Food Science of Animal Products

Review Article

Improvement of emulsification of egg yolk powder: protein modification techniques

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Abstract: As a high nutritional value egg processing product, egg yolk powder has a wide range of applications, However, its emulsification is affected by the processing conditions and is not satisfactory, which limits its wide application in the food industry. Based on this, this paper presents a systematic review of emulsification modification techniques for egg yolk powder, including physical, chemical, and enzyme modification techniques, to improve its emulsification properties and processing adaptability, and to provide a reference for solving such problems. The characteristics of various modification methods were analysed and compared. Future research should focus on optimising the modification process, gaining a deeper understanding of the modification mechanism and developing more mechanisms for the joint application of modification techniques, to maximise the application potential of egg yolk powder and to meet the growing and diversified needs of the food industry.

Keywords: egg yolk powder; emulsification; modification technique; enzyme modification; modification mechanism

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1 Introduction

The yolk is a complex system, 28%–29% of the dry matter of an egg, containing about 16% protein (Figure 1)[1], consisting of suspended low-density lipoprotein (LDL) and insoluble particles, which contain high-density lipoprotein (HDL), lecithin, phosphoproteins, sialic acid, salivary oligosaccharides, and other bioactive macromolecules, is a highly nutritious food ingredient. Egg yolk is widely used as an ingredient in many food emulsifiers, it has good organoleptic properties and as an effective emulsifier it can stabilise emulsified foods such as mayonnaise, salad dressings, and creams[1]. The functional properties of proteins determine their performances and behaviors during preparation, processing, storage, and consumption in food systems[2], but their poor emulsification stability limits the use of yolk and its related products in food applications[3]. Egg yolk, as a natural emulsifier, also has a strong affinity for oil and water. However, egg yolk is sensitive to high temperatures and tends to form aggregates even under mild heat treatment, which will affect its functional properties[4]. Therefore, heat treatments such as pasteurisation and spray-drying during the processing of egg yolk powder may lead to a significant reduction in emulsification capacity[5]. Meanwhile, the emulsification stability of egg yolk protein is poor at low protein concentrations[6], these drawbacks have severely limited the application of egg yolk in food industry. Therefore, methods to improve the thermal and emulsification stability of egg yolk have been continuously explored.

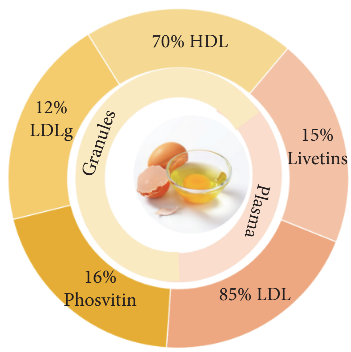

Figure 1 Overview of granules and plasma of egg yolks. LDLg, low-density lipoprotein granules.

Protein modification, as an important means to improve the processing characteristics of egg powder, has always been valued by the industry. At present, the research on egg protein modification mainly focuses on physical, chemical, and enzymatic modification to find new modification methods and investigate the modification mechanism, and the research on enzyme compound treatment has also made progress and achieved better results. The emulsifying properties of untreated egg yolks are significantly reduced at high temperatures[7]. In order to improve the emulsification properties, different methods have been used to modify egg yolk. For example, high hydrostatic pressure is used to modify the physicochemical properties and structure of egg yolk proteins. High-intensity sonication is also an attractive technique that can be used to improve the functional properties of regulated egg yolks[8]. Whereas

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phosphorylation treatment of proteins increases their solubility and emulsification capacity[9]. Enzymatic hydrolysis is an effective class of methods that modify the physicochemical and functional properties of proteins by altering their primary structure. It has been shown that enzymatic hydrolysis can increase the thermal stability of arachidonin, while selective hydrolysis can improve the emulsification properties of soy proteins because hydrolysed proteins have a relatively small molecular size and a more flexible structure that allows for rapid uptake at oil/water interfaces where adsorption is high[8]. These studies suggest that enzymatic hydrolysis may be a potential method to improve the thermal stability and functional properties of egg yolk. At the same time, there are some problems in modification, such as the balance between modification effect and food safety under high temperature treatment[7], introduction of by-products and reagent residues in chemical modification process. There are fewer enzymes suitable for the modification of egg yolk powder and some modification mechanisms have not been thoroughly investigated. At present, solving these problems and finding new modification methods and making the existing modification methods more significant and effective are still the key to the modification of egg yolk powder.

2 Physical modification

Physical modification is the modification of protein molecules by changing the molecular structure and aggregation mode of proteins by means of heat treatment, electromagnetic radiation treatment, high-pressure treatment or machinery. Compared with other modification methods, physical modification has the advantages of excellent safety, low cost, and high efficiency. Traditional physical modification methods such as sugar-salt-assisted heat treatment and freeze-thaw treatment have been widely used in egg processing.

2.1 Sugar-salt-assisted heat treatment

Egg yolks are sensitive to high temperatures, and heat treatment processes such as pasteurisation and spray-drying present during the processing of egg yolk powder can lead to a reduction in emulsification capacity. It has been found that the proteins of egg yolk can withstand more intense heat treatment when salt is present during the heating process, the reason is that the ionisation of NaCl in solution can provide an ionic environment in which the anions in the dielectric bind to the proteins, increasing the negative charge of the proteins and enhancing the ability to bind to water molecules, thus increasing the ability to adsorb proteins with high surface activity such as the LDLs in liquid eggs and enhancing adsorption capacity at the oil-water interface, and finally improving the emulsification activity of liquid egg yolks. The addition of the complex salt improved the heat resistance of liquid egg yolks, so that they could maintain good emulsifying activity even after higher heat treatment, which increased the denaturation temperature of the egg yolk liquid to more than 77 °C[10]. Sugars can also inhibit water migration in egg yolks. And sugars can also protect egg yolk proteins from aggregation by inhibiting aggregation and denaturation caused by water migration and changes in the amino acid microenvironment[11].

Studies on egg white proteins have shown that the emulsification of heat-treated egg white proteins is improved due to more hydrophobic amino acids and net charge exposure on the surface of the heat-treated proteins, which transforms the tertiary structure of egg white proteins[8]. It has been found that the heating process of egg white powder induces changes in the secondary and tertiary structure of its proteins, which are mainly manifested in the reduction of the characteristic fluorescence intensity, the increase of surface hydrophobicity and free sulfhydryl content. Correspondingly, the changes in the secondary structure were mainly characterised by the loss of α-helix and the formation of β-turn. The emulsification properties of egg white protein were significantly enhanced with increasing temperature, reaching a maximum at 80 °C[12]. Heat treatment at 50–60 °C improved the emulsification of thick egg whites[13], which had the same results as the treatment of yolks or whole eggs[4]. However, it is still necessary to pay attention to the temperature control of the heating process for egg yolks and actively explore other effective sterilisation methods.

Pasteurisation is a common thermal processing technique in the food sector, and the nutrient content and organoleptic quality of heat-sensitive foods are often adversely affected by high temperatures[14]. With the growing consumer demand for less-processed and fresher foods, non-thermal processing techniques such as high hydrostatic pressure, freeze-thaw cycles, and ultrasonic modification have become the focus of scholarly attention.

2.2 Freeze-thaw treatment

Freeze-thaw treatment can alter the molecular properties of proteins by changing their surface hydrophobicity, secondary structure, and thermal properties[15], due to the conversion of free sulfhydryl groups into disulfide bonds and oxidative aggregation in proteins, the free sulfhydryl content tends to increase and then decrease. It has been found that the more hydrophobic groups expose during freeze-thaw treatment of peanut isolates, the higher the free sulfhydryl group content, the higher the emulsification capacity of peanut isolates[16]. It was shown that the freeze-treated egg yolk samples also had high emulsion stability, which could be attributed to the significant increase in free sulfhydryl groups, which in turn led to the exchange of S–S or S–SH bonds[17]. In contrast, the emulsification activity of egg yolk phosphoproteins was enhanced after several freeze-thaw treatments, which may be attributed to the freeze-thaw treatment leading to conformational rearrangement and burial of hydrophobic groups, thus increasing the adsorption capacity at the oil-water interface[15].

It has been suggested that soybean isolate proteins have significantly higher emulsification activity and emulsion stability than natural proteins after 3–5 freeze-thaw cycles[18], which has similar results to the treatment of egg yolk protein. In the application of freeze-thaw cycles to egg yolk solutions, it is important to consider the freeze-induced denaturation of proteins as well as the effect of the freezing rate on the proteins themselves. In a study of the freeze-thaw stability of egg yolk solutions, it was found that too fast or too slow a freezing rate was more likely to lead to instability of the more yolk solution, which the researchers suggested could be caused by the growth of larger ice crystals at a low rate and an increase in the denaturation of the proteins when in contact with the dry ice in order to achieve a high freezing rate[19].

Pickering emulsions have attracted a lot of attention in the food field due to their high functionality and their freeze-thaw stability is very important when used in frozen foods. It has been shown that soy protein particles are heat-treated and then cross-linked with glutamine aminotransferase enzyme to obtain Pickering emulsions that have better freeze-thaw stability and are better used in frozen foods such as ice-cream[20]. This provides a referable idea for improving the functionality of egg yolk powder and applying it to the preparation of Pickering emulsions.

2.3 High hydrostatic pressure treatment

High pressure (also known as high hydrostatic pressure) is a technique that involves immersing a product in water and exposing it to hundreds of MPa of hydrostatic pressure in a high-pressure vessel[21]. High hydrostatic pressure treatment leads to protein aggregation, gradual decrease in solubility and significant increase in viscosity. It was shown that high hydrostatic pressure treatment at 100–500 MPa resulted in a gradual decrease in surface hydrophobicity and sulfhydryl content, which could be attributed to protein defolding and subsequent aggregation of unfolded proteins. Whereas the 100 MPa treatment significantly improved the yolk emulsion stability, the yolk emulsion stability significantly decreased when the pressure was higher than 200 MPa. These results suggest that moderate high-pressure treatments can de-fold proteins and improve the emulsion stability of egg yolks, while severe high-pressure treatments can impair their emulsion stability[22].

The increase in emulsification activity during high hydrostatic pressure and pH shift treatments of soy proteins can be attributed to the unfolded protein structure and the increased exposure of hydrophobic sites after treatment at moderate pressure, the synergistic effect of pH change and high hydrostatic pressure treatments improves surface hydrophobicity, proteolysis, and molecular flexibility, which in turn improves the emulsification properties[23], which is similar to the results obtained for egg yolk emulsions. It has been shown that high hydrostatic pressure treatment at 150 MPa significantly improves the emulsification properties of myosin, with a reduction in emulsion particle size, an increase in interfacial protein film viscoelasticity, and a significant increase in both emulsification activity and stability compared to the control. The authors attributed the improved emulsification activity of myosin to the moderate depolymerisation of the protein structure induced by the high hydrostatic pressure treatment, resulting in the exposure of hydrophobic groups, which enhanced the surface activity and protein adsorption capacity of the protein at the oil/water interface[24]. This study showed similar results to other proteins, and new ways to improve emulsification by exposing more hydrophobic groups could be explored in the future.

It is important to note that inappropriate high hydrostatic pressure treatments may impair protein function, and possible adverse effects on the properties of proteins and other compounds, such as oxidation of proteins, must also be considered. Due to the complexity of the relationship between interfacial elasticity and emulsion stability, further studies are still needed in future research to determine the effect of high hydrostatic pressure on the properties of egg yolk powder.

2.4 High-intensity ultrasonic treatment

Ultrasonic modification has the potential to improve protein emulsification properties by reducing protein size, increasing surface hydrophobicity and molecular mobility[25]. Yolk particles are insoluble compounds consisting of HDLs and phosphoproteins under natural conditions and can form stable oil-in-water emulsions[1]. It has been shown that high-intensity ultrasonication enhances the ζ-potential of the yolk components in solution, thereby increasing the free sulfhydryl content of yolk proteins, which in turn enhances their emulsification properties[26]. The free sulfhydryl group content of liquid egg yolk was also significantly increased by high-intensity sonication, and the emulsification activity index of diluted liquid egg yolk at 45 and 60 °C was significantly increased by 75 W high-intensity ultrasonic treatment, whereas the highest emulsification stability index was observed at 30 °C, 210 W for 9 min, and it was hypothesised that protein-oil interactions were enhanced due to the ultrasonication treatment that exposed more hydrophobic groups, thereby improving the emulsification of liquid egg yolks[27]. It has been noted that in the treatment of wheat germ proteins, sonication increases the solubility of wheat germ proteins and decreases the particle size and surface charge. At the same time, ultrasonication leads to an increase in the surface hydrophobicity of protein molecules and the level of surface free sulfhydryl groups, and the emulsification activity index and emulsion stability index of wheat germ protein are significantly improved, and the emulsion droplets are smaller and more uniform after ultrasonication treatment[28].

High-intensity ultrasound treatment also demonstrated good modification effects when used in combination with other modification means. Some scholars in the process of modifying pea protein found that ultrasound and pH change synergistic treatment effectively improved the solubility and emulsification stability of pea protein, which the authors attributed to the disintegration of highly ordered rigid polymers induced by the change in pH, while the strong physical force exerted by ultrasound further unfolded the proteins, leading to the exposure of the internal polar and hydrophobic groups, increasing the solubility and accelerating the adsorption and rearrangement of proteins at the oil-water interface, promoting the formation of strong viscoelastic interfacial membranes, and improving the stability of emulsification[29]. In the future, it should be further explored whether pH co-treatment can have similar positive effects on egg yolk emulsions. Proteins such as egg yolk and wheat germ protein were ultrasonically treated to increase the absolute values of ζ-potential and free sulfhydryl group content, and reduce the average particle size; pea protein exposed more hydrophobic groups after co-treatment, and these treatments led to a significant improvement in the emulsification performance of the solutions, but whether the same results would be obtained for other protein species needs to be further investigated.

Compared with the traditional physical modification methods, the new physical modification methods such as high hydrostatic pressure, high-intensity ultrasonic treatment, and microwave treatment have the advantages of excellent safety, low cost, and high efficiency.

3 Chemical modification

Chemical modification is the use of chemical methods to make the amino acid residues in the protein molecule of the side chain groups or polypeptide chain break, polymerisation or the introduction of new groups, resulting in changes in the spatial structure of the protein molecule and the functional properties of the protein molecule, with the characteristics of directional modification and high efficiency. In the process of preparing egg yolk powder, the emulsification system of egg yolk liquid itself is the focus of attention.

3.1 Phosphorylation

Phosphorylation treatment, as a chemical treatment, can improve the electrostatic interactions between protein molecules by introducing negatively charged phosphate groups, thus altering the spatial structure of proteins[30]. It has been shown that phosphorylation treatment enhances the surface hydrophobicity of proteins, leading to a good balance between the hydrophobic and hydrophilic ratios required for emulsification, which promotes rapid absorption of proteins in the biphasic interfacial layer. Moreover, the increase in protein solubility and structural changes in egg yolk can enhance the interaction between protein and water, resulting in a 2–3-fold increase in the stability of the modified egg yolk emulsion[9]. Meanwhile, sodium tripolyphosphate modification can significantly improve the emulsification capacity of *Perilla* isolate protein. After the phosphorylation treatment, a large number of phosphate groups were bound to the *Perilla* isolate protein backbone through covalent interactions, which increased the electrostatic repulsion between protein molecules. At the same time, the structure of the protein unfolded, indicating that more hidden hydrophobic groups were exposed on the protein surface, which led to an increase in the surface hydrophobicity and further enhanced the emulsification ability as well as the thermal stability of *Perilla* isolate protein[31].

During the phosphorylation of soybean isolate proteins, the emulsification stability was increased 8-fold when sodium trimetaphosphate was added at 100 g/kg. The emulsification activity was closely related to the solubility, and the phosphorylation improved the solubility of soybean isolate proteins, greatly increased the protein content adsorbed at the interface of the two phases, and improved the emulsification performance of the proteins[32]. Phosphorylation of walnut isolate protein altered the surface hydrophobicity and surface charge of the protein, and the modification significantly increased the solubility of the protein, increased the emulsification activity index by 2.5–4-fold, and increased the emulsion stability index by 6-fold. This study demonstrated that phosphorylation modification could effectively regulate the surface hydrophobicity and charge of walnut isolate protein, and greatly improve its solubility and emulsification ability[33]. Phosphorylation of *Perilla* isolate, soybean isolate, and walnut isolate showed similar results to egg yolk in that they all enhanced protein surface hydrophobicity and improved electrostatic interactions, increased protein solubility and protein intermolecular interactions, and improved emulsification, which suggests that phosphorylation can be an effective way to modify proteins, but there are some food safety risks associated with chemical modification. Therefore, some of the chemical modifications to egg yolk powder also have certain food safety risks, and the issues related to phosphorylation such as the high number of by-products should be further studied in the future.

3.2 Succinylation

Succinylation is a chemical derivatisation of the ε-amino group of lysine in which the positive charge of the lysine is replaced by a negatively charged succinyl group[34]. Using succinic anhydride for yolk protein modification, a decrease in the emulsification activity of egg yolk after succinylation was observed, which was deduced to be due to the disruption of the balance between hydrophilic and hydrophobic groups of lipoproteins, and on the contrary, the emulsion stability of the samples showed an increase due to the decrease in the interfacial tension at the oil-water interface[9]. Succinylation of milk proteins significantly increased their emulsification activity and the increase in emulsification activity was commensurate with the increase in degree of succinylation. In addition, succinylation likewise significantly improved its emulsion stability, and the increase in solubility and structural flexibility of the modified proteins facilitated the diffusion of the proteins at the oil-water interface, which led to an increase in the emulsifiability of the modified proteins[35]. During the application of ultrasound-assisted succinylation of egg white proteins, the α-helix content of egg white proteins was significantly increased, the content of random coil was decreased, the secondary structure of egg white proteins was shifted from disorder to order, and their emulsification properties were significantly improved. Meanwhile, the succinylation modification introduces a large number of succinyl groups into the protein, which enhances the interaction between the protein molecules and water in the emulsion system, and further improves the solubility quality of the protein[36], and whether this rule can be applied to egg yolk lipoproteins needs to be further investigated in the future. After succinylation of soybean isolate proteins, the ζ-potential of emulsion droplets increased, the particle size decreased, the macroscopic stability improved, and the interfacial tension decreased. Correlation analysis showed that the emulsification and interfacial properties of soybean isolate protein emulsions were closely related to the conformational flexibility of the interfacially adsorbed proteins, while the interfacial adsorption process was also affected by the ζ-potential of the unabsorbed proteins and particle size[37]. This study can provide theoretical guidance for the regulation of protein emulsification properties by succinylation, and it is promising to combine it with other modification means in the future to further improve the emulsification properties of egg yolk powder. Many proteins still lack corresponding functional properties in practical applications, and although succinylation is an effective option for protein modification, its use in industry is rather limited[38], the future application of succinylation in the field of modified proteins should still be further explored.

4 Enzyme modification

Enzymatic modification has been applied to improve the functional properties of proteins due to its mild reaction, low equipment requirements, and high safety. Subtilisin, trypsin, alkaline protease, and neutral enzymes can be used to improve the emulsification of proteins, in addition to various types of phospholipases can also improve the emulsification of egg yolk powder, and a combination of multiple enzymes can be used to enhance the modification effect.

4.1 Subtilisin

Subtilisin are predominantly endopeptidases, known for their heat stability, non-specificity, and are particularly active at neutral or weakly alkaline conditions[39]. Subtilisin treatment can significantly improve the water dispersibility, solubility, and stability of egg yolk powder due to the binding of hydrophobic groups and lipoproteins. This treatment exposes a large number of hydrophobic groups and these side chains can bind to free lipoproteins through hydrophobic interactions, resulting in a decrease in surface hydrophobicity. In addition, the number of small molecules is significantly increased and the electrostatic force of small particles helped the enzyme-treated egg yolk powder to exhibit better solubility[40]. Enzymatically hydrolysed egg yolk particles are potential Pickering particles with higher emulsion stability compared to untreated egg yolk particles. This effect may be attributed to the changes in the protein composition of the egg yolk particles due to the subtilisin treatment, and the structural changes in the egg yolk particles subsequently triggered a series of positive changes in the surface properties: strengthened internal hydrogen bonding, improved surface wettability, increased surface charge, and improved emulsification of the egg yolk powder[41].

During the application of subtilisin to wheat gluten proteins, the hydrolysed products obtained exhibited enhanced functional properties, including higher solubility (43%) and emulsifying activity (93.08 m^2/g), compared to the unenzymatically digested proteins[42], which had similar results to the treatment of egg yolk particles. In the current study, some subtilisin have been applied to protein engineering as well as enzyme immobilisation techniques for the development of human dietary and nutritional supplements, however, in the practical application to the production of egg yolk powder, extra attention should be paid to the pH range of the action of subtilisin and the specific emulsion conditions, and whether the subsequent spray-drying process would have any influence on the enzyme-modified egg yolk emulsions needs to be further studied.

4.2 Trypsin

It has been shown that the hydrolysis of egg yolk particles using trypsin can effectively improve their emulsification, and the diffusion of peptides in the solution phase and the rapid adsorption at the oil-water interface refers to the emulsification of egg yolk. Meanwhile, the increase of surface hydrophobicity and the decrease of ζ-potential of the hydrolysed products were also important factors affecting the stability of the emulsion. The emulsification properties of the trypsin-treated group peaked at 3.5 h[43]. After enzymatic digestion not only the flexibility of the protein was improved, but also the thermal stability of the emulsion, which was conducive to the egg yolk emulsion to maintain a high emulsification activity when undergoing spray-drying process. It has been noted that the use of trypsin and alkaline protease for treating soybean proteins, respectively, the trypsin-produced soybean protein fragments shows significantly better emulsification properties than the alkaline protease-treated ones. These differences are related to the physical form of soy protein, with trypsin being quite selective for the peptide bonds it cleaves[44]. The results can be used as a new research idea to produce fine submicron oil-in-water emulsion systems.

Trypsin showed similar results in the treatment of walnut protein, with walnut protein hydrolysates exhibiting higher surface activity, significantly improving the foaming and emulsifying properties of walnut protein, and also showing higher loading capacity for hydrophobic bioactive molecules (curcumin and quercetin), as compared to natural non-hydrolysed proteins[45]. This is an inspiration for modification in the field of egg yolk powder, and the application of enzymatic hydrolysis to improve the loading capacity of actives should be further explored. Moreover, the combination of enzymatic modification and high-intensity ultrasound treatment can significantly improve the emulsification properties of egg yolk. High emulsifiability is closely related to modified surface properties such as ζ-potential, hydrophobicity, and total sulfhydryl content, and the reduction of α-helix and the increase of β-sheet promote the improvement of egg yolk emulsification properties. However, high rates and prolonged high-intensity sonication reduce the β-sheet content and consequently the hardness. Overall, the combined enzymatic and high-intensity sonication treatment at 240 W for 30 min showed the best improvement in egg yolk emulsification properties[46].

4.3 Alkaline proteases

Hydrolysis by alkaline proteases increases protein solubility, exposes hidden hydrophobic groups, improves surface hydrophobicity, and reduces protein molecular weight, resulting in better adhesion at the oil-water interface[47]. Alkaline proteases can improve the thermal and emulsification stability of egg yolk. Enzymatic digestion reduces the molecular weight of egg yolk proteins and significantly hydrolyses poorly soluble yolk particles into smaller sized proteins or peptides, leading to a significant increase in protein solubility and thermal stability of the yolk liquid. The increased solubility of yolk particles also results in better emulsification properties. The emulsions prepared by enzymatic digestion of egg yolk liquid had smaller particle sizes and higher electrostatic charges, resulting in a significant increase in emulsification stability[48]. When HDL was extracted from eggs and treated with alkaline protease, its solubility increased from 7.69% to 27.54% at 1.5 h of hydrolysis, and accordingly its emulsification reached a maximum at 1.5 h, the reason may be the production of soluble peptide fragments and the exposure of ionisable residues[43].

In addition to a single type of enzyme treatment, scholars have found that the synergistic action of multiple enzymes can better improve the emulsification of egg yolk emulsions. Dual enzyme hydrolysis, especially neutral enzyme and trypsin, has been proposed as an effective method for the preparation of liquid egg yolk emulsions. The solubility of yolk protein increased with the prolongation of hydrolysis time, and the emulsifying activity, capacity, and stability of liquid egg yolk after hydrolysis were improved due to the diffusion of hydrolysed proteins or peptide chains in the solution phase and the rapid adsorption to the oil-water interface[49]. Despite the many advantages of protease hydrolysis, the application of protease treatment is still limited due to the high requirements of suitable enzymes and hydrolysis conditions. Considerable interest has arisen in the use of lipases, particularly phospholipases, which have been shown to be an effective method to improve the emulsifying properties of egg yolk powder. Phospholipases can hydrolyse ester bonds or acyl groups of triglycerides to form lysophospholipids or phosphatidic acid. Egg yolks treated with phospholipase A2 have higher emulsification activity compared to untreated yolks due to the presence of lysophospholipids after the enzyme reaction as well as higher protein solubility[50]. Synergistic treatment with phospholipase and protease resulted in an emulsification stability index of egg yolk powder in the synergistically treated group that was approximately 16 times higher than that of unmodified egg yolk powder and 1.44 times higher than that of the single phospholipase treatment due to reduced surface hydrophobicity. Scanning electron microscopy showed that dual enzyme hydrolysis promoted the formation of fine hydroxyproline with pore structure for more efficient rehydration[51]. However, it should still be noted that excessive enzymatic hydrolysis by proteases may lead to degradation of emulsification properties. The effect of enzymatic modifications on the physicochemical and functional properties of egg yolk proteins also requires further elaboration, and in general, specific restriction sites for hydrolysis may have a considerable impact on the degree of substrate digestion and hence emulsion properties. However, how protease treatment affects the different physical or chemical properties of hydrolysed egg yolk at different degrees of hydrolysis is not clear, which could be of considerable value in understanding substrate interactions and evaluating industrially prepared egg yolk emulsions[49].

Based on the current status of research on improving the emulsification of egg yolk powder by protein modification, the advantages and disadvantages of each modification method were analysed and compared with each other (Figure 2).

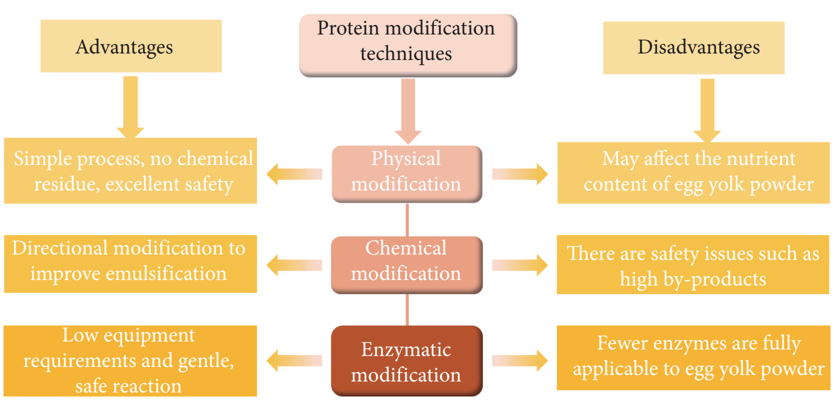

Figure 2 Overview of the advantages and disadvantages of egg yolk protein modification methods.

5 Conclusion and outlook

In recent years, the modification technology to improve the emulsifying properties of egg yolk powder through protein modification has made great progress, new physical modification methods, such as high hydrostatic pressure treatment, ultrasonic treatment, and pulsed electric field treatment, etc., show the potential to significantly improve the emulsifying properties of egg yolk powder without destroying the protein structure, but the research on highly emulsifiable egg yolk powder still faces many challenges. From the sterilisation of egg yolk emulsion to spray-drying, there are many factors affecting the emulsification performance of egg yolk powder, and modification at a later stage is an important means to improve the functional properties of egg yolk powder. Existing studies have shown that physical, chemical, and enzyme modification technologies have their own advantages, and have shown different effects in different application scenarios. Among them, enzyme modification technology is becoming a hot spot for future research because of its mild reaction conditions and high specificity.

With the diversified demands in the food field, the limitations of a single modification technology in practical application are gradually emerging in response to complex product demands. Therefore, future research should be more inclined to the joint application of multiple modification techniques to maximise the modification effect. With the continuous exploration of protein modification technology, the scope of its application will continue to expand, and the research on the comprehensive use of egg proteins will continue to deepen.

Conflict of interest

The authors have no conflicts of interest to declare.

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