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Scientific perspectives towards the maximizing the shelf life and utility of eggs

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Abstract
The excellent nutritional content of eggs and the flexibility with which they may be used in a variety of culinary applications have contributed to their central position in dietary regimens all over the globe. However, due to the fact that they are perishable, they are susceptible to quick microbial contamination and degradation, which presents a considerable issue in terms of assuring their durability and safety for consumption. The purpose of this in-depth analysis is to investigate the many scientific approaches and innovations that have been developed with the intention of extending the shelf life of eggs and increasing their usefulness without affecting the nutritional content or safety of the food itself. This article aims to provide a comprehensive overview of the operational mechanisms, efficacy, and broader implications for food security and sustainability by meticulously examining both age-old techniques and cutting-edge technologies in egg preservation. This will be accomplished by examining both ancient techniques and cutting-edge technologies. This analysis covers a wide range of techniques, from more conventional methods such as refrigeration and coating to more cutting-edge approaches such as Modified Atmosphere Packaging (MAP), edible coatings, and the application of nanotechnology. It provides insights into the potential of these techniques to revolutionise egg storage and reduce food waste. This investigation not only emphasises the significance of integrated preservation strategies, but it also emphasises the necessity of ongoing research to refine these methods. This will ensure that eggs continue to be a food source that is safe, nutritious, and easily accessible in the context of the global community.

Keywords: Eggs, preservation, shelf life, microbial contamination, nutritional integrity, food safety, traditional practices, innovative approaches, refrigeration, coating

Introduction
According to Zhang W *et al*. (2013) [64], eggs include a natural source of an exceptionally high concentration of many nutrients, including proteins, lipids, minerals, and vitamins. Chicken eggs are continually carrying out life activities while they are being stored. These activities are accompanied by a variety of complicated variations in their physical, chemical, and physiological states. In addition, they are susceptible to contamination by bacteria, which may lead to deterioration, which in turn can have an impact on their quality. One of the most essential aspects of egg quality is its freshness, and the degree to which it deteriorates is mostly determined by the passage of time and the temperature. The most important things to consider when determining the freshness of eggs are the albumen height, albumen pH, and egg weight. These three factors are significantly impacted by the length of time the eggs are stored and the temperature. Egg quality is measured using the Haugh unit (HU), which is a complete indication that reflects egg quality converted based on egg weight and protein height. The Haugh unit is commonly used as an indicator to assess egg quality.
There are multiple imperatives that are driving the quest to maximise the shelf life of eggs and preserve their quality. These imperatives include protecting public health by preventing foodborne illnesses, maintaining the nutritional benefits of eggs, which are essential for human health, and reducing food waste, which is a growing concern that has significant environmental, economic, and social ramifications. For the purpose of addressing these challenges, both conventional approaches, such as refrigeration and coating with mineral oils, and contemporary technologies, such as advanced packaging solutions and the utilisation of natural preservatives, have been investigated and put into practise, with varying degrees of success.

The purpose of this research is to investigate the diverse range of methods for preserving eggs, following their development from time-honoured ways to cutting-edge developments. It provides an in-depth analysis of the effectiveness of various techniques in preventing the development of microorganisms, postponing the deterioration of eggs, and preserving the eggs' fundamental properties over lengthy periods of time. Furthermore, it acknowledges the dynamic interaction that exists between a number of parameters, such as the management of humidity, the control of temperature, and the physical and chemical characteristics of packaging materials, in the process of determining the efficacy of preservation measures. This study aims to shed light on the path towards integrated, sustainable approaches that optimise egg storage conditions and enhance their utility in both household and commercial contexts. This will be accomplished by synthesising the findings of current research as well as the insights of experts. As a result of this investigation, the article contributes to the continuing discussion on food preservation by providing ideas that have the potential to improve food safety, enhance nutritional security, and advance sustainability objectives in the global food system.

Microbiology of Eggs

The transmission of foodborne infections has often been associated with egg intake. Salmonella species have been shown to be the most common bacteria in these outbreaks. Not only may this specific bacterium enter the pores, but it can also create biofilms on the eggshell. The most frequent species that may be found in eggs is S. enteritidis. Salmonella-contaminated eggs usually have ten or fewer cells per infected egg due to the infection that occurs in the hen, and the bacterium will be in the albumen. However, Salmonella may be able to cross the vitelline membrane and infect the yolk region of the egg if it is left to stand at room temperature. Moreover, this bacterium tends to concentrate and multiply more in the yolk of tainted eggs because of the rich and varied makeup of the yolk. Winter and Wilkin, 1946) [61]. There are two ways that diseases may infect eggs: vertical transmission and horizontal transmission. The way the bacterium and the egg come into touch determines the mechanism of transmission. In the process of developing in the chicken's reproductive system, the egg becomes infected with a disease during the vertical transmission process. All of the egg's ingredients, including the yolk, albumen, and shell membranes, might become contaminated with illness if the chicken has a bacterial infection. The most extensively studied microorganism and the most common in vertical transmission is salmonella. Conversely, in horizontal transmission, the eggs get contaminated by contact with any bacterially-rich surface after they have been placed. This covers everything, including humans, animals, containers, animal feed, faeces, and dust (Aygun, 2017) [9]. However, one of the most important problems related to Salmonella contamination of eggs is the existence of S. enterica serotype Enteritidis. There is a specific serotype that may infect chicken eggs without showing any symptoms of illness in the chickens. Other factors that affect the microbiological quality of eggs include the season, the chickens' age, the strain or genotype, the housing arrangement, and the temperature at which the eggs are kept (Aygun, 2017) [9].

Shelf-life and quality factors of eggs

Throughout the storage process, eggs go through a variety of physicochemical changes that may affect the final product's overall quality. Each egg has 7,000-17,000 pores, and the eggshell is a layered structure made up of both inorganic and organic materials. The eggshell's porous structure allows for the constant exchange of gases, namely carbon dioxide, and moisture between the inside of the egg and its surrounding environment. Furthermore, the eggshell's permeability allows odours and bacteria from the outside to seep within. Caner and Yuceer (2015) [18] state that all of these exchanges result in chemical reactions within the egg, and that the changes that happen in the albumen and yolk are known to degrade the egg's quality. In American retail stores and households alike, eggs are stored in refrigerators (preferably at a temperature of 7 degrees Celsius). This minimises physicochemical alterations that take place inside the product and stops the growth of microorganisms. It is significant to remember that this fact varies throughout the countries of the European Union and Asia.

Several distinct factors are evaluated to determine the quality of eggs. Some of the quality characteristics that fall under this area include the Haugh unit (HU), yolk index (YI) and colour, shell strength and quality, vitelline membrane quality, albumen turbidity, albumen foaming capacity, egg weight, albumen and yolk pH, and weight loss.

Haugh Unit

The HU is a statistic that is often used in the poultry industry to assess the quality of egg protein. The horizontal unit (HU) measures the height of the thick albumen or egg white that envelops the yolk. Fresh eggs have a pH of between 5.6 and 7.5, which is influenced by the surrounding environment including gases and moisture. About sixty percent of the weight of fresh eggs is made up of the thick albumen. Two of the most significant factors that might cause the albumen to shorten while the eggs are being stored are temperature changes and time. As the egg matures, the thick albumen will become thinner due to the enzymatic activity of ovomucin lysozyme, disulfide connections or interactions between α and β ovomucins, and a general rise in the product's pH. Wang *et al*., 2020 [14], and Caner and Yuceer (2015) [18] have all noted this phenomenon (2019). HU may be kept at an almost constant level throughout the storage procedure with the use of refrigeration temperature. Data on the capacity to maintain a nearly constant HU were provided by Fikiin *et al*. (2020) when eggs were incubated at 10 degrees Celsius for around 20 days. On the other hand, the HU decreased from 85 to 35 when the eggs were kept at 30 degrees Celsius, significantly shortening the product's shelf life. The DSM (2018) states that fresh eggs from young hens have a HU value of 85 or higher; however, as the egg ages, this value decreases (Caudill *et al*., 2010) [21]. A few studies have successfully used different protein coverings for eggshells to postpone the HU decline (Caner, 2005; Caner & Yuceer, 2015; Xie *et al*., 2002) [19, 18, 62]. Both the treated and control eggs had an initial HU of 81.2 when Caner and Yuceer (2015) [18] conducted their study. After being kept at room temperature (24 degrees Celsius) for five weeks, the coated eggs had a HU of 74.10, whereas the control eggs had a HU of 58.93. These protein coatings act as barriers against the exchange of gases and moisture with the environment or as sealers of the porosity on the shells, extending the egg's shelf life (Caner & Yuceer, 2015) [18].

Shell Quality

Among the eggshell's qualitative attributes are its weight, thickness, strength, and density. In some situations, these measures provide information about the egg's quality.

Examples of common quality characteristics include the shell-breaking strength and the shell thickness, both of which decrease with extended egg storage. The strength of the eggshell strongly correlates with the amount of force required to break it. The units of measurement for it are kilogrammes per foot or Newtons (N). The average score is around 4.2, while the lowest acceptable range is between 3 and 3.5. Depending on a number of factors, including the hen's age and size, the figure might range from 1 to 7.5. (DSM, 2018). The shell's thickness typically ranges from 0.2 to 0.57 millimetres, with an average of 0.4 millimetres; 0.3 millimetres being the lowest permitted thickness (DSM, 2018). It was shown that the breaking strength and thickness homogeneity had a positive correlation.

Traditional preservation methods

Refrigeration

Egg preservation requires chilling as a necessary step in the procedure. Refrigeration works by employing low temperatures to significantly slow down the rate of enzymatic processes that lead to quality degradation and the growth of germs that spoil eggs. Eggs must be stored in the optimal temperature range, which is typically between 1 and 4 degrees Celsius (33.8- and 39.2-degrees Fahrenheit), and at a relative humidity of between 75 and 85 percent, for refrigeration to be effective. These elements aid in maintaining the internal quality of eggs by limiting the amount of moisture that may escape through the shell and slowing down the air cell's expansion over time.

The amount of time that eggs may be kept in storage after being bought is greatly influenced by refrigeration. When eggs are stored under the right refrigerated conditions, they may retain their Grade A quality for a lot longer than when they are kept at room temperature. Longer shelf lives contribute to less food waste in addition to ensuring that eggs with high nutritional content are always accessible. However, it is crucial to keep the eggshell continuously refrigerated since temperature fluctuations may lead to condensation on the eggshell, which creates a surface where bacteria can grow and provide a risk of contamination.

Coating

The use of coatings on eggshells is an additional traditional method employed to preserve egg quality. Coatings hinder the exchange of gases, especially carbon dioxide and oxygen, and they also reduce the amount of moisture lost from the eggshell by forming a barrier on its surface. This barrier effect is crucial because it keeps the egg's interior humidity at a constant level and keeps out outside contaminants like bacteria that might jeopardise food safety.

In summary, two crucial steps that are often included in the traditional methods of egg preservation are coating and refrigeration. By virtue of its unique mechanism, each approach contributes to slowing down the process of deterioration, hence extending the shelf life of eggs. Coatings provide a tangible barrier against the impacts of the outside environment, while refrigeration depends on the optimal conditions of temperature and humidity. In order to meet dietary needs and minimise food waste, it is essential that eggs stay safe and fresh for a prolonged duration. This can only be achieved by implementing both of these techniques.

Modern preservation techniques

Modified Atmosphere Packaging (MAP)

An innovative technique for egg preservation is called Modified Atmosphere Packing, or MAP. Its main objective is to modify the composition of gases inside the packaging's environment. MAP may delay the oxidation processes that lead to egg spoiling and significantly slow down the growth of aerobic microorganisms. This is achieved by adjusting the levels of nitrogen, carbon dioxide, and oxygen in the surrounding environment of the eggs. The specific gas mixture used determines how effective MAP is in extending the shelf life of eggs; generally speaking, an environment with a lower oxygen level and a greater carbon dioxide content is the most beneficial. MAP offers a potentially useful way to prolong the freshness period, but putting it into practise is not without challenges. Among these challenges are the need for exact control over gas ratios and the potential for packing material permeability to gradually affect gas concentrations.

Edible Coatings and Biopolymers

The development of innovative methods for egg preservation has advanced significantly with the advent of biopolymers and edible coatings. These coatings may be put straight onto the eggshell. Natural polymers such as chitosan, cellulose, and alginate are used to make these coatings. In addition to adding antibacterial and antioxidant substances to further guard against breakdown and contamination, they serve a second purpose by strengthening the barrier properties against the flow of gas and moisture. The ability of these biopolymer-based coverings to maintain the egg's internal integrity while being entirely edible and non-toxic makes them beneficial. They thus have no effect on the nutritional value or sensory aspects of the egg. But these coatings' effectiveness depends on their composition, how well the active compounds work, and how well they work with the eggshell's surface.

Irradiation

Utilizing a variety of energy sources, including X-rays, electron beams, and gamma rays, radiation is a powerful tool in the current preservation toolbox. It is used to inactivate germs and organisms that cause rotting on or inside eggs. By using this method, the egg's shelf life might be significantly extended while retaining its nutritional value and sensory appeal. The most crucial element in determining the effectiveness of irradiation is dose optimization, which aims to achieve microbial inactivation without adversely affecting egg quality. Different countries have different levels of regulatory tolerance when it comes to radiation. Concerns about consumer safety and the potential for a change in food composition serve as the basis for determining the acceptable dose limits. Despite its potential, the use of radiation in egg preservation necessitates a delicate balancing act between regulatory compliance, consumer perception, and microbial control while maintaining product quality.

Innovations in egg preservation

Active Packaging

The advancement of egg preservation technology has advanced significantly with the advent of active packaging, which does more than merely passively contain the product. By either releasing preservative compounds that extend shelf life and enhance safety or by absorbing gases and pollutants that might possibly compromise product quality, these novel technologies work directly with the packed eggs. Based on the idea of establishing a dynamic environment within the box, the purpose of active packaging is to create a dynamic environment that actively maintains or improves the status of the eggs.

For example, certain active packaging materials are designed to produce antimicrobial compounds that prevent harmful germs from growing on the eggshell. This guarantees that there are no germs on the eggshell. Another option would be to include carbon dioxide emitters or oxygen scavengers into the packaging to change the atmosphere within the container and deal directly with the factors that cause the product to deteriorate. Carefully chosen materials that are safe to use with food, effective in their active function, and compatible with current package manufacturing techniques are necessary for the development of these technologies.

Nanotechnology

Egg packaging takes a dramatic turn thanks to nanotechnology, which makes use of the unique properties of materials at the nanoscale. Coatings and packaging sheets may benefit from the use of nanomaterials to enhance their mechanical strength, improve their resistance to gases and moisture, and add antibacterial properties, among other desired properties. To reduce the quantity of microbiological contamination that is accessible on eggshells, for instance, packing materials may include nanoparticles of zinc oxide or silver, which are well-known for their antibacterial activity.

The development of intelligent packaging solutions is made possible by the use of nanotechnology in food packaging. The development of indicators that may change colour in response to temperature fluctuations or the presence of gases that promote spoiling is one instance of this. Real-time information on the product's freshness is provided by these signs. These innovations have the potential to significantly improve food safety and reduce consumer waste by offering more precise indicators of product quality than traditional expiry dates.

Functional properties of albumen

Ovalbumin, ovalbumin, ovotransferrin, ovomucoid, ovoglobulins, ovomucin, and lysozymes are the most common proteins present in egg albumen. Egg albumen is known to include trace levels of several proteins, including avidin, ovoflavoproteins, and ovastatin. Egg albumen is utilised in many different products, such as cookies, meringues, and baked goods, since it can create foam (Jia *et al*., 2019) [38]. Among the functional characteristics that are often researched are the foaming capacity, foaming stability, and foam viscoelasticity. In contrast, albumen exhibits sensitivity and instability towards certain processing factors, such as pH, temperature, length of storage, and protein concentration.

The albumen goes through many changes as a consequence of the storage procedure. A increase in pH, thinning of the protein, and separation of carbon dioxide and water are some of these changes. If the albumen is processed in an alkaline medium, lysinoalanine and lanthionine production as well as amino acid racemization will occur. Despite this, albumen seems to be stable at a pH of neutral, and adding salt may lessen the quantity of heat damage. Heat will affect the albumen via the process of denaturation of the ovomucin-lysozyme complex, which stabilises the protein's capacity to foam. All of these physicochemical alterations in the albumen may have a direct effect on its functional properties. Nevertheless, novel interventions like as high pressure, supercritical carbon dioxide, or ultrasound may alter these functional attributes and be used to the development of more inventive goods.

Commercialization of novel technologies

The commercialization of breakthrough technologies in the food industry has been a long process. Numerous barriers exist in the manufacturing chain that hinder the full use of these emerging technologies. These technologies can perfectly match the needs of the current industry (foodborne outbreaks, consumer awareness about safety and nutrition, requirements of high quality and longer shelf-life), even though many benefits (productivity, efficiency, better quality, safety, and product stability) have been demonstrated while using them to process food (Knoerzer, 2016;) [45]. However, the transfer from the laboratory bench to the settings of industry is very slow due to the barriers that have been presented. Performed research and released a complete list of the challenges connected with each breakthrough technology that is included in this study (2016). Economic, technological, environmental, and social issues are some of the categories that may be used to group the factors influencing the food industry's adoption of new technology. The overall cost or availability of resources, the level of understanding about the technology, and the risks related to the market are some of the challenges impeding the quick adoption of these technologies. Furthermore, one of the obstacles preventing the use of revolutionary technologies is a lack of understanding. It is probable that the need for more information from customers, business, and academics will cause the adoption of these technologies to go much more slowly than expected. For instance, there are barriers to the international trade of irradiated goods since some techniques, like irradiation, are not widely accepted worldwide. Only a small number of emerging technologies have reached full success and are now suitable for commercial usage (Knoerzer, 2016) [45].

One of the most important steps that has to be completed before breakthrough technology can be commercialised is process validation. A considerable number of mathematical models that match microorganism inactivation curves under new technologies have been published (Allende *et al*., 2022; Alvarenga *et al*., 2022; Atilgan *et al*., 2020; Bermudez-Aguirre & Corradini, 2012) [6, 7, 8, 13]. These models are an essential tool in the technology validation process. The information pertaining to the processing conditions, food composition, microbe characteristics, and other processing factors are considered while creating mathematical techniques for forecasting the behaviour of an organism. These models may be used to assess a product's safety, which can help with decision-making all along the way (Alvarenga *et al*., 2022) [7].

Verification of these emerging technologies has been the subject of some recent study, and comprehensive publications are available for further reference (Koutchma, 2022a, 2022b; Koutchma & Keener, 2022) [47, 48, 49].

However, for the very few products that are not eggs, the assessment of costs and environmental effects using emerging technologies and contrasting them with conventional thermal processing has been reported quite seldom. Numerous novel strategies covered in this study have recently undergone evaluations, and some of the benefits they provide in terms of sustainability have been looked at (Chakka *et al*., 2021) [23]. For instance, room temperature application of cold plasma is possible, produces no waste, and does away with the requirement for hazardous materials and chemicals. This technology is not only very versatile and advantageous for the environment, but it is also relatively expensive. Furthermore, ozone is included in the category of substances known as Generalized Recognized as Safe (GRAS) and is considered to be safe. It has a low degree of toxicity and leaves no chemical residues behind. Ozone is environmentally friendly and requires very little in the way of initial investment and continuing upkeep. Electrolyzed water is an additional illustration of a green technology. This kind of water is inexpensive, safe for the environment, and useful for cleaning and disinfecting. It poses no threat to human health. Despite this, judgments on the use of emerging technologies regarding the expense and environmental effect of processing eggs and egg products can only be reached by means of a thorough research. Research is now needed to determine how much it costs and how long it will last to pasteurise and disinfect eggs and egg products using emerging technologies. This has to be done as soon as possible.

Conclusion

Salmonella species provide a current risk to human health when it comes to eggs and products manufactured using eggs. A rise in this risk is caused by the lack of guidelines for pasteurisation of eggs and the wide range of processing and storage conditions for eggs seen across the world. By using the right pasteurisation technique, it is feasible to lessen the risk of Salmonella in eggs while still maintaining their functional qualities. Several emerging technologies are gaining popularity as alternatives to conventional thermal processing. A few cutting-edge techniques may pasteurise an egg in a couple of minutes without compromising its nutritional value or quality. Other cutting-edge technologies are also available that have the ability to sterilise the eggshell and lessen the quantity of bacteria on the egg's surface. The most efficient option for egg pasteurisation will be a mix of two or more technologies in order to meet pasteurisation requirements in the egg and sanitise the product's surface. These cutting-edge technologies provide environmentally friendly alternatives to ensure the safety of eggs. However, more validation is required before these therapies may be commercialised in the chicken industry.

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