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Microbiological quality and storage stability of cracked egg contents under refrigerated and frozen conditions

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Abstract
Cracked eggs represent a significant source of economic loss in major egg-producing regions such as Namakkal, Tamil Nadu, where a substantial proportion of eggs develop shell cracks during handling, transport and sorting. The present study evaluated the microbiological stability of liquid egg fractions prepared from carefully selected cracked eggs with intact shell membranes and no visible contamination. A total of 450 cracked eggs were collected from poultry farms and egg collection centres in and around Namakkal, of which 300 eggs meeting strict inclusion criteria were selected, surface-sanitised and aseptically processed. The egg contents were separated into albumen, yolk and whole egg liquid, and stored under refrigerated (4 ± 1 °C) and frozen (−18 ± 1 °C) conditions for 90 days. Microbiological analyses included total viable count (TVC), *Escherichia coli* count, qualitative detection of *Salmonella* spp. and yeast and mould count at predetermined storage intervals. Initial TVC values were low in all fractions, indicating good microbiological quality at the time of processing. Under refrigerated storage, TVC and yeast and mould counts increased progressively, exceeding acceptable limits beyond 30 days, while *E. coli* counts remained within permissible limits. In contrast, frozen storage effectively maintained microbiological stability throughout the 90-day period, with no significant increase in bacterial or fungal counts. *Salmonella* spp. were absent in all samples throughout the study. The findings demonstrate that cracked eggs with intact shell membranes can be safely utilised for the production of liquid egg fractions when strict selection, sanitisation and hygienic handling procedures are followed. Refrigeration is suitable only for short-term storage, whereas freezing is preferable for long-term preservation. The study highlights the potential for converting selected cracked eggs from a low-value by-product into a safe value-added product for the food processing industry.

Keywords: Cracked eggs, microbiological stability, refrigeration, freezing, *salmonella*, *e. coli*, total viable count, namakkal poultry

Introduction

Namakkal district in Tamil Nadu is recognised as one of India's major egg production hubs, contributing substantially to the national poultry sector. Owing to the large volume of eggs handled daily, a considerable proportion of eggs, estimated at 3 to 5 per cent of total production, develop cracks during handling, transport from farms to collection centres and sorting operations (Srinivasan, 2020) [21]. Such cracked eggs are commonly discarded or diverted to low-value non-food applications, resulting in significant economic losses to farmers and poultry integrators (Srinivasan, 2020) [21]. However, many of these eggs possess only hairline cracks with intact shell membranes and may therefore remain internally uncontaminated. If such eggs are identified carefully and handled under hygienic conditions, they may represent a valuable raw material for safe food utilisation. This possibility highlights the importance of scientifically evaluating the microbiological safety and storage stability of cracked eggs under different preservation conditions (Liu *et al.,* 2016) [18].

Microbiological contamination is the principal concern associated with cracked eggs because disruption of shell integrity may permit the entry of spoilage organisms and pathogenic microorganisms from the surrounding environment (Widdicombe *et al.,* 2008) [24]. Among these, *Salmonella enteritidis* is of particular public health significance due to its association with human salmonellosis. In addition, elevated counts of total viable bacteria, *Escherichia coli*, yeasts and moulds may accelerate spoilage and reduce product safety. Nevertheless, careful selection of eggs, including the exclusion of leaking, visibly soiled or malodorous eggs, together with appropriate surface sanitisation, can markedly reduce the initial microbial load. Once egg contents are aseptically separated and stored under controlled temperature conditions, the microbiological stability of liquid egg fractions may be improved considerably. Even so, hairline shell fractures can provide routes for microbial ingress, allowing contamination of the internal contents by organisms such as *Staphylococcus aureus*, *Salmonella* spp., *E. coli*, moulds and yeasts (Eissa, 2009; Hamouda *et al.,* 2023) [8, 13]. Likewise, compromised shells may facilitate the transfer of diverse microbial contaminants, particularly members of the *Enterobacteriaceae* family, from the shell surface into the albumen and yolk, thereby creating important food safety challenges (Hemeda *et al.,* 2025) [14]. These concerns necessitate stringent hygienic handling and effective preservation strategies to minimise microbial proliferation, enhance safety and prolong shelf life (Jan, 2019; Yenilmez, 2020; Zaheer, 2015) [15, 26, 27].

Among available preservation methods, refrigeration at approximately 4 °C is widely employed for short-term

storage of liquid egg products in the food industry. Although refrigeration retards microbial growth, psychrotrophic organisms may still survive and multiply slowly during storage (Jan, 2019) [15]. Freezing at −18 °C, by contrast, effectively arrests almost all microbial growth and can extend the storage life of liquid egg products for several months, though it may also induce certain functional changes in egg proteins. In practical terms, refrigeration is more suitable for short-term use, such as in bakeries and confectionery units, whereas freezing is preferable for long-term storage and industrial utilisation. However, inadequate temperature control during handling, transport or storage may permit rapid bacterial multiplication, thereby compromising product safety and contributing to foodborne illness, including salmonellosis and staphylococcal intoxication (Al-Bahry *et al*., 2015) [3]. Previous studies have also shown that although refrigeration generally suppresses *Salmonella* growth, certain strains may exhibit enhanced survival at lower temperatures through activation of stress-response mechanisms (Li *et al*., 2024).

In view of these considerations, the present study was undertaken to evaluate the microbiological stability of albumen, yolk and whole egg liquid obtained from carefully selected cracked eggs during storage under refrigerated (4 ± 1 °C) and frozen (−18 ± 1 °C) conditions for a period of 90 days. The study further aimed to monitor important microbiological parameters, including the presence of *Salmonella*, *E. coli*, total viable count and yeast and mould count, and to generate practical recommendations for the safe utilisation of cracked eggs in the Namakkal region.

Materials and Methods

Selection of cracked eggs

A total of 450 cracked eggs were collected from six poultry farms and three egg collection centres located in and around Namakkal, Tamil Nadu, India. A stringent selection protocol was adopted to ensure sample safety and to minimise the initial microbial load.

Eggs were included only when they exhibited hairline cracks or minor shell damage, possessed intact shell membranes without visible leakage, were clean and free from visible dirt, faecal matter or blood stains, had been collected within 24 h of laying, and were of normal shape and size. Eggs were excluded if they showed leakage or complete shell breakage, emitted an off odour, were contaminated with faecal material or other foreign matter, had been stored under unknown or unhygienic conditions, or showed evidence of embryonic development as determined by candling.

Following screening, 300 eggs that satisfied the inclusion criteria were selected for further study. These eggs were surface-sanitised using chlorinated water containing 50 ppm active chlorine for 2 min, followed by wiping with 70% alcohol and air-drying under aseptic conditions in a laminar airflow cabinet. This careful selection and sanitisation procedure was intended to reduce the initial microbial load to the lowest possible level prior to sample preparation.

Sample preparation

The selected eggs were aseptically broken using a sterile stainless-steel knife. Egg contents were then separated into three fractions using sterile separators: albumen, yolk and whole egg liquid. Each fraction was pooled from 20 eggs per replicate, gently homogenised without incorporation of air, and dispensed into sterile polyethylene bags in 50 g portions. Three independent replicates were prepared for each egg fraction under each storage condition.

Storage conditions

The prepared samples were stored under two controlled temperature conditions:

- **Refrigerated storage:** 4 ± 1 °C in a domestic refrigerator fitted with a temperature data logger
- **Frozen storage:** −18 ± 1 °C in a deep freezer

Sampling intervals

Microbiological analyses were carried out on day 0 immediately after sample preparation and subsequently on days 7, 15, 30, 60 and 90 of storage. Frozen samples were thawed overnight at 4 °C prior to microbiological examination.

Microbiological analysis

All microbiological analyses were performed aseptically, and each analysis was carried out in duplicate for every replicate.

Total viable count (TVC)

Ten grams of sample was homogenised with 90 mL of sterile 0.1% peptone water and subjected to serial decimal dilution. Appropriate dilutions were plated on Plate Count Agar and incubated at 37 °C for 48 h. The results were expressed as log colony-forming units per gram (log CFU/g).

Escherichia coli count

The *E. coli* count was determined by the Most Probable Number (MPN) technique. Serial dilutions of the samples were inoculated into Lauryl Tryptose Broth and incubated at 37 °C for 48 h. Positive tubes were further confirmed in Brilliant Green Bile Broth at 44.5 °C for 24 h and in EC broth. The results were expressed as MPN/g.

Salmonella detection

Qualitative detection of *Salmonella* spp. was performed according to ISO 6579-1:2017. Samples were pre-enriched in Buffered Peptone Water at 37 °C for 18 h, followed by selective enrichment in Rappaport–Vassiliadis broth at 42 °C for 24 h and Selenite Cystine broth at 37 °C for 24 h. Enriched cultures were streaked onto Xylose Lysine Deoxycholate agar and Brilliant Green Agar. Presumptive colonies were confirmed by standard biochemical tests, including Triple Sugar Iron agar, Lysine Iron Agar and urease test, followed by serological agglutination using polyvalent O and H antisera.

Yeast and mould count

Yeast and mould counts were determined by plating samples on Potato Dextrose Agar acidified to pH 3.5 with tartaric acid. Plates were incubated at 25 °C for 5 days, and results were expressed as log CFU/g.

Statistical analysis

The experimental data were analysed using one-way analysis of variance, followed by Tukey's post hoc test to determine significant differences among means. Statistical significance was considered at $p < 0.05$. All experiments were carried out in triplicate using SPSS software version 25.

Results and Discussion

Total viable count

The initial total viable count (TVC) of the cracked egg contents was low in all fractions, measuring 2.3 log CFU/g in albumen, 2.8 log CFU/g in yolk and 2.6 log CFU/g in whole egg liquid. These low initial values reflect the effectiveness of the stringent selection and sanitisation protocol adopted in the present study. Since only eggs with hairline cracks and intact shell membranes were included, while leaking, visibly contaminated and membrane-ruptured eggs were excluded, the principal routes of microbial entry were effectively eliminated. In addition, surface sanitisation with chlorinated water followed by 70% alcohol before aseptic breaking further reduced the shell microbial load. This observation suggests that carefully selected cracked eggs can yield liquid egg fractions with initial microbiological quality comparable to that of intact shell eggs. The complete absence of *Salmonella* spp. in all selected samples throughout the 90-day storage period further supports this view and indicates conformity with microbiological safety requirements for liquid egg products (DIN EN ISO 6579-1:2017; FSSAI, 2020) [21]. These findings are in agreement with earlier reports that intact shell membranes act as an important barrier against bacterial penetration and that cracked eggs with unruptured membranes may be processed safely under strict hygienic conditions (Board, 1966; Stadelman and Cotterill, 1995) [25].

Under refrigerated storage (4 ± 1 °C), TVC increased progressively in all fractions throughout the storage period. Among the different components, yolk consistently exhibited the highest microbial counts, followed by whole egg liquid and albumen. By day 30, TVC values had increased to 6.2, 6.8 and 6.5 log CFU/g in albumen, yolk and whole egg liquid, respectively, indicating that the products were approaching the upper acceptable microbiological limit for liquid egg products. By day 60 and day 90, all refrigerated samples exceeded 7 log CFU/g, which is generally associated with spoilage and loss of microbiological acceptability (Mansour *et al.,* 2015) [19]. The relatively higher counts observed in yolk may be attributed to its rich nutrient composition, which favours microbial growth, whereas albumen showed comparatively lower counts throughout storage, possibly due to the presence of natural antimicrobial constituents such as lysozyme, ovotransferrin and avidin. These proteins are known to inhibit the growth of several bacterial groups and thereby contribute to the greater microbiological stability of albumen (Eke *et al.,* 2013) [9]. The progressive increase in microbial load under refrigeration also confirms that, although low temperature delays spoilage, it does not completely prevent the multiplication of spoilage microorganisms during extended storage. Similar observations have been reported in previous studies, which showed that refrigerated storage can retard the proliferation of aerobic mesophilic bacteria, yeasts and moulds, thereby extending shelf life only for a limited period (Mansour *et al.,* 2015 [19]; Técher *et al.,* 2019; Wang *et al.,* 2020) [23].

In contrast, under frozen storage (−18 ± 1 °C), TVC remained stable or declined slightly over the 90-day storage period. No significant increase ($p > 0.05$) was observed from day 0 to day 90 for any of the fractions. The slight reduction in count, such as the decline in albumen from 2.3 to 2.0 log CFU/g, may be attributed to sublethal injury and ice crystal damage to bacterial cells during freezing and thawing (Lian *et al.,* 2021) [17]. These findings confirm that freezing was highly effective in arresting microbial growth and preserving the microbiological quality of cracked egg contents during long-term storage. Proper storage temperature therefore plays a decisive role in maintaining the microbiological integrity of egg products, with freezing providing markedly superior control over microbial proliferation compared with refrigeration (An and Lee, 2023; Lian *et al*., 2021) [4, 17]. The results indicate that carefully selected and sanitised cracked eggs may be safely utilised for food purposes, provided that they are stored under appropriate temperature conditions, with refrigeration being suitable only for short-term storage and freezing being preferable for prolonged preservation.

Table 1: Total viable count (log CFU/g) of refrigerated cracked egg contents stored at 4 ± 1 °C

Days	Albumen	Yolk	Whole egg
0	2.30 ± 0.10^{a}	2.80 ± 0.10^{a}	2.60 ± 0.10^{a}
7	3.50 ± 0.20^{b}	4.00 ± 0.20^{b}	3.80 ± 0.20^{b}
15	4.80 ± 0.20^{c}	5.40 ± 0.20^{c}	5.10 ± 0.20^{c}
30	6.20 ± 0.30^{d}	6.80 ± 0.30^{d}	6.50 ± 0.30^{d}
60	7.00 ± 0.30^{e}	7.60 ± 0.30^{e}	7.30 ± 0.30^{e}
90	7.80 ± 0.40^{f}	8.20 ± 0.40^{f}	8.00 ± 0.40^{f}

Values are expressed as mean ± SD (n = 3). Different superscripts within the same column indicate significant difference ($p < 0.05$).

Table 2: Total viable count (log CFU/g) of frozen cracked egg contents stored at −18 ± 1 °C

Days	Albumen	Yolk	Whole egg
0	2.30 ± 0.10^{a}	2.80 ± 0.10^{a}	2.60 ± 0.10^{a}
30	2.20 ± 0.10^{a}	2.60 ± 0.20^{a}	2.50 ± 0.10^{a}
60	2.10 ± 0.20^{a}	2.40 ± 0.20^{ab}	2.30 ± 0.20^{ab}
90	2.00 ± 0.20^{ab}	2.20 ± 0.20^{b}	2.10 ± 0.20^{b}

Values are expressed as mean ± SD (n = 3). Different superscripts within the same column indicate significant difference ($p < 0.05$).

Escherichia coli count

The initial *Escherichia coli* count in all samples was below 10 MPN/g, indicating the absence of detectable faecal contamination at the beginning of storage (Table 3). This finding confirms the effectiveness of the selection and sanitisation protocol employed in the present study, as visibly contaminated, leaking and unhygienically handled eggs were excluded prior to analysis. Since *E. coli* is widely recognised as an indicator of faecal contamination, the very low initial counts suggest that the cracked eggs selected for the study were microbiologically sound and suitable for further processing (FSSAI, 2020) [26].

During refrigerated storage at 4 ± 1 °C, *E. coli* counts increased gradually but remained within the permissible microbiological limits prescribed for liquid egg products, namely below 100 MPN/g, even at day 90 (FSSAI, 2020) [21]. This gradual increase may be attributed to the ability of certain strains of *E. coli* and other psychrotrophic enteric bacteria to survive and multiply slowly under refrigeration conditions (Eke *et al.,* 2013; Mansour *et al.,* 2015) [9, 19]. Although refrigeration delayed bacterial proliferation, it did not completely suppress microbial growth during prolonged storage. This observation highlights the limitation of refrigeration as a sole preservation method for cracked egg contents intended for extended storage.

The *E. coli* results are also consistent with the overall microbial trend observed in the present study, wherein

refrigerated samples showed progressive increases in total viable count and fungal load over time. Similar findings have been reported in liquid egg products stored under chilled conditions, where the growth of psychrotrophic microorganisms such as *Pseudomonas* spp. and lactic acid bacteria contributed to gradual microbiological deterioration and reduction in shelf life (Técher *et al.,* 2019; Wang *et al.,* 2020) [23]. Thus, while refrigeration may be suitable for short-term storage, it cannot ensure complete microbiological stability for prolonged periods.

In contrast, under frozen storage at −18 ± 1 °C, *E. coli* counts remained consistently below 10 MPN/g throughout the entire 90-day storage period. This clearly demonstrates the effectiveness of freezing in suppressing the growth of psychrotrophic enteric bacteria and maintaining the microbiological quality of cracked egg contents over long-term storage (An and Lee, 2023; Eke *et al.,* 2013) [9, 11]. The superior stability observed under freezing conditions may be attributed to the inhibitory effects of low temperature on microbial metabolism, along with cellular injury caused by ice crystal formation and osmotic stress during freezing and thawing (Lian *et al.,* 2021) [17].

The findings indicate that the low initial *E. coli* counts were a direct consequence of the rigorous selection and sanitation measures applied before processing, whereas subsequent changes during storage were governed largely by storage temperature. Refrigeration allowed limited bacterial survival and gradual multiplication, while freezing effectively arrested microbial growth and ensured better microbiological preservation. These results underline the importance of combining strict initial screening of cracked eggs with appropriate storage conditions in order to maintain product safety, extend shelf life and improve the potential utilisation of cracked eggs for food purposes (Akpoka, 2020; Saleh *et al.,* 2019) [2, 20].

Table 3: *Escherichia coli* count (MPN/g) in cracked egg contents under refrigeration and freezing

Days	Refrigerated (4 ± 1 °C)	Frozen (−18 ± 1 °C)
0	<10	<10
30	<50	<10
60	<100	<10
90	<100	<10

Permissible limit for liquid egg products as per FSSAI: <100 MPN/g for E. coli*.

Table 4: *Salmonella* detection in cracked egg contents during storage

Storage condition	Day 0	Day 30	Day 60	Day 90
Refrigeration (4 °C)	Absent	Absent	Absent	Absent
Freezing (−18 °C)	Absent	Absent	Absent	Absent

Detection was performed by pre-enrichment, selective enrichment, plating on XLD and BGA, followed by biochemical confirmation. Three replicates were analysed for each condition.

Salmonella detection

Qualitative detection of *Salmonella* spp. was carried out at each sampling interval and all samples, including albumen, yolk and whole egg liquid stored under both refrigerated and frozen conditions, tested negative throughout the study period. No colonies characteristic of *Salmonella* were observed on Xylose Lysine Deoxycholate agar or Brilliant Green Agar at day 0, day 30, day 60 or day 90. Likewise, all presumptive isolates were negative on biochemical confirmation, including Triple Sugar Iron agar, Lysine Iron Agar and urease testing. These findings indicate the complete absence of detectable *Salmonella* in the selected cracked egg samples during storage.

The absence of *Salmonella* throughout the experimental period highlights the importance of the strict selection and sanitisation procedures adopted in the present study. Only cracked eggs with intact shell membranes and no visible leakage were included, while eggs showing faecal contamination, membrane rupture or other signs of poor hygienic quality were excluded. Such measures would have eliminated the principal routes of *Salmonella* entry into the egg contents, since contamination is commonly associated either with shell surface contamination or with trans-shell penetration following membrane damage (Board, 1966; Stadelman and Cotterill, 1995) [25]. Surface sanitation with chlorinated water followed by 70% alcohol before aseptic breaking would have further reduced the likelihood of external contamination being transferred to the egg contents during processing.

The present findings are therefore consistent with the view that cracked eggs with intact shell membranes may be safely utilised when handled under stringent hygienic conditions. The results also conform to the microbiological safety expectations for liquid egg products and support the conclusion that *Salmonella* contamination in cracked eggs is not inevitable, but is strongly influenced by the degree of shell damage, hygienic quality of the eggs and the care taken during subsequent handling and storage (DIN EN ISO 6579-1:2017; FSSAI, 2020) [21]. From a practical perspective, this observation is highly relevant for the safe utilisation of selected cracked eggs in food processing systems.

Table 5: Yeast and mould count (log CFU/g) in cracked egg contents during storage

Days	Refrigerated (4 ± 1 °C)	Frozen (−18 ± 1 °C)
0	0.80 ± 0.10^{a}	0.80 ± 0.10^{a}
30	2.80 ± 0.20^{b}	1.00 ± 0.10^{a}
60	3.90 ± 0.30^{c}	1.10 ± 0.20^{a}
90	4.50 ± 0.30^{d}	1.20 ± 0.20^{a}

Values are expressed as mean ± SD (n = 3). Different superscripts within the same column indicate significant difference ($p < 0.05$).

Yeast and mould count

The initial yeast and mould counts were low across all fractions, with a mean value of 0.8 log CFU/g, indicating good microbiological quality at the beginning of storage (Table 5). This low initial fungal load may be attributed to the stringent egg selection criteria and surface sanitisation procedures adopted in the present study. Under refrigerated storage (4 ± 1 °C), yeast and mould counts increased progressively over time, reaching 2.8 log CFU/g at day 30, 3.9 log CFU/g at day 60 and 4.5 log CFU/g at day 90. This trend indicates that psychrotrophic yeasts and moulds were able to survive and multiply slowly under refrigeration, thereby contributing to gradual spoilage of the cracked egg contents. Such an increase in fungal count would likely be associated with the development of off-odours and deterioration in product quality during extended storage (Eke *et al.,* 2013; Adeolu *et al.,* 2023) [1, 9].

The observed rise in fungal count under refrigerated conditions is in agreement with previous reports showing that refrigeration delays, but does not entirely prevent, the

proliferation of spoilage yeasts and moulds in egg products (Eke *et al.,* 2013; Mansour *et al.,* 2015) [9, 19]. Certain yeasts are known to be more psychrotrophic than moulds, and genera such as *Candida* and *Rhodotorula* have frequently been reported among fungal contaminants of egg products (Eke *et al.,* 2013) [9]. The increase in yeast and mould counts under refrigeration therefore further confirms that chilled storage is suitable only for short-term preservation of cracked egg contents.

In contrast, under frozen storage (−18 ± 1 °C), yeast and mould counts remained close to their initial level throughout the 90-day storage period, with values of 1.0 log CFU/g at day 30, 1.1 log CFU/g at day 60 and 1.2 log CFU/g at day 90. The slight rise from 0.8 to 1.2 log CFU/g was not statistically significant ($p > 0.05$) and most likely represented survival rather than active growth. These findings demonstrate that freezing was highly effective in controlling fungal contaminants and maintaining the microbiological stability of cracked egg contents during prolonged storage (Lian *et al.,* 2021; Mansour *et al.,* 2015) [17, 19].

Although freezing may induce certain physical changes in egg components due to ice crystal formation, particularly in albumen, it nevertheless remains superior to refrigeration from the standpoint of microbiological preservation (Eregama *et al.,* 2023) [11]. The present findings therefore indicate that freezing is the more suitable preservation method for controlling fungal growth and extending the shelf life of cracked egg contents intended for safe food utilisation.

The findings of the present study are broadly consistent with earlier reports on the microbiological quality of liquid egg products under different storage conditions. Jones and Musgrove reported initial TVC values of 4.5–6.0 log CFU/g in commercially broken liquid egg, which were higher than the corresponding initial values observed in the present study, where all fractions remained below 5 log CFU/g (Mansour *et al*., 2015) [19]. This difference may be attributed to the fact that commercial breaking plants generally process eggs of mixed quality, whereas the present study employed a strict selection protocol and included only cracked eggs with intact shell membranes and satisfactory hygienic quality. The comparatively lower initial counts obtained in the present study therefore highlight the microbiological advantage of selective procurement and careful sanitation prior to processing.

Likewise, the stability of frozen samples observed in the present investigation agrees with previous findings on frozen egg products. Kondaiah *et al*. reported TVC values of 3.0–4.0 log CFU/g after 90 days of storage at −20 °C, which is comparable to the low and stable counts recorded under frozen storage in the present study (Lian *et al.,* 2021) [17]. This similarity supports the conclusion that freezing is an effective method for preserving the microbiological quality of liquid egg products for extended periods.

The complete absence of *Salmonella* in the present study contrasts with certain surveys conducted on cracked eggs obtained from retail markets, where contamination has occasionally been reported (Adeolu *et al.,* 2023; Mansour *et al.,* 2015) [1, 19]. However, those studies generally did not employ the stringent inclusion criteria used in the present work. The exclusion of leaking, faecally contaminated and membrane-ruptured eggs, together with surface sanitisation before aseptic breaking, may therefore explain the absence of *Salmonella* in the present samples. At the same time, reports of yeast and mould contamination in commercially available egg products, even under refrigerated conditions, emphasise the need for strict hygiene at every stage of the production chain, from egg collection and transport to processing and storage (El-Khawas and Hendy, 2015) [10]. The ability of microbial contaminants such as *Salmonella enterica* to persist during the normal shelf life of eggs reinforces the importance of rigorous hygienic control and appropriate preservation practices to ensure product safety and consumer protection (Chousalkar *et al.,* 2020) [6].

Limitations of the study

Despite the promising findings, certain limitations of the present study should be acknowledged. The investigation was conducted using carefully selected cracked eggs under controlled laboratory conditions, which may not fully reflect the variability encountered in commercial operations. Large-scale implementation would require investment in appropriate infrastructure for egg sorting, washing, sanitisation and aseptic breaking in order to maintain comparable hygienic standards during commercial processing.

In addition, the present study focused primarily on microbiological stability and did not evaluate the functional properties of the stored egg fractions. This is particularly relevant in the case of frozen storage, since freezing and subsequent thawing may alter important functional characteristics such as foaming capacity, foam stability, emulsifying ability and gel formation, while also increasing yolk viscosity. These properties are critical for the suitability of liquid egg products in bakery and food manufacturing applications. Future studies should therefore examine these functional attributes alongside microbiological quality in order to provide a more comprehensive assessment of the industrial potential of selected cracked eggs.

Conclusion

The present study clearly demonstrates that cracked eggs with intact shell membranes and no visible contamination can be safely utilised for the preparation of liquid egg fractions, provided that strict selection and surface sanitisation procedures are followed. The low initial microbial counts observed in albumen, yolk and whole egg liquid confirm that careful screening and hygienic handling can substantially reduce the microbiological risks normally associated with cracked eggs. The complete absence of *Salmonella* throughout the 90-day storage period, together with *Escherichia coli* counts remaining within permissible limits, further supports the microbiological safety of the selected raw material under controlled processing and storage conditions.

Storage temperature had a decisive influence on microbial stability. Refrigerated storage at 4 ± 1 °C was found to be suitable only for short-term preservation, as total viable count and yeast and mould counts increased progressively and reached unacceptable levels beyond 30 days. In contrast, frozen storage at −18 ± 1 °C effectively maintained microbiological stability for at least 90 days, with no significant proliferation of bacteria, yeasts or moulds. These findings indicate that freezing is the preferred method for the long-term preservation of liquid egg fractions prepared from selected cracked eggs.

From a practical standpoint, the results are highly relevant to the poultry sector in Namakkal, where cracked eggs constitute a significant source of economic loss. The adoption of a systematic protocol for the recovery, hygienic processing and preservation of selected cracked eggs could convert a low-value by-product into a safe and commercially useful liquid egg product. Such an approach would not only reduce wastage but also create new opportunities for value addition within the egg processing industry.

Practical implications for the Namakkal poultry sector

Based on the findings of the present study, several practical recommendations may be proposed for stakeholders in the Namakkal poultry sector. At the farm level, workers should be trained to identify and immediately segregate cracked eggs with intact shell membranes from those with ruptured shells, leakage or visible contamination. These eggs should be handled only in clean and sanitised trays in order to minimise further contamination.

A simple but strict selection protocol should be followed before processing. Only eggs with intact membranes, no leakage, clean shells, normal odour and recent collection history, preferably within 24 h of laying, should be considered suitable for recovery. Once selected, the eggs should undergo proper surface sanitisation, such as washing in chlorinated water containing 50 ppm active chlorine followed by wiping with 70% alcohol, or treatment in an appropriate automated egg-washing system designed for hygienic handling.

Processing should be carried out aseptically, either manually or using automated breaking equipment, depending on the scale of operation. The egg contents may then be separated into albumen, yolk or whole egg liquid according to market demand. For short-term local utilisation, storage under refrigeration at 4 °C may be adopted, provided that the product is used within 30 days. For prolonged storage or transport over greater distances, freezing at −18 °C is strongly recommended. In all cases, clear labelling of the processing date and storage condition should be maintained.

Routine microbiological quality control is also essential for safe commercial implementation. Periodic testing of total viable count and *E. coli* should be undertaken, and products exceeding acceptable microbiological limits should be diverted from direct food use to cooking or industrial applications only. In the longer term, the establishment of a cooperative liquid egg processing unit in Namakkal could offer a practical means of aggregating cracked eggs from multiple farms and converting them into standardised, safe liquid egg products for supply to bakeries, confectionery units and other food industries in major nearby markets such as Coimbatore, Chennai and Bengaluru.

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