Amol University of Special Modern Technologies

Caspian Journal of Veterinary Sciences

doi: 10.22034/cjvs.2026.599430.1101

Journal homepage: https://cjvs.ausmt.ac.ir/

Beyond enrichment: precision-designed eggs as food-based nutrient delivery systems

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Article Info

Article history:

Submit Date: 27 August 2026

Accept Date: 5 September 2026

Online Date: 12 November 2026

Keywords:

Bioavailability

Designer eggs

Functional foods

Nutrient deposition

Precision nutrition

Abstract

Designer eggs offer a food-based approach to modifying egg composition through targeted changes in laying-hen nutrition. Although enrichment with *n*-3 fatty acids, selenium, vitamin D, vitamin E, carotenoids, and other bioactive compounds is well established, nutrient concentration alone does not determine nutritional value. Deposition depends on nutrient source, dose, dietary context, absorption, metabolism, and transport, while retention and bioaccessibility may change during storage and cooking. This review examined the transition from conventional enrichment to precision-designed eggs, focusing on nutrient deposition, multi-nutrient interactions, stability, bioavailability, and human nutritional relevance. Evidence showed that enrichment strategies can affect feed intake, laying performance, egg quality, and production efficiency, creating trade-offs that limit practical application. High supplementation costs, variable deposition efficiency, nutrient interactions, oxidative instability, and difficulty in maintaining a consistent nutritional profile further constrain large-scale production. Consequently, producers may face limited economic incentives when nutritional gains are not proportional to additional feed inputs or when enrichment compromises production traits. Human intervention studies indicated that fortified eggs can increase the intake and improve biomarkers of selected nutrient status, particularly *n*-3 fatty acids and carotenoids, whereas evidence for sustained physiological or clinical benefits remained limited and heterogeneous. Future development should therefore integrate nutritional targets with deposition efficiency, product quality, production cost, stability, bioavailability, consumer acceptance, and sustainability. Precision feeding and egg nutriomics may support this transition by enabling more targeted and reproducible nutritional profiles. The central shift is from producing eggs with more nutrients to designing eggs with a defined, stable, and demonstrable nutritional function.

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Introduction

Eggs are nutrient-dense animal-source foods providing high-quality protein, vitamins, minerals, essential fatty acids, choline, carotenoids, and other bioactive compounds. Their nutritional density, versatility, and relative affordability make them relevant to dietary quality and nutrient adequacy (Walker and Baum, 2022; Caffa *et al.,* 2025).

Egg composition can be modified through the nutrition of the laying hen because dietary nutrients are absorbed, metabolized, and selectively deposited into the developing egg. This has enabled enrichment with *n*-3 fatty acids, selenium, vitamins, carotenoids, and other bioactive compounds (Chauhan and Sreeja, 2025; Ma *et al.,* 2026). However, deposition is nutrient-specific and depends on nutrient source, dose, metabolic fate, and dietary interactions. Therefore, dietary supplementation does not necessarily translate proportionally into egg composition (Elkin and Harvatine, 2023).

The scientific challenge is consequently shifting from nutrient enrichment to nutritional design. A successful food-based delivery system must also account for nutrient interactions, stability, bioaccessibility, bioavailability, production efficiency, and human relevance (Ding *et al.,* 2026; Ma *et al.,* 2026). Increased concentration alone does not establish improved bioavailability, altered biomarkers, physiological effects, or clinical benefit. Human intervention evidence supports fortified eggs as potential nutrient-delivery vehicles, but remains heterogeneous across nutrients and populations (Wang *et al.,* 2026).

This framework connects designer eggs with precision nutrition, in which the nutritional objective guides nutrient selection, feeding strategy, and optimization of the resulting egg composition (Kang and Zivkovic, 2022). Precision-designed eggs (PDEs) therefore integrate target-nutrient selection with deposition efficiency, stability, bioavailability, and human nutritional relevance rather than simply maximizing individual nutrient concentrations.

Accordingly, this review examined the transition from conventional enrichment toward functional and designer eggs, focusing on the mechanisms governing nutrient deposition and interactions, nutrient stability and delivery, evidence for human nutritional relevance, and the production, economic, sustainability, and consumer constraints affecting practical translation.

Terminology in this field is not fully standardized. Here, an enriched egg is an egg in which one or more nutrients or bioactive compounds have been deliberately increased through modification of the hen's diet. A functional egg is an egg whose modified composition is intended to provide a physiological or health-related function beyond basic nutritional contribution. Designer egg denotes an egg intentionally designed for a defined nutritional objective and may therefore also be enriched or functional. PDE refers to the more advanced concept in which nutrient selection, feeding strategy, deposition, stability, bioavailability, and human relevance are integrated into the design process. Healthier egg is not treated as a scientific category because it implies a comparative health claim requiring an appropriate reference product and outcome.

From egg enrichment to nutritional design: What can actually be modified?

Egg composition as a modifiable nutritional matrix

Egg composition is not fixed; it is a modifiable outcome of the interaction among dietary supply, hen physiology, metabolism, and nutrient deposition. Feeding strategies can alter yolk fatty acids, carotenoids, vitamins, and trace minerals, providing the biological basis for nutritionally differentiated eggs. However, recent work increasingly frames enrichment as a design problem in which the target composition must be considered alongside deposition efficiency, egg quality, production efficiency, stability, and sustainability (Akram *et al.,* 2025; El-Sabrout and Abd El-Aziz, 2026).

Determinants of nutrient deposition and nutritional response

Modification is not proportional to dietary input. Before incorporation into the developing egg, a nutrient must be digested, absorbed, metabolically processed, transported, and deposited. Each step can be influenced by nutrient source and chemical form, dose, basal diet, hen characteristics, and nutrient interactions. Zurak *et al*. (2025) demonstrated this context dependence for yolk carotenoids: corn hybrid, vitamin A level, and trace-mineral form interacted to affect carotenoid concentration and deposition efficiency. Thus, the same supplementation strategy may produce different outcomes depending on the nutritional matrix in which it is applied.

Dietary interventions may also alter traits beyond the intended target. Iron and iodine supplementation increased deposition of the respective minerals but also affected egg quality and laying responses according to supplementation level and combination (Sarlak *et al.,* 2025). Similarly, a meta-analysis of microalgae supplementation identified coordinated effects on laying performance, egg quality, yolk pigmentation, and fatty-acid composition (Anam *et al.,* 2025). Such responses indicate that nutrient enrichment cannot be optimized independently of hen performance and product quality. The same principle applies to attempts to modify yolk cholesterol, for which nutritional, metabolic, physiological, and genetic determinants interact rather than acting as isolated controls (Balhara *et al.,* 2026).

From enrichment to nutritional design

These findings support a functional distinction between enrichment and nutritional design. An enriched egg is defined by an increase in selected nutrients, whereas a designer egg is developed around a predefined nutritional objective that integrates nutrient source, deposition efficiency, nutrient interactions, egg quality, and nutritional relevance. The design target is therefore an optimized and reproducible nutrient profile rather than the maximum concentration of a single compound.

Nutritional targets for designer eggs: what has been achieved and what comes next?

The development of designer eggs has focused predominantly on nutrients for which dietary manipulation can produce measurable changes in egg composition. *n*-3 polyunsaturated fatty acids (PUFA), selenium, vitamin D, and carotenoids are among the most established targets, although their responses differ in deposition efficiency and sensitivity to dietary context (Table 1). This heterogeneity is central to nutritional design: the feasibility of enrichment depends not only on dietary supply but also on the metabolic pathways that determine which fraction is ultimately incorporated into the egg.

n-3 PUFA provide a clear example. Dietary lipid source strongly affects the fatty-acid profile of the yolk, but conversion and partitioning of dietary precursors limit the extent to which increased precursor intake translates into long-chain *n*-3 PUFA deposition. Consequently, enrichment strategies based on direct provision of preformed EPA and DHA can differ substantially from those relying primarily on precursor fatty acids (Elkin and Harvatine, 2023). Selenium presents a related but chemically distinct problem. Egg selenium deposition depends on the form supplied: comparative feeding studies have shown differences among selenium-enriched yeast, selenomethionine, and nanoselenium in egg selenium accumulation, antioxidant responses, and product quality (Chen *et al.,* 2024). Vitamin D further illustrates the value of controlling nutrient form and metabolic availability. Co-supplementation of vitamin D_3 and 25-hydroxyvitamin D_3 markedly increased vitamin D activity in eggs while maintaining or improving selected production and physiological responses in late-stage hens (Thamteerasathian *et al.,* 2026).

Carotenoids demonstrate even more explicitly why deposition efficiency should be treated as a design variable rather than an incidental outcome. Their transfer to yolk depends on the carotenoid profile of the basal diet as well as vitamin A concentration and trace-mineral form. A factorial feeding study showed that corn hybrid, vitamin A level, and mineral source altered yolk carotenoid concentration and deposition efficiency, indicating that the response to supplementation is conditioned by the surrounding dietary matrix (Zurak *et al.,* 2025). Thus, the relevant question is not simply whether a target nutrient can be increased, but under which dietary conditions the desired compound is deposited efficiently and reproducibly.

Other targets remain less mature. Iron and iodine can be increased in eggs through dietary supplementation, but the usable range is constrained by simultaneous effects on egg quality and hen performance (Sarlak *et al.,* 2025). These examples illustrate a broader principle: nutritional targets cannot be optimized independently of the biological and technological consequences of their deposition.

The next step is therefore to move beyond single-nutrient enrichment toward coordinated nutritional profiles. Evidence from microalgae supplementation is illustrative: across 36 studies, microalgae altered yolk *n*-3 PUFA and pigmentation while also affecting several production and egg-quality traits, with responses varying among dietary and biological contexts (Anam *et al.,* 2025). Such coupled responses suggest that future designer eggs should be evaluated against multiple criteria-target-nutrient deposition, deposition efficiency, egg quality, stability, production efficiency, and nutritional relevance-rather than concentration alone. Recent reviews similarly identify bioavailability, oxidative stability, production efficiency, and human evidence as unresolved priorities for enriched eggs (El-Sabrout and Abd El-Aziz, 2026).

Table 1. Nutritional targets for functional and designer eggs: current evidence and research gaps.

Nutritional target	Main dietary strategies	Major egg response	Current status & key limitation	Research gap / next opportunity
n-3 PUFA	Fish oil, algae, flaxseed	↑ ALA, EPA, DHA; improved n-6/*n*-3 profile	Established; source, dose, oxidation and sensory effects	Optimize fatty-acid profile, oxidative stability and nutritional delivery
Selenium	Organic/inorganic Se	↑ Egg Se	Established; source-dependent deposition and bioavailability	Optimize form, dose, stability and nutrient interactions
Vitamin D	Vitamin D_3 and related sources	↑ Yolk vitamin D	Established–developing; variable retention and response	Improve retention, bioavailability and demonstrated human benefit
Carotenoids	Marigold, algae, corn, plant sources	↑ Lutein, zeaxanthin and pigmentation	Established; deposition depends on source, matrix and dose	Optimize carotenoid profile and bioavailability, not pigmentation alone
Iodine	Organic/inorganic iodine	↑ Egg iodine	Emerging; limited human evidence and stability concerns	Develop targeted iodine eggs and establish nutritional effectiveness
Iron	Organic/inorganic Fe	↑ Egg Fe	Emerging; limited deposition and mineral interactions	Improve deposition efficiency and bioavailable iron
Choline	Choline supplementation	↑ Yolk choline-related compounds	Emerging; relatively limited evidence	Establish dose, delivery efficiency and human nutritional relevance
Multiple nutrients	Combined PUFA, vitamins, minerals, antioxidants	Multi-dimensional nutritional profile	Emerging; interaction and optimization challenges	Move from single-nutrient enrichment toward objective-driven nutritional design
Lipid/cholesterol profile	Modified fatty-acid diets	Altered yolk lipid profile	Developing; complex metabolic/genetic regulation	Integrate lipid quality, cholesterol and consumer health objectives

Notes: ↑, increased concentration; ALA, α-linolenic acid; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid; PUFA, polyunsaturated fatty acids; Se, selenium; Fe, iron. Evidence-status categories indicate the relative maturity of the available literature and are not formal evidence grades.

Beyond single-nutrient enrichment: designing the nutritional profile

The transition from enrichment to nutritional design requires coordinating multiple dietary inputs rather than optimizing individual nutrients in isolation. As summarized in Table 2, single-nutrient strategies provide a useful proof of concept, whereas multi-nutrient approaches address the composition of the egg as an integrated nutritional profile. Their advantage is not simply the simultaneous increase of several compounds, but the possibility of combining complementary functions while accounting for interactions among nutrients and their deposition pathways.

Attia *et al*. (2024a) provide an illustrative example by combining whole flaxseed and fish oil with vitamin E and different sources of selenium, zinc, and iron. The intervention altered yolk fatty-acid composition, mineral deposition, antioxidant status, and lipid-related indices, demonstrating that one feeding strategy can influence several nutritional dimensions simultaneously. However, such responses also show why multi-nutrient enrichment is an optimization problem. Nutrients differ in absorption, metabolism, and deposition, so increasing their dietary supply does not necessarily produce proportional or independent changes in the egg.

Nutritional enhancement must also remain compatible with acceptable physical and sensory quality. In a related study, Attia *et al*. (2024b) evaluated combinations of flaxseed, fish oil, vitamin E, and trace minerals together with egg quality, sensory attributes, and protein metabolites. The absence of major adverse effects on egg quality and sensory characteristics under the tested conditions illustrates an important design criterion: a successful nutritional intervention must improve the intended nutritional profile without creating unacceptable product-level trade-offs.

A further dimension is when nutrients are supplied. Precision feeding extends the concept of dietary optimization from nutrient amount and composition toward temporal matching of supply with physiological demand. Because yolk, albumen, and shell formation impose changing requirements during the laying cycle, split-feeding strategies may improve the alignment of energy, protein, calcium,

and other nutrients with the processes involved in egg formation (do Nascimento *et al.,* 2025). For designer eggs, this principle could potentially improve deposition efficiency while reducing nutrient oversupply, although direct evidence linking split feeding to targeted enrichment remains limited.

These developments point toward objective-driven nutritional design. The target should be defined before the feeding strategy is selected: rather than asking how much *n*-3, selenium, or vitamin D can be deposited, the design process should specify the intended nutrient combination and then identify the sources, levels, and feeding strategy capable of producing it reproducibly. Recent discussions of designer eggs similarly position precision feeding, bioavailability, and targeted modification as components of a broader nutritional-design framework (Akram *et al.,* 2025).

Multi-nutrient enrichment is therefore better viewed as an intermediate stage than as the endpoint of designer-egg development. Its next step is objective-driven formulation, in which nutrient combinations are selected according to defined nutritional goals while maintaining deposition efficiency, product quality, and reproducibility.

Table 2. From single-nutrient enrichment to objective-driven designer eggs.

Design approach	Primary objective	Typical strategy	Key optimization target	Research gap / next opportunity
Single-nutrient enrichment	Increase one target nutrient	Targeted supplementation	Deposition efficiency	Move beyond maximizing a single nutrient
Dual-nutrient design	Combine complementary nutrients	e.g., PUFA + antioxidant	Nutrient ratio and interaction	Define optimal combinations and synergistic effects
Multi-nutrient design	Improve several nutritional attributes	PUFA + vitamins/minerals/antioxidants	Overall nutrient balance	Understand nutrient–nutrient interactions and trade-offs
Precision feeding	Match nutrient supply with hen requirements	Phase-, time- or requirement-specific feeding	Nutrient utilization and efficiency	Integrate physiological timing with nutritional objectives
Targeted designer egg	Address a defined nutritional need	Tailored multi-nutrient formulation	Bioavailability and nutritional relevance	Link egg composition to specific consumer needs
Objective-driven designer egg	Deliver a predefined nutritional profile	Integrated precision nutrition	Composition + stability + bioavailability	Demonstrate that the designed profile translates into meaningful nutritional benefit

Notes: PUFA, polyunsaturated fatty acids. "Designer egg" refers here to an egg whose nutritional composition is deliberately formulated toward a predefined nutritional objective rather than simply increased in one or more nutrients.

Stability of nutritional quality during storage and handling

Successful nutrient deposition does not guarantee that a designer egg will deliver the intended nutritional profile at consumption. After laying, eggs undergo moisture and CO_2 loss, albumen alkalization, protein structural changes, lipid hydrolysis, and oxidative reactions that progressively alter the egg matrix (Deng *et al.,* 2025; Khademi Shurmasti *et al.,* 2026). These changes can affect conventional quality traits as well as the retention and chemical stability of enriched nutrients. Thus, the performance of a designer egg should be evaluated across the interval from production to consumption rather than at the point of deposition alone.

DHA-enriched eggs provide a clear example because their high degree of unsaturation increases susceptibility to lipid peroxidation. In a controlled study, astaxanthin supplementation reduced the loss of DHA during 42 days of refrigerated storage to less than 3%, compared to more than 17% in eggs enriched with DHA alone. Lipidomic analysis indicated that free astaxanthin preferentially protected non-esterified DHA from oxidation, while formation of secondary oxidation products was also reduced (Wang *et al.,* 2022). This illustrates a design strategy in which nutrient enrichment is coupled with protection against post-depositional oxidation.

Other antioxidant strategies support the same principle. In *n*-3-enriched eggs, dietary vitamin E, polyphenols, and lutein reduced malondialdehyde accumulation, maintained antioxidant enzyme activity, and prolonged retention of *n*-3 fatty acids and DHA during storage. These effects were accompanied by increased expression of Nrf2, P38MAPK, HO-1, SOD-1, and glutathione peroxidase,

linking improved storage stability to activation of endogenous antioxidant defenses (Shahid *et al.,* 2022). The implication is that a co-enriched antioxidant need not represent a second independent nutritional target; it can function as a protective component that preserves the primary target.

This interaction becomes particularly relevant in multi-enriched eggs. Representative studies integrating PUFA, selenium, vitamin E, lutein, and other micronutrients, together with their storage and quality outcomes, were summarized in Table 3. Kralik *et al*. (2023) demonstrated the feasibility of simultaneously increasing *n*-3 PUFA, selenium, vitamin E, and lutein in eggs, illustrating how several nutritional components can be incorporated within a single product. More recent evidence directly links such interactions with storage stability: in DHA-enriched eggs, selenium supplementation-particularly selenium yeast-increased selenium deposition and glutathione peroxidase activity, reduced lipid oxidation, and helped preserve internal egg quality during storage (Zou *et al.,* 2025). These findings reinforce the principle that the nutritional profile and its stability should be considered as an interacting system rather than as independent enrichment outcomes.

Not all nutrients, however, are equally vulnerable to storage and cooking. In 25-hydroxyvitamin D_3-enriched eggs, true retention of 25-hydroxyvitamin D_3 ranged from 72% to 111% across storage and cooking conditions, while calculated vitamin D activity remained higher than that of non-enriched eggs. Nevertheless, retention varied with processing conditions, showing that nutrient form and preparation can influence the amount ultimately delivered (Clark *et al.,* 2023). Post-production handling also affects the surrounding egg matrix. Refrigerated eggs generally retained greater albumen height and Haugh unit over four weeks than eggs stored at room temperature, while washing altered several physicochemical responses (Kim *et al.,* 2024).

Table 3. Examples of nutritionally designed eggs and evidence on nutritional stability.

Designer egg	Nutritional design	Storage/processing challenge	Main finding	Research gap / next opportunity	Reference
DHA + selenium-enriched egg	DHA + organic/inorganic Se	Lipid and protein oxidation during storage	Selenium yeast increased Se deposition and GPx activity, reduced TBARS, and better preserved internal quality during 30-day storage than sodium selenite	Optimize DHA–Se combinations and Se source for long-term oxidative stability	Zou *et al.* (2025)
25- OH-D_3-enriched egg	25-hydroxyvitamin D_3	Storage and cooking	25-OH-D_3 showed high retention across storage/cooking conditions, demonstrating that chemical form affects nutrient stability	Evaluate retention and bioavailability under realistic household and commercial conditions	Clark *et al.* (2023)
n-3 PUFA + antioxidant-enriched egg	*n*-3 PUFA + vitamin E/Se/lutein	PUFA oxidation during storage	Antioxidant enrichment improved oxidative stability and helped preserve the nutritional quality of *n*-3-enriched eggs	Define optimal PUFA–antioxidant ratios rather than maximizing individual nutrients	Kralik *et al.* (2023)
Multi-enriched egg	*n*-3 PUFA + Se + vitamin E + lutein	Nutrient interactions and oxidative stability	Simultaneous enrichment produced a broader nutritional profile with complementary antioxidant protection	Determine whether combined enrichment improves bioavailability and measurable consumer benefit	Kralik *et al.* (2023)
n-3 + vitamin E + trace-element-enriched egg	*n*-3 PUFA + vitamin E + Se/Zn/Fe	Nutrient interactions and egg quality	Combined feeding modified yolk fatty acids, mineral deposition, and antioxidant-related characteristics	Move from empirical combinations toward objective-driven formulation	Attia *et al.* (2024a)
n-3 + micronutrient-enriched egg	Whole flaxseed/fish oil + vitamin E + trace elements	Nutritional enhancement versus product quality	Combined supplementation was evaluated for nutritional composition, egg quality, sensory attributes, and protein metabolites	Integrate nutritional enhancement, sensory acceptability, stability, and consumer relevance	Attia *et al.* (2024b)

Note: 25-OH-D_3, 25-hydroxyvitamin D_3; DHA, docosahexaenoic acid; *n*-3 PUFA, omega-3 polyunsaturated fatty acids; Se, selenium; Zn, zinc; Fe, iron; GPx, glutathione peroxidase; TBARS, thiobarbituric acid-reactive substances.

These findings indicate that the nutritional performance of a designer egg should be evaluated at consumption rather than immediately after

laying. Future formulations should therefore consider nutrient retention after storage and cooking together with deposition efficiency and oxidative stability, particularly for oxidation-sensitive PUFA. Nutrient stability should consequently be treated as a design criterion rather than solely as a post-production quality-control issue.

From nutrient enrichment to meaningful nutritional benefit

The nutritional value of a designer egg ultimately depends on how much of a target nutrient reaches the consumer in a usable form and produces a measurable biological response. This requires a continuous pathway from deposition and retention to digestion, bioaccessibility, absorption, nutrient status, and, where evidence permits, physiological or clinical effects. The egg can therefore be viewed as a food-based nutrient-delivery system in which feed formulation, metabolic transport, egg-matrix interactions, processing, and human utilization are interconnected (Ma *et al.,* 2026; Wang *et al.,* 2026).

Table 4 illustrated how the nutritional contribution of a designer egg can be quantified without equating enrichment with health benefit. For EPA+DHA, the EFSA adequate intake for adults is 250 mg/day. The enriched eggs studied by Stupin *et al*. (2018) provided 91 mg EPA + DHA per egg, equivalent to approximately 36% of this reference value, whereas the Nutri4 formulation reported by Masle *et al*. (2024) provided approximately 154 mg per egg, or 62%. Similarly, the Nutri4 egg contained approximately 23.1 µg selenium, corresponding to about 42% of the adult selenium RDA of 55 µg/day (EFSA NDA Panel, 2010; Masle *et al.,* 2024; NIH ODS, 2025). These examples show that "omega-3-enriched" or "selenium-enriched" eggs are not nutritionally uniform categories; their contribution depends on formulation and deposition efficiency.

The transition from nutrient delivery to biological response requires human evidence. In a randomized intervention, consumption of three *n*-3 PUFA-enriched eggs daily for three weeks increased serum *n*-3 PUFA status and improved post-occlusive microvascular reactivity in healthy young adults (Stupin *et al.,* 2018). A subsequent clinical study using *n*-3 PUFA-enriched eggs also reported changes in endothelial function and inflammatory mediators, including IL-10 and interferon-γ (Stupin *et al.,* 2020). These findings provide evidence beyond egg composition because the intervention altered human biomarkers and physiological responses; however, they do not establish long-term clinical benefit.

Multi-nutrient eggs provide a further test of the precision-design concept. Masle *et al*. (2024) used eggs enriched simultaneously with *n*-3 PUFA, lutein, vitamin E, and selenium in patients recovering from acute coronary syndrome. The intervention altered nutrient status and several measures related to endothelial function and antioxidant defense, although these short-term findings do not establish sustained physiological or clinical benefits.

This distinction is reinforced by the broader human evidence. A 2026 scoping review of 37 human intervention studies found relatively consistent improvements in intake estimates and biomarkers of targeted nutrient status, particularly for *n*-3 fatty acids and carotenoids, but substantially less consistent evidence for downstream health outcomes (Wang *et al.,* 2026).

Evidence should therefore be interpreted hierarchically. Increased nutrient concentration establishes enrichment, whereas increased intake demonstrates dietary delivery. Improved bioavailability indicates utilization, while changes in circulating or tissue biomarkers indicate a biological response. Physiological changes provide stronger functional evidence, whereas clinical outcomes require appropriately designed trials.

These findings demonstrate the potential of enriched eggs to deliver selected nutrients and influence short-term biological responses, but they should not be interpreted as evidence of long-term disease prevention or clinical benefit.

Translation from experimental enrichment to a reproducible product remains challenging because final egg composition varies with nutrient source and dose, hen genotype, age, physiological stage, basal diet, and production conditions. These factors can also interact when several nutrients are supplied simultaneously, increasing variability in the final nutritional profile (Chauhan and Sreeja, 2025; Ma *et al.,* 2026). Precision feeding and split-feeding may help reduce this variability by matching nutrient supply more closely with physiological and egg-formation requirements (do Nascimento *et al.,* 2025).

Commercial translation adds further constraints. Enriched eggs require additional feed inputs, formulation control, quality assurance, and, for some products, analytical verification of nutrient content. Their economic value therefore depends on

whether nutritional differentiation is sufficiently consistent and meaningful to justify additional production costs. Consumer acceptance and willingness to pay also influence commercial viability (Chen *et al.,* 2023; Edobor *et al.,* 2026). Sustainability should be considered within the same framework because increasing nutrient inputs without improving deposition efficiency can increase resource use and cost without producing a proportional nutritional return.

A cost–benefit comparison with conventional eggs is therefore important when evaluating the practical value of PDEs. Relative to conventional eggs, PDEs may involve additional costs for specialized feed ingredients, diet formulation, feeding management, quality control, and analytical verification. These costs may be justified when the resulting nutritional improvement is consistent, nutritionally meaningful, and sufficient to support consumer willingness to pay a price premium. Conversely, limited deposition efficiency, variability in nutrient content or adverse effects on production performance may reduce the economic return from enrichment. Thus, the economic advantage of PDEs depends on the balance between incremental production costs and the magnitude, consistency, and consumer value of the nutritional benefit. Direct comparative cost–benefit data remain limited, emphasizing the need for future economic assessments that integrate production costs with verified nutritional outcomes and consumer acceptance.

A PDE should be defined by the performance of the entire delivery pathway, from deposition to human utilization. The design objective is to achieve a reproducible nutrient profile that remains stable through handling and preparation, contributes meaningfully to dietary intake, is biologically available, and-where supported by adequate human evidence-improves nutrient status or a relevant physiological outcome. This shifts the endpoint from the hen to the consumer and establishes the central research challenge for next-generation designer eggs: integrating deposition efficiency, nutrient interactions, stability, bioavailability, human evidence, production efficiency, affordability, and sustainability into a single food-based nutrient-delivery system.

Table 4. Estimated nutritional contribution of selected designer eggs to daily nutrient reference values.

Designer egg / study	Target nutrient	Reported amount per egg	Reference value used	Estimated contribution of one egg	Interpretation	Evidence
n-3 PUFA-enriched egg	EPA + DHA	91 mg/egg (7 mg EPA + 84 mg DHA)	250 mg/day EPA+DHA*	~36.4%	A single enriched egg can make a meaningful contribution without requiring supplementation	Stupin *et al.* (2018)
n-3 PUFA-enriched egg	EPA + DHA	154 mg/egg (19 mg EPA + 135 mg DHA)	250 mg/day EPA+DHA*	61.6%	Higher enrichment substantially increases the potential contribution of one egg	Masle *et al.* (2024)
Nutri4 multi-enriched egg	Selenium	23.1 µg/egg	55 µg/day (adult RDA)	42.0%	One egg provides ~two-fifths of the adult selenium requirement	Masle *et al.* (2024)
Nutri4 multi-enriched egg	DHA	135 mg/egg	250 mg/day EPA+DHA*	54.0%†	DHA alone represents 54.0% of the combined EPA + DHA reference value	Masle *et al.* (2024)
25-OH-D_3-enriched egg	Total vitamin D activity	Estimated ~2.1–3.3 µg/egg‡	15 µg/day (adult RDA)	~14–22%	Estimated contribution remains meaningful after storage/cooking, although retention depends on processing conditions	Clark *et al.* (2023)
Vitamin D-enriched egg	Total vitamin D	8.52 µg/whole egg	15 µg/day (adult RDA)	56.8%	An optimized formulation can potentially provide more than half of the adult vitamin D requirement from one egg	Thamteerasathian *et al.* (2026)

* EFSA's adequate intake for long-chain *n*-3 PUFA is 250 mg/day of combined EPA + DHA for adults. The comparison is therefore made specifically with EPA + DHA rather than total *n*-3 PUFA.
† The egg contained 135 mg DHA + 19 mg EPA = 154 mg EPA + DHA. DHA alone (135 mg) represents 54.0% of the 250-mg EPA + DHA reference value; considering the combined EPA + DHA content (154 mg), the contribution would be 61.6%.
‡ The value is estimated from the reported post-storage/cooking concentration per 100 g and an assumed ~60-g edible egg; therefore, it should be interpreted as an approximate per-egg equivalent rather than a directly reported per-egg concentration.
Lutein and vitamin E are not expressed as percentages because no universally accepted adult RDA/PRI appropriate for this comparison is available.

Future perspectives and research priorities for PDEs

The next stage of designer-egg development should move from empirical enrichment toward precision-designed systems that integrate nutrient selection, deposition, stability, and nutritional objectives. Recent advances in nutriomics and metabolic profiling may help identify nutrient combinations and biological pathways that support more targeted modification of egg composition (Ding *et al.,* 2026; Ma *et al.,* 2026). The key challenge is to define nutritional targets that are reproducible and meaningful rather than simply increasing the number or concentration of fortified compounds.

Precision at the production level is equally important. Laying hens have time-dependent nutrient requirements during egg formation, and split-feeding strategies seek to match nutrient supply with these changing physiological demands while improving nutrient utilization and feed efficiency (do Nascimento *et al.,* 2025). A logical next step is to determine whether temporal precision can be linked directly to nutrient deposition. This could involve optimizing the timing, source, and dose of specific nutrients to improve transfer into yolk or albumen while limiting excess intake. This could make precision feeding a tool for controlling both production efficiency and the reproducibility of the final nutritional profile.

The human evidence base remains a major research gap. The scoping review by Wang *et al*. (2026) found relatively consistent effects on intake and biomarkers of targeted nutrient status, but less consistent evidence for downstream health outcomes. Future trials should therefore be designed around predefined nutritional or physiological objectives, with standardized formulations, adequate sample sizes, longer intervention periods, defined target populations, appropriate comparators, and meaningful endpoints. Populations with specific nutrient inadequacies may be particularly relevant for determining the practical value of PDEs.

Stability and reproducibility should also be treated as design criteria. Future studies should evaluate nutrient retention and bioaccessibility after realistic storage and cooking conditions alongside initial deposition, particularly for oxidation-sensitive PUFA and multi-nutrient formulations. Standardized reporting of feed composition, nutrient source and dose, hen characteristics, deposition efficiency, storage, cooking, and post-processing retention would improve cross-study comparability and commercial standardization (Ma *et al.,* 2026).

Commercial translation introduces a further constraint: nutritional differentiation must justify its additional biological and economic costs. Consumer acceptance depends on perceived quality, information, and price; limited awareness of functional eggs and the influence of health-information formats on willingness to pay illustrate this challenge (Chen *et al.,* 2023; Edobor *et al.,* 2026). Future development should therefore integrate scientifically defensible claims, transparent labeling, competitive pricing, and environmental assessment. Importantly, sustainability should be considered together with deposition efficiency because increasing dietary inputs without proportional nutrient transfer can increase resource use without improving nutritional return.

In summary, designer eggs represent a transition from conventional nutrient enrichment toward purpose-driven food design. Although dietary strategies can modify the concentrations of *n*-3 fatty acids, selenium, vitamin D, vitamin E, carotenoids, and other nutrients in eggs, concentration alone is insufficient to establish nutritional value. A meaningful designer egg should deliver a defined and reproducible nutrient profile that remains stable through storage and preparation and contributes measurably to nutrient intake and status.

The practical development of such products requires consideration of deposition efficiency, egg quality, production cost, bioavailability, and consumer acceptance alongside nutritional targets. Given the limited evidence for long-term physiological and clinical benefits, health-related claims should remain proportionate to the strength of available human evidence. Future research and product development should therefore prioritize reproducible nutritional performance and demonstrable consumer value rather than simply maximizing nutrient concentration.

Acknowledgement

The authors acknowledge the institutional support of Islamic Azad University.

Conflict of Interest

The authors declare no conflict of interest.

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