electrophoresis studies have identified interactions between whey protein and salivary proteins (Vardhanabhuti et al., 2010) which are not accounted for in the mucoadhesion theory. This suggests that the oral

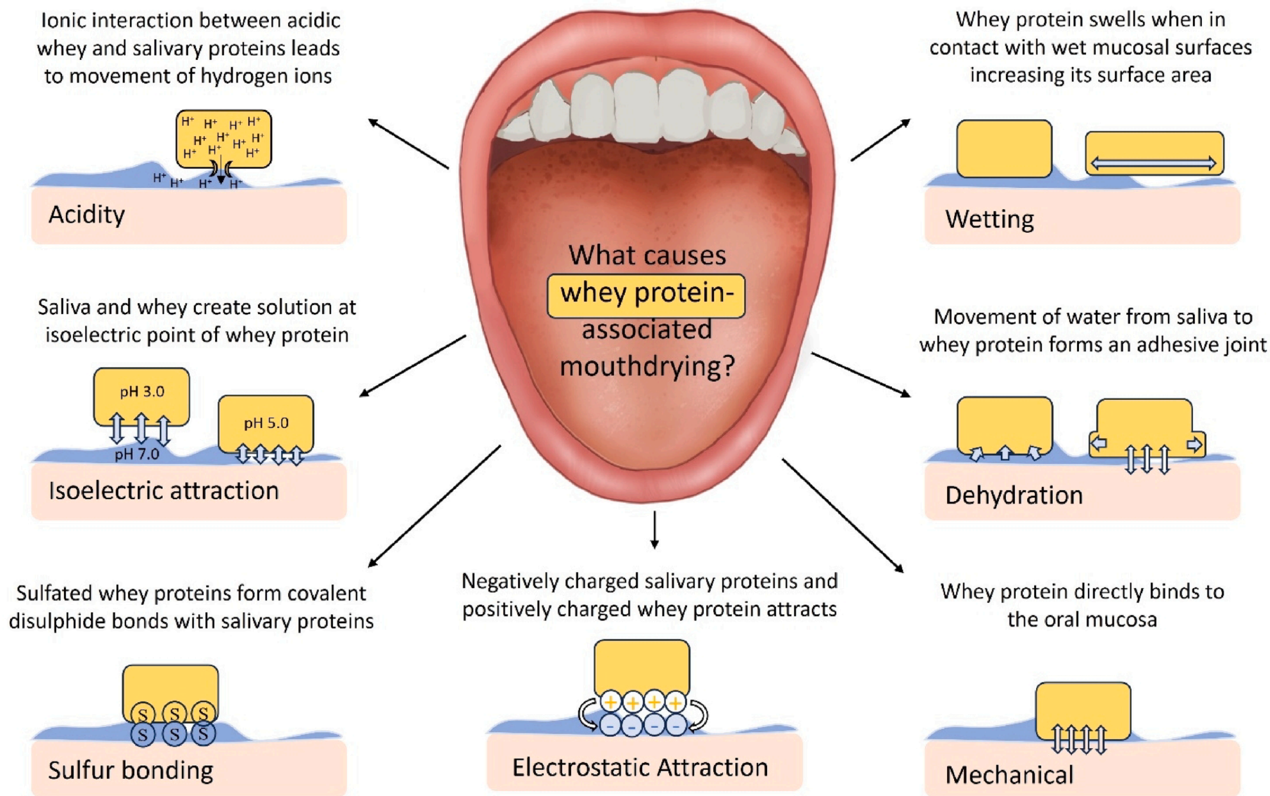

Fig. 1. Diagram summarising proposed mechanisms of whey protein-associated mouthdrying: acidity, isoelectric attraction, sulfur bonding, electrostatic attraction, mechanical adhesion, dehydration and wetting. (Theories discussed and referenced in section 4.1)(()).
Adapted from Cook, Bull, Methven, Parker, & Khutoryanskiy, 2017

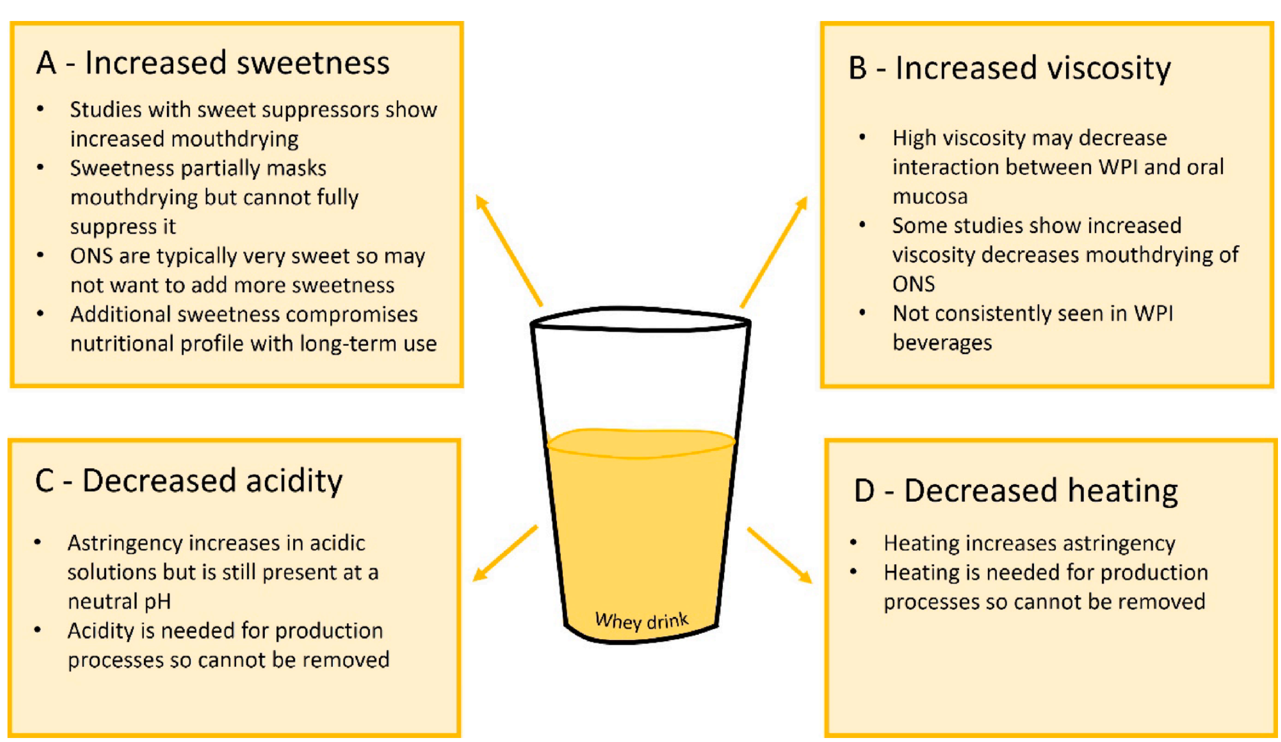

Fig. 2. Previous mitigation attempts to reduce whey protein associated mouthdrying. A - (Tan et al., 2020),(Courregelongue et al., 1999), (Norton et al., 2021a). B - (Withers et al., 2014), (Beecher et al., 2008). C - (Beecher et al., 2008), (Vardhanabhuti et al., 2010). D - (Bull et al., 2017).

mucosa is not the only target for whey protein as/ sincewhey proteins are known to form covalent disulphide bonds and hydrophobic interactions with salivary proteins irrespective of electrostatic charge (White, Fox, Jervis, & Drake, 2013, Bull, Khutoryanskiy, Parker, Faka, & Methven, 2022). These changes reflect the increased mouthdrying seen with heating when the conformational structure of whey protein is altered (Bull et al., 2017), exposing these groups and increasing the number of interactions possible.

Much of the literature has focused on these theories in isolation, but as discussed above and in Table 3, the evidence suggests that whey protein associated mouthdrying acts through numerous simultaneous mechanisms. Many factors influence protein interactions including temperature, pH, ionic strength, the presence of additional reagents, hydrophobicity, surface features, conformational structure, isoelectric point and flexibility (Zhang, Cheng, Wang, & Fu, 2021). Increased understanding of this complex mechanism would facilitate the design of better mitigation methods. At present, with limited understanding of the mechanism, a product's acidity, electrostatic charge and ability to bind to the oral mucosa must all be considered for a successful mouthdrying mitigation attempt.

4.2. Previous mitigation strategies have not been sufficient to prevent mouthdrying

Previous studies, summarised in Fig. 2, have attempted to mitigate whey protein-associated mouthdrying with limited success. Considering that one of the main theories for the mechanism of mouthdrying is acidity it is expected that a mitigation strategy could be to increase the pH. However, astringency is still reported at neutral pH levels (Vardhanabhuti et al., 2010), meaning that this alone is insufficient to mitigate mouthdrying. This can be explained by the dual mechanism theory (where multiple mechanisms simultaneously contribute to mouthdrying) as decreasing acidity is able to stop one pathway of mouthdrying but is insufficient to prevent the sensation overall. In addition, low pH levels are required to create heat-stable whey products and to provide the clear appearance in beverages desired by consumers. Therefore, increasing the pH is not always feasible. Similarly, heating of whey proteins increases mouthdrying by changing the conformation of the protein and increasing binding groups (Bull et al., 2017). Whilst reduced heat processing may improve mouthdrying, some heat treatment is necessary in the manufacturing process to give products a long shelf-life; therefore, this mitigation strategy cannot be used for commercial whey protein products.

It is possible to manipulate other sensory attributes of whey protein to reduce mouthdrying. Previous research using the sweet suppressor lactisole demonstrated a significant increase in mouthdrying when sweetness was suppressed (Methven et al., 2010). The authors suggested that the sweeter sample was perceived as less mouthdrying due to the sweet taste interacting with the perception of drying. Tan, Wee, Tomic, and Forde (2020) supported this with a significant reduction in astringency in a yoghurt sweetened with sucrose (Tan et al., 2020). Courregelongue, Schlich, and Noble (1999) also reported that sucrose and vanilla decreased mouthdrying in whey protein beverages (Courregelongue et al., 1999). The mechanism for this beneficial effect is not known; sweetened whey protein will still demonstrate mucoadhesion, meaning the reduction in mouthdrying is a result of a cross-modal cognitive effect rather than a physical change. It is suggestive of a masking effect which could ameliorate mouthdrying. This was investigated by Norton, Lignou, Faka, Rodriguez-Garcia, and Methven (2021) in their manipulation of lactose levels: increased lactose led to reduced perception of sourness, WPI taste, powdery, mouthdrying and metallic notes. However, the addition of lactose increased sweetness, cooked milk, aftertaste strength and sweet aftertaste. Whilst this seems positive, it is worth noting that the effect on mouthdrying was small and only became significant with 9.4% lactose where high sweetness intensity was also reported (Norton et al., 2021a). A high level of lactose is not desirable in nutritional applications where a low sugar content is a requirement. It is possible that this sweetness would negatively impact consumer acceptance: 38% of older adults reported disliking the sweetness of ONS (Gosney, 2003), suggesting that the addition of further sweeteners may not be appropriate. Commercial products fortified with whey protein are already very sweet meaning there is no room to increase their sweetness; mouthdrying persists despite high sweetness, necessitating other mitigation strategies to completely remove mouthdrying sensations.

Viscosity has also been manipulated in an attempt to ameliorate mouthdrying. Withers, Lewis, Gosney, and Methven (2014) suggested that high viscosity could mask mouthdrying by reducing the ability of drying proteins to interact with the oral mucosa. When manipulating the viscosity of a protein-enriched milk with a starch thickener, the enhanced-viscosity sample scored significantly lower for mouthdrying over repeated consumption (Withers et al., 2014). This difference became more enhanced in later sips. However, this trend was not conserved for an ONS beverage, when no significant differences in mouthdrying were recorded. Specifically for whey protein, Beecher et al. (2008) reported no changes in astringency despite a near 5-fold increase in viscosity (Beecher et al., 2008). This suggests that viscosity manipulation is not a sufficient mitigation strategy in isolation and supports the need for novel mitigation methods.

4.3. Justification for lubrication as a mitigation strategy to ameliorate mouthdrying

Previous methods have focused on a singular cause of mouthdrying. However, as discussed, mouthdrying is likely to be the result of multiple mechanisms working simultaneously. Therefore, manipulating one of these causes is insufficient. Focusing on a common component to each mechanism may enable mouthdrying to be effectively reduced: one mitigation strategy is to increase lubrication. Rosenthal and Yilmaz (2015) hypothesised that foods that are hard to swallow remove moisture from saliva to form a hydrated and lubricated bolus that can be swallowed; this suggests that additional lubrication could eliminate this hard-to-swallow phenomenon from occurring (Rosenthal & Yilmaz, 2015). Increasing lubrication has the potential to decrease oral friction, to decrease interaction between whey proteins, oral mucosa and salivary proteins, and to decrease protein aggregation, all of which are associated with mouthdrying. The targeting of multiple mouthdrying pathways makes lubrication a promising option and justifies further research into this mitigation strategy.

5. Lubrication as a potential mitigation method for mouthdrying

Previous work investigated the potential of additional lubrication to reduce whey protein-associated mouthdrying. Proof of concept was provided by Norton et al. (2021) where the addition of a clotted cream topping led to reduced mouthdrying and an increased rate of oral clearance of a fortified scone fortified (Norton et al., 2021a). This highlights the potential of increased lubrication to reduce mouthdrying by limiting oral friction. However, the addition of a cream topping does not consider the health implications, the additional expense, nor impracticalities of manufacturing and administrating this on a large scale. Previous work in healthcare settings has shown that the ease of administration is a determining factor in the amount of ONS that patients receive (Lester et al., 2022), so must be considered in product design. This study provides the rationale for increasing lubrication as a mitigation strategy but highlights the need for further research to achieve this in a more subtle way.

The literature addressing additional lubrication of whey protein can be divided into two possible theories: lubricating the mouth prior to whey protein consumption, as seen with the administration of hydrogels; and directly lubricating the whey protein, via manipulation of the ingredient itself. Both have been investigated in this review to comprehensively summarise the work completed in this field.

5.1. Polysaccharides as lubricants for whey protein

Polysaccharides are commonly used to modulate the texture of products, acting as thickeners, emulsifiers and stabilisers (Cook, Woods, Methven, Parker, & Khutoryanskiy, 2018). In these roles polysaccharides increase the viscosity of liquid and semi-solid food products. However, various polysaccharides respond to given environments differently enabling a large range of functions. An example of this is their propensity to adhere to the oral mucosa, giving them the classification of mucoadhesive or non-mucoadhesive. This is dependent on polymer structure, molecular weight, environment and form of administration. As some polysaccharides are expected to be substantially more mucoadhesive than whey protein, it has been hypothesised that such polysaccharides may decrease mouthdrying by competitively binding to the oral mucosa, decreasing the adhesion of whey protein. A contrasting hypothesis is that if polysaccharides can bind to whey proteins this may reduce their ability to interact with the oral mucosa and salivary proteins, and hence reduce mouthdrying. It is also possible that a lubricating polysaccharide may mitigate the sensation of mouthdrying by increasing the rate of oral clearance, reducing the time available for whey protein to interact with proteins in the oral cavity. These proposed theories are summarised in Fig. 3.

5.1.1. Gums (mucoadhesive polysaccharides)

Arguably, gums such as xanthan gum (XG) and guar gum (GG), are the most commonly utilised polysaccharide to modulate the viscosity of food products. XG is an anionic polysaccharide formed of repeat units of glucose, mannose and glucuronic acid; it is capable of forming a gel through interactions with other polysaccharides or cross-linkages in the presence of metallic ions. This increases the thickness of whey protein beverages, shown by an increase in instrumental viscosity upon addition of XG (Song et al., 2020).

The use of gum-whey protein complexes to mitigate negative sensory attributes was studied by Ji, Otter, Cornacchia, Sala, and Scholten (2023) who investigated the use of XG, GG and carboxymethyl cellulose gum in combination with whey protein and an oil emulsion. This mixed model system was created by the continuous stirring of oil dissolved into a 0.8% whey protein solution, a 7.5% WPI solution and the addition of the relevant gum. The study reported that the addition of GG decreased the friction coefficient of a whey protein aggregate (WPA) solution, compared with WPA alone. This was seen over the entire measured speed range but was largest at speeds in excess of 30 mm/s (Ji et al., 2023). Contrastingly, the addition of XG increased the friction of WPA, leading the authors to conclude that GG was more efficient at promoting lubrication. The authors' offered a potential explanation for the results: XG and GG have contrasting confirmations which may subsequently effect entrainment. GG is more flexible so is less easily entrained in the gap between the rheological plates than XG, with its rigid rod conformation. This trend was mirrored in a sensory panel where mixtures with lower friction coefficients were associated with more creamy, thick and fatty sensations (Ji et al., 2023). When comparing the addition of different gums, the sensory panel reported a negative correlation

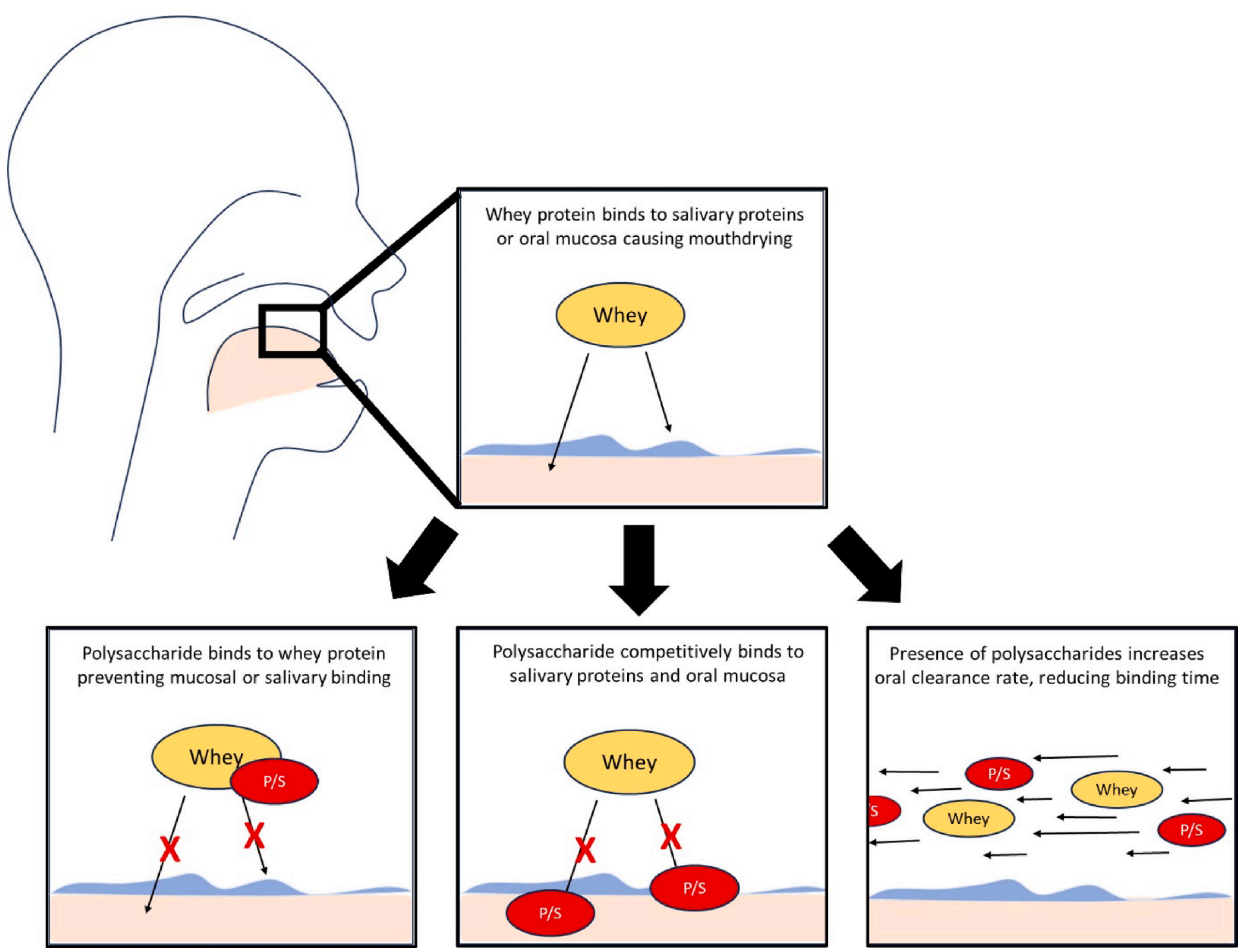

Fig. 3. Potential mechanisms for the addition of polysaccharides (P/S, red) to increase oral lubrication of whey protein (yellow) as a method to reduce whey protein-associated mouthdrying. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between friction coefficients and mouthcoating attributes: XG was reported as less mouthcoating and less drying than GG. These scores are not absolute as the panel only scored mixed solutions (containing oil and gum). The authors hypothesised that the increase in mouthcoating seen with GG was due to beverages remaining on the oral surface for longer due to their increased thickness, forming a coating layer. The varying results seen with GG and XG supports further research into polysaccharides for this purpose. Other gums have also been investigated for this purpose including basil seed gum, which has been shown to interact with whey protein and influence rheological parameters (Behrouzain, Razavi, & Joyner, 2020). Berg, Vliet, Linden, Boekel, and Velde (2007) reported altered sensory attributes for firmness, spreadable, melting, watery and separating factors for different polysaccharide-WPI gels (Berg et al., 2007). This study did not quantify mouthdrying but showed that the number of particles was positively correlated with spreadable mouthfeel (Berg, Vliet, Linden, Boekel, & Velde, 2008).

An alternative approach is the use of polysaccharide gums to lubricate the mouth prior to whey protein consumption. Stribitcaia et al. (2021) administered a hydrogel of carrageenan gum as a preload to increase oral lubrication. Hydrogels are water-insoluble cross-linked networks of polymer chains and water which can be used to lubricate the mouth and increase hydration levels. The study compared the effect of consumption of high and low lubricating hydrogels before administration of a whey protein beverage. Hydrogels with varying properties were created by altering the composition: the highly lubricating gel contained a mixture of carrageenan and sodium alginate, and the low lubricating gel contained three layers of carrageenan and calcium alginate (unmixed). The lubricating properties of these gels were previously characterised through tribological measurements (Stribitcaia, Krop, Lewin, Holmes, & Sarkar, 2020). The study did not quantify mouthdrying directly but monitored thirst: there were no significant differences between water, low lubricating and high lubricating hydrogels on thirst after whey protein consumption (Stribitcaia et al., 2021). This suggests that in this context, preloading the mouth with a gum is insufficient to mitigate mouthdrying. However, this study did not address mouthdrying specifically nor the effect of combining gums with whey protein directly. In addition, the study contained a small panel ($n = 17$), which the authors recognised was lower than the number suggested by their power calculations ($n = 24$); this increases the likelihood of type I error. The mean values for thirst with both gums were lower than the water control after *ad libitum* lunch but no significant difference was seen, which could have been a type I error resulting from the small panel. Cumulatively, these studies suggest that polysaccharide gums have the potential to mitigate mouthdrying by impacting the friction coefficient of whey protein (Ji et al., 2023, Berg et al., 2007). They also propose that directly modifying whey protein with gums may be more applicable than preloading.

5.1.2. Maltodextrin (weak mucoadhesive polysaccharide)

Maltodextrin is a polysaccharide mixture of amylose and amylopectin, produced by the partial hydrolysis of vegetable starch. Due to its high emulsification properties, maltodextrin is a good candidate for physically reducing mouthdrying as a lubricant. Additionally its sweet taste may also contribute to its ability to reduce mouthdrying cognitively. Although not tested with whey protein, Blok, Bolhuis, and Stieger (2020) investigated the sensory impact of adding maltodextrin to iced coffees and showed that increased maltodextrin levels were associated with increased perceptions of creaminess and slipperiness. For this study slipperiness was defined as "how easily your tongue moves over your palate when you consume the product" meaning this can be attributed to reduced oral friction. This was confirmed by rheological measures of the friction coefficient which reduced with the addition of maltodextrin (Blok et al., 2020); this observation was maintained but reduced in the presence of saliva, suggesting an interaction with salivary proteins.

The ability of maltodextrin to alter the sensory properties of whey protein was investigated by Yang *et al.* (2012): the study reported a reduction in bitterness through spray drying whey protein hydrolysate and maltodextrin, compared with the components mixed without spray drying. This alternative method to increase lubrication was also tested by Ma et al. (2014) who encapsulated whey protein hydrolysate, a highly bitter compound, with whey protein concentrate and sodium alginate. This led to a significant reduction in bitterness (Ma et al., 2014). Whilst not directly applicable to mouthdrying, these studies suggest that encapsulation is a potential method to reduce interactions between whey proteins and taste receptors. If this extends to changes in mouthfeel, this could have commercial significance for the development of new products with an enhanced sensory profile.

Encapsulation has also been used by Ji, Cornin, Fitzpatrick, and Miao (2017); the study encapsulated WPI with different concentrations of lecithin using fluidised bed agglomeration and Wurster coating process. They reported that the encapsulated WPI had altered particle size, bulk density, porosity and particle shape (Ji et al., 2017). Overall, the wettability of WPI was increased through encapsulation with a high concentration of lecithin, leading to a more rapid influx of water and improved solubility: this increase was attributed to the larger particle size increasing the radius of the particle pores and a more porous shape enabling water to penetrate faster. Whilst outside the scope of the paper, it is possible that encapsulation may alter interactions between WPI and saliva, supporting its use as a future mitigation strategy for mouthdrying.

5.1.3. Other weak mucoadhesive polysaccharides

Pectin is an anionic polysaccharide present in fruit that can be used in combination with whey protein to increase viscosity. The isoelectric point of pectin is pH 3.0, compared with pH 5.5 for whey protein, meaning that at low pH levels strong electrostatic attraction exists between these two components. This interaction was highlight by Chevalier, Rioux, Angers, and Turgeon (2019) in their study adding WPI to blueberry puree, containing 0.5% pectin decreased solubility was seen at pH 3.5 compared with 6.5, proving the complex formation between whey protein and pectin is pH-dependent. At pH 3.5 pectin is negatively charged and whey protein is positively charged, leading to electrostatic interactions and the formation of whey protein-pectin complexes, resulting in a decrease in pectin solubility (Chevalier et al., 2019). This was prevented at a pH 6.5 where both components were positively charged. Sensory attributes were outside the scope of the study, but the authors did report an increased viscosity at the low pH demonstrating that pectin and whey proteins interact at an acidic pH to form a complex. The sensory profile of whey protein-pectin complexes was investigated by Krzeminski, Prell, Busch-Stockfisch, Weiss, and Hinrichs (2014) for a fat-reduced yoghurt, as it has been hypothesised that these complexes can substitute fat in mouthfeel and sensory attributes. When compared to full-fat yoghurt and low-fat yoghurt, whey protein-pectin samples had higher viscous attributes than the low-fat yoghurt including creamy texture, creamy taste and fatty mouthfeel (Krzeminski et al., 2014). This suggests it could partially attenuate changes to mouthfeel reported with fat reduction.

Algin is a hydrophilic polysaccharide that forms a viscous gel when hydrated. This can be combined with sodium to form a stable gum and added to whey protein to create a gelation mixture. This was utilised by Leon, Medina, Park, and Aguilera (2018) which embedded oil micro-droplets in a gel matrix of whey protein and sodium alginate. This used whey protein as an encapsulating material, rather than being the encapsulated substance, but it showed that a paste was created that was stable when heated to 60 °C (Leon et al., 2018). This means it could be used in the production of fortified foods that require cooking. To the author's knowledge, no studies have assessed the sensory profile achieved by combining sodium alginate and whey protein as the majority of the research has focused on the utilisation of sodium alginate and whey protein gels as emulsifiers of other components.

5.2. Manipulating lipid content as a lubricant for whey protein

Fat is an important component of food due to its role in aroma release, flavour and mouthfeel attributes such as creaminess, smoothness and lubrication. These properties can be utilised in the context of mouthdrying: Li, Joyner, Carter, and Drake (2018) compared the sensory profile of raw skimmed milk (<0.2% fat), 2% fat and 5% fat milk and found a significant reduction in astringency with increased fat content (Li et al., 2018). Shamil and Kilcast (1992) also reported a reduction in astringency of dairy products with increased fat; this was partnered with a decrease in swallow time for full fat cheese compared with reduced fat cheese (Shamil & Kilcast, 1992). This supports the findings of Norton et al. (2021) that an increased rate of oral clearance, provided by lipid lubrication, reduces sensations of mouthdrying.

Contrastingly, some studies have demonstrated a negative effect on mouthdrying with increased lipid content: Cheng, Barbano, and Drake (2019) demonstrated that increased fat content of milk-based beverages led to increased sensations of mouthcoating and throat cling. The authors estimated that the increase in fat explained 21% of the additional astringency seen (Cheng et al., 2019). Quinones, Barbano, and Phillips (1998) compared the sensory attributes of milk with 2% and 3.3% fat and various protein levels. A trained sensory panel reported that fat content was significantly correlated with mouthcoating during consumption and after swallowing but had no impact on astringency or chalkiness (Quinones et al., 1998). This finding is seconded by Misawa, Barbano, and Drake (2016) who reported increased sensations of throat cling and mouthcoating in milk beverages with 2% fat compared with 1% fat (Misawa et al., 2016). Whilst these studies contrast the findings of Norton et al. (2021), it is likely that the results can be partially explained by confounding factors; the addition of lipids may increase the viscosity, leading to decreased lubrication and increased oral friction. To the author's knowledge these studies did not correct for viscosity changes. In addition, the studies used different fat sources and methods to incorporate the fat and whey protein, specific differences include the type of emulsion and processing used. These methodological differences may have influenced the properties of the product, highlighting the need for additional research to increase understanding of methodological effects and to standardise preparation protocols. To the author's knowledge Norton et al. (2021) is the only study that has varied lipid content of whey protein to successfully impact mouthdrying. Whilst it is possible this effect is specific to whey protein and not comparable with other milk proteins, it is more likely to be a solid-dependent effect, as suggested by Norton et al. (2021) who showed differing results upon addition of double cream to a liquid model. The contradictory studies above used milk beverages and a gel so were closer to a liquid model, supporting the suggestion of a solid-dependent effect. More research is needed using liquid models to ameliorate mouthdrying in a liquid.

Manipulation of the lipid content has been investigated through whey protein emulsions. Arancibia, Jublot, Costell, and Bayarri (2011) showed that increasing the fat content of oil emulsions (from 5% to 30% oil) was associated with increased sensations of thickness, mouthcoating and creaminess. Flavour intensity was also reduced with increased fat (Arancibia et al., 2011); this could be of benefit in products with off-flavours. These emulsions can be incorporated with whey protein to vary its sensory attributes by altering the physicochemical properties of the product. Emulsions of chitosan, a mucoadhesive polysaccharide, and WPI were investigated by Kumar et al. (2020). Whilst outside of a sensory context, it was shown that the addition of 1% chitosan to 10% WPI to create an emulsion at pH 5.5, significantly increased stability through lowering particle size and increasing zeta potential (Kumar et al., 2020). This is significant as 10% protein content is similar to a typical protein shake.

An alternative method to achieve this effect is through the use of oleogels. An oleogel is defined as an anhydrous, viscoelastic self-standing material composed of oil and water in a structured formation. Oleogels enable the use of oil rather than a solid fat, without compromising the sensory profile of products. Therefore, their possible use in whey protein to increase lubrication would be advantageous compared with the addition of oil, as it would decrease the saturated fat consumption. This could have health benefits over long-term consumption. Recent studies have documented the use of oleogels with whey protein, using whey protein aggregates as a carrier for oils (Park, Campanella, & Maleky, 2022, de Vries, Gemez, van der Linden, & Scholten, 2017). de Vries et al. (2017) induced polarity changes to sequentially replace the water in WPI aggregates with oil. To the author's knowledge no study has utilised oleogels to manipulate the sensory profile of whey protein or addressed their use for mouthdrying.

5.3. The effect of increasing lubrication on food intake

A possible limitation that needs to be considered when manipulating lubrication is the potential effect on appetite and food intake, as well as the nutritional value. Older adults are at an increased risk of malnutrition through reduced food intake so any decrease in appetite would likely be detrimental. Stribitcaia *et al.* hypothesised that more lubricating foods may be more mouthcoating, increasing the oro-sensory exposure time, leading to increased released of appetite-supressing hormones and decreasing total food intake. Stribitcaia *et al.* reported that highly lubricating preloads, made with carrageenan and sodium alginate, led to increased feelings of fullness and decreased hunger compared with low lubricating samples. However, subsequent food intake at an *ad libitum* meal was unaffected (Stribitcaia et al., 2021, Stribitcaia et al., 2022), leading the authors to conclude that manipulating lubrication does not significantly impact overall daily food consumption. It must be recognised that, this conclusion may not be representative of a real-life scenario as the study had a limited sample size ($n = 17$), was not specific to older adults (aged 18–55) and did not consider the effect of repeated consumption or consumption in a home setting where food choice is required. Therefore, it is possible that increased lubrication of whey protein may impact food intake in older adults. Research with older adults is needed to better understand the relationship between lubrication and appetite for this demographic.

6. Conclusion

Whey protein has previously been shown to be an appropriate protein source for supplementation for active consumers and fortification of products for older adults owing to its high bioavailability and proportion of branched chain amino acids. However, the mouthdrying perception associated with whey protein limits its consumer acceptance and consumption. The nature of whey protein derived mouthdrying was reviewed through a narrative literature search identifying 50 relevant peer-reviewed journal articles. The review of the literature suggests that whey protein-associated mouthdrying is a result of electrostatic interactions between whey protein and salivary proteins, mucoadhesion between whey protein and the oral mucosa, and the inherent astringency of acidity. The evidence suggests it is the combination of these mechanisms that is likely to be responsible for whey protein-associated mouthdrying. Previous strategies to combat this mouthdrying have included modifications of viscosity, sweetness and lipid content but these were not sufficient to fully remove mouthdrying. In light of this, the literature reveals support for the proposal to increase lubrication as a strategy to reduce mouthdrying derived from whey proteins. However, of the 50 papers reviewed, none have proposed and tested a method by which whey protein ingredients could be modified as an ingredient before their addition into formulated products to substantially and consistently reduce mouthdrying. We identify the need for future research to investigate methods to increase lubrication of whey proteins and reduce interactions between whey protein and salivary proteins. It is anticipated that this will improve the sensory profile of whey protein containing products, leading to increased consumer acceptance and consumption.

CRediT authorship contribution statement

Holly Giles: Investigation, Writing – original draft. **Stephanie P. Bull:** Conceptualization, Supervision. **Stella Lignou:** Conceptualization, Supervision. **Joe Gallagher:** Conceptualization, Supervision. **Marianthi Faka:** Conceptualization, Supervision. **Lisa Methven:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This studentship is funded by Volac International, a manufacturer of whey protein ingredients with a commercial interest in increasing whey protein consumption. Volac were not involved in the evaluation or interpretation of results to ensure impartiality and only took a reviewing role.

Data availability

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

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References

Aiqian, Y., Tao, Z., Ye, J. Z., & Harjinder, S. (2012). Potential role of the binding of whey proteins to human buccal cells on the perception of astringency in whey protein beverages. *Physiology & Behavior, 106*, 645–650.

Alhalaweh, A., Vilinska, A., Gavini, E., Rassu, G., & Velaga, S. P. (2011). Surface thermodynamics of mucoadhesive dry powder formulation of zolmitriptan. *AAPS PharmSciTech, 12*, 1186–1192.

Aragon, A. A., Tipton, K. D., & Schoenfeld, B. J. (2023). Age-related muscle anabolic resistance: Inevitable or preventable? *Nutrition Reviews, 81*, 441–454.

Arancibia, C., Jublot, L., Costell, E., & Bayarri, S. (2011). Flavor release and sensory characteristics of o/w emulsions. Influence of composition, microstructure and rheological behavior. *Food Research International, 44*, 1632–1641.

Bajec, M. R., & Pickering, G. J. (2008). Astringency: Mechanisms and perception. *Critical Reviews in Food Science and Nutrition, 48*, 858–875.

Beaudart, C., Locquet, M., Reginster, J. Y., Delandsheere, L., Petermans, J., & Bruyere, O. (2018). Quality of life in sarcopenia measured with the SarQoLA (R): Impact of the use of different diagnosis definitions. *Aging Clinical and Experimental Research, 30*, 307–313.

Beecher, J. W., Drake, M. A., Luck, P. J., & Foegeding, E. A. (2008). Factors regulating astringency of whey protein beverages. *Journal of Dairy Science, 91*, 2553–2560.

Beelen, J., de Roos, N. M., & de Groot, L. C. P. G. (2017). A 12-week intervention with protein-enriched foods and drinks improved protein intake but not physical performance of older patients during the first 6 months after hospital release: A randomised controlled trial. *The British Journal of Nutrition, 117*, 1541–1549.

Behrouzain, F., Razavi, S. M. A., & Joyner, H. (2020). Mechanisms of whey protein isolate interaction with basil seed gum: Influence of pH and protein-polysaccharide ratio. *Carbohydrate Polymers, 232*, Article 115775.

Berg, L. V. D., Vliet, T. V., Linden, E. V. D., Boekel, M. A. J. S. V., & Velde, F. V. D. (2007). Breakdown properties and sensory perception of whey proteins/polysaccharide mixed gels as a function of microstructure. *Food Hydrocolloids, 21*, 961–976.

Berg, L. V. D., Vliet, T. V., Linden, E. V. D., Boekel, M. A. J. S. V., & Velde, F. V. D. (2008). Physical properties giving the sensory perception of whey proteins/polysaccharide gels. *Food Biophysics, 3*, 198–206.

Blok, A. E., Bolhuis, D. P., & Stieger, M. (2020). Contributions of viscosity and friction properties to oral and haptic texture perception of iced coffees. *Food & Function, 11*, 6446–6457.

Bull, S. P., Hong, Y. C., Khutoryanskiy, V. V., Parker, J. K., Faka, M., & Methven, L. (2017). Whey protein mouth drying influenced by thermal denaturation. *Food Quality and Preference, 56*, 233–240.

Bull, S. P., Khutoryanskiy, V. V., Parker, J. K., Faka, M., & Methven, L. (2022). Oral retention of thermally denatured whey protein: In vivo measurement and structural observations by CD and NMR. *Food Chemistry, 374*.

Burd, N., Yang, Y., Moore, D., Tang, J., Tarnopolsky, M., & Phillips, S. (2012). Greater stimulation of myofibrillar protein synthesis with ingestion of whey protein isolate v. micellar casein at rest and after resistance exercise in elderly men. *British Journal of Nutrition, 108*.

Cawood, A. L., Stratton, R. J., & Elia, M. (2011). Systematic review and meta-analysis of the effects of high protein oral nutritional supplements on strength. *Proceedings of the Nutrition Society, 70*, E270–E.

Cheng, N., Barbano, D. M., & Drake, M. (2019). Effects of milk fat, casein, and serum protein concentrations on sensory properties of milk-based beverages. *Journal of Dairy Science, 102*, 8670–8690.

Chevalier, L. M., Rioux, L. E., Angers, P., & Turgeon, S. L. (2019). Study of the interactions between pectin in a blueberry puree and whey proteins: Functionality and application. *Food Hydrocolloids, 87*, 61–70.

Childs, J. L., & Drake, M. A. (2010). Consumer Perception of Astringency in Clear Acidic Whey Protein Beverages. *Journal of Food Science, 75*, S513–S521.

Colonetti, T., Grande, A. J., da Rocha, F. R., Ronconi Dondossola, E., Tuon, L., Gomes Batista Teles, H., … Da Rosa, M. I. (2023). Whey protein and vitamin D supplementation in institutionalized older adults: A randomized trial. *Nutrition and Health, 29*, 129–138.

Cook, S. L., Bull, S. P., Methven, L., Parker, J. K., & Khutoryanskiy, V. V. (2017). Mucoadhesion: A food perspective. *Food Hydrocolloids*, 281–296.

Cook, S. L., Woods, S., Methven, L., Parker, J. K., & Khutoryanskiy, V. V. (2018). Mucoadhesive polysaccharides modulate sodium retention, release and taste perception. *Food Chemistry, 240*, 482–489.

Courregelongue, S., Schlich, P., & Noble, A. C. (1999). Using repeated ingestion to determine the effect of sweetness, viscosity and oiliness on temporal perception of soymilk astringency. *Food Quality and Preference, 10*, 273–279.

de Vries, A., Gemez, Y. L., van der Linden, E., & Scholten, E. (2017). The effect of oil type on network formation by protein aggregates into oleogels. *Royal Society of Chemistry Advanced, 7*, 11803–11812.

Deutz, N. E. P., Bauer, J. M., Barazzoni, R., Biolo, G., Boirie, Y., Bosy-Westphal, A., … Calder, P. C. (2014). Protein intake and exercise for optimal muscle function with aging: Recommendations from the ESPEN Expert Group. *Clinical Nutrition, 33*, 929–936.

Elia, M., Parsons, E. L., Cawood, A. L., Smith, T. R., & Stratton, R. J. (2018). Cost-effectiveness of oral nutritional supplements in older malnourished care home residents. *Clinical Nutrition, 37*, 651–658.

Etzel, M. R. (2004). Manufacture and use of dairy protein fractions. *Journal of Nutrition, 134*, 996S–1002S.

Fukagawa, N. K., Bandini, L. G., & Young, J. B. (1990). Effect of age on body-composition and resting metabolic-rate. *American Journal of Physiology, 259*, E233–E238.

Geirsdottir, O. G., Arnarson, A., Ramel, A., Jonsson, P. V., & Thorsdottir, I. (2013). Dietary protein intake is associated with lean body mass in community-dwelling older adults. *Nutrition Research, 33*, 608–612.

Gosney, M. (2003). Are we wasting our money on food supplements in elder care wards? *Journal of Advanced Nursing, 43*, 275–280.

Hanach, N. I., McCullough, F., & Avery, A. (2019). The Impact of Dairy Protein Intake on Muscle Mass, Muscle Strength, and Physical Performance in Middle-Aged to Older Adults with or without Existing Sarcopenia: A Systematic Review and Meta-Analysis. *Advances in Nutrition, 10*, 59–69.

Hengeveld, L. M., Boer, J. M. A., Gaudreau, P., Heymans, M. W., Jagger, C., Mendonça, N., … Visser, M. (2020). Prevalence of protein intake below recommended in community-dwelling older adults: A meta-analysis across cohorts from the PROMISS consortium. *Journal of Cachexia, Sarcopenia and Muscle, 11*, 1212–1222.

Hernández-Lepe, M. A., Miranda-Gil, M. I., Valbuena-Gregorio, E., & Olivas-Aguirre, F. J. (2023). Exercise Programs Combined with Diet Supplementation Improve Body Composition and Physical Function in Older Adults with Sarcopenia: A Systematic Review. *Nutrients, 15*.

Hsein, H., Garrait, G., Beyssac, E., & Hoffart, V. (2015). Whey protein mucoadhesive properties for oral drug delivery: Mucin-whey protein interaction and mucoadhesive bond strength. *Colloids and Surfaces B-Biointerfaces, 136*, 799–808.

Jabbari, E., Wisniewski, N., & Peppas, N. A. (1993). Evidence of mucoadhesion by chain interpenetration at a poly(acrylic acid)/mucin interface using ATR-FTIR spectroscopy (VOL 26, PG 99, 1993). *Journal of Controlled Release, 27*, 89.

Ji, J., Cornin, K., Fitzpatrick, J., & Miao, S. (2017). Enhanced wetting behaviours of whey protein isolate powder: The different effects of lecithin addition by fluidised bed agglomeration and coating processes. *Food Hydrocolloids, 71*.

Ji, J., Fitzpatrick, J., Cronin, K., Crean, A., & Miao, S. (2016). Assessment of measurement characteristics for rehydration of milk protein based powders. *Food Hydrocolloids, 54*, 151–161.

Ji, L., Otter, D. D., Cornacchia, L., Sala, G., & Scholten, E. (2023). Role of polysaccharides in tribological and sensory properties of model dairy beverages. *Food Hydrocolloids, 134*.

Jobse, I. L., Bartram, Y., Delantonio, M., Uter, K., Stehle, W., Sieber, P., Inken Volkert, D. (2015). Compliance of nursing home residents with a nutrient- and energy-dense oral nutritional supplement determines effects on nutritional status. <*i data-test=“journal-title” style=“margin: 0px; box-sizing: inherit;”*>*The journal of nutrition, health & aging volume*, 19, 356–364.

Kamińska, M. S., Rachubińska, K., Grochans, S., Skonieczna-Żydecka, K., Cybulska, A. M., Grochans, E., & Karakiewicz, B. (2023). The Impact of Whey Protein Supplementation on Sarcopenia Progression among the Elderly: A Systematic Review and Meta-Analysis. *Nutrients, 15*.

Kang, L., Gao, Y., Liu, X., Liang, Y., Chen, Y., Zhang, L., … Peng, L. N. (2019). Effects of whey protein nutritional supplement on muscle function among community-dwelling frail older people: A multicenter study in China. *Archives of Gerontology and Geriatrics, 83*, 7–12.

Krzeminski, A., Prell, K. A., Busch-Stockfisch, M., Weiss, J., & Hinrichs, J. (2014). Whey protein-pectin complexes as new texturising elements in fat-reduced yoghurt systems. *International Dairy Journal, 36*, 118–127.

Kumar, L. R. G., Anas, K. K., Tejpal, S. C., Chatterjee, S. N., Vishnu, V. K., Asha, K. K., … Matthew, S. (2020). Chitosan: Whey Protein Isolate: An Effective Emulsifier for Stabilization of Squalene Based Emulsions. *Waste and Biomass Volarization, 11*, 3477–3483.

Kuo, Y. Y., Chang, H. Y., Huang, Y. C., & Liu, C. W. (2022). Effect of Whey Protein Supplementation in Postmenopausal Women: A Systematic Review and Meta-Analysis. *Nutrients, 14*.

Lawless, H. T., Horne, J., & Giasi, P. (1996). Astringency of organic acids is related to pH. *Chemical Senses, 21*, 397–403.

Lee, C. A., & Vickers, Z. M. (2008). The astringency of whey protein beverages is caused by their acidity. *International Dairy Journal, 18*, 1153–1156.

Leon, A. M., Medina, W. T., Park, D. J., & Aguilera, J. M. (2018). Properties of microparticles from a whey protein isolate/alginate emulsion gel. *Food Science and Technology International, 24*, 414–423.

Lester, S., Kleijn, M., Cornacchia, L., Hewson, L., Taylor, M. A., & Fisk, I. (2022). Factors Affecting Adherence, Intake, and Perceived Palatability of Oral Nutritional Supplements: A Literature Review. *Journal of Nutrition Health & Aging, 26*, 663–674.

Li, Y., Joyner, H. S., Carter, B. G., & Drake, M. A. (2018). Effects of fat content, pasteurization method, homogenization pressure, and storage time on the mechanical and sensory properties of bovine milk. *Journal of Dairy Science, 101*.

Lieberman, H. R., Marriott, B. P., Williams, C., Judelson, D. A., Glickman, E. L., Geiselman, P. J., … Mahoney, C. R. (2015). Patterns of dietary supplement use among college students. *Clinical Nutrition, 34*, 976–985.

Lim, S. K. & Kong, S. (2022). Prevalence, physical characteristics, and fall risk in older adults with and without possible sarcopenia. *<i data-test="journal-title" style="margin: 0px; box-sizing: inherit;">Aging Clinical and Experimental Research,* 34**,** pages 1365–1371.

Liu, J., Shim, Y. Y., Shen, J., Wang, Y., & Reaney, M. J. T. (2017). Whey protein isolate and flaxseed (Linum usitatissimum L.) gum electrostatic coacervates: Turbidity and rheology. *Food Hydrocolloids, 64*, 18–27.

Ma, J. J., Mao, X. Y., Wang, Q., Yang, S., Zhang, D., Chen, S. W., & Li, Y. H. (2014). Effect of spray drying and freeze drying on the immunomodulatory activity, bitter taste and hygroscopicity of hydrolysate derived from whey protein concentrate. *Lwt-Food Science and Technology, 56*, 296–302.

Methven, L., Rahelu, K., Economou, N., Kinneavy, L., Ladbrooke-Davis, L., Kennedy, O. B., … Gosney, M. A. (2010). The effect of consumption volume on profile and liking of oral nutritional supplements of varied sweetness: Sequential profiling and boredom tests. *Food Quality and Preference, 21*, 948–955.

Misawa, N., Barbano, D. M., & Drake, M. (2016). Influence of casein as a percentage of true protein and protein level on color and texture of milks containing 1 and 2% fat. *Journal of Dairy Science, 99*, 5284–5304.

Mitchell, W. K., Williams, J., Atherton, P., Larvin, M., Lund, J., & Narici, M. (2012). Sarcopenia, dynapenia, and the impact of advancing age on human skeletal muscle size and strength; a quantitative review. *Frontiers in Physiology, 3*.

Morilla-Herrera, J. C., Martín-Santos, F. J., Caro-Bautista, J., Saucedo-Figueredo, C., García-Mayor, S., & Morales-Asencio, J. M. (2016). Effectiveness of Food-Based Fortification in Older People. A Systematic Review and Meta-Analysis. *The Journal of Nutrition, Health & Aging, 20*, 178–184.

Mulet-Cabero, A.-I., Torcello-Gómez, A., Saha, S., Mackie, A. R., Wilde, P. J., & Brodkorb, A. (2020). Impact of caseins and whey proteins ratio and lipid content on in vitro digestion and ex vivo absorption. *Food Chemistry, 319*.

Nasimi, N., Sohrabi, Z., Nunes, E. A., Sadeghi, E., Jamshidi, S., Gholami, Z., … Phillips, S. M. (2023). Whey Protein Supplementation with or without Vitamin D on Sarcopenia-Related Measures: A Systematic Review and Meta-Analysis. *Advances in Nutrition, 14*, 762–773.

Norton, V., Lignou, S., Bull, S. P., Gosney, M. A., & Methven, L. (2020). Consistent Effects of Whey Protein Fortification on Consumer Perception and Liking of Solid Food Matrices (Cakes and Biscuits) Regardless of Age and Saliva Flow. *Foods, 9*.

Norton, V., Lignou, S., Faka, M., Rodriguez-Garcia, J., & Methven, L. (2021). Investigating Methods to Mitigate Whey Protein Derived Mouthdrying. *Foods, 10*.

Norton, V., Lignou, S., & Methven, L. (2021). Whey Protein Derived Mouthdrying Found to Relate Directly to Retention Post Consumption but Not to Induced Differences in Salivary Flow Rate. *Foods, 10*.

Nunes, E. A., Colenso-Semple, L., McKellar, S. R., Yau, T., Ali, M. U., Fitzpatrick-Lewis, D., … Phillips, S. M. (2022). Systematic review and meta-analysis of protein intake to support muscle mass and function in healthy adults. *Journal of Cachexia, Sarcopenia and Muscle, 13*, 795–810.

Park, C., Campanella, O., & Maleky, F. (2022). The effects of whey protein and oleogel interactions on mechanical properties of oleocolloids and hydro-oleocolloids matrices. *Food Hydrocolloids*.

Pennings, B., Boirie, Y., Senden, J. M. G., Gijsen, A. P., Kuipers, H., & van Loon, L. J. C. (2011). Whey protein stimulates postprandial muscle protein accretion more effectively than do casein and casein hydrolysate in older men. *American Journal of Clinical Nutrition, 93*, 997–1005.

Prokopidis, K., Mazidi, M., Sankaranarayanan, R., Tajik, B., McArdle, A., & Isanejad, M. (2023). Effects of whey and soy protein supplementation on inflammatory cytokines in older adults: A systematic review and meta-analysis. *British Journal of Nutrition, 129*, 759–770.

Quinones, H. J., Barbano, D. M., & Phillips, L. G. (1998). Influence of protein standardization by ultrafiltration on the viscosity, color, and sensory properties of 2 and 3.3% milks. *Journal of Dairy Science, 81*, 884–894.

Rosenthal, A. J., & Yilmaz, S. (2015). Possible Mechanism behind the Hard-to-Swallow Property of Oil Seed Pastes. *International Journal of Food Properties, 18*, 2077–2084.

Sano, H., Egashira, T., Kinekawa, Y., & Kitabatake, N. (2005). Astringency of bovine milk whey protein. *Journal of Dairy Science, 88*, 2312–2317.

Shamil, S., & Kilcast, D. (1992). Improving the flavour acceptability of reduced-fat foods. *Nutrition and Food Science, 23*, 7–10.

Sobestiansky, S., Michaelsson, K., & Cederholm, T. (2019). Sarcopenia prevalence and associations with mortality and hospitalisation by various sarcopenia definitions in 85–89 year old community-dwelling men: A report from the ULSAM study. *Bmc Geriatrics, 19*.

Song, X., Sun, X., Ban, Q., Cheng, J., Zhang, S., & Guo, M. (2020). Gelation and microstructural properties of a millet-based yogurt-like product using polymerized whey protein and xanthan gum as thickening agents. *Journal of Food Science, 85*.

Sowalsky, R. A., & Noble, A. C. (1998). Comparison of the effects of concentration, pH and anion species on astringency and sourness of organic acids. *Chemical Senses, 23*, 343–349.

Spoelder, M., Koopmans, L., Hartman, Y. A. W., Bongers, C. C. W. G., Schoofs, M. C. A., Eijsvogels, T. M. H., & Hopman, M. T. E. (2023). Supplementation with Whey Protein, but Not Pea Protein, Reduces Muscle Damage Following Long-Distance Walking in Older Adults. *Nutrients, 15*.

Stribitcaia, E., Blundell, J., You, K. M., Finlayson, G., Gibbons, C., & Anwesha, S. (2022). Viscosity of food influences perceived satiety: A video based online survey. *Food Quality and Preference, 99*.

Stribitcaia, E., Gibbons, C., Sier, J., Boesch, C., Blundell, J., Finlayson, G., & Anwesha, S. (2021). Effects of oral lubrication on satiety, satiation and salivary biomarkers in model foods: A pilot study. *Appetite, 165*.

Stribitcaia, E., Krop, E. M., Lewin, R., Holmes, M., & Sarkar, A. (2020). Tribology and rheology of bead-layered hydrogels: Influence of bead size on sensory perception. *Food Hydrocolloids, 104*.

Suryadinata, R. V., Wirjatmadi, B., Adriani, M., & Lorensia, A. (2020). Effect of age and weight on physical activity. *Journal of Public Health Research, 9*, 187–190.

Tan, V. W. K., Wee, M. S. M., Tomic, O., & Forde, C. G. (2020). Rate-All-That-Apply (RATA) comparison of taste profiles for different sweeteners in black tea, chocolate milk, and natural yogurt. *Journal of Food Science, 85*.

Vardhanabhuti, B., Kelly, M. A., Luck, P. J., Drake, M. A., & Foegeding, E. A. (2010). Roles of charge interactions on astringency of whey proteins at low pH. *Journal of Dairy Science, 93*, 1890–1899.

White, S. S., Fox, K. M., Jervis, S. M., & Drake, M. A. (2013). Influence of heating and acidification on the flavor of whey protein isolate. *Journal of Dairy Science, 96*, 1366–1379.

Withers, C. A., Cook, M. T., Methven, L., Gosney, M. A., & Khutoryanskiy, V. V. (2013). Investigation of milk proteins binding to the oral mucosa. *Food & Function, 4*, 1668–1674.

Withers, C. A., Lewis, M. J., Gosney, M. A., & Methven, L. (2014). Potential sources of mouth drying in beverages fortified with dairy proteins: A comparison of casein- and whey-rich ingredients. *Journal of Dairy Science, 97*, 1233–1247.

Woo, J., Leung, J., & Morley, J. E. (2015). Defining Sarcopenia in Terms of Incident Adverse Outcomes. *Journal of the American Medical Directors Association, 16*, 247–252.

Ye, A., Streicher, C., & Singh, H. (2011). Interactions between whey proteins and salivary proteins as related to astringency of whey protein beverages at low pH. *Journal of Dairy Science, 94*, 5842–5850.

Zhang, Q., Cheng, Z., Wang, Y., & Fu, L. (2021). Dietary protein-phenolic interactions: Characterization, biochemical-physiological consequences, and potential food applications. *Critical Reviews in Food Science and Nutrition, 61*, 3589–3615.