A review on the development of pickled eggs: rapid pickling and quality optimization

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ABSTRACT Pickled eggs enjoy a long processing history with unique flavor and rich nutrition but suffer from long pickling cycle due to the limitations of traditional processing methods. In terms of quality, salted egg whites have the disadvantage of high sodium content, and salted egg yolks have problems such as hard core and black circle around outer layer. Likewise, the quality of preserved eggs is challenged by the black spots (dots) on the eggshells and the high content of heavy metals in the egg contents. The sustainable development of traditional pickled eggs are hindered by these defects and extensive research has been carried out in recent years. Based on the elaboration of the quality formation mechanism of salted eggs and preserved eggs, this paper reviewed the processing principles and applications of rapid pickling technologies like ultrasonic technology, magnetoelectric-assisted technology, water cycle technology, vacuum decompression technology, and pulsed pressure technology, as well as the quality optimization methods such as controlling the sodium content of the salted egg whites, improving the quality of salted egg yolks, promoting the quality of lead-free preserved eggs, and developing heavy metal-free preserved eggs. In the end, the future development trend of traditional pickled eggs was summarized and prospected in order to provide theoretical guidance for the actual production.

Key words: pickled eggs, formation mechanism, rapid pickling, quality optimization, development trend

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INTRODUCTION

Pickled eggs are a kind of egg product that does not change the shape of eggs, which are processed from fresh poultry eggs with salt, alkali, rice wine, and other main accessories, including salted eggs, preserved eggs, and eggs preserved in rice wine. Pickled eggs have a long history and are currently the main product form of the egg processing industry, with salted and preserved eggs being the main ones. High-quality cooked salted eggs should be fresh, tender, fine, loose, gritty, and oily. Salted egg whites are smooth, tender, and delicate; the egg yolks are orange-red, oily, gritty, and rich in nutrients. Apart from direct consumption, salted egg yolks are often used as filling in the processing of some traditional Chinese foods such as mooncakes and zongzi (traditional Chinese rice pudding). The traditional processing method of salted eggs includes wrapping and pickling fresh eggs with a mixture of soil (or plant ash), salt, and water, or the fresh eggs are directly soaked and pickled in a specific concentration of salt solution for 20 to 35 days (Chi and Tseng, 1998). The preserved eggs, also known as pidan, have anti-inflammatory (Zhao et al., 2017; Mao et al., 2018; Zhang et al., 2018, 2019; Batool et al., 2021), and anti-cancer (Batool et al., 2021; Liang et al., 2020; Mao et al., 2018) effects, all beneficial to human health. Poultry eggs are usually pickled in a mixture of alkali, salt, black tea, and heavy metal compounds at room temperature for 4 to 6 wk (Tu et al., 2012; Su and Lin, 1993). The finished preserved eggs have a unique flavor, and the egg white gels formed by the action of alkali are usually brownish-red or brownish-brown. In some regions, preserved eggs are characterized by golden gel. The egg white gels of high-quality preserved eggs are easy to separate from eggshells and are transparent and elastic. Preserved egg yolks are solidified, dark green, and very delicious.

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Saturated salt water has been used for pickling salted eggs to fasten the pickling speed and shorten the pickling time. However, this could cause over-salting of the finished product. Because most of the over-salted egg whites are discarded, high-quality proteins go to waste and could cause environmental pollution. On the other hand, long-term consumption of high-sodium-based salt increases the concentration of sodium ions in the human body, and the resultant sodium-potassium imbalance could cause diseases such as hypertension and arteriosclerosis (Zheng et al., 2021). Preserved eggs also have a long maturation period, and the heavy metal compounds used in the pickling liquid raise consumer concerns about their safety (Fu et al., 2014). Disposing of the pickling liquid of preserved eggs containing heavy metal compounds could cause environmental pollution. To solve the aforementioned problems, there is a need to explore how to shorten the processing time and improve the quality of pickled eggs. This paper reviewed the relevant research progress in the sustainable processing of pickled eggs.

MATURATION MECHANISM OF PICKLED EGGS

The Maturation Mechanism of Salted Eggs

Salted eggs are the products of fresh poultry eggs pickled with several auxiliary ingredient, and salt is the most important pickling ingredient. The pickling process of salted eggs involves the diffusion and penetration of salt into the eggs through the pores on the eggshells and the inner membrane of the eggshells. After the salt dissolves in water, osmotic pressure is generated by the concentration difference formed inside and outside the eggs. The high osmotic pressure causes the sodium chloride (NaCl) to diffuse rapidly in the egg whites, while the water inside the eggs gradually drains outwards. The egg whites gradually lose viscosity and undergo thinning (Figure 1; Cheng et al., 2018). Under the continuous action of osmotic pressure, NaCl enters the yolks and induces the formation of gels. The amount of NaCl that penetrates the yolks is lower compared to the egg whites. On the one hand, both the high-fat content in egg yolks and the barrier of the yolk membranes slow down the infiltration of NaCl into egg yolks (Kaewmanee et al., 2009). On the other hand, the protein molecules in yolks and protein and lipid molecules interact and aggregate, causing the gradual formation of gels (Xu et al., 2018). To some extent, the formation of gels prevents the excessive infiltration of NaCl into the egg yolks (Chi and Tseng, 1998).

During the pickling process with salt, the moisture and pH values of both egg whites and yolks decrease while the salt content increases significantly, along with the obvious change in the status of egg whites and yolks. At the same time, the oil yield, hardness, chewiness, and elasticity of the egg yolks increase (Xu et al., 2017, Ai et al., 2018). However, the viscosity of the egg whites decreases, whereas that of egg yolks increases. Unlike the gradual thinning of egg whites, the most important feature of egg yolks is salt-induced gelation. The changes in the plasma and granules in the yolks during this process are shown in Figure 2 (Xu et al., 2019b). When the dispersion system of yolks is disrupted and aggregation occurs, the granule particle size and zeta potential of yolks decrease significantly, which promotes the hardening of the egg yolk, creating favorable conditions for achieving egg yolk grittiness (Ai et al., 2018). The final formation of the gritty structures is due to the random aggregation of several proteins released after the destruction of plasma and granules in yolks, which dehydrates and solidifies the yolks, and the shape of spherical egg yolk granules changes (Bao et al., 2020). It is worth noting that the aggregation of proteins in yolks is accompanied by changes in the spatial structure under the action of NaCl, in which structural changes in low-density lipoprotein (**LDL**) and enhanced interactions between apolipoproteins and lipids promote the release of apolipoproteins, phospholipids, and neutral lipids, all

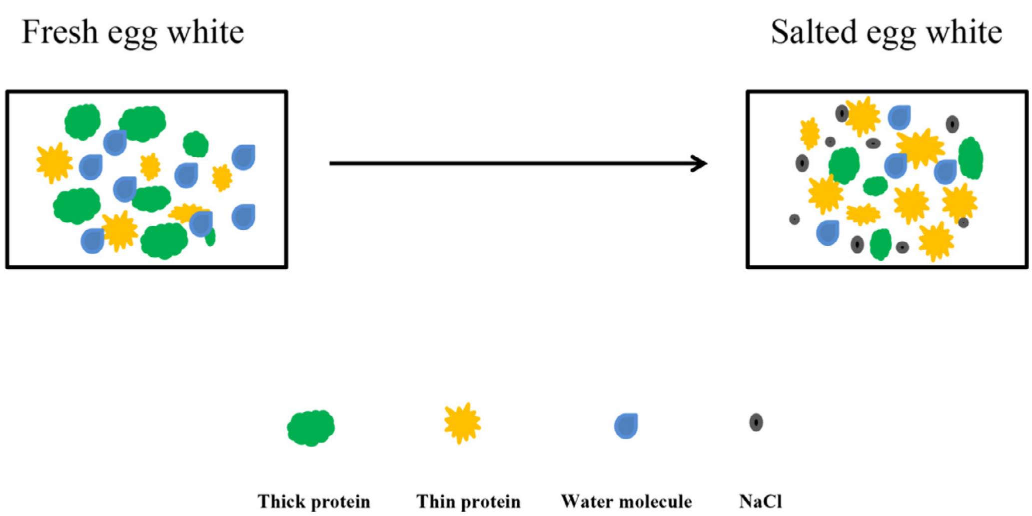


Figure 1. A schematic of the change of egg white before and after pickling with salt.

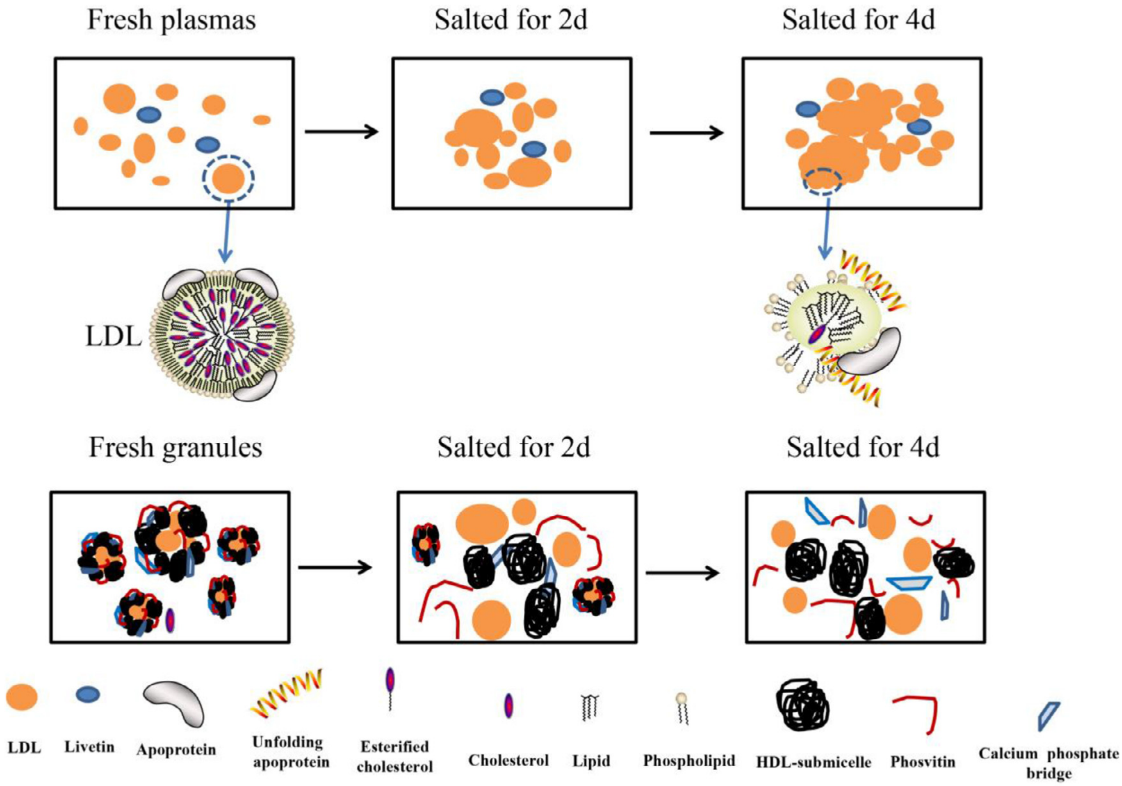


Figure 2. A schematic of the behavior of the plasma and granules in egg yolk during pickling with salt.

of which causes a gradual increase in free lipids in the yolk (Xu et al., 2019a). These free lipids accumulate as oil droplets, increasing the solubility of fat-soluble pigments and deepening the color of yolks (Xu et al., 2019b). The grittiness and oiliness of egg yolks are important factors that affect consumers' acceptance of salted eggs. However, longer pickling time increases water loss in egg yolks to the point a hard core appears inside. At this point, the oiliness and grittiness reduce, and the overall quality decreases.

The Maturation Mechanism of Preserved Eggs

At present, preserved eggs are commonly processed using alkaline liquids including food-grade sodium hydroxide (NaOH), salt, and small amounts of non-lead metal ions. When alkali liquids penetrate poultry eggs, proteins undergo hydrolysis, and the preserved eggs form characteristic gels due to multiple interactions between proteins and between proteins and solvent molecules (Wang and Fung, 1996).

The "sol-gel" transition mechanism of egg whites (Figure 3) has been systematically studied. The results show that ovalbumin and other proteins in egg whites are completely denatured under a strong alkali. The proteins fully unfold, and the resulting conformational changes expose the hydrophobic groups inside the molecule. At the same time, some protein groups are ionized, forming ionic bonds with other surrounding ions. The exposed sulfhydryl groups generate disulfide bonds from oxidation-reduction reactions or ion exchange reactions, and eventually, egg whites gel mainly through the action of ionic and disulfide bonds (Zhao et al., 2016b). In the initial stage of egg white gel formation, proteins are denatured, but the primary and secondary structures are not yet damaged, the free water content in fresh egg whites gradually increases, and the viscous egg whites gradually turn into a thin, transparent solution. In the solidification stage, the secondary proteins structures are damaged, hydrogen bonds are broken, the disulfide bonds tend to rise, and a large amount of free water becomes bound water again and connects with the protein molecules to form a transparent elastic colloid, all under the action of infiltrating alkali. During the color change phase, the primary structures of the proteins are destroyed, and at the same time, the Maillard reaction occurs, and the elasticity of egg white gels decrease while the color slowly changes from yellow to brown. The final stage of maturation is the complete denaturation of proteins when gels turn completely dark brown and retain a certain degree of elasticity (Ma et al., 2006). The microstructure of mature preserved egg white gels shows that it is a fine three-dimensional gel network interwoven with a loose linear fibrous mesh structure, and the mesh structure becomes more regular, finer, and compact with the alkali treatment time. Moreover, the egg white gels are maintained by numerous ionic bonds (85%), a few disulfide bonds (5%), and very few hydrophobic interactions and hydrogen bonds (Chen et al., 2015; Zhao et al., 2016a,2016b). The preserved egg white gels have specific textural properties, which may result from changes in the protein in response to the alkali action.

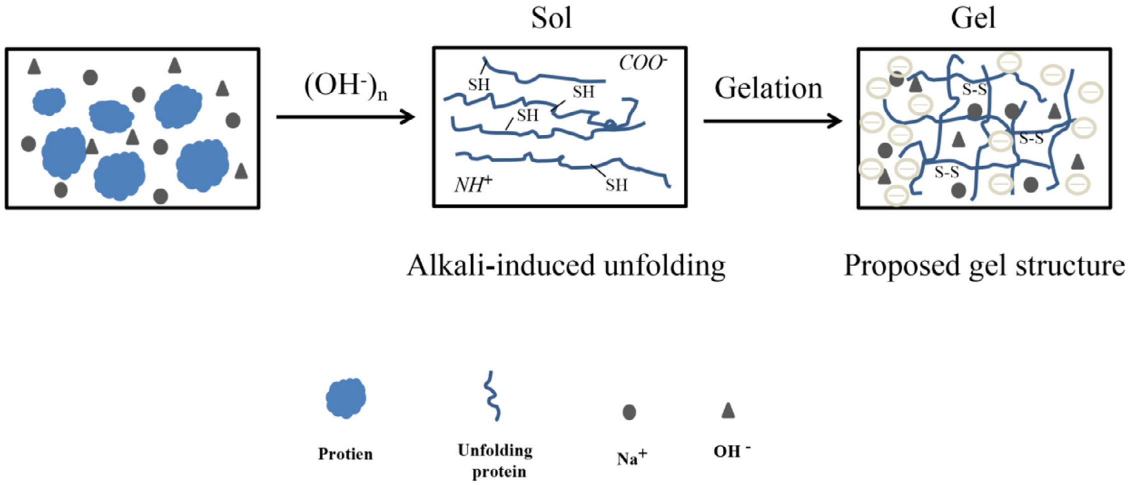


Figure 3. A schematic of the formation mechanism of preserved egg white gel induced by strong alkali.

Chang et al. (1999) found that the content of 2 basic amino acids, lysine and arginine, decreased significantly during the processing of preserved eggs, whereas threonine, cysteine, and serine also decreased significantly. However, the sulfur generated by the decomposition of sulfur-containing amino acids and the reaction products of sulfur and metal ions form the special flavor and texture of preserved eggs. Eiser et al. (2009) used modern analytical technologies to analyze the physical phase changes of the preserved egg whites during processing and found that the preserved egg whites eventually formed fine chains of denatured globule polymer proteins. Handa et al. (1998) found that the hardness, elasticity, and chewiness of the preserved egg white gels were stronger at pH 11 than at pH 3, 5, 7, and 9, and the microstructure of the preserved egg white gels was uniform and had finely cross-linked microfilaments at pH 11. Therefore, the formation of the special texture of egg white gels is also inseparable from its good microstructure.

The coagulation of egg yolks starts from the exterior to the interior. The exterior egg yolk first solidifies, and the egg yolk interior becomes viscous. The sol range gradually decreases with the prolonging of pickling time (Figure 4; Yang et al., 2019). The exterior egg yolks produce small molecular proteins and high-molecular-weight cross-linked proteins, both with relatively stable β-structures, and the intermolecular forces mainly include ionic bonds, hydrophobic interactions, and disulfide bonds. The protein structures of the yolk interior are similar to that of fresh duck eggs, with more β-structures undergoing interconversion between secondary structures and intermolecular forces consisting mainly of ionic bonds, hydrogen bonds, and hydrophobic interactions (Yang et al., 2019). The solidification of yolks is accompanied by a gradual deepening of the color. Sulfur-containing amino acids in egg yolk proteins degrade to produce sulfur ions (S^{2-}) under a strong alkaline conditions. S^{2-} reduces the ferric iron of phosvitin in egg yolks to ferrous iron, forming ferrous sulfide with ferrous iron. The resultant product is a characteristic blue-green product, the inherent yellow pigment in the yolk complexes with this blue-green product to turn it into yellow-green or dark green (Li et al., 1992). The resulting yellow-green or dark-green opaque agglomerated gels have a unique and delicious flavor. Yang et al. (2020a) revealed the different gelation behavior of LDL and high-density lipoprotein (**HDL**), abundant in egg yolks, under alkaline environments. LDL and HDL play a crucial role in the aggregation behavior of whole egg yolks. The alkali treatment destroys the yolk plasma and granules, releasing various protein components, including LDL and HDL. Under strong alkaline conditions, the spatial structures and peptide chains of LDL are altered, producing unknown proteins. Relying on ionic bonds, hydrophobic interactions, and disulfide bonds, LDL forms gels in which proteins and lipids bind and hold abundant water. While HDL undergoes extensive unfolding and reorganization, network structures with high thermal stability and uniform density are formed mainly through the support of ionic and disulfide bonds, increasing the hardness and binding force of whole egg yolk gels (Yang et al., 2020a,2020b).

During the pickling process of preserved eggs, if the concentration of NaOH in the pickling solution is too high, the coagulated preserved egg whites are hydrolyzed and liquefied, and the yolks become harder (Ganasen and Benjakul, 2010,2011,2014). This is because the high alkali concentration denatures proteins that rapidly aggregate to form gels, while some unfold to expose more hydrophobic groups. With continuous penetration of lye, the disulfide bonds of the translucent elastic gels are broken, and they easily and gradually decompose into amber-colored sols through a phenomenon called alkali liquefaction (Gao et al., 2020). Adding an appropriate amount of heavy metal compounds to the pickling solution prevents excessive alkali damage to the egg white gels (Yan and Zhu, 2006; Ganasen and Benjakul, 2010; Tu et al., 2012). Heavy metal compounds regulate the penetration of alkaline compounds by forming insoluble sulfides that plug the eggshell stomata and the corrosion pores produced by alkali treatment, thereby inhibiting the liquefaction of gels during the pickling process (Ma et al, 2006). Therefore, it is very important to regulate the total amount and

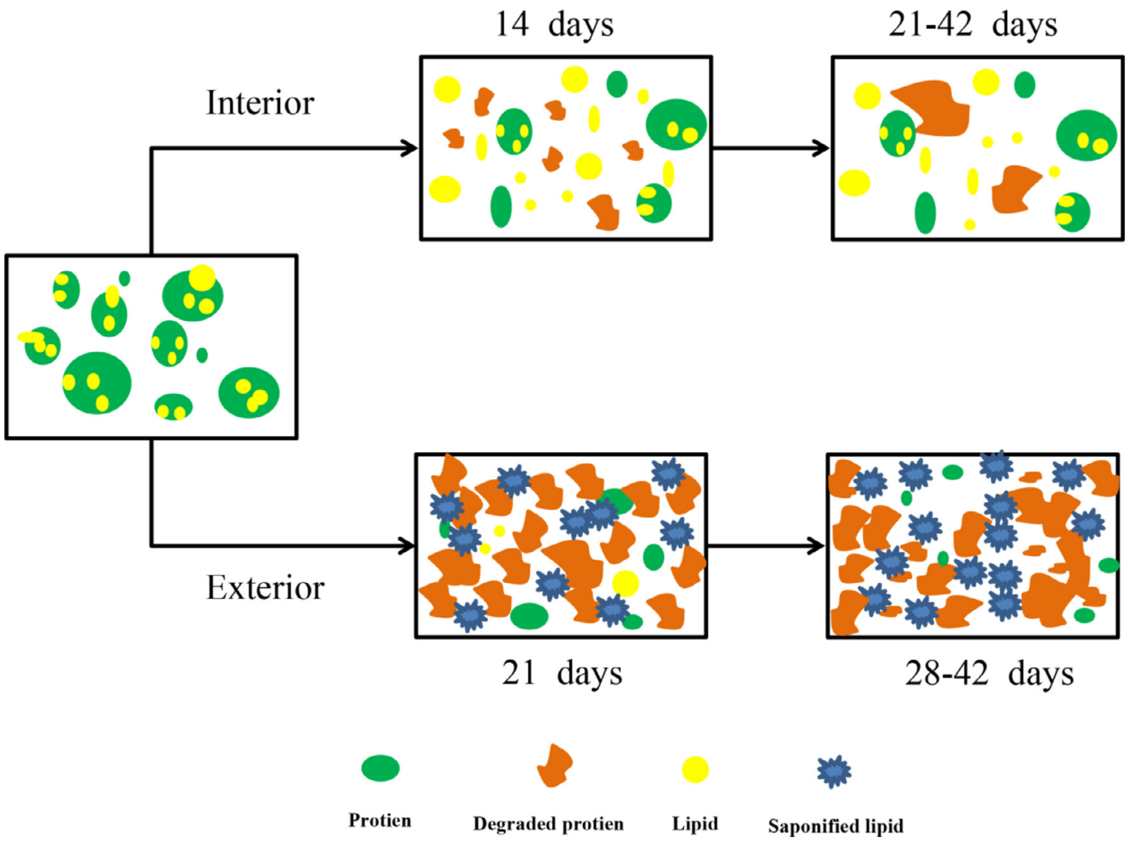


Figure 4. A schematic of the gelation behavior of internal and external egg yolk under strong alkali treatment.

rate of NaOH penetration into poultry eggs during the processing of preserved eggs. Factors affecting alkali penetration include alkali concentration, processing temperature, processing time, type and content of heavy metal ions, and the concentration of other additives, which directly or indirectly affect the quality of preserved eggs.

RAPID PICKLING TECHNOLOGIES FOR PICKLED EGGS

The lengthy production cycle of traditional pickled eggs has been a major obstacle to the expansion of the egg processing industry, and the development of rapid pickling technologies has been ongoing to address this issue. Several emerging technologies have been evaluated for application in the processing of pickled eggs. The classification, application principle, and application object of each type of technology are shown in Table 1.

Ultrasonic-Assisted Pickling Technology

Ultrasound is an elastic mechanical vibration wave that produces strong vibrations accompanied by mechanical, thermal, and cavitation effects, which affect the physicochemical, biological, and structural characteristics of food products (Xie et al., 2020b). Ultrasound also has emulsification, concentration, comminution, sterilization, and chemical effects (Xie et al., 2020a; Geng et al., 2021). Ultrasound has been widely used in the food industry, in detecting certain compounds (Krautkrämer and Krautkrämer, 2013), assisted extraction (Jiang et al., 2019), tenderization (Hu et al., 2018), preservation, and storage (Yüceer and Caner, 2020).

Principle of Ultrasonic-Assisted Pickling Technology Ultrasonic technology accelerates the diffusion of the pickling liquid through mechanical effects and cavitation, while increasing the permeability of the eggshell membranes and yolk membranes (Figure 5). Pickling after ultrasound treatment rapidly reduces the viscosity of the egg whites, increases the hardening rate of the yolks (Dang et al., 2014). Specific studies (Sheng et al., 2018; Chen et al., 2019) have found that ultrasound reduces the surface tension of egg whites and increases the protein solubility and the content of free sulfhydryl and surface hydrophobicity. These changes induce molecular rearrangements and flexibility of egg white proteins. In conclusion, ultrasonic treatment changes the aggregation and surface morphology of egg whites. For egg yolks, ultrasound treatment induces the aggregation of LDL and partial dissociation of yolk granules, directly altering the functional properties of yolks (Xie et al., 2020b).

Application of Ultrasonic-Assisted Pickling Technology Ultrasound pretreatment once (5 min, 80 kHz, 180 W) ensured salted duck eggs matured in 25 d (Lin et al., 2011). Thus, ultrasonic pretreatment reduces the pickling period. Compared with the traditional method, repeated ultrasonic treatment of duck eggs during the pickling process (ultrasonic treatment 3 times, each time for 30 min, ultrasonic power 350 W, ultrasonic frequency 20 kHz) further reduced the pickling time to

Table 1. The main rapid pickling technologies for the pickled eggs.

Pickling technology	Application principle	Application object	References
Ultrasonic- assisted	Use the mechanical effect and cavitation to promote the diffusion of material and liquid, while improving the permeability of eggshell and yolk membranes	Salted eggs	Lin et al., 2011; Dang et al., 2014; Sun et al., 2018; Yu et al., 2022
Magnetoelectric- assisted	The alternating electric field force and alternating magnetic field force (Lorentz force) cause large-scale directional motion of free ions, accelerating the rate of penetration, and diffusion of the marinade	Salted eggs	Yang et al., 2015
Water cycle	Enhancement of solute permeability while improving fluid uniformity	Salted eggs	Pu et al., 2010
Vacuum decompression	Hydrodynamic mechanism (HDM) and deformation relaxation phenomenon (DRP)	Salted eggs preserved eggs	Ji et al., 2013; Xu et al., 2015; Shao et al., 2017; Sun et al., 2020; Chen et al., 2022
Pulsed pressure	The pressurization phase promotes the penetration of the marinade into poultry eggs, while the depressurization phase accelerates the gas and water leaking out of poultry eggs	Salted eggs preserved eggs	Sun et al., 2012; Guo et al., 2013; Wang et al., 2013a, b, c; Yuan et al., 2018

20 days, and the oil yield increased significantly, the color was more appealing, and the size of the hard core decreased (Sun et al., 2018). In addition, Yu et al. (2022) demonstrated that high-intensity ultrasound treatment of the pickling liquid also shortens the pickling cycle.

Evaluation of Ultrasonic-Assisted Pickling Technology Ultrasonic treatment can improve the pickling efficiency and shorten the pickling time, and enhances effective salt distribution between the egg whites and the yolks, which to a certain extent, improves the overall quality of salted eggs. Ultrasound should be performed in a regulated manner. Excessive ultrasound may break the eggshells and allow air into the egg whites, which gives the egg whites a honeycomb-like appearance after cooking. In addition, it is not clear how the thermal effect of ultrasound impacts the quality of the salted eggs. Theoretically, ultrasound could be applied in processing preserved eggs because it shortens the pickling time. However, the hypothesis has not been validated.

Magnetoelectric-Assisted Pickling Technology

Magnetoelectric technology is a method that assembles components such as function signal generators, power amplifiers, toroidal silicon steel cores, coil windings, and platinum silicone tubes to produce variable alternating induced electric fields (**AIEF**) and rotating magnetic fields (**RMF**). At present, the application of

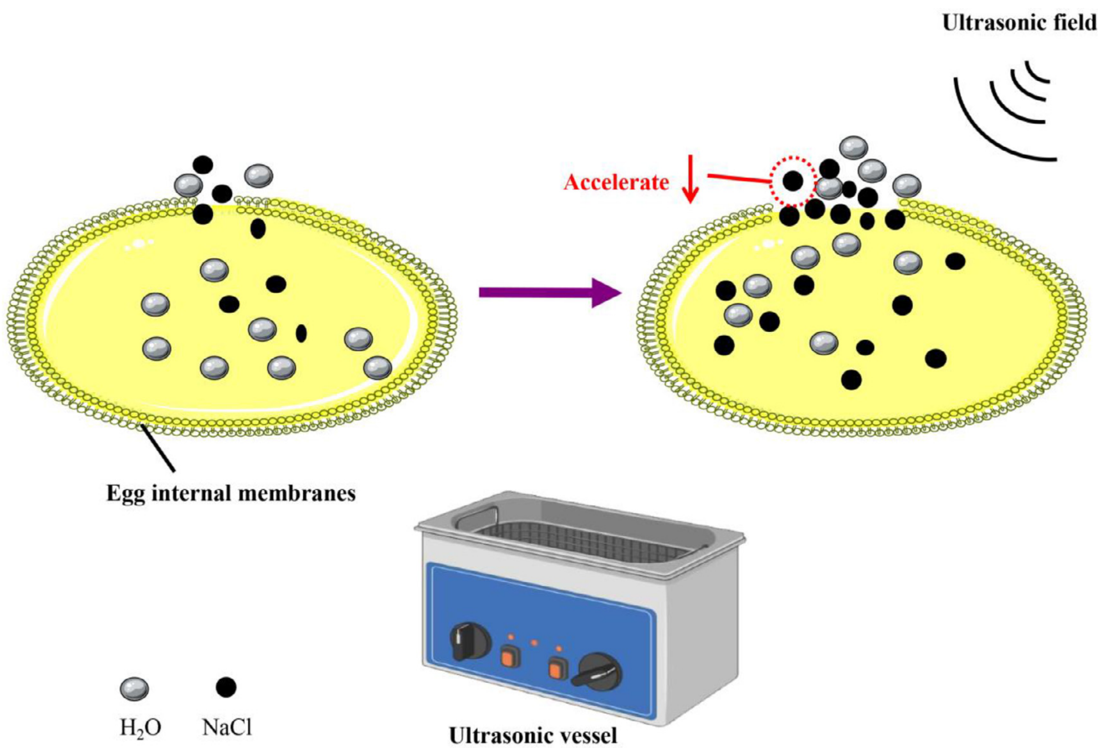


Figure 5. A schematic of the mechanism of ultrasonic-assisted pickling salted eggs. Note: Ultrasound vessel material from BioRender.com

this technology in the food industry focuses on sterilization (Torgomyan and Trchounian, 2013) and freeze preservation (Zhan et al., 2019), among others.

Principle of Magnetoelectric-Assisted Pickling Technology It has been reported (Pryor, 2013; Jin et al., 2014) that electrolyte solutions (salt solutions) can absorb voltages and induced currents and undergo significant ionic conduction in AIEF. RMF can enhance the diffusion of ions in the solution (Rakoczy et al., 2017). Therefore, the use of AIEF and RMF to accelerate the pickling of salted eggs exploits the movement property of ions in an alternating electric field and alternating magnetic force (Lorentz force). During the pickling process, sodium and chloride ions move directionally in the alternating electromagnetic field, increasing the pickling rate by improving the mass transfer efficiency of sodium chloride in the egg white and yolk.

Application of Magnetoelectric-Assisted Pickling Technology Yang et al. (2015) successfully designed and manufactured magnetoelectric pickling equipment according to the relevant technical principles (Figure 6) and demonstrated that the pickling rate could be adjusted by altering the voltage amplitude, electric field frequency, radial magnetic field rotation frequency, magnetic field strength, and the specification of relevant equipment parameters. Through this process, salted eggs could be obtained in about one week, and the oil yield of yolks increases significantly. The salt content and oil yield of the salted eggs increased with the system voltage and magnetic field strength.

Evaluation of Magnetoelectric-Assisted Pickling Technology The magnetoelectric-assisted treatment substantially accelerates the pickling speed and has a significant incremental effect on the important physicochemical indicators of salted eggs. Future studies should explore the possibility of replacing the low-frequency silicon steel cores commonly used now with high-frequency ferrite core materials or using energized solenoids with strong corrosion resistance to obtain higher magnetic field strengths, which could enhance the pickling effect (Yang et al., 2015). This technology is still in the experimental stage, and it requires complex and expensive equipment. Therefore, it is challenging to promote this technology. Magnetoelectric induction without using energized pole plates or electrodes could be a novel method for the rapid pickling of salted eggs. Theoretically, magnetoelectric technology should enhance the pickling speed of preserved eggs. However, the practical application of this technology remains to be validated. Overall, the application of magnetoelectric technologies for pickling eggs, both theoretically and practically, needs further validation.

Water Cycle Pickling Technology

In this method, a pump is fixed at the bottom of the pickling container, and the pump outlet is higher than the height of the container. The pickling solution is pumped daily to move the brine in the tank up and down in a circular manner.

Principle of Water Cycle Pickling Technology The water cycle pickling technology effectively improves the homogeneity of the salt solution. It also induces conformational changes in the hydrophilic substances within the eggs, promoting hydrogen bonding between these substances and the hydroxyl or hydrogen of the water (Cheng et al., 2009), this reduces the resistance of

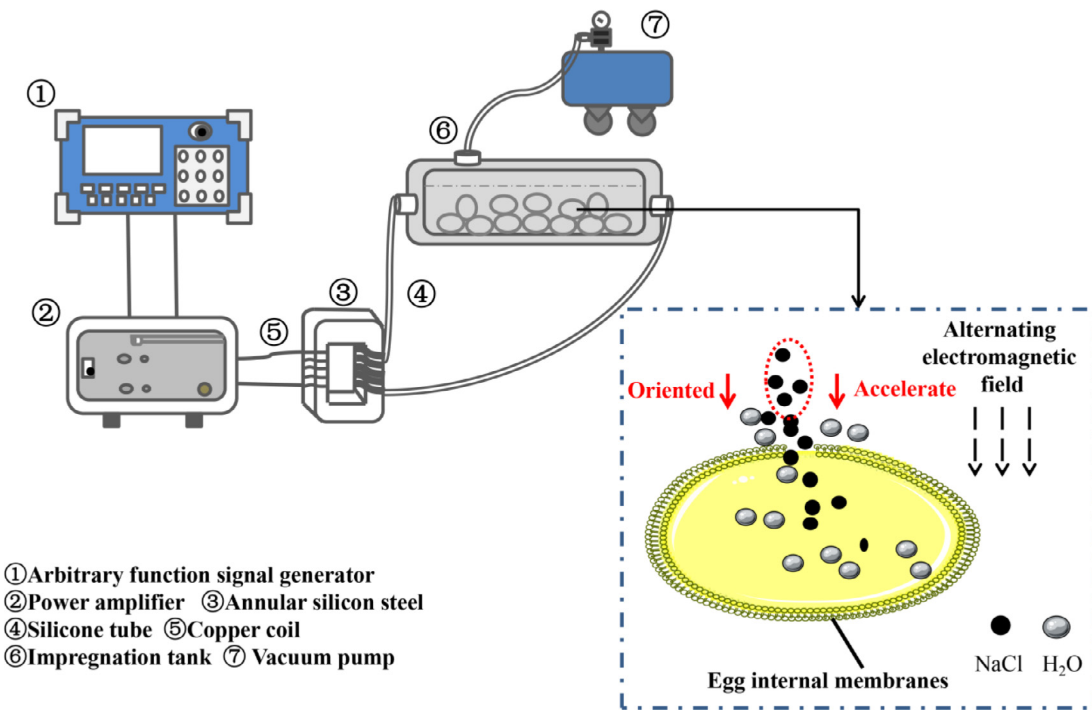


Figure 6. A schematic of magnetoelectricity equipment for salted eggs processing.

transferring the brine and ensures that the salt penetrates evenly and rapidly into poultry eggs.

Application of Water Cycle Pickling Technology Pu et al. (2010) demonstrated that salted eggs pickled with water cycle technology matured more quickly, the salt concentration in egg whites was more homogeneous, the difference in salt content between the egg whites and yolks reduced, and the proportion of muddied yolks was also greatly reduced.

Evaluation of Water Cycle Pickling Technology In recent years, the high salt concentration immersion method has been used for pickling salted eggs because it is simple, clean, and suitable for mass production. However, because the salt concentration of the pickling solution is not uniform, there salting degree of each salted egg varies considerably. Water cycle technology can reduce the salinity difference of salted eggs based on shortening pickling time. Compared with other rapid pickling technologies, the water cycle technology is slightly inferior in accelerating the pickling rate, and the specific operation and effect of the process also need further investigation. However, it is simple, cheap, and easy to operate, which could enhance its application. As for preserved eggs, the technology is not suitable because the pickling liquid commonly contains certain heavy metal compounds. However, there is need to explore using the water cycle technology in the pickling preserved eggs without using heavy metal.

Vacuum Decompression Pickling Technology

Vacuum decompression pickling technology is a processing method that applies vacuum technology to the pickling industry and is now commonly used in the pickling process of meat, fruits, and vegetables (Ramírez et al., 2020; Santarelli et al., 2021; Demir et al., 2022).

Principle of Vacuum Decompression Pickling Technology The vacuum stage involves a gas below atmospheric pressure. After vacuuming, a certain pressure difference is formed inside and outside the confined space, and the degree of the pressure difference depends on that of the vacuum. The pressure difference accelerates the movement of molecules in the material, increasing the speed and improving the uniformity of the processing. A large amount of gas and free water escapes from pickled eggs under the vacuum, and the eggshell membrane integrity changes or is even destroyed. Meanwhile, the movement of molecules in the pickling liquid is accelerated, increasing the penetration of the liquid into the eggs (Yongsawatdigul and Gunasekaran, 1996). Vacuum technology utilizes a combination of hydrodynamic mechanism (**HDM**) and deformation relaxation phenomenon (**DRP**) to improve the pickling efficiency (Derossi et al., 2012). Thus, this method could be applied to processing other foods in the future.

Application of Vacuum Decompression Pickling Technology Vacuum equipment for pickled eggs comprises a vacuum pump, confined container (pickling tank), vacuum pressure gauge, control valves, and other components. The main equipment components and the processing principle are shown in Figure 7. The function of the vacuum pump is to reduce the air pressure inside the pickling tank. The vacuum pressure gauge monitors the air pressure in the pickling tank. Adjusting the control valve allows the device to reach a predetermined vacuum level, and the vacuum holding time can also be regulated. The vacuum pickling method of salted eggs can shorten the pickling process by half, and the higher the vacuum degree, the shorter the pickling time (Chen et al., 2022). There is no significant difference in the oil yield of salted egg yolks between the traditional methods and the vacuum method, but the vacuum method imparts better color and taste. There is no difference in the nutritional quality of salted egg yolks processed with the traditional and vacuum methods (Xu et al., 2015). Acid pretreatment has been used to further increase the pickling speed. Specifically, fresh duck eggs are pre-treated with citric acid to alter the permeability of eggshells, the pickling temperature is adjusted to 40°C, and the vacuum is maintained for 23 h per day. Under these conditions, the maturity index is achieved in just 6 d (Shao et al., 2017). Thus, combining the decompression technology with other methods could effectively increase the pickling speed. Some research has shown that the vacuum technology reduces the pickling time of the preserved eggs by about 2/3 (Sun et al., 2020). Vacuum pickling induces rapid changes in preserved egg whites, in which the sulfhydryl group and surface hydrophobicity increase, whereas disulfide bonding reduces. The secondary structures of proteins in preserved egg whites are also altered, marked by a decrease in non-random structures and an increase in disordered structures. There are no significant differences in the protein patterns among fresh and processed egg whites for up to 4 d, but most proteins in the processed egg whites disappeared on d 5, and a single ovalbumin band usually appears from d 6 to the end of the maturation period (Ji et al., 2013). Similar changes are observed for the preserved egg whites pickled by the traditional method, except that the time for these changes is considerably longer than the vacuum method. Research on vacuum-pickled preserved egg yolks remains scanty, but there is no difference in the flavor for eggs processed by the traditional and the vacuum method.

Evaluation of Vacuum Decompression Pickling Technology Research on food vacuum technology is currently on the rise, and there is a continuous search for technologies that can replace or complement traditional pickling methods. The vacuum processing technique is one such method because it is suitable for pickling various egg products and reduces the pickling time. Although the pickling speed is inferior to magnetoelectric-assisted technology, it is stronger than ultrasonic-assisted technology. The performance of the

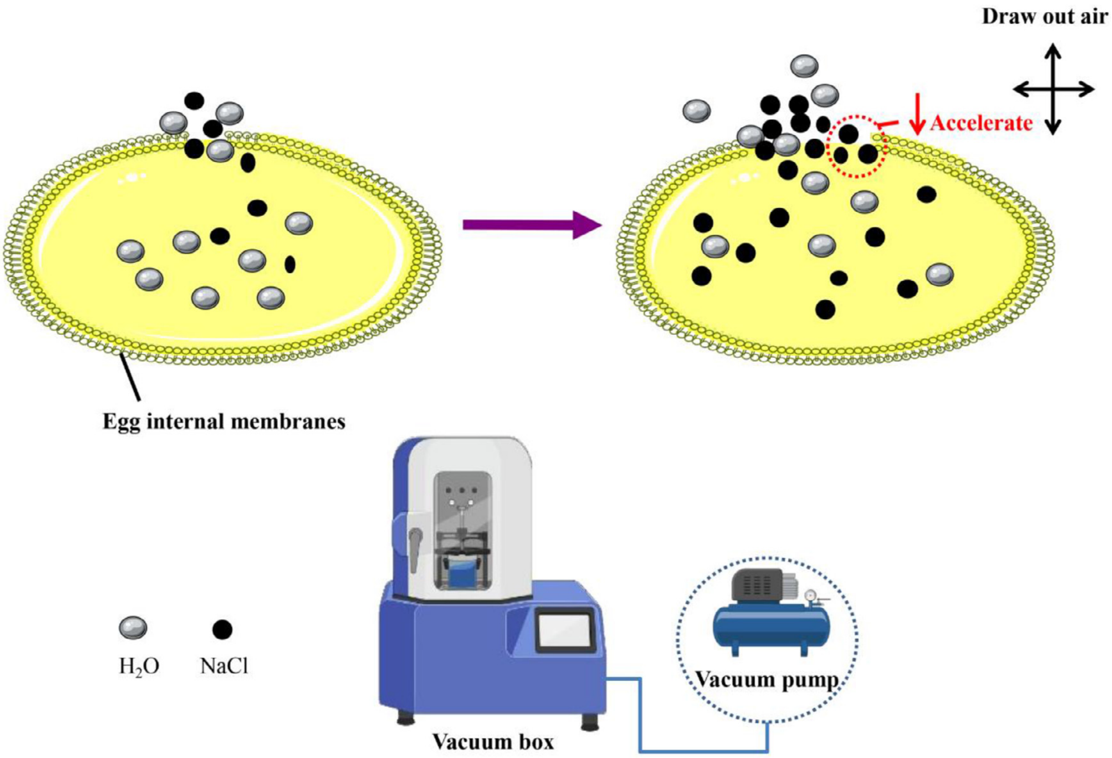


Figure 7. A schematic of the vacuum equipment and the mechanism of accelerating pickling eggs by vacuum decompression. Note: Vacuum box material and vacuum pump material from BioRender.com.

current vacuum pickling equipment is reasonably reliable. They are made of stainless steel, have a compact structure and low noise, and are easy to operate. Despite these, the uniformity of pickling needs improvement if this technology is to achieve industrial application. In vacuum processing, the vacuum level, duration, and speed of breaking the vacuum should be highly regulated to avoid cracking the eggshells.

Pulsed Pressure Pickling Technology

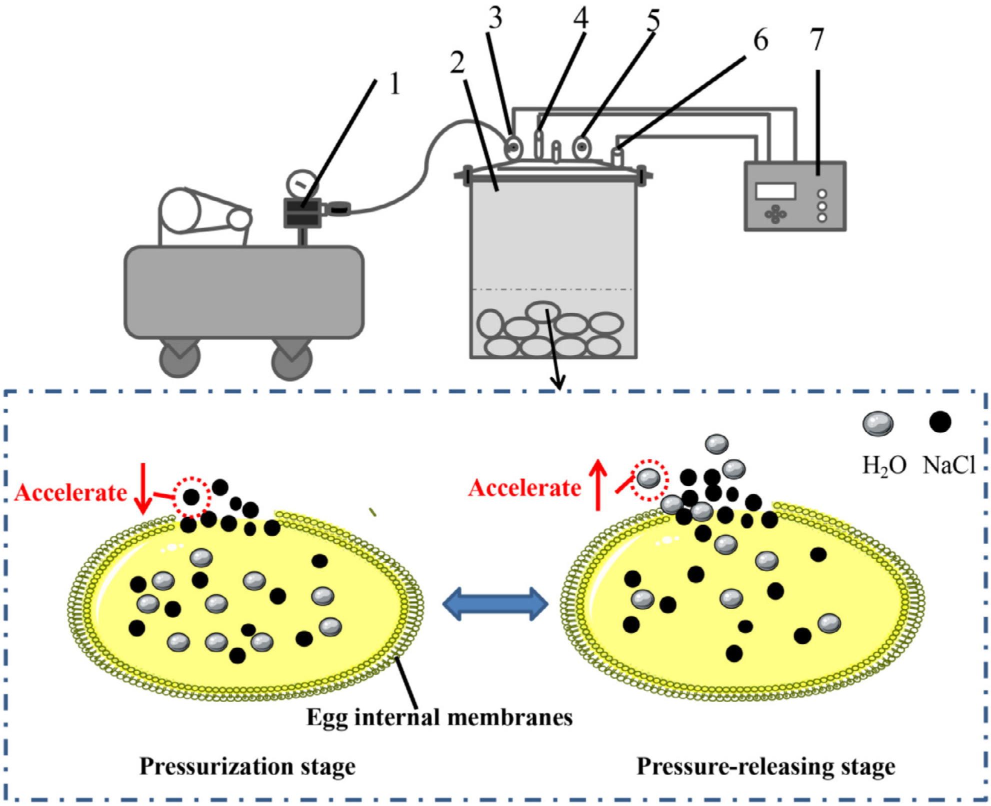
As an emerging highly efficient technology for controlling pressure, pulsed pressure is applied to enhance the mass transfer and quality properties of different foods (Jin et al., 2015). The pressurization and pressure-releasing of the pressure vessel are controlled using the on-off solenoid valve to achieve pressure pulsation, creating a constantly changing environment of stress for pickling. When applied to pickled eggs, this method can substantially increase the speed of pickling compared with traditional pickling.

Principle of Pulsed Pressure Pickling Technology

In the pressurization stage, osmotic pressure is increased to accelerate the penetration of the liquid into the eggs. In the pressure-releasing stage, the pressure inside the eggs is higher than the outside pressure, which accelerates the exudation of gas and water from poultry eggs, providing space for the infiltration of the high-concentration solution in the pressurized section. This cycle can be used to shorten the processing time (Wang et al., 2013a).

Application of Pulsed Pressure Pickling Technology

Wang et al. (2013c) described in detail the equipment used for pickling (Figure 8) and optimized the process by comparing different pressures and pulsation frequencies. With salt and moisture content of salted eggs as indicators, they established that the optimal pressure and pulsation frequency were 160 kPa and 7.5 min/15 min, respectively. This process resulted in a significantly higher salt content in salted eggs after 48 h, solidified egg yolks, oil exudation, and gritty structures. Yuan et al. (2018) found that pulsed pressure increased the exudation rate of salted egg yolks oil and concluded that pulsed pressure facilitated gas and salt penetration by changing the microstructure of the shells and membranes as well as the distribution of water. There have also been attempts in recent years to combine pulsed pressure technology with other technologies to pickle salted eggs. For example, a combined ultrasonic-pulsed pressure technology (Wang et al., 2013b) has been used to pickle mature salted eggs in 3 d. As this method reduces the difference in salt content between the egg whites and yolks, the taste of salted eggs is improved compared with a single pulsed pressure treatment. Further, Wang et al. (2013a) combined pulsed pressure and water cycle technology, selecting water cycle and pulsed pressure parameters, to investigate the optimal combination of process parameters. For preserved eggs, the pressurization amplitude, pressurization time, and pressure-releasing time had a highly significant effect on the weight gain rate of preserved eggs and the size of the unconsolidated part of yolks (Guo et al., 2013). Under the optimized pulsed pressure conditions, it took only



1. air compressor; 2. pressure vessel; 3. pressure adding electro-magnetic valve; 4.pressure sensor; 5. pressure releasing electromagnetic valve; 6. relief valve; 7. control system.

Figure 8. A schematic of pulsed pressure equipment for salted eggs processing.

8 days to obtain the mature preserved eggs. The pickling time could be further reduced by increasing the pickling temperature (Sun et al., 2012).

Evaluation of Pulsed Pressure Pickling Technology Pulsed pressure pickling is a fast pickling technology that can be efficiently used with both salted eggs and preserved eggs, to greatly shorten the pickling cycle and improve the quality of egg products. The pulsed pressure equipment has been developed rapidly in recent years, with significant improvements in the automatic pressure-releasing control, successfully simplifying the operation process of the equipment. To overcome the shortcoming of uneven pickling, oscillating devices are used. Overall, the pulsed pressure technology can significantly improve the pickling rate of egg products and quality. Because the equipment is stable and easy to operate, and has low operational costs, it is a worthwhile investment for major poultry egg processing enterprises.

QUALITY OPTIMIZATION OF PICKLED EGGS

Quality Optimization of Salted Eggs

Since the 20th century, scientists have been advocating for a healthier lifestyle – a low sodium diet (Mayer, 1971). Scientific research has proved a strong association between high dietary salt content and poor health outcomes. The dietary guidelines for Chinese residents recommend a maximum daily salt intake of 6 g for adults. Countries such as Finland and the United Kingdom have successfully reduced the mean blood pressure, risk of stroke in their populations, and number of deaths from ischemic heart disease by limiting salt intake in their populations (He et al., 2021). The high sodium content of traditionally salted eggs is not good for human health and is not aligned with low-salt dietary recommendations. With the growth in incomes, consumers are increasingly preferring a healthy low-salt diet. To meet the growing market demand, the development of low-sodium foods and sodium salt substitutes is urgent. Therefore, to optimize the quality of salted eggs, one approach is to reduce the sodium content, mainly in egg whites. Notably, as the quality of salted egg yolks often determines the popularity and market prospects of salted eggs, the quality of yolks is constantly being improved. Mature raw salted egg yolks are orange-red and have a firm texture. After high-temperature treatment, the egg yolks become gritty and rich in oil, but usually develop an outer black layer and inner hard core, which reduce the sensory quality and edible quality of salted eggs. How to achieve oil yield and grittiness in salted egg yolks and avoid the outer black layer and the inner hard core are the key to improving the overall quality of salted eggs.

Controlling Sodium Content of Salted Egg White S-cientists have explored different ways to control the amount of sodium consumed by humans, including use of sodium substitutes. Tada et al. (1984) accidentally discovered the peptide Orn-β-Ala equally as salty as NaCl but without sodium ions, suggesting its potential as an alternative to sodium. In-depth studies revealed that the salty properties of Orn-β-Ala were strongly influenced by pH, and it had a synergistic taste effect with NaCl (Seki et al., 2002). In 1996, the salt peptide L-ornithyltaurine·HCl was successfully synthesized. In the presence of HCl, the product produced a good salty taste in the absence of Na^+, which increased in HCl dependent manner (Nakamura et al., 1996). However, because these salt peptides are expensive to synthesize, they have not been mass produced for common use. At present, chlorinated salts such as potassium chloride (KCl) or other novel salts have been successfully used to partially replace sodium chloride (NaCl) in meat pickling to develop low-NaCl meat products (Aliño et al., 2010; Gou et al., 1996; Guardia et al., 2008; Kumar, 2021). Studies have also shown that people who consume more potassium and less sodium have a significantly lower incidence of hypertension (Anggara and Prayitno, 2013). Therefore, it is not only theoretically possible to use potassium salt instead of sodium salt for salted eggs, but it is also more beneficial to health. Compared with magnesium, calcium, and zinc salt, sodium and potassium salt have no significantly different effect on the pickling process of salted eggs, and the changes in the relevant physicochemical indicators are not significant (Tian et al., 2022). Therefore, potassium salt is a viable alternative to the sodium salt in the processing of salted eggs. Low-sodium salted eggs with antioxidant potential were produced by Ariviani et al (2018), using potassium chloride and different concentrations of teak leaf extract instead of sodium salt. The sensory quality of the salted eggs, including taste, color, and flavor, was reduced to some extent by substituting NaCl with only KCl, but the addition of teak leaf extract (rich in flavonoids and phenolic compounds with antioxidant capacity) not only improved the sensory quality but also increased the total phenolic content of salted eggs. Liu et al. (2022) also recommended KCl as a partial substitute for NaCl, suggesting that this method could accelerate the water migration in salted eggs and increase the oil yield of salted egg yolks without affecting the rheological properties and microstructure. With quail eggs as raw material, Bao et al. (2021) extensively screened alternative salts of NaCl (K_2CO_3, $CaCl_2$, $MgCl_2$, $ZnCl_2$, and $FeC_6H_5O_7$) for their effects on water migration, physicochemical properties, and structural characteristics. Ultimately, $ZnCl_2$ and $FeC_6H_5O_7$ caused many adverse effects on quail eggs and were determined as not suitable for low sodium pickling, whereas K_2CO_3, $CaCl_2$, and $MgCl_2$ showed no such effects. Therefore, these salts, in 2 or more combination could be used as partial substitutes for sodium salt. In the future, in the process of screening or developing low-salt pickling preparations, synergistic, or antagonistic effects between pickling preparations should be considered.

In addition to directly replace sodium salt, the two-stage pickling method can also effectively reduce the total sodium content in salted eggs. Lian et al. (2014) pretreated fresh duck eggs in 0.5% (w/v) sodium dodecyl sulfate (**SDS**) solution for 15 min at room temperature to promote the penetration of NaCl during the pickling process and then used 25% (w/v) NaCl for about 18 d in the first stage and 4% (w/v) NaCl for approximately 15 d in the second stage. The two-stage pickling method not only reduced the final salt content of egg whites and yolks to about 4% and less than 1.5%, respectively, but also promoted the maturation of yolks, improving the oil yield, and making the yolks grittier. However, SDS is not a food additive and can cause some harm to humans (Chaturvedi and Kumar, 2010). Therefore, food-grade citric acid, and acetic acid can be considered as safer alternatives when pretreating fresh eggs. The optimized two-stage method also significantly reduced the pickling time to 20 to 25 days compared with the traditional one-stage pickling method (Zou et al., 2018). When producing low-NaCl salted eggs, adding some traditional Chinese spices such as star anise, fennel, and pepper can give the salted eggs a unique flavor.

Improving the Quality of Salted Egg Yolk As desirable characteristics of cooked salted egg yolks, oily, and gritty are important indicators of the quality of salted eggs. Oil oozes from the cooked salted eggs after cutting because salting denatures proteins, which interact with the yolk lipids and are exuded with free lipids (Xu et al., 2019a). Grittiness refers to the unique granulation texture of cooked salted egg yolks in the mouth, which is associated with the change in the shape of spherical yolk granules (Bao et al., 2020). To improve the oil yield of salted egg yolks, pickling methods can be used. Plant ash wrapping method and the salt mud coating method have been demonstrated to produce higher oil yields in salted eggs pickled than saline soaking method (Kaewmanee et al., 2011). The addition of alcohol to the pickling liquid can improve the egg yolk index, oil yield, and salt content of yolks (Zou et al., 2018). The addition of maltodextrin relieved the problem of excessive saltiness while increasing oil secretion (Wang, 2017). Some technologies such as magnetoelectricity (Yang et al., 2015) and pulsed pressure (Yuan et al., 2018) can also improve the oil yield of yolks. In addition, the oil yield varies with different cooking methods. For example, high-pressure cooking is better than direct cooking with water, and the longer the cooking time, the more oil is produced (Yang et al., 2016). Compared with oil yield characteristics, there are few related studies on enhancing grittiness. It has been proposed that grittiness is related to the permeation rate of NaCl, with faster NaCl penetration resulting in better gritty effect of yolks (Lai et al., 1997). Of course, the concentration of pickling liquid, pickling time, and cooking temperature can also affect the gritty structures of salted egg yolks.

The outer black layer of salted egg yolks is a major problem that has long plagued the development of the salted egg industry. It is a circle of gray-black or gray-green material that tends to form at the junction of salted egg whites and yolks after the salted eggs are cooked at a high temperature, which is considered to be the result of the combined action of protein, iron, S^{2-} and pigment (Li et al., 2021). Although the outer black layer has been shown to be more easily formed under alkaline conditions (Baker et al., 1967; Tinkler and Soar, 1920), its specific formation mechanism has not been clarified. However, three hypotheses have been proposed. First, the black material is hydrogen sulfide (H_2S) produced by thermal degradation of sulfur-containing amino acids in the egg white (Schutte & Teranishi, 1974). Second, it is believed that H_2S released from egg white further reacts with iron from egg yolk phosvitin to form ferrous sulfide compounds, which is the discolored substance (Greengard et al., 1964; Baker et al., 1967). Third, the substance is considered to be phosvitin-sulfur-iron complex produced when phosvitin combines with more iron ions after heating. The tightly bound phosvitin and iron may directly interact with H_2S produced from egg white to form the phosvitin-sulfur-iron complex (Albright et al., 1984). The outer black layer phenomenon becomes more pronounced with prolonged storage or shelf life of salted eggs, which affects the sensory evaluation and raises consumers concerns about the quality of salted eggs. Therefore, there is an urgent need to solve this problem. Evidence on the formation of black substances suggests that the formation of black substances can be inhibited by blocking the formation of hydrogen sulfide, ferrous sulfide, and phosvitin complexes. It has been reported that adding acidic additives such as hypochlorous acid, citric acid, sorbic acid, and glycine to the pickling solution can lower the pH of the egg white, reducing the degradation of sulfur-containing amino acids into hydrogen sulfide under heating conditions, thereby prevent the formation of the outer black layer (Sun et al., 2021a). It is speculated that the formation of black substances can also be inhibited by adding metal chelating agents such as ethylenediaminetetraacetic acid to chelate iron in egg yolks or combining acidic additives and chelating agents (Yilmaz and Agagunduz, 2020). However, the safety of some additives as pickling agents of salted eggs needs to be explored in more depth.

At present, despite an increasing concern about the inner hard core of the cooked salted egg yolks, fewer targeted studies have investigated this problem. The hard core is a pale yellow or white inelastic induration located in the center of the yolks. Some scholars believe that the formation of the inner hard core is caused by lipid peroxidation (Sun et al., 2021b). It has also been suggested that this is due to the composition structures of yolks themselves (Lai et al., 2010). Therefore, the presence of a hard core is unavoidable in cooked salted egg yolks and occurs in varying sizes. At present, the main solution is adding antioxidants to the salted egg pickling solution to inhibit the production of fat peroxide. Notably, 3 antioxidants are commonly used to the pickling mud, namely, yeast selenium, tea polyphenols, and astaxanthin. The addition of these agents significantly decreased the incidence of egg yolk hard core, but not its size (Sun et al., 2021b). In addition, each antioxidant has a different effect on salted eggs. Therefore, future research should consider the combinatorial effect and synergistic action of these agents. In addition, the causes of inner hard core formation and improvement methods needs more in-depth research.

Quality Optimization of Preserved Eggs

Preserved eggs are rich in nutrients and have functional properties such as anti-inflammatory (Zhao et al., 2017; Mao et al., 2018; Zhang et al., 2018, 2019; Batool et al., 2021) and anticancer (Mao et al., 2018; Liang et al., 2020; Batool et al., 2021). The unique processing method of preserved eggs promotes penetration of the heavy metal elements in the pickling liquid into the eggs through the porous egg shells. Heavy metals in the eggs, especially the lead oxide once used in preserved eggs, pose a health risk to consumers, while the residual heavy metals in the pickling liquid can harm the environment if not properly disposed. At present, the use of lead in preserved eggs is strictly prohibited; the addition of other heavy metal compounds in the pickling liquid is still an impediment to the healthy development of the preserved egg industry to provide quality heavy metal-free preserved eggs.

Promoting the Quality of Lead-Free Preserved Eggs Lead has a serious toxic health effect, especially on the growth and development of children. To protect consumers' health, several studies have investigated lead-free processing of preserved eggs over the years, resulting in safer lead-free preserved egg processing system. Therefore, improving the quality of preserved eggs based on lead-free technology is a key trend in the preserved egg industry. For the quality control, research on lead-free preserved eggs has focused on alleviating eggshell black spots (dots), using alternatives to the commonly used alkali NaOH for processing, and the improvement of nutritional value.

At present, the mainstream methods for processing preserved eggs are the copper or copper-zinc compound pickling methods. In the actual production process, black spots (dots) appear on the surface of the eggs processed with copper sulfate, which affects their appearance and raises safety concerns. The mixture of zinc and iron has been shown to have a positive synergistic effect and reduce spotting. In addition, the combined pickling effect of iron and zinc is also better than adding only single iron or zinc, and is comparable to the effect of adding copper salt to pickle preserved eggs but does not cause spots on pickle preserved eggs. The pickling of the preserved eggs by combining iron and zinc is effective under strictly controlled conditions such as the pickling time and temperature to achieve a high yield. Moreover, the iron-zinc mixture method also supplements zinc and iron elements in preserved eggs, suggesting its good development prospect and nutritional supplementation value (Yan and Zhu, 2006). Preserved eggs are usually made by soaking in NaOH solution, many research groups are exploring safer and greener low-alkali processing method. Hou et al. (2022) used incinerated eggshell powder and alkaline electrolytic oxidized water instead of NaOH, supplemented with low concentrations of non-lead metal ions for pickling and obtained preserved eggs with no significantly different physicochemical and sensory characteristics ($p < 0.05$) compared with the commercially available products. Zhang et al. (2011) used KOH instead of NaOH, supplemented with Cu^{2+}, Zn^{2+}, and Fe^{2+}, and finally obtained K^{+}-type preserved eggs with good quality and healthier than the high-sodium Na^{+}-type preserved eggs. To enhance the nutritional value of preserved eggs, selenium-rich poultry eggs can be treated with alkali, which supplement the body with essential trace element selenium. As the active ingredient of glutathione peroxidase, selenium can effectively protect the body against degenerative processes of peroxidation and aging (Kieliszek et al., 2019). There is also a new trend of adding some Chinese herbal medicines to the processing liquid of preserved eggs, which is believed to not only retain the unique flavor of preserved eggs but also enrich their functional properties and medicinal value. However, whether Chinese herbal medicines produce harmful substances after treatment with strong alkali needs to be further studied.

To meet the diverse needs of the market, the range of lead-free preserved eggs has been increased to include not only duck eggs, but also chicken eggs, quail eggs, and local specialties such as yellow preserved eggs, and salted preserved eggs. How to further improving the safety, flavor, and nutritional value of these lead-free preserved eggs requires continuous and systematic research.

Developing Heavy Metal-Free Preserved Eggs At present, lead has been replaced with heavy metal elements such as copper, iron, and zinc in the production of preserved eggs. However, the use of these heavy metal elements has raised public concerns about the safety of preserved eggs. Therefore, it is necessary to develop and implement heavy metal-free pickling technology. Compared with the most common preserved eggs with the copper method, the eggshells of the heavy metal-free preserved eggs are clean and spotless, and the egg yolk achieves a standard coagulation effect (Figure 9). In terms of flavor, the alkaline taste of heavy metal-free preserved eggs is lighter and more acceptable to the public. The role of heavy metals in the processing of preserved eggs is to block the pores of the eggshells, regulate the penetration rate of lye, and inhibit the liquefaction of egg white gels. The challenge is how to effectively inhibit the "alkali injury liquefaction" of preserved egg white gels in the later stage without adding heavy metal ions. Current research mainly investigates 2 aspects: 1) to add heavy metal-free pickling agents that can strengthen the protein gel state and 2) to control the total amount of lye entering eggs by changing the alkali concentration in different stages.

Figure 9. The comparison between preserved eggs without heavy metals and preserved eggs with copper sulfate.

Ai et al. (2020a, b;2019) comparatively investigated the different effects of tea polyphenols (**TP**) and calcium hydroxide ($Ca(OH)_2$) on preserved egg white (**PEW**) gels to explore possible alternative pickling agents. The results showed that TP enhanced the nonspecific cross-linking between proteins in egg white and increased surface hydrophobicity, forming a porous three-dimensional network microstructure, but reduced the hardness and mechanical properties of PEW, making it unsuitable for heavy metal-free pickling of preserved eggs. By comparison, $Ca(OH)_2$ enhanced the hydrogen bonding and hydrophobic interactions, and the egg white proteins aggregated to form clustered or granular microstructures through calcium bridges and other interactions, resulting in a gradual increase in the storage modulus and mechanical strength of PEW. Therefore, $Ca(OH)_2$ has a more positive effect on the gel quality characteristics. The addition of $Ca(OH)_2$ also accelerated the formation of gel network structure and significantly improved the hardness of PEW. At high concentration, $Ca(OH)_2$ delayed the denaturation of the proteins, thus retarding the rate of liquefaction of PEW in the presence of sustained alkali action. However, addition of a highly concentrated $Ca(OH)_2$ to the pickling liquid produced precipitation at the bottom, resulting in the uneven pickling liquid, which affected the quality of the pickled preserved egg. How to use $Ca(OH)_2$ to pickle heavy metal-free preserved eggs and achieve stable quality needs further research. The water cycle technology could be used to homogenize the pickling solution. Jin et al. (2022) found that high concentrations of sodium ascorbate significantly altered the protein structure, leading to protein reaggregation, increasing β-sheet, and decreasing surface hydrophobicity in the later stage. In general, high concentrations of sodium ascorbate could potentially inhibit the "alkali injury liquefaction" of PEW without heavy metals. Other non-metallic additives that have a positive effect on PEW are glucose, glucono-δ-lactone, xanthan gum, sodium alginate, and propylene glycol (Zhao et al., 2014). Subsequent screening of additives can be expanded to find more stable and effective heavy metal-free pickling agents, focusing on agents with positive synergistic effects.

Adjusting the concentration of alkali for preserved eggs can significantly reduce the total amount of alkali in eggs without affecting the egg white and yolk gels formation, thus effectively inhibiting the liquefaction of preserved egg whites. In a three-stage pickling process, the duck eggs were first placed in 6% NaOH solution to solidify, then transferred to 0.3% NaOH solution to fully turn color, and finally soaked in 0.1% NaOH solution until fully matured (Wang et al., 2021). In this process, no heavy metal compounds were added to the pickling solution, and the processed preserved eggs had a low content of heavy metal elements and were no different in quality from the copper preserved eggs. But the pickling steps are tedious. Feng et al. (2020) adopted a two-stage alkali adjustment method, which not only suppressed alkali damage but also shortened the pickling period. Specifically, duck eggs were first pickled in a 5.5% NaOH pickling solution for 11 d at 25°C, and then in 0.3% NaOH for 13 d. The egg whites of the obtained preserved eggs did not stick to the shells and had good elasticity. In addition, the uncoagulated part of the egg yolks was small, the color layer was obvious, and the flavor was good. In comparison, the quality of preserved eggs can be improved by adjusting the alkali concentration periodically, but the process is complicated, more labor-intensive, and time-consuming. In the future, we can try to control the temperature when adjusting the alkali concentration. The selected eggs should be placed in a low temperature and high alkalinity environment to form the complete egg white gels before they can be transferred to a high temperature and low alkalinity environment to mature them. This operation can further reduce the total amount of lye in eggs, making the egg white gels more stable and achieve unique color and flavor of preserved eggs, which are quality indicators of the heavy metal-free preserved eggs.

CONCLUSIONS AND FUTURE PERSPECTIVES

In recent years, increasing amount of comprehensive and profound researches on pickled eggs have been carried out, and many achievements have been made in terms of pickling mechanism, processing methods, and quality improvement. However, pickled eggs still have great potentials for making further progress in term of pickling technology and quality optimization. In the long run, the mainstream development trend of egg product industry in the future will go to the rapid production of a large number of pickled eggs using mechanical equipment, and the establishment of key technology systems to produce low-NaCl salted eggs and heavy metal-free preserved eggs.

Further research can be systematically carried out from the following aspects: 1) Continue to develop key technologies and equipment for rapid pickling of traditional pickled egg products, optimize and determine technical parameters to promote mechanization and standardization. 2) Develop heavy metal-free and low-NaCl pickling agents for the production of preserved and salted egg respectively to replace heavy metal ions and high sodium chloride. 3) Establish a rapid pickling process for low-NaCl salted eggs and non-heavy metal preserved eggs to promote the upgrading of whole industry. 4) Study specifically why salted egg yolks are oily and gritty, why the yolk have outer black layer and inner hard core, and further explore techniques to promote salted oily and gritty texture without black layer and hard core. 5) Strengthen the research on the appearance, color, flavor, and nutritional value of preserved eggs to improve the quality. 6) Explore the preservation mechanism and methods of heavy metal-free preserved eggs to prevent water loss and inhibit microbial growth, so as to ensure convenient storage, color, and flavor in the shelf life.

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DISCLOSURES

No conflict of interest exits in the submission of this manuscript.

SUPPLEMENTARY MATERIALS

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