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Review

Unlocking the Power of Eggs: Nutritional Insights, Bioactive Compounds, and the Advantages of Omega-3 and Omega-6 Enriched Varieties

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Abstract: This study explores the nutritional benefits and health implications of omega-3- and omega-6-enriched eggs, positioning them within the context of functional foods aimed at improving public health outcomes. With rising consumer interest in nutritionally fortified foods, omega-enriched eggs have emerged as a viable source of essential fatty acids, offering potential benefits for cardiovascular health, inflammation reduction, and cognitive function. This research examines enrichment techniques, particularly dietary modifications for laying hens, such as the inclusion of flaxseed and algae, to enhance omega-3 content and balance the omega-6-to-omega-3 ratio in eggs. The findings indicate that enriched eggs provide significantly higher levels of essential fatty acids and bioactive compounds than conventional eggs, aligning with dietary needs in populations with limited access to traditional omega-3 sources like fish. This study further addresses consumer perception challenges, regulatory constraints, and environmental considerations related to sustainable production practices. The conclusions underscore the value of omega-enriched eggs as a functional food that aligns with health-conscious dietary trends and recommend ongoing research to refine enrichment methods and expand market accessibility.

Keywords: omega-3-enriched eggs; functional foods; public health nutrition; sustainable farming; consumer perception

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1. Introduction

Eggs are an affordable and highly nutritious food source, widely recognised as a healthy component of human diets [1–3]. According to Réhault-Godbert [4], eggs are rich in high-quality proteins, vitamins, and minerals, making them a valuable dietary recommendation from nutritionists for enhancing health. Beyond their basic nutritional value, eggs also contain bioactive compounds with potential health benefits, which have garnered increasing scientific interest in recent decades.

Historically, egg consumption was controversially associated with high cholesterol levels, leading to negative public perceptions. For instance, in 1968, the American Heart Association (AHA) recommended limiting egg consumption to fewer than three per week due to the prevailing belief that dietary cholesterol contributed significantly to elevated blood cholesterol levels and the development of cardiovascular diseases (CVD) [5,6]. This guidance dramatically shifted public attitudes, with many people avoiding eggs despite their high nutritional value.

However, extensive research conducted over the past 50 years has demonstrated that dietary cholesterol, including cholesterol from eggs, has minimal impact on blood cholesterol levels for most individuals [7]. It is now well established that saturated fats, rather than dietary cholesterol, play a more significant role in elevating blood cholesterol. Consequently, organisations such as the AHA and the British Heart Foundation have updated their recommendations, clarifying that eggs do not inherently contribute to cardiovascular disease. These updated guidelines suggest that individuals with healthy hearts can safely include eggs in their diets, while those with specific cholesterol-related conditions should consult healthcare professionals for tailored advice [8–10].

Recent scientific advancements have further elevated the status of eggs, highlighting their role as a source of bioactive compounds, such as peptides, free radical scavengers, and other biologically active molecules. These compounds, primarily concentrated in the yolk, offer anti-inflammatory, antimicrobial, and antioxidant properties, positioning eggs as a functional food with benefits beyond basic nutrition [11]. Today, eggs are recognised as a valuable dietary component for both disease prevention and health enhancement [12].

One promising area of egg-based nutrition involves the enrichment of eggs with polyunsaturated fatty acids, particularly Omega-3 and Omega-6. These essential nutrients play critical roles in cellular maintenance, regulating inflammatory processes, and supporting cardiovascular health [13]. The Western diet is characterised by an imbalance, with an excess of Omega-6 and a deficiency in Omega-3 fatty acids, contributing to chronic inflammatory disorders, cardiovascular disease, and other health conditions [14]. Enriched eggs, particularly those fortified with Omega-3 fatty acids, help address this imbalance by providing a healthier Omega-6-to-Omega-3 ratio.

The enrichment process involves modifying the diet of laying hens by incorporating Omega-3-rich feed sources, such as flaxseed or fish oil. This strategy enhances the fatty acid profile of eggs, increasing the levels of long-chain polyunsaturated fatty acids, including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) [15–17]. These enriched eggs serve as a convenient dietary source of Omega-3 fatty acids, particularly for individuals who consume insufficient fish or other sources of healthy fats.

By combining bioactive compounds and advancements in Omega-3 and Omega-6 enrichment, eggs are now positioned as a functional food capable of addressing some of the most pressing health challenges of our time. This development underscores the potential of enriched eggs to improve public health by offering a practical approach to incorporating functional foods into daily diets [18].

The primary objective of this research is to provide a comprehensive review of the nutritional composition and bioactive elements of eggs, with a focus on recent advancements in Omega-3 and Omega-6 fatty acid supplementation. This study aims to elucidate the nutritional significance of eggs in human diets, particularly their potential for promoting health through regular consumption. It seeks to summarise and analyse the current literature on the bioactive compounds present in eggs and their effects on health, while exploring strategies to enhance the nutritional profile of eggs through dietary enrichment. Additionally, this study examines the health implications of egg consumption, focusing on its role in cardiovascular health, weight management, and muscle development, and addresses misconceptions surrounding dietary cholesterol. Emerging trends and advances in egg production, including their potential in functional and personalised nutrition, are also discussed. Finally, this study considers ethical and sustainability issues associated with large-scale egg production and offers recommendations for future research to address existing gaps. By adopting a structured approach, this research provides valuable insights into the evolving role of eggs in nutrition and health.

2. Nutritional Profile of Eggs

Global egg consumption continues to rise, driven by economic growth and their universal appeal across all age groups, genders, and regions, including both rural and urban settings. Eggs are an integral part of a balanced diet and a staple in numerous international cuisines. Recognised by nutritionists and healthcare professionals worldwide for their exceptional nutritional value, eggs are a highly recommended source of protein. Health and nutrition institutions, such as the European Food Information Council (EUFIC), support the inclusion of eggs as part of a healthy and balanced diet. In Romania, dietary guidelines align with European requirements, which emphasise the importance of eggs as a valuable component of daily nutrition. Studies further highlight that eggs form the foundation of a balanced diet and contribute to maintaining a healthy body weight [19].

Today's consumers demand high-quality eggs with robust shells, free from microbiological contamination, and produced using ethically acceptable farming systems. Breeding programmes for egg-laying hens prioritise egg quality, focusing on shell durability, egg weight stability, and the quality of egg white and yolk. Key indicators of egg-white quality include the albumen height, which reflects freshness, and its ability to inhibit microbial growth, reducing the risk of foodborne illnesses such as salmonellosis [20,21].

According to Valverde et al. [22], eggs are predominantly consumed in fried or prepared forms, but they are also versatile ingredients that enhance a variety of dishes. Enrichment is an innovative approach to improving the biological value of foods by incorporating amino acids, fibres, vitamins, minerals, and antioxidants. The high utilisation of eggs is largely due to their complex protein content, which, alongside lipids and carbohydrates, forms one of the three primary macronutrient categories. Eggs provide 100% of dietary energy and 90% of dry weight [23]. Egg proteins are evenly distributed between the egg white and yolk, while lipids, vitamins, and minerals are primarily concentrated in the yolk. The macronutrient composition of a fresh, uncooked egg consists of approximately 76.1% water, 12.6% protein, 9.5% fat, 0.7% carbohydrates, and 1.1% ash [4,24].

Table 1 provides a comprehensive examination of the nutritional value, categorised by macronutrients and micronutrients, for both the white and yolk components.

Table 1. Comprehensive nutritional breakdown of chicken eggs by components (per 100 g of egg white and yolk).

Nutrient	Egg White	Egg Yolk	Whole Egg	References
Energy (kcal)	52	322	155	[4,24,25]
Protein (g)	10.9	15.9	12.6	[7,10]
Total lipids (fat) (g)	0.2	27.0	10.6	[4,10,26]
Saturated fat (g)	0.0	9.6	3.3	[4,27,28]
Monounsaturated fat (g)	0.0	12.7	4.0	[4,27,29]
Polyunsaturated fat (g)	0.0	4.2	1.2	[25,30,31]
Cholesterol (mg)	0	1085	373	[25,27,30]

Table 1. *Cont.*

Nutrient	Egg White	Egg Yolk	Whole Egg	References
Carbohydrates (g)	0.3	0.4	0.7	[4,27,30]
Sugars (g)	0.4	0.5	1.0	[23,27,30]
Fiber (g)	0.0	0.0	0.0	[25,30,31]
Vitamins				[4,27,30,31]
Vitamin A (µg)	0	770	160	[4,26,29,31]
Vitamin D (IU)	0	145	87	[26,29,31]
Vitamin E (mg)	0	3.0	1.05	[4,26,29,31]
Vitamin B2 (Riboflavin) (mg)	0.44	0.528	0.457	[4,25,32,33]
Vitamin B12 (µg)	0	2.0	1.11	[4,26,29]
Folate (µg)	4	146	47	[27,30,33]
Minerals				[25,30,32]
Calcium (mg)	7	129	50	[26,29,30,33]
Iron (mg)	0.1	7.0	1.2	[29,31,33]
Potassium (mg)	163	109	126	[26,29,30]
Magnesium (mg)	11	3.0	7.0	[26,29,31]
Phosphorus (mg)	15	586	172	[25,27,30]
Sodium (mg)	166	48	124	[4,10,26,30]
Zinc (mg)	0.0	5.3	1.0	[26,29,30]
Selenium (mg)	20	60	30.7	[20,26,30,31]

Note: Percent Daily Value (DV) based on a 2000-calorie diet.

Egg proteins are recognised as one of the best sources of high-quality protein for humans, with only breast milk offering comparable benefits [34,35]. These proteins include ovalbumin, which enhances antioxidant activity through covalent bonding with polysaccharides, ovotransferrin, which chelates Fe^{3+}, and phosvitin, rich in phosphoserines. Proteins such as apolipoproteins and riboflavin-binding proteins are specific to the yolk, while compartment-specific proteins support embryonic development [36]. Compared to other protein sources, egg proteins, particularly those in the yolk, demonstrate higher satiety effects, contributing to a reduced energy intake and promoting weight loss during hypocaloric diets [37].

Proteomic analyses have identified nearly one thousand unique proteins in chicken eggs, including peptides with antioxidant, anticancer, and antimicrobial properties. The average protein content in a whole, raw egg is 12.5 g per 100 g, with egg white and yolk contributing 10.9 g and 15.9 g, respectively. Minor variations occur due to age and genetics [38–40].

The lipid content of eggs is predominantly found in the yolk, ranging from 8.7 to 11.2 g per 100 g. These lipids are essential components of yolk lipoproteins, comprising cholesterol, phospholipids, and triglycerides. While the yolk-to-egg-white ratio determines the fat content, dietary modifications significantly influence the fatty acid profile. Studies have shown that feeding hens with marigold powder increases yolk lutein content and enhances its fatty acid composition, contributing to its nutritional value [41–43].

Eggs contain approximately 0.7% carbohydrates, primarily as glucose distributed between the yolk and albumen. Glycoproteins, resulting from post-translational glycosylation during egg formation, represent a significant portion of egg carbohydrates. Additionally, eggs are rich in micronutrients, including zinc, selenium, and fat-soluble vitamins. Their proteins are highly digestible, with cooked egg proteins exhibiting a digestibility rate of 90.9% in humans. Branched-chain amino acids such as leucine, isoleucine, and valine further support muscle protein synthesis [44,45].

Vitamins in eggs include A, D, E, K, and the B-complex, with the yolk containing the majority [46]. The hen's diet directly affects the levels of fat-soluble vitamins such as A, D, E, and K in the yolk. For instance, dietary supplementation with retinol or vitamin D3 can significantly enhance their concentration in eggs [47,48]. Similarly, carotenoids, such as lutein and zeaxanthin, derived from feed sources like marigold petals or corn, contribute to the yolk's orange–yellow hue while promoting visual health and reducing the risk of age-related macular degeneration [49].

Eggs are also a primary source of choline, a nutrient essential for cellular maintenance, brain development, and neurotransmission. The yolk contains approximately 680 mg of choline per 100 g, making eggs a leading dietary source. Supplementation through hen nutrition further enhances egg nutrient profiles, addressing specific consumer needs [50].

Minerals such as calcium, phosphorus, and potassium are present in moderate amounts in eggs, with the yolk serving as the primary reservoir for iron and zinc. Trace elements like selenium and iodine can be increased through dietary supplementation of hens. Selenium-enriched eggs, for example, provide up to 40 µg of selenium per egg, supporting antioxidant functions and reducing deficiency risks [51,52].

Eggs are highly valued for their nutritional benefits and play a critical role in diverse diets, particularly for vulnerable groups such as children, the elderly, and athletes. They are increasingly used in food manufacturing due to their affordability, versatility, and ease of storage. Pasteurised egg products are preferred in the food industry for their safety and convenience. The growing interest in functional foods, driven by an ageing population and dietary trends, highlights the continued relevance of eggs in addressing global nutritional needs [1,4,34].

While concerns regarding cholesterol and cardiovascular risk persist, recent studies confirm that egg consumption does not significantly impact cardiovascular health in most individuals. For high-risk groups, moderation and personalised dietary recommendations remain essential. Overall, eggs offer an affordable, sustainable, and nutrient-dense food source with broad health benefits, underscoring their role in human nutrition [49,50].

3. Bioactive Compounds in Eggs

Eggs contain a diverse range of nutrients and bioactive compounds that significantly contribute to human health and nutrition. These include proteins, peptides, phospholipids, omega-3 fatty acids, vitamins, and minerals, all of which have been recognised for their potential health benefits and functional properties [12]. The growing interest in these compounds stems from their dual roles in supporting nutrition and their potential applications in biomedical fields, establishing eggs as a key focus in functional food research [11].

Egg proteins, such as ovalbumin and ovotransferrin, have demonstrated several health-promoting properties, including antioxidant, antimicrobial, and anticancer effects [53]. Additionally, omega-3-enriched eggs have been associated with improvements in cardiovascular health and cognitive function, further enhancing their value as a functional food [54,55].

These findings reinforce the perception of eggs as functional foods capable of improving overall well-being, especially for health-conscious consumers. Bioactive compounds in egg white and yolk are classified based on their antioxidant, antimicrobial, immunomodulatory, anti-inflammatory, and antihypertensive properties. This highlights the extensive nutritional and health benefits of eggs [56–58].

Despite their benefits, eggs have been the subject of ongoing debate due to concerns about cholesterol content and its potential impact on cardiovascular health. Some studies indicate that moderate egg consumption does not significantly increase the risk of cardiovascular diseases and may even confer protective effects against certain conditions [59]. However, uncertainties remain regarding the influence of saturated fats in eggs on heart health, emphasising the need for further investigation [60,61].

Recent developments in egg enrichment, such as incorporating bioactive compounds from herbs and employing genetic modifications, have underscored the innovative potential of eggs in functional food development. These advancements aim to enhance the nutritional benefits of eggs while addressing dietary challenges, solidifying their position as an essential source of bioactive compounds in modern diets [62,63].

3.1. Types of Bioactive Compounds in Eggs

Eggs are a rich source of bioactive compounds, which provide notable health benefits and possess functional properties. These compounds are essential not only for human nutrition but also for their potential applications in biomedical research and therapeutic interventions [57,64].

3.1.1. Proteins and Peptides

Eggs contain a variety of proteins, including ovalbumin and ovotransferrin, both of which have been extensively studied for their health-promoting effects. Ovotransferrin exhibits antioxidant, antibacterial, and anticancer properties, making it vital for embryonic development and overall health [58]. Hydrolysed ovotransferrin, in particular, has shown significant anticancer activity, particularly against colon and breast cancer cells, underscoring its therapeutic potential [65–67].

Additionally, lysozyme, the first protein identified from hen eggs, has demonstrated the ability to enhance immune responses and inhibit the proliferation of cancer cells, further reinforcing the importance of egg-derived peptides in health and disease management [68–71].

3.1.2. Phospholipids and Lecithin

Phospholipids, a major component of egg yolks, play a critical role in lipid metabolism and the absorption of fat-soluble vitamins. They also function as emulsifiers, making them essential in both the food and pharmaceutical industries [40]. Lecithin, another key component extracted from eggs, is widely used as a natural emulsifier and is in high demand globally due to its economic and industrial significance [40,72].

3.1.3. Omega-3 Fatty Acids

Eggs can be enriched with omega-3 fatty acids, which are recognised for their cholesterol-lowering and anti-inflammatory effects. Omega-3-enriched eggs have been associated with improved cardiovascular health and enhanced cognitive function, making them a functional food option for health-conscious individuals [73,74]. Studies indicate that dietary modifications in hens, such as the inclusion of flaxseed, can elevate alpha-linolenic acid (ALA) to 200 mg per egg and docosahexaenoic acid (DHA) to 90 mg per egg, further enhancing their nutritional value [75]. Furthermore, achieving an optimal omega-6-to-omega-3 ratio, which is critical for balancing pro-inflammatory and anti-inflammatory effects, is an essential consideration in the production of these enriched eggs, ensuring their alignment with modern dietary recommendations [76].

3.1.4. Vitamins and Minerals

Eggs provide essential vitamins and minerals, including selenium and vitamin D, which support immune function, bone health, and other physiological processes. These micronutrients make eggs a vital component of a balanced diet [3,4,77].

3.1.5. Immunomodulatory Compounds

Bioactive compounds in eggs have shown immunomodulatory effects, aiding in the management of diseases by influencing immune pathways and enhancing the body's defence mechanisms against infections [78].

Recent advancements in egg enrichment have focused on the incorporation of specific bioactive compounds derived from herbs. Such modifications have demonstrated promising outcomes, including reductions in triglyceride levels and improvements in immunity among human volunteers [79]. Additionally, genetic engineering techniques have been employed to produce eggs enriched with proteins or peptides of pharmaceutical interest, offering innovative opportunities for functional food development [80].

3.2. Health Benefits of Bioactive Compounds in Eggs

Eggs are recognised for their comprehensive nutritional profile, containing high-quality proteins, vitamins, and minerals. Increasingly, they are also regarded as a significant source of bioactive compounds with the potential to deliver substantial health benefits. The bio-accessibility of these compounds, even in cooked eggs, highlights their potential as functional foods capable of improving various health outcomes [4,12].

3.2.1. Immune System Modulation

Egg-derived compounds have demonstrated immunomodulatory effects, which enhance the body's defence mechanisms against pathogens. Research highlights that proteins such as lactoperoxidase can inhibit viral infectivity, including HIV (Human Immunodeficiency Virus) and the herpes simplex virus, suggesting a critical role for eggs in supporting immune health [4,11,81].

3.2.2. Anti-Cancer Properties

Eggs possess pharmacological properties, including anti-cancer effects. Bioactive peptides in eggs are linked to anti-inflammatory and antibacterial activities, which may contribute to disease prevention and treatment. These properties, combined with the nutrient density and high-quality protein content of eggs, underscore their potential as functional foods in both general and therapeutic contexts [1,57,82].

3.2.3. Cardiometabolic Health

Egg consumption has been associated with various aspects of cardiometabolic health. A meta-analysis indicated that a moderate egg intake does not significantly increase cardiovascular disease risk and may even provide protective benefits. Furthermore, dietary components such as choline, lutein, and zeaxanthin present in eggs are thought to support cognitive function and protect against neurodegenerative diseases [83–85].

Egg consumption has also been shown to improve dietary quality. Studies report that individuals consuming eggs experience increased postprandial satiety, reduced ghrelin responses, and lower intake of total and added sugars compared to non-consumers [34,36,86]. Findings from Andersen et al. [87] further demonstrate that the proportion of kilocalories derived from carbohydrates decreased during the whole-egg diet phase compared to egg-free or egg white-only diets, while the overall energy intake remained stable. Additionally, whole eggs contributed to the intake of nutrients associated with cardiometabolic health, such as total fats, arachidonic acid, and sodium.

3.2.4. Muscle Protein Synthesis

Although limited research exists on the effects of eggs on muscle protein synthesis, existing studies suggest promising outcomes. Research by Moore et al. [88], cited by Puglisi et al. [89], demonstrated that consuming 20 g of whole-egg protein post-resistance training optimised muscle protein synthesis in young men. This aligns with findings from Witard et al. [90], who reported similar results with whey protein, and with the recommendations of the International Society of Sports Nutrition advocating 20–40 g of quality protein per serving [91].

3.2.5. Weight Management and Body Composition

Epidemiological and intervention studies present mixed findings regarding egg consumption and body weight. A cross-sectional study by Garrido-Miguel et al. [92] found that consuming more than five eggs per week was associated with a lower body mass index and body fat percentage in young adults (aged 18–30), compared to those consuming less than one egg per week. Similarly, a study involving 2241 Chinese adults (aged 18–80 years) showed that consuming over 50 g of eggs daily reduced the risk of central obesity and body fat in women, with stronger protective effects observed in men [93,94].

Research by Emrani et al. [95] further suggests that incorporating whole eggs into an energy-restricted diet can enhance weight loss in healthy individuals. However, the lack of direct long-term studies on the effects of whole-egg consumption on weight and body composition highlights the need for further clinical trials, particularly to examine the impact of a sustained egg intake on anthropometric indices.

3.3. Clarifying Misconceptions About Egg Consumption and Its Impact on Cardiovascular and Bone Health

One of the primary concerns in studies evaluating egg consumption has been its cholesterol content, with a single egg containing approximately 200 mg of cholesterol. This level has often been considered potentially significant for cardiovascular disease (CVD) risk [58]. However, research has shown that egg consumption only slightly elevates LDL cholesterol levels when included in a balanced diet that already contains dietary cholesterol. This contrasts with lactovegetarian diets, which typically feature a low cholesterol intake. The findings suggest that individuals with a higher baseline cholesterol intake exhibit a diminished response to additional dietary cholesterol, such as that from eggs [96].

Meta-analyses of controlled, randomised studies have reported minimal increases in plasma LDL and HDL cholesterol levels following egg consumption. Importantly, these studies indicate no significant changes in the total cholesterol ratio or the LDL:HDL ratio, both of which are key markers for cardiovascular disease risk [97]. Additionally, experimental research conducted by McDonald et al. [98] demonstrated that egg consumption does not adversely affect endothelial function in human subjects. As noted by Godos et al. [99], the observed correlation between egg consumption and a reduced risk of stroke may reflect the interplay of dietary cholesterol with other bioactive constituents present in eggs.

Beyond cardiovascular health, eggs provide several nutrients that may support bone health, particularly in older adults. Rich in high-quality protein, eggs supply essential amino acids necessary for the formation and maintenance of the bone matrix [100]. As Rizzoli et al. [101] explain, eggs also serve as a natural source of vitamin D, a critical nutrient that enhances calcium absorption and facilitates bone mineralisation. This unique nutritional composition positions eggs as an important dietary component for preserving bone density and reducing fracture risk among the elderly [85].

Adopting a holistic approach that integrates eggs into the diet, alongside adequate physical activity and lifestyle adjustments, may significantly contribute to healthier ageing [100,101]. A study conducted by Olagunju et al. [102] on a cohort of 176 individuals aged 65 and older investigated the impact of egg consumption on bone density. The study found that eggs' bioactive components positively influenced bone mineral density, with a statistically significant association between a higher egg intake and increased whole-body T-scores. Participants who consumed more eggs exhibited improved bone density and a lower incidence of fractures [103]. The analysis also highlighted that gender and the body mass index (BMI) played critical roles in bone health outcomes, with females showing higher T-scores and individuals with a higher BMI displaying enhanced bone density [104].

Interestingly, the study also revealed a negative correlation between daily egg consumption and the incidence of fractures, suggesting that regular egg consumption may reduce fracture risk. A positive association between HDL cholesterol levels and multiple fractures was also identified, indicating that cholesterol may influence bone health. These findings provide novel insights into the relationship between egg consumption and bone strength in older adults, suggesting that incorporating eggs into the diet may reduce the risk of osteoporosis and fractures in this population [5,8,85].

3.4. Factors Affecting Bioactive Compound Levels Dietary Influences

The levels of bioactive compounds in eggs are influenced by multiple factors, including dietary practices, oxidative stress, and environmental conditions, which collectively affect their nutritional and functional properties.

Dietary influences. The concentration of bioactive substances in eggs is significantly influenced by the dietary practices of laying hens. The inclusion of specific feed additives, such as phytogenic substances, has been shown to enhance the production of bioactive peptides. For example, bioactive components derived from herbs, such as menthol from peppermint and chlorogenic acid from various plant extracts, exhibit antimicrobial, antifungal, and antioxidant properties. These additions have been demonstrated to improve protein synthesis and enhance albumen quality in eggs, particularly through increasing the ovomucin content, which is critical for the functional properties of the thick albumen [105].

Furthermore, the use of fermented feeds has been reported to increase nutrient availability, thereby improving the overall protein content and enhancing the levels of bioactive compounds in eggs. Fermentation processes contribute to the breakdown of antinutritional factors, maximising nutrient absorption and utilisation in hens [106,107].

Oxidative stress and its impact. Oxidative stress is another significant factor affecting the levels of bioactive compounds in eggs. Elevated oxidative products in the body can impair the activities of antioxidant enzymes, which are vital for cellular protection. High levels of reactive oxygen species (ROS) can cause damage to cellular structures, leading to diminished egg quality, particularly with regard to albumen properties. Such oxidative damage not only compromises the physical characteristics of eggs but also reduces their nutritional and antioxidant capacities, ultimately impacting consumer health [108].

Environmental factors. The environmental conditions in which hens are raised, including factors such as temperature and housing, also play a critical role in determining the levels of bioactive compounds in eggs. Hens raised in suboptimal conditions are more likely to experience heightened stress, which contributes to increased oxidative stress and a subsequent decline in egg quality. Ensuring balanced environmental conditions can help to alleviate these stressors and promote higher levels of bioactive compounds in eggs [109].

4. Omega-3 and Omega-6 Enrichment in Eggs

The enrichment of eggs with omega-3 and omega-6 fatty acids involves enhancing their fatty acid profile by incorporating specific omega-3 and omega-6 sources into the diets of laying hens [110,111]. This nutritional intervention has garnered considerable attention due to the increasing consumer interest in functional foods that provide health benefits beyond basic nutrition. Omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), are well known for their positive effects on cardiovascular health, cognitive function, and inflammation reduction. In contrast, omega-6 fatty acids play a critical role in cell signalling and inflammatory responses [108].

Research indicates that omega-3-enriched eggs can contain significantly elevated levels of these beneficial fatty acids compared to conventional eggs, with some studies reporting up to a twelvefold increase in omega-3 content [112]. These enriched eggs have gained popularity among health-conscious consumers, particularly those seeking alternative dietary sources of omega-3s, such as individuals who do not consume fish, a traditional source of these nutrients [14,113].

However, the optimal omega-3-to-omega-6 ratio for health remains a topic of debate among researchers, with ongoing discussions surrounding the ideal balance to achieve favourable health outcomes [114,115]. The production of omega-3-enriched eggs typically involves feeding hens diets supplemented with sources such as flaxseed or fish oil, which significantly increases the levels of these beneficial fatty acids in the eggs [116,117].

Despite their enhanced nutritional profile, omega-3-enriched eggs are often more expensive than standard eggs, raising accessibility concerns for price-sensitive consumers. Nevertheless, the market for these speciality eggs continues to expand, driven by the growing consumer demand for healthier food options. This trend reflects a broader shift towards dietary awareness and an increasing preference for functional nutrition [118,119].

In addition to their health benefits, omega-3-enriched eggs are subject to regulatory oversight to ensure their safety and proper labelling. Regulatory bodies, such as the U.S. Food and Drug Administration (FDA) and the U.S. Department of Agriculture (USDA), enforce compliance with specific standards to safeguard consumer interests and maintain market credibility [120].

As awareness of the health advantages of omega-3 fatty acids continues to rise, the demand for omega-3- and omega-6-enriched eggs is expected to grow further. This presents both opportunities and challenges for producers operating within the dynamic and evolving food market [121].

Omega-3 and omega-6 fatty acids are indispensable components of a balanced diet, playing vital roles in numerous physiological processes and overall health. Both types of fatty acids are crucial for maintaining the structural integrity and functionality of cell membranes, with omega-3 fatty acids particularly recognised for their extensive health benefits [107,118,119].

4.1. Methods of Enrichment

The enrichment of eggs with omega-3 fatty acids involves strategic nutritional interventions for laying hens, primarily through the inclusion of alpha-linolenic acid (ALA) in their diet. Research has demonstrated that varying the dietary concentration of ALA, ranging from 0.3% to 6% of energy, significantly alters the fatty acid profile of eggs. Diets containing 6% ALA, for instance, have been shown to increase total n-3 fatty acids in eggs nearly ninefold while simultaneously reducing the n-6/n-3 ratio from 7.17 to 1.29, thereby enhancing the nutritional quality of the eggs produced [110,122].

4.1.1. Oil Sources for Enrichment

Various oils are used as ALA sources in the diets of laying hens, including macadamia oil, vegetable oil blends, and flaxseed oil. A diet composed of 60% canola oil and 40% flaxseed oil has been employed to achieve moderate ALA levels, whereas pure flaxseed oil is utilised for higher ALA content [122]. The composition and fatty acid profiles of these oils are crucial in optimising the nutritional value of enriched eggs [123].

To evaluate the effectiveness of these dietary interventions, Oliveira et al. [124] employed a controlled experimental design. Hens were allocated to cages, and dietary treatments were applied randomly, allowing for a rigorous statistical analysis via One-Way ANOVA. Significant differences in fatty acid profiles across treatments were identified using Tukey's multiple comparison test, with a significance threshold of $p < 0.05$. This methodological rigour ensures that findings on omega-3 enrichment are scientifically reliable.

4.1.2. Considerations for Eggshell Quality

While enriching eggs with omega-3 fatty acids, it is essential to address the impact of dietary interventions on eggshell integrity. An imbalanced diet may cause eggshell abnormalities, which are not solely attributable to calcium deficiency. Providing hens with a well-balanced feed is recommended to maintain both optimal fatty acid enrichment and eggshell quality [125,126].

4.1.3. Types of Enriched Eggs

To provide a clear comparison and overview, the different types and characteristics of enriched eggs are presented in Table 2, highlighting their nutritional composition and benefits.

Table 2. Types of enriched eggs.

Type of Egg	Dietary Modification	Key Nutritional Benefits	Additional Notes	Reference
Omega-3-enriched eggs	Diets fortified with omega-3 sources, such as flaxseed	Contain significantly higher levels of omega-3 fatty acids, including ALA, DHA, and EPA. Reported to improve cardiovascular health, brain function, and reduce inflammation	Some studies show up to a 12-fold increase in omega-3 content compared to conventional eggs. May have lower cholesterol levels	[74,124–126]
Standard eggs	Conventional poultry diets	Lower omega-3 fatty acid levels compared to enriched varieties.	Australian study reports 1.3% omega-3 fatty acids in yolks	[127]
Organic eggs	Organic feed and farming practices	Slightly higher nutrient levels than standard eggs but lower omega-3 content than omega-3-enriched eggs	Australian study reports similar omega-3 levels as standard eggs (approximately 1.3%)	[127]

4.1.4. Other Specialty Eggs

Apart from omega-3-enriched eggs, other types of specialty eggs include organic and cage-free varieties. Organic eggs are produced by hens raised in cage-free environments and fed organic grains free from pesticides and animal by-products [128]. Cage-free eggs, by contrast, are laid by hens that roam freely within a hen house, enhancing animal welfare. While both types offer distinct benefits, omega-3-enriched eggs stand out for their superior nutritional profile, particularly their higher omega-3 content [129].

4.2. Regulatory Oversight

The safety and labelling of omega-3-enriched eggs in the United States fall under the jurisdiction of the U.S. Food and Drug Administration (FDA) and the U.S. Department of Agriculture (USDA). The FDA regulates the production, transport, and storage of shell eggs under the Federal Food, Drug, and Cosmetic Act to ensure consumer protection against unsafe or mislabelled products [21].

4.2.1. Egg Safety Final Rule

The Egg Safety Final Rule, established to mitigate foodborne illnesses such as Salmonella Enteritidis, requires egg producers to implement stringent safety measures throughout production. It is estimated that these regulations prevent approximately 79,000 cases of foodborne illness annually [4]. This rule is particularly pertinent for omega-3-enriched eggs, which must also comply with rigorous safety standards to safeguard consumer health.

4.2.2. Egg Regulatory Program Standards

The Egg Regulatory Program Standards (ERPS) [130] provide a comprehensive framework for the state-level oversight of eggs and egg products in the United States. These standards are designed to harmonise regulatory activities among partner agencies, thereby enhancing overall egg safety, including that of omega-3-enriched varieties [127]. Compliance with these standards is critical for producers seeking to market omega-3-enriched eggs within the U.S. regulatory system.

In contrast, the European Union operates under its own regulatory frameworks for eggs and egg products. Key regulations include Regulation (EC) No 853/2004 [131], which establishes specific hygiene rules for food of animal origin, and Regulation (EC) No 178/2002 [132], which lays down the general principles and requirements of food law. Additionally, the Council Directive 1999/74/EC [133] outlines minimum welfare standards for laying hens, further influencing the production of enriched eggs.

Producers aiming to market omega-3-enriched eggs across different regions must ensure adherence to both ERPS in the U.S. and the corresponding EU regulations. This dual compliance not only supports safety and quality but also ensures alignment with the diverse regulatory requirements of international markets.

4.2.3. Nutritional Claims and Labelling

Producers of omega-3-enriched eggs must comply with stringent labelling guidelines to accurately convey their nutritional benefits and maintain consumer trust. In the United States, the USDA oversees labelling practices for enriched eggs, ensuring that claims regarding omega-3 content are substantiated and not misleading [134]. For instance, eggs derived from hens fed omega-3-enriched diets, such as those containing flaxseed, can be labelled as having higher omega-3 levels than conventional eggs.

Similarly, in the European Union, food labelling is regulated under Regulation (EU) No 1169/2011 [135] on the provision of food information to consumers. This regulation requires that any nutritional claim, such as "high in omega-3 fatty acids", must meet strict compositional criteria as outlined in Regulation (EC) No 1924/2006 [136] on nutrition and health claims made on foods. Furthermore, the labelling must be clear, accurate, and not mislead consumers regarding the nutritional qualities of the product.

Adhering to both USDA and EU labelling standards ensures that producers of omega-3-enriched eggs can effectively market their products in compliance with regulatory requirements across these regions. This dual compliance also enhances transparency and consumer confidence in the functional benefits of enriched eggs.

4.3. Market Trends and Consumer Demand

The market for omega-3- and omega-6-enriched eggs has expanded considerably in recent years, driven by increased consumer awareness of the health benefits associated with omega-3 fatty acids. These enriched eggs are viewed as a convenient and accessible source of essential nutrients, particularly appealing to health-conscious individuals seeking functional food options [137].

4.3.1. Demand Drivers and Challenges

The growing focus on health and wellness has fuelled demand for omega-3-enriched eggs, which offer additional benefits such as enhanced cardiovascular health and cognitive function. This unique value proposition enables producers to differentiate their products in a competitive market [126]. However, the production of omega-3-enriched eggs involves higher costs due to the need for specialised feed, potentially resulting in higher retail prices. This price differential may deter price-sensitive consumers, limiting market growth [6]. Furthermore, while consumer awareness of omega-3 benefits is rising, a significant portion of the population remains unaware, which could hinder further market expansion [138].

4.3.2. Future Opportunities

Despite these challenges, the omega-3-enriched egg market presents abundant growth opportunities. Producers can capitalise on the increasing demand for functional foods by diversifying product offerings, expanding into untapped markets, and collaborating with health professionals to raise consumer awareness. This trend towards health-focused nutrition is expected to create favourable conditions for the omega-3 egg market, ultimately benefiting both consumers and the food industry [139].

5. Health Benefits of Regular Egg Consumption

Eggs are recognised as a highly nutritious, accessible, and cost-effective dietary option. Recent studies have demonstrated that their consumption has either a neutral or beneficial effect on various health markers, without posing significant risks when consumed regularly as part of a balanced diet. Eggs are particularly valuable for populations with elevated nutritional requirements, such as athletes, elderly individuals, infants, children, and pregnant women. They provide high-quality protein and essential micronutrients, including vitamin D, iodine, folate, and choline—nutrients that are frequently deficient in standard diets [140,141].

Globally, Europe ranks as the second-largest egg producer, surpassed only by China, which significantly leads in production volume. In 2021, the average annual per capita egg consumption in Europe was estimated at 220–225 eggs, lower than consumption levels in the United States and Canada, which recorded 285 and 253 eggs per capita, respectively [142,143]. Mexico remains among the highest egg-consuming nations, with recent figures estimating annual per capita consumption at 409 eggs [144–146].

Haward et al. [147] reviewed studies suggesting that consuming only egg whites while excluding yolks could serve as a preventive measure against cardiovascular diseases; however, the evidence regarding cardiac outcomes remains inconclusive. A three-month investigation by de'Ogburn et al. [84] involving participants with metabolic syndrome revealed that consuming three eggs daily reduced tumour necrosis factor and C-reactive protein levels compared to a placebo group, highlighting the anti-inflammatory properties of eggs.

Wang et al. [148] reported that consuming more than four eggs per week did not significantly affect blood pressure or lipid profiles compared to an intake of four eggs or fewer weekly. Similarly, Rouhani et al. [97] found that while egg consumption led to increases in total cholesterol (TC), low-density lipoprotein cholesterol (LDL-C), and high-density lipoprotein cholesterol (HDL-C), it had no notable impact on the TC/HDL ratio or triglycerides—key markers of cardiovascular risk. Furthermore, Li et al. [96] observed that a higher egg consumption correlated with elevated LDL-C and an increased LDL-C/HDL-C ratio, though the effect on HDL-C levels was not significant. These findings suggest that while eggs may influence lipid levels, their overall effect on cardiovascular risk factors, such as the TC/HDL ratio and triglycerides, is negligible or insignificant.

A meta-analysis spanning 54 years of research found no significant association between egg consumption and cardiovascular disease risk. Interestingly, consuming more than one egg per day was linked to a reduced risk of coronary heart disease. Another review of eight observational studies similarly concluded that there was no substantial relationship between egg consumption and cardiovascular diseases [149]. Drouin-Chartier et al. [150] confirmed that a moderate egg intake (≤1 egg per day) is not associated with an increased risk of cardiovascular disorders, aligning with findings by Krittanawong et al. [151], who reported no link between consuming one or more eggs daily and cardiovascular disease.

Additional studies indicate that dietary cholesterol, including that derived from eggs, does not significantly heighten the risk of coronary heart disease or stroke [152]. Notably, substituting 3% of energy from plant-based proteins with egg protein was associated with a reduced risk of cardiovascular disease mortality, particularly from heart disease and stroke in men [153]. Bechthold et al. [154], in a meta-analysis of 12 key food groups, including eggs, demonstrated that moderate egg consumption might reduce coronary heart disease risk. Moreover, Krittanawong et al. [151] suggested that egg consumption could prevent coronary heart disease through carotenoid-enhanced absorption, which improves HDL cholesterol functionality and increases the availability of bioactive compounds, such as lutein and zeaxanthin, thereby providing protection against atherosclerosis.

5.1. Impact of Eggs on Cardiovascular Health, Weight Management, and Muscle Growth

Regular egg consumption is associated with a broader dietary pattern that often includes a diverse range of protein sources, fish, vegetables, fresh fruits, whole grains, and dairy products, contributing to overall healthier eating habits [155]. Additionally, individuals who consume eggs report greater postprandial satiety, reduced ghrelin responses, and lower consumption of both total and added sugars compared to those who do not include eggs in their diet [156]. These findings are consistent with research by Andersen [87], which highlighted a reduction in the proportion of kilocalories derived from carbohydrates during a whole-egg dietary phase, as opposed to egg-free or egg-white diet phases, while maintaining a consistent total energy intake. Furthermore, the inclusion of whole eggs significantly increased the intake of nutrients associated with cardiometabolic health, such as total fats, arachidonic acid, and sodium.

The role of eggs in muscle protein synthesis has been explored in limited studies; however, available evidence suggests promising outcomes. Research by Moore et al., [88], cited by Puglisi et al. [89], evaluated the impact of consuming 0, 5, 10, 20, and 40 g of protein derived from whole eggs on muscle protein synthesis in healthy young men following leg resistance training [150]. The findings indicated that 20 g of protein were sufficient to maximise muscle protein synthesis. This observation aligns with similar findings by Witard et al. [90], who reported improved muscle protein synthesis with 20 g of whey protein. These results correspond with the International Society of Sports Nutrition's recommendations, which advocate for 20–40 g of high-quality protein per serving to support optimal muscle protein synthesis [84].

The relationship between egg consumption and body weight or composition has yielded mixed results in epidemiological and intervention studies. A cross-sectional study conducted by Garrido-Miguel et al. [92] revealed that consuming more than five eggs per week was associated with a lower body mass index (BMI) and reduced body fat percentage compared to individuals consuming fewer than one egg per week. These findings were based on a young adult population (ages 18–30) and support existing evidence suggesting that eggs enhance satiety and dietary quality [12]. A separate study involving 2241 Chinese adults aged 18 to 80 years demonstrated that consuming more than 50 g of eggs daily was linked to a reduced risk of central obesity and lower body fat levels in women [61]. Conversely, in men, stronger protective associations were observed between egg consumption and a reduced likelihood of being classified as metabolically unhealthy obese [90].

Research by Emrani et al. [95] further suggests that whole-egg consumption, when integrated into an energy-restricted diet, can facilitate greater weight loss in healthy individuals. Given the absence of direct, long-term studies examining the effects of whole-egg consumption on weight and body composition, these findings underscore the need for future clinical trials to explore the impact of eggs on anthropometric measures and overall body weight management.

5.2. Clarifying Misconceptions Around Egg Consumption and Cholesterol

A primary concern in research on egg consumption relates to their cholesterol content (approximately 200 mg per egg), which has often been considered a potential contributor to cardiovascular disease (CVD) risk [157,158]. However, studies have demonstrated that egg consumption only marginally increases low-density lipoprotein (LDL) cholesterol levels when incorporated into a well-balanced diet that includes other dietary cholesterol sources. This contrasts with lactovegetarian diets, which typically involve lower cholesterol intakes. These findings suggest that individuals with higher baseline cholesterol intakes exhibit a reduced physiological response to additional dietary cholesterol, such as that derived from eggs [159].

Meta-analyses of controlled, randomised studies indicate minimal elevations in plasma LDL and high-density lipoprotein (HDL) cholesterol levels associated with egg consumption. Furthermore, these studies report negligible changes in critical cardiovascular markers, such as the total HDL and the LDL:HDL cholesterol ratio [94]. According to McDonald et al. [98], experimental research involving human participants has shown that egg consumption does not adversely affect endothelial function. Similarly, Zappala et al. [156] identified a correlation between egg consumption and a reduced risk of stroke, which may be attributed to interactions between cholesterol and other bioactive constituents present in eggs.

Beyond cardiovascular health, eggs represent an important source of nutrients that may positively impact bone health, particularly in elderly populations. Eggs provide high-quality protein and essential amino acids critical for the formation and maintenance of the bone matrix. Moreover, as noted by Rizzoli et al. [101], eggs serve as a natural source of vitamin D, a nutrient essential for calcium absorption and bone mineralisation. This unique nutritional profile positions eggs as a valuable dietary component for addressing the nutritional requirements necessary to support bone health in older adults [85]. A holistic approach, combining egg consumption with physical activity and other lifestyle interventions, could play a significant role in promoting healthier ageing [152].

Olagunju et al. [158] conducted a study involving 176 individuals aged 65 and older to explore the potential effects of egg consumption on bone mineral density. Their findings highlighted the bioactive compounds in eggs as potential contributors to improved bone health. A statistically significant positive correlation was identified between whole-body T-scores and egg intake, with a higher egg consumption linked to greater T-scores, indicative of improved bone density. The study also revealed that gender and the body mass index (BMI) significantly influence bone health [160,161]. Females demonstrated significantly higher T-scores, while individuals with elevated BMIs exhibited superior bone density. Furthermore, a negative correlation was observed between frequent fractures and daily egg consumption, suggesting that those who consumed more eggs were less likely to experience multiple fractures. Interestingly, HDL cholesterol concentrations were positively associated with fracture frequency, suggesting a potential link between cholesterol and bone health [162]. These findings offer new insights into the relationship between egg consumption and bone strength in the elderly, suggesting that regular consumption of whole eggs may enhance bone mineral density and contribute to a reduced risk of fractures and osteoporosis in ageing populations [163].

6. Future Directions and Emerging Trends in Omega-3- and Omega-6-Enriched Eggs

The ongoing advancements in the production and marketing of omega-3- and omega-6-enriched eggs highlight their increasing prominence as functional foods. These enriched eggs have gained recognition for their significant health benefits, including improved cardiovascular health, enhanced brain function, and reduced inflammation. As consumers place greater emphasis on nutritional quality and preventive healthcare, omega-enriched eggs have emerged as an essential dietary option, particularly for individuals who do not frequently consume fish, the conventional source of these essential fatty acids [164]. Research has demonstrated that some omega-enriched eggs can contain up to 100 mg of omega-3 fatty acids per egg, making them a substantial contributor to mitigating dietary deficiencies [165].

Innovative approaches in poultry nutrition, such as incorporating flaxseed and algae into chicken feed, enable the precise manipulation of fatty acid profiles in eggs. Additionally, the transition towards sustainable farming practices, including free-range systems and environmentally conscious feed options, addresses not only consumer health preferences but also broader environmental concerns. These efforts respond to increasing warnings regarding the depletion of marine resources often associated with conventional omega-3 sourcing [166].

Despite the growing demand for omega-enriched eggs, several challenges remain. Regulatory restrictions may hinder flexible marketing strategies, while some consumers remain sceptical about the health claims associated with these products [167]. Furthermore, competition from alternative sources of omega-3, such as fish oil and plant-based supplements, may affect the adoption of enriched eggs in consumer diets. As the market for omega-enriched eggs continues to expand, sustained research and development will be critical to overcoming these obstacles. Such efforts will focus on enhancing the nutritional benefits of enriched eggs while ensuring sustainable and environmentally friendly production practices [168].

6.1. Impact on Nutritional Profile

Enhancing chicken feed with omega-3 sources, such as flaxseed, has been shown to significantly improve the nutritional composition of eggs, particularly by increasing the omega-3 fatty acid content. Studies indicate that omega-enriched eggs may provide up to 100 mg of omega-3 fatty acids per egg, thereby serving as a superior dietary source of these vital nutrients. The inclusion of omega-enriched eggs in regular diets is vital for addressing nutritional gaps and supporting overall health, particularly among populations with an inadequate omega-3 fatty acid intake from traditional dietary sources [87].

6.2. Production Methods

6.2.1. Innovative Feeding Practices

Advancements in feeding strategies have emerged as a pivotal approach for enhancing the nutritional quality of eggs [159]. Nutritionists are increasingly formulating specialised feed mixtures rich in polyunsaturated fatty acids (PUFAs), including omega-3 and omega-6 fatty acids, to augment poultry products with these essential nutrients. This involves the strategic inclusion of various lipid sources in the diets of laying hens, enabling precise adjustments to the fatty acid profile of the eggs produced [160].

6.2.2. Tailored Feed Formulations

Recent developments in the poultry industry have seen producers collaborating closely with nutritionists to design bespoke feed formulations tailored to meet specific nutritional objectives. For instance, St Ewe Eggs, a UK-based brand, partnered with Humphrey Feeds & Pullets to develop a unique feed blend enriched with selenium and algae, resulting in nutritionally superior eggs. This focus on customisation reflects a wider trend within the poultry feed sector, wherein manufacturers are transitioning from generic approaches to specialised strategies that cater to the distinct requirements of different bird species [161].

6.2.3. Sustainable Practices

Sustainability has become a central tenet of contemporary poultry farming, shaping both production methodologies and feeding practices. Farmers are increasingly adopting eco-friendly measures that not only promote animal welfare but also align with environmental sustainability goals. For example, free-range systems allow hens to engage in natural behaviours while simultaneously enhancing soil health and biodiversity through their foraging activities. Additionally, the integration of trees and hedgerows into free-range environments supports local ecosystems and minimises reliance on chemical pest control interventions [162].

6.2.4. Impact on Egg Quality

Sustainable farming practices have a notable influence on the quality of eggs produced. Hens reared in enriched environments typically lay eggs with enhanced nutritional profiles, benefiting from diverse diets and opportunities for natural foraging behaviours. This dual approach, prioritising both bird welfare and product quality, addresses the increasing consumer demand for nutritionally enriched food products [163].

6.2.5. Regulatory Considerations

As the demand for omega-enriched eggs continues to grow, regulatory frameworks are evolving to ensure product quality and safety. Emerging regulations are anticipated to emphasise the nutritional composition of poultry products and establish standards for producers to follow in the manufacture of enriched eggs. These quality assurance measures are expected to shape the future of the poultry sector, guiding producers towards innovative and diversified product offerings [126,132,164].

By integrating specialised feeding techniques, sustainable farming methods, and compliance with regulatory standards, the production of omega-enriched eggs is well positioned for significant growth. This aligns with consumer preferences for food products that prioritise health and wellness [165].

6.3. Research and Development

6.3.1. Overview of Omega-Enriched Eggs

An overview of omega-enriched eggs highlights their increasing significance within nutritional science, particularly because of the health benefits associated with omega-3 and omega-6 fatty acids. Research has demonstrated that targeted dietary interventions for laying hens can significantly improve the fatty acid composition of eggs. For instance, "Benefic eggs" are produced by supplementing standard poultry feed with autoclaved linseed, combined with specific vitamins, minerals, and lutein to enhance the nutritional profile of the eggs.

Empirical data supports these advancements. Standard eggs typically contain approximately 0.1% omega-3 fatty acids relative to their total fat content, whereas omega-enriched eggs have been shown to contain between 0.5% and 1.5% omega-3 fatty acids, depending on the dietary modifications applied. For example, a study by Simopoulos et al. [114] demonstrated that eggs from hens fed a linseed-enriched diet contained 300–600 mg of omega-3 fatty acids per egg, compared to 60 mg in conventional eggs. Similarly, the ratio of omega-6 to omega-3 fatty acids, a critical marker of nutritional balance, was reduced from a conventional value of 15:1 to approximately 3:1 in omega-enriched eggs.

Such quantitative improvements underline the efficacy of fortification strategies, making omega-enriched eggs a valuable nutritional option for consumers seeking to address dietary deficiencies in omega-3 and omega-6 fatty acids while benefiting from a holistic nutritional profile. These advancements align with the growing demand for functional foods that address both health and convenience [17,166].

6.3.2. Health Benefits, Consumer Awareness, and Allergy Considerations

The nutritional profile of enriched eggs, particularly Benefic eggs, exhibits marked improvements over conventional eggs, rendering them a valuable dietary option. Benefic eggs contain a significantly higher concentration of essential nutrients, including a sixfold increase in alpha-linolenic acid (ALA) compared to standard eggs, contributing approximately 15% of the recommended daily allowance (RDA) in France. Moreover, the omega-3 fatty acid docosahexaenoic acid (DHA) is enriched to three times the level found in standard eggs, meeting 100% of the RDA. The enrichment process not only boosts omega-3 fatty acid levels but also incorporates key nutrients such as vitamin D, folic acid, vitamin E, lutein, zeaxanthin, iodine, and selenium. These enhancements are achieved while maintaining an optimal omega-6-to-omega-3 fatty acid ratio, aligning with modern nutritional guidelines and promoting a balanced intake of essential fatty acids [18,167].

However, it is also essential to consider potential allergenic risks associated with eggs, as they are a common food allergen. While enrichment enhances the nutritional profile, it is vital to ensure that these modifications do not increase the allergenicity of the product, particularly for sensitive individuals. Further research could explore the allergenic potential of enriched eggs to ensure consumer safety and acceptance [36].

6.3.3. Methodological Considerations

Future research on omega-enriched eggs should prioritise the utilisation of comprehensive and detailed data sets, encompassing both wholesale and retail-level cost analyses. Such an approach would facilitate a more nuanced understanding of the supply and demand dynamics within the omega-enriched egg market. This methodology offers the potential to estimate unconditional elasticities, providing a broader and more accurate representation of market responses. These insights are particularly relevant for policymaking, as they move beyond the current reliance on conditional elasticity estimates, which may inadequately capture the complexities of consumer behaviour and market interactions [14]. By expanding the scope of elasticity estimates, future studies could offer policymakers more robust and actionable data, enabling informed decisions regarding the production and regulation of nutritionally enriched egg products [166,168].

6.3.4. Market Trends and Opportunities

Emerging trends in the global omega-3 market are expected to significantly influence the development and diversification of omega-enriched egg products. Recent market analyses highlight a growing consumer preference for foods with enhanced nutritional value and health-promoting properties, fostering a favourable environment for innovation within this sector [95,169]. This increasing demand emphasises the necessity for continued research and development to optimise the nutritional composition of omega-enriched eggs, aligning with evolving consumer expectations.

To fully exploit these trends, collaboration between researchers and industry stakeholders is essential, leveraging advanced methodologies and technologies. Such cooperative efforts could facilitate the creation of enriched egg products with superior nutritional profiles, while also increasing their accessibility and appeal in an increasingly competitive global marketplace [98].

6.3.5. Environmental Impact

The production and consumption of omega-3- and omega-6-enriched eggs carry significant environmental implications, particularly in terms of sustainability and resource utilisation. Marine ecologists have warned of the potential collapse of global fish stocks by 2050 if current exploitation rates continue, highlighting the urgent need for alternative strategies to meet health and environmental objectives [6]. The increasing popularity of omega-3-enriched eggs is partly driven by heightened consumer awareness of the health benefits of omega-3 fatty acids, traditionally sourced from fish [3]. However, this reliance on marine-derived omega-3s, such as fish oils, poses substantial sustainability challenges, as enhancing hen diets with these ingredients could exacerbate the strain on already overexploited marine ecosystems [170].

In light of these ecological concerns, some producers are turning to more sustainable dietary alternatives for hens, such as plant-based sources like algae, which provide omega-3 fatty acids without directly impacting marine life. This shift is essential not only to reduce dependence on marine resources but also to mitigate the environmental damage caused by pollution and habitat destruction associated with conventional fishing practices [171,172]. Furthermore, the growing consumer preference for organic and cage-free egg options reflects a broader movement towards sustainable agricultural practices that prioritise animal welfare and minimise chemical inputs [173,174].

Recent studies indicate that the demand for omega-3-enriched eggs is influenced not only by health benefits but also by environmental considerations [175,176]. Products perceived as both nutritionally superior and environmentally sustainable are increasingly favoured, offering a competitive advantage in the marketplace [177]. Therefore, addressing the environmental impact of omega-3-enriched egg production is critical for the future of this sector. By integrating health benefits with eco-friendly practices, the industry can safeguard marine ecosystems while advancing sustainable agricultural methods to meet consumer demands [178].

6.3.6. Challenges and Barriers

The regulatory framework governing enriched eggs, particularly in relation to the addition of vitamins and minerals, presents significant challenges for producers. According to Regulation (EC) No. 852/2004 [175] on the hygiene of foodstuffs, the addition of vitamins and minerals to unprocessed foods is explicitly prohibited. This regulation aims to preserve the transparency of the natural nutritional value of fresh food products, preventing potential consumer confusion regarding their nutrient content. However, such restrictions may obstruct marketing strategies for omega-3- and omega-6-enriched eggs, as consumers may perceive the inclusion of added nutrients as misleading, potentially undermining the authenticity of these products.

The regulatory landscape is further complicated by the Nutrition (Amendment etc.) (EU Exit) Regulations 2019, which have reallocated certain regulatory functions from the European Commission to national authorities within the United Kingdom. Responsibilities are now distributed among distinct entities, including the Secretary of State for England, the Scottish Ministers, and the Welsh Ministers, resulting in a fragmented regulatory framework [176]. This decentralisation may lead to inconsistencies in regulatory interpretation and enforcement across the UK, creating challenges for producers seeking to distribute enriched egg products across multiple regions. Consequently, compliance with varying requirements may hinder producers' ability to maintain uniform operations within the UK market [177].

Addressing these regulatory complexities is critical for advancing the development and commercialisation of nutritionally enhanced egg products. Harmonising regulations and improving clarity in compliance requirements will be essential to support producers in meeting both consumer expectations and market demands.

6.3.7. Market Acceptance

The acceptance of omega-3- and omega-6-enriched eggs by consumers presents several challenges that warrant consideration. Although public awareness of the health benefits associated with these essential fatty acids is on the rise, certain consumer segments remain sceptical regarding the claims made by producers. This scepticism is often rooted in a limited understanding of the nutritional science underlying these enhancements, which can lead to consumer resistance, especially in markets where traditional egg consumption habits are firmly established [102]. Such resistance underscores the importance of effective communication strategies that can demystify the benefits of enriched eggs and align consumer perceptions with scientifically substantiated health advantages [178].

Economic factors are also critical in determining the market adoption of enriched eggs. Research indicates that tariff reductions and other economic measures can have a tangible impact on consumer welfare, as fluctuations in pricing directly influence demand [179]. Enriching eggs with additional nutrients entails higher production costs, which are typically reflected in elevated retail prices. This price increase may deter consumers who are particularly sensitive to cost, which is a significant consideration in regions where purchasing decisions are heavily influenced by price rather than by nutritional content. Consequently, the higher cost of enriched eggs could limit their market penetration, particularly in price-sensitive demographics, thereby posing a challenge to the overall economic viability of these products [74].

Additionally, the market for omega-3- and omega-6-enriched eggs faces competition from alternative sources of these fatty acids, such as fish oil supplements and plant-based omega-3 products. These alternatives often appeal to consumers due to their convenience and the comparable health benefits they offer, without requiring major adjustments in dietary habits. The ready availability of such alternatives could potentially erode the market share of enriched eggs unless producers can effectively communicate the distinct benefits that their products provide. For enriched eggs to secure a competitive position, producers must emphasise unique selling points, such as the integration of these nutrients into a familiar food format and the potential for broader nutritional benefits beyond those provided by isolated supplements [172].

In summary, the successful market adoption of omega-3- and omega-6-enriched eggs depends on addressing consumer scepticism through education, managing the economic factors that influence purchasing decisions, and differentiating enriched eggs from alternative omega-3 sources. These strategies are essential to overcome the barriers posed by consumer acceptance, economic constraints, and competitive pressures within the omega-enriched food market.

6.3.8. Production Challenges

The production of omega-3- and omega-6-enriched eggs requires a meticulous and methodical approach to feed formulations and farming procedures, as these elements are essential for attaining the needed nutritional enhancements. To enhance the concentrations of omega-3 and omega-6 fatty acids in eggs, chickens require a meticulously formulated diet that fulfils their nutritional requirements while maximising the incorporation of these critical fatty acids into the egg yolk [137]. This dietary supplementation often includes sources rich in omega-3, such as flaxseed or algae, which must be incorporated in a way that maintains animal health and productivity while enhancing egg quality. However, designing and maintaining such specialised feed formulations can be complex, requiring substantial investment in research and development to refine and validate feeding protocols that yield consistent results [173].

Furthermore, the scalability of omega-enriched egg production presents logistical issues, especially in maintaining uniformity in product quality across increased production quantities. As the demand for these nutritionally fortified eggs increases, manufacturers must retain the integrity of nutritional profiles while expanding operations. Variability in nutritional composition resulting from disparities in feed formulation, environmental factors, and hen health between production locations may affect the uniformity of enhanced egg products. Confronting these problems is crucial to fulfil consumer expectations and comply with legal criteria for product labelling. Consequently, continuous progress in agricultural and nutritional science is essential for developing dependable procedures that promote both the nutritious improvement of eggs and the scalability of production [180].

7. Conclusions

The nutritional profile of omega-3- and omega-6-enriched eggs establishes them as a significant advancement in functional foods, offering health benefits such as improved cardiovascular function, reduced inflammation, and enhanced cognitive performance. Through dietary modifications for poultry, incorporating polyunsaturated fatty acid-rich sources such as flaxseed and algae, producers can effectively address common dietary deficiencies, particularly in populations with limited fish consumption.

The rising demand for functional foods among health-conscious consumers has driven innovation in omega-enriched egg production. This trend is particularly evident in regions such as North America, Europe, and Asia–Pacific, where awareness of the health benefits of omega-3 fatty acids is increasing. Consequently, omega-enriched eggs are positioned to occupy a substantial segment of the functional food market, aligning with the growing consumer preference for preventive health measures and wellness-oriented diets.

Despite their potential, challenges remain in terms of consumer perception and regulatory frameworks. Misunderstandings about the health benefits and science behind enriched eggs may foster scepticism, particularly in regions with deeply rooted traditional diets. Additionally, regulatory restrictions, such as those in the European Union that limit nutrient additions to unprocessed foods, complicate the marketing of these products. Overcoming these barriers will be critical to ensuring the long-term success of omega-enriched eggs in the marketplace.

The environmental impact of omega-enriched egg production must also be addressed. Traditional omega-3 sources, such as fish oils, place significant strain on marine ecosystems. Transitioning to sustainable feed sources, such as algae, presents a viable solution to mitigate ecological pressures while maintaining the nutritional integrity of enriched eggs. Moreover, the increasing demand for organic and cage-free options reflects consumer interest in sustainable and ethical farming practices, aligning with broader environmental goals.

Future research should focus on personalised feed formulations, improving bioactive compound enrichment, and analysing economic implications to facilitate widespread adoption. Studies examining market dynamics, including cost elasticity at wholesale and retail levels, will inform effective pricing and policy strategies. Enhanced feed sources could enable the development of products targeting specific health concerns, such as cardiovascular disease and cognitive decline.

From a public health perspective, omega-enriched eggs offer an affordable, nutrient-dense food option that can contribute to meeting dietary recommendations for essential fatty acids. Their regular consumption could significantly address nutritional gaps and improve health outcomes, particularly for vulnerable groups such as the elderly, athletes, and pregnant women.

In summary, omega-enriched eggs represent a crucial intersection of nutrition, sustainability, and innovation in functional food development. By addressing consumer health needs and environmental sustainability, these products are well positioned within the evolving landscape of personalised and preventive nutrition. Continued growth in this market will depend on overcoming regulatory challenges, fostering consumer trust, and advancing research to demonstrate the comprehensive benefits of these enriched egg products.

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