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(Unstructured) Abstract (up to 350 words)

The commercial egg industry is increasingly interested in extending laying cycles toward 100 weeks to improve resource efficiency and distribute pullet-replacement costs over a greater number of eggs. However, feeding programs based mainly on fixed crude protein (CP) concentrations tend not to adequately account for age-related changes in feed intake, egg mass output, amino acid utilization, energy balance, and eggshell formation. Extended laying cycles also present increasing challenges related to liver health, skeletal integrity, and eggshell quality. This review examines precision-feeding strategies based on standardized ileal digestible (SID) amino acids and the ideal protein concept. Phase-specific adjustment of nutrient supply may align amino acid and energy intake more closely with changes in production, maintenance requirements, and feed intake during early, mid, and late lay. Crystalline amino acid supplementation can facilitate reductions in dietary CP while maintaining a balanced digestible amino acid profile; however, excessive CP reduction may impair egg mass output, body condition, or productivity unless all limiting amino acids are adequately supplied. The review also considers the integration of precision livestock farming technologies. Sensor-based monitoring, nutritional response models, and artificial intelligence-assisted decision support can enable more frequent evaluation of flock performance and more responsive feeding and environmental management. Nevertheless, fully autonomous systems linking real-time data directly to diet reformulation and feed delivery remain largely experimental in commercial laying-hen production. Overall, phase-specific precision feeding can improve nitrogen-use efficiency, support metabolic health and eggshell quality, and enhance the economic and environmental sustainability of extended laying cycles. Its practical benefits depend on diet formulation, flock performance, ingredient prices, housing conditions, manure management, and the reliability of data-driven technologies.

Keywords (3 to 6): Precision feeding, Laying persistency, Ideal protein, Smart farming, Low crude protein

Introduction

The modern laying hen industry is undergoing a substantial transition. Advances in genetic selection have shifted the production frontier toward the "long-life" layer, which has the potential to produce approximately 500 eggs by 100 weeks of age [1,2]. This transition from conventional cycles of 70–80 weeks to cycles extending beyond 100 weeks requires a shift in emphasis from maximizing short-term peak production to sustaining productivity over the long term [3,4].

Several converging pressures are accelerating this transition. Environmentally, increasingly stringent regulations targeting nitrogen (N) and phosphorus (P) emissions, together with concerns regarding ammonia emissions and associated odors, are placing growing pressure on the poultry industry to reduce excess dietary nitrogen [5,6]. Economically, the variability in the nutrient composition and cost of major protein ingredients, such as soybean meal, places substantial pressure on least-cost feed formulation [7]. Concurrently, there is a growing societal demand for improved animal welfare and extended economic lifespans, pushing producers away from early depopulation practices [3,8].

Despite these pressures, and although digestible amino acid formulation is increasingly adopted in commercial practice, many layer diets are still formulated primarily on a total crude protein (CP) percentage basis, with generous safety margins [9]. This one-size-fits-all approach is structurally limited; it fails to account for individual feed intake variations and the shifting metabolic demands of aging hens [10,11]. Consequently, CP-centric formulation can result in amino acid imbalances, where surplus amino acids undergo hepatic deamination. This not only wastes metabolic energy but also increases nitrogen excretion, thereby increasing the substrate available for subsequent ammonia formation in manure [12], with implications for both flock health and environmental compliance.

In this review, precision feeding refers to matching the supply of digestible nutrients, particularly amino acids, to the changing requirements of laying hens across the production cycle. This is achieved primarily through diet formulation based on the ideal protein concept and phase-specific adjustment of nutrient density. Data-driven and smart-farm technologies are considered enabling tools that may extend this approach toward more responsive management. This review explores the paradigm shift from conventional, flock-level feeding based on fixed crude protein to this precision-feeding approach. It examines the role of this transition in optimizing laying persistency, metabolic health, and environmental sustainability of egg production, with an emphasis on key concepts of phase-specific nutrition. Finally, it identifies critical areas warranting further exploration in integrating data-driven decision-support systems into smart poultry production. This review draws on peer-reviewed studies and commercial breeder recommendations, focusing primarily on literature published over the past two decades on amino acid nutrition and precision feeding in laying hens.

Physiological and Metabolic Challenges in Late Laying

Extending the laying cycle from the conventional endpoint of 70–80 weeks of age to 100 weeks or beyond is associated with multiple age-related physiological and metabolic challenges that are often interrelated [1,13,14]. Understanding these changes is essential for designing effective nutritional interventions.

Aging and Declining Productive Efficiency

As hens age, the efficiency with which dietary nutrients are utilized for egg production tends to decline. Changes in egg production, feed intake, body composition, and metabolic activity may alter the partitioning of nutrients between productive functions and maintenance. In particular, maintenance accounts for a relatively greater proportion of total protein requirements during late lay as egg mass output declines [15]. Advancing age also affects amino acid availability and overall protein utilization [16,17]. These changes have important implications for amino acid formulation. Absolute amino acid requirements associated with egg mass production decline as egg output decreases, whereas maintenance represents a relatively greater component of total amino acid requirements [15,18]. Changes in body protein turnover, tissue maintenance, and physiological status with advancing age further influence amino acid requirements.

Hepatic Lipid Metabolism and Fatty Liver Hemorrhagic Syndrome

The liver is a major metabolic organ in laying hens and the principal site of yolk-precursor synthesis. During extended production cycles, older hens become increasingly susceptible to disturbances in hepatic lipid metabolism. Fatty liver hemorrhagic syndrome (FLHS) is one of the most consequential metabolic disorders affecting commercial laying flocks and may be exacerbated by prolonged excessive energy intake [19,20]. Some studies have suggested that dietary composition and lipotropic factors may influence hepatic lipid accumulation under certain experimental conditions [21,22]. When dietary energy intake exceeds the amount required for maintenance and egg production, the resulting positive energy balance promotes hepatic lipogenesis and lipid deposition [23,24]. These findings highlight the importance of adjusting dietary energy density according to feed intake, egg mass output, and body condition during late lay. Amino acids, including methionine, should be supplied at balanced levels that support egg production and hepatic metabolism while avoiding both excessive and deficient intake. Such an approach may help limit excessive egg size and body fat accumulation without unnecessarily compromising egg production [25,26].

Age-Related Changes in Protein Metabolism and Amino Acid Digestibility

An important consideration in extended production cycles is the potential effect of advancing age on protein metabolism and amino acid digestibility. Older laying hens may exhibit increased endogenous amino acid losses and reduced ileal digestibility of certain limiting amino acids, including

lysine, methionine, and arginine [16,17]. The magnitude of these age-related changes, however, may vary among amino acids and experimental conditions.

These changes highlight the importance of formulating late-lay diets on the basis of standardized ileal digestible (SID) amino acids rather than total amino acid concentrations. SID-based formulation does not directly increase nutrient absorption but enables dietary amino acid supply to be more accurately matched to the digestible amino acid availability and physiological requirements of older hens. The strategic inclusion of crystalline amino acids can further improve dietary amino acid balance, whereas exogenous proteases may enhance protein and amino acid digestibility under certain dietary conditions [16,27,28].

Eggshell Quality Decline and Calcium–Bone Metabolism

The deterioration of eggshell quality is one of the major physiological and economic challenges associated with extended laying cycles [29,30]. This decline is closely related to the interactions among dietary calcium supply, skeletal calcium metabolism, and eggshell formation. Medullary bone serves as a readily mobilizable calcium reservoir that helps support eggshell calcification when absorbed dietary calcium is insufficient [31]. With advancing age and prolonged egg production, repeated mobilization of skeletal calcium may contribute to a progressive loss of bone mineral and an increased risk of osteoporosis, particularly when dietary calcium supply is inadequate or poorly synchronized with eggshell formation [13,32,33]. These changes often occur concurrently with a decline in eggshell quality.

Nutritional strategies for late-laying hens should therefore provide an appropriate combination of fine and coarse calcium particles. Coarse calcium particles are retained for longer periods in the gastrointestinal tract and improve calcium availability during nocturnal eggshell calcification, whereas fine particles provide more rapidly available calcium earlier in the calcification cycle [34]. The use of coarse calcium sources may also be combined with afternoon feeding or split-feeding strategies to improve the synchronization between calcium intake and eggshell formation [35]. The optimal ratio of fine to coarse calcium particles, however, may vary according to hen age, calcium source, particle size, and feeding system.

Feed Intake Variation and Individual Nutrient Disparities

A limitation of conventional flock-level feeding is that average feed intake does not fully represent the intake of individual hens. Considerable variation in daily feed intake occurs among individual hens within a flock because of differences in body weight, production level, and feeding behavior [10,36,37]. As a result, hens consuming less feed than the flock average may receive lower daily intakes of essential amino acids, including lysine and methionine, even when all birds are offered the same diet. These hens may therefore be at greater risk of inadequate amino acid intake when dietary nutrient concentrations are formulated solely on the basis of mean flock intake [38]. Yet the consequences of lower individual intake may depend on the magnitude and duration of the intake

difference and should not automatically be interpreted as severe deficiency or premature cessation of egg production. Individual variation in feed intake supports the development of precision-feeding strategies that adjust nutrient density according to the intake and productive performance of individual hens or relatively homogeneous subgroups. Such approaches may be complemented by feeder-management practices that promote uniform feed consumption, reduce selective feeding, and improve the distribution of nutrients within the flock [37,39].

From Crude Protein to Precision Feeding: A Conceptual Shift

Limitations of Crude Protein-Based Formulation

Conventional approaches to laying-hen diet formulation have traditionally used dietary crude protein (CP) concentration as a major formulation criterion. This approach has several limitations when applied to extended production cycles. First, CP concentration alone does not adequately describe the concentrations, balance, or digestibility of individual amino acids in the diet and may therefore result in an amino acid supply that does not accurately match the hens' requirements [40-42]. Second, formulating diets with excessive CP to ensure that the requirements for limiting amino acids are met results in the oversupply of other amino acids. Surplus amino acids cannot be stored directly and are therefore catabolized, with their amino groups removed primarily in the liver. This process incurs a metabolic cost and increases nitrogen excretion, primarily in the form of uric acid. Following excretion, microbial degradation of nitrogenous compounds in manure may contribute to ammonia (NH₃) emissions within the housing environment [5]. Third, an imbalanced amino acid supply may reduce nitrogen-use efficiency, adversely affect feed efficiency, and increase the environmental footprint of egg production [43]. Thus, the transition from formulating diets primarily according to total CP concentration to balancing digestible amino acids according to physiological requirements represents a fundamental component of precision feeding.

The Ideal Protein Concept

The ideal protein concept provides a theoretical framework for precision amino acid formulation [44]. It addresses the limitations of CP-based formulation by expressing the requirements for essential amino acids as optimal ratios relative to a reference amino acid, most commonly lysine, which is assigned a value of 100 [45]. Lysine is commonly used as the reference amino acid because its requirement is closely associated with productive performance and the requirements for other essential amino acids can be expressed relative to it [45-47]. In White Leghorn-type laying hens at 28–34 weeks of age, Bregendahl et al. [45] proposed true digestible amino acid ratios, relative to lysine, of 94% for total sulfur amino acids (TSAA), 77% for threonine (Thr), 93% for valine (Val), 79% for isoleucine (Ile), and 22% for tryptophan (Trp). However, these ratios should not be regarded as universally fixed values because amino acid requirements may vary with genotype, age, productive

performance, basal diet composition, and the response criterion used to estimate the requirement [47,48]. Nevertheless, the underlying principle remains applicable: matching the dietary supply of digestible amino acids more closely to the hens' physiological requirements can improve amino acid balance and reduce unnecessary amino acid excesses. This approach permits dietary CP to be reduced through the appropriate supplementation of crystalline amino acids, potentially decreasing nitrogen excretion while maintaining productive performance, provided that all essential amino acid requirements are adequately met [9].

Formulation Based on Standardized Ileal Digestible Amino Acids

The transition toward precision feeding supports the formulation of laying-hen diets on a standardized ileal digestible (SID) amino acid basis rather than solely on total amino acid concentrations. SID values estimate dietary amino acid disappearance from the gastrointestinal tract up to the terminal ileum after correction for basal ileal endogenous amino acid losses [49,50]. Therefore, SID values provide a more appropriate estimate of digestible amino acid supply, although they should not be interpreted as direct measurements of amino acid absorption rate or metabolic utilization.

The application of SID-based formulation may be particularly relevant during late lay because advancing age may affect amino acid digestibility [16,17]. In addition, as egg mass output declines, maintenance may account for a relatively greater proportion of total protein requirements [9,26]. These changes suggest that amino acid supply should be matched to feed intake, egg mass output, body condition, and physiological status rather than chronological age alone.

Total amino acid concentrations do not account for differences in ingredient digestibility, whereas apparent ileal digestibility values are influenced by basal endogenous amino acid losses [49,51]. Correcting apparent values for these losses enables SID-based formulation to provide a more consistent estimate of digestible amino acid supply. When combined with balanced amino acid supplementation and appropriate reductions in dietary CP, this approach may reduce the risk of amino acid deficiencies and excesses and contribute to lower nitrogen excretion while maintaining productive performance [9,49].

Changes in Ideal Amino Acid Ratios Across the Production Cycle

A key consideration in precision feeding is that the recommended amino acid profile may require modest adjustment across the laying cycle. Phase-specific amino acid ratios may vary with genotype, physiological status, and production objectives. Table 1 presents practical phase-specific digestible amino acid ratios relative to lysine, derived primarily from Hy-Line Brown recommendations [52], with experimental context provided by published studies [45,53,54]. Bregendahl et al. [45] is included as an academic reference for the ideal protein concept; however, the ratios reported in that study were determined on a true digestible basis in White Leghorn-type hens at 28–34 weeks of age and are not

directly equivalent to the phase-specific values presented in Table 1. The table values should therefore be regarded as practical reference ratios rather than universally applicable biological constants.

Based on the values presented in Table 1, most amino acid ratios remain relatively stable across the production cycle. The TSAA-to-lysine ratio declines gradually from 92% in early lay to 91% in mid lay and 90% during late lay. The threonine-to-lysine and tryptophan-to-lysine ratios remain constant at 70% and 22%, respectively. In contrast, the valine-to-lysine ratio gradually decreases from 90% to 88%, while the isoleucine-to-lysine ratio decreases from 82% to 80%.

These modest changes indicate phase-related adjustments in the recommended balance of individual amino acids relative to lysine rather than major shifts in the ideal amino acid profile. Moreover, because these are relative ratios, they should not be interpreted as direct evidence of changes in the absolute daily requirement for each amino acid. Absolute amino acid intake should be determined by considering the recommended ratio together with daily lysine requirements, actual feed intake, egg mass output, target egg weight, environmental conditions, and strain-specific recommendations.

Phase Feeding Strategies

Phase feeding is a practical implementation of precision nutrition in which diets with different nutrient specifications are provided at successive stages of the production cycle. Each diet is formulated to reflect the predominant physiological and productive demands of the corresponding phase. Therefore, transitions between diets should be based on production status rather than chronological age alone [53].

Phase 1: Early Laying (18–24 Weeks)

Early lay is a period of rapid physiological transition. Pullets entering production must simultaneously support increasing egg production, continued body and skeletal development, and the metabolic demands associated with sexual maturity. Because feed intake may not increase as rapidly as egg mass output during this period, early lay diets generally require a relatively high concentration of standardized ileal digestible (SID) amino acids.

Amino acid specifications should be set in line with actual feed intake, body weight development, egg production, and egg mass output. Based on the phase-specific reference ratios presented in Table 1, lysine is assigned a reference value of 100, with recommended ratios of 92 for total sulfur amino acids (TSAA), 70 for threonine, 90 for valine, 82 for isoleucine, and 22 for tryptophan during early lay. These values should be considered practical formulation targets rather than fixed biological requirements.

Maintaining an adequate digestible amino acid supply relative to feed intake is important during continued growth and the onset of egg production [55]. Calcium management is also important during the transition into lay. A combination of fine and coarse limestone can provide both rapidly and more

slowly available calcium, thereby supporting medullary bone development and preparing pullets for eggshell formation [34,56,57]. The appropriate calcium concentration and limestone particle distribution should be adjusted according to the stage of sexual maturity, feed intake, and breeder recommendations [52].

Phase 2: Mid Laying (25–47 Weeks)

The mid-lay phase is characterized by sustained production at or near peak levels, with the primary nutritional objective of maintaining persistency of lay while adjusting nutrient supply according to feed intake, egg mass output, body weight, and target egg weight, rather than being fixed at a single daily value [55,58]. Based on the practical reference ratios presented in Table 1, the TSAA ratio remains at approximately 91% during mid lay. Because this value is expressed relative to lysine, it should not be interpreted as evidence that the absolute sulfur amino acid requirement remains constant throughout this phase.

The Thr ratio presented in Table 1 is 70%. This value is broadly consistent with the ratio of approximately 72% reported for brown-egg laying hens at 42–54 weeks of age, although published estimates may vary according to genotype, age, basal diet composition, and the response criterion used to estimate the requirement [59]. The corresponding Val, Ile, and Trp reference ratios during the mid-laying period are 89%, 81%, and 22%, respectively.

Egg weight management becomes increasingly important during this phase because excessive increases in egg size may adversely affect eggshell quality later in the production cycle [29,30]. Because dietary amino acid supply can influence egg mass, coordinated management of dietary energy and digestible amino acid supply is preferable to restricting a single amino acid [58,60].

Maintaining an appropriate balance between dietary energy and amino acid supply also helps avoid an excessive positive energy balance and reduce the risk of metabolic disturbances, including fatty liver hemorrhagic syndrome [9,61].

Phase 3: Late Laying (48 Weeks Onward)

Precision feeding may provide substantial nutritional benefits during late lay because egg production, egg mass output, feed intake, and eggshell quality change progressively as hens age. As egg mass output declines, maintenance represents a relatively greater proportion of total protein requirements [11,15]. Digestible lysine supply should therefore follow actual intake and body condition rather than being assigned a single fixed daily value [60,62,63].

Based on the phase-specific reference ratios presented in Table 1, the late-lay TSAA, Thr, Val, Ile, and Trp ratios are 90%, 70%, 88%, 80%, and 22%, respectively [52]. These values should be regarded as practical reference ratios rather than fixed biological requirements, and they should not be interpreted as direct evidence of changes in the absolute daily requirement for each amino acid.

Advancing age also affects amino acid availability. Layers at 70 weeks of age have been reported to exhibit lower standardized ileal digestibility of arginine, lysine, and methionine than younger hens

[16]. These findings support consideration of age-dependent amino acid digestibility when formulating diets for late-laying hens.

Calcium management remains a major nutritional priority during late lay because eggshell quality generally becomes more difficult to maintain as hens age [30]. Partial replacement of fine limestone with coarse calcium particles helps support eggshell quality in aged laying hens, although the optimal proportion depends on dietary calcium concentration, calcium source, particle size, and feeding conditions [56,57]. Feeding hens three times daily has also been shown to improve eggshell thickness and increase serum calcium concentrations compared with conventional twice-daily feeding in aged hens [64]. In late-laying hens, increasing the proportion of feed provided in the afternoon can further improve calcium metabolism and eggshell quality by more closely synchronizing dietary calcium availability with nocturnal eggshell calcification [65].

Nutritional Changes Across the Production Cycle

Across the production cycle, the absolute supply of digestible amino acids should track these production variables rather than chronological age. In contrast, calcium supply, particle size, and feeding time become increasingly important considerations for maintaining eggshell quality during late lay [11,15,30,56,57,64]. Because the amino acid ratios presented in Table 1 change only modestly among production phases, the nutritional transition from early to late lay is more appropriately characterized by adjustments in daily nutrient intake and dietary concentration. It does not require a major restructuring of the ideal amino acid profile. A change of this magnitude, no more than one to two percentage points across the entire cycle, falls within the range of variation reported among studies, which itself reflects differences in breed, age, basal diet, and assessment method [47]. Such small differences are therefore unlikely to be nutritionally meaningful in practice.

Synthetic Amino Acid Supplementation in Reduced-CP Diets

The strategic inclusion of crystalline amino acids is a key nutritional tool for implementing precision feeding. Supplementation with amino acids such as L-lysine HCl, DL-methionine, L-threonine, and L-tryptophan—and, when necessary, L-isoleucine and L-valine—enables dietary crude protein (CP) to be reduced while meeting target standardized ileal digestible (SID) amino acid specifications [47,48].

In laying hens from 21 to 34 weeks of age, reducing dietary CP from 18% to 16% while maintaining a balanced digestible amino acid profile did not adversely affect most production variables, although egg weight was reduced [48]. These findings indicate that crystalline amino acid supplementation can improve nitrogen-use efficiency, but the extent of CP reduction must be carefully controlled to avoid deficiencies in essential, nonessential, or conditionally essential amino acids.

Lysine and Sulfur Amino Acids as Key Formulation Targets

Lysine and sulfur amino acids are key considerations in the formulation of laying-hen diets. Lysine is commonly assigned a value of 100 as the reference amino acid in the ideal protein concept, with the requirements for other essential amino acids expressed relative to it [45,47]. In White Leghorn-type laying hens at 28–34 weeks of age, Bregendahl et al. [45] proposed true digestible Met and Met+Cys ratios of 47% and 94%, respectively. Sulfur amino acids, particularly methionine, are commonly among the first limiting amino acids in practical laying-hen diets. Inadequate sulfur amino acid supply can impair egg production and egg mass, whereas increasing the supply can increase egg weight. The optimal methionine or TSAA supply, however, varies according to genotype, age, feed intake, egg mass output, basal diet composition, and the digestibility system used to express amino acid concentrations [47,66]. Methionine supply should therefore be formulated on the basis of daily digestible amino acid intake and its ratio to lysine rather than according to a single fixed percentage of the diet. Excessive supplementation should also be avoided because increasing methionine beyond the level required for the target production response may increase feed cost without providing a proportional improvement in performance.

Threonine in Reduced-CP Diets

Threonine tends to become increasingly limiting as dietary crude protein (CP) is reduced, particularly in diets containing less than approximately 140 g/kg CP [47]. In addition to its role in protein synthesis, threonine contributes to intestinal mucin production, maintenance of the intestinal mucosa, antibody synthesis, and immune function. Consequently, an adequate threonine supply may be particularly important under conditions that increase mucin secretion or immune activity [47]. The Thr ratio remains at 70% across the three production phases presented in Table 1. A constant Thr ratio should not be interpreted as evidence that the absolute daily threonine requirement remains unchanged. Daily threonine intake should be scaled to lysine intake and production status.

Tryptophan and Isoleucine: Balancing the Peripheral Ratios

Tryptophan is a precursor of serotonin and other biologically active metabolites and can therefore influence appetite, stress responses, behavior, immune function, and protein synthesis [47]. Conventional laying-hen diets generally provide sufficient tryptophan, but supplementation can become necessary when dietary CP is substantially reduced and greater quantities of crystalline amino acids are included. Inadequate tryptophan supply may reduce feed intake; however, the magnitude of this response varies among studies [47]. Isoleucine can also become limiting when dietary CP is reduced. Parenteau et al. [67] evaluated Shaver White hens from 20 to 46 weeks of age using a two-phase feeding program in which dietary CP was reduced by 2 percentage points during each phase. When the reduced-CP diets were supplemented with methionine, lysine, threonine, tryptophan, and isoleucine, optimal production responses were observed at SID Ile ratios between 82% and 88%. Still,

these values were obtained under specific experimental conditions and should not be interpreted as universally applicable ratios for all genotypes or production phases.

As dietary CP is progressively reduced, amino acids beyond methionine, lysine, threonine, and tryptophan can become limiting. Formulation should therefore account for isoleucine, valine, arginine, and other potentially limiting amino acids rather than focusing exclusively on the amino acids supplemented first.

Nitrogen Reduction Outcomes

Reduced-CP diets supplemented with limiting amino acids can reduce nitrogen excretion while maintaining productive performance, although the magnitude of the response depends on the extent of CP reduction and the completeness of the amino acid profile. Representative reduced-CP and split-feeding studies are summarized in Table 2. Based on the nitrogen excretion values reported by Ji et al. [48], reducing dietary CP from 18% to 16% corresponded to reductions in nitrogen excretion of approximately 20–23%, which were statistically significant at 24 and 28 weeks but not at 32 weeks. Most production variables were maintained, although egg weight declined at the lowest CP level [48]. Whether these reductions in excreted nitrogen translate into lower barn-level ammonia emissions depends on additional manure- and housing-related factors, which are considered in a later section. Split feeding offers an additional means of adjusting protein and amino acid supply according to the timing of egg formation. Horváth et al. [68] reported lower protein and nitrogen intake, improved feed conversion, and reduced nitrogen emission with a split-feeding treatment in one experiment. However, a separate reduced-CP split-feeding treatment did not significantly reduce nitrogen emission, indicating that the response depends on the specific formulation and feeding strategy.

Data-Driven Smart Farm Integration

The precision-feeding framework described in the preceding sections can be further enhanced through data-driven precision livestock farming (PLF) technologies. These technologies enable continuous collection and analysis of production, behavioral, and environmental data and can support the transition from periodically adjusted feeding toward more adaptive management [69-71]. However, the studies reviewed to date have focused primarily on monitoring and decision support rather than on fully autonomous linkage of sensor data to real-time diet reformulation and feed delivery [69-71].

The Closed-Loop Framework

Drawing on general principles of model-based precision livestock farming [69,70], we propose a five-stage conceptual closed-loop framework (Fig. 1): sensor-based data acquisition; data cleaning, integration, and normalization; model-based estimation of nutrient requirements; decision support or

automated feed delivery; and evaluation of observed outcomes against predefined key performance indicators.

Sensor Monitoring Systems

The data-acquisition layer can integrate several sensor modalities. Load cells beneath feed bins or in feeding stations measure feed disappearance at the flock, housing-unit, or individual-station level and, combined with body-weight and production records, help identify changes in feed intake and efficiency [70]. Radio-frequency identification (RFID) tags permit bird-specific identification and, when combined with precision weighing, can support estimation of individual feeding behavior, body weight, and feed intake in group-housed birds, although large-scale commercial deployment remains logistically and economically challenging [71,72]. Computer-vision systems non-invasively analyze flock distribution, activity, and welfare-related behavior, though accuracy can be affected by occlusion, stocking density, lighting, and loss of individual identification over time [70,71].

Environmental sensors record barn temperature, humidity, carbon dioxide, and, where reliable systems exist, ammonia, providing context for ventilation decisions and for interpreting changes in intake and performance; these data affect housing conditions directly only when integrated with an automated environmental-control system [70].

AI-Assisted Decision Support

The decision layer can combine statistical analysis, machine-learning algorithms, optimization, and mechanistic nutritional models to translate sensor data into feeding recommendations, integrating feed intake, body weight, egg production and mass, and environmental conditions to update short-term nutrient requirement estimates and predict responses [69-71]. Mechanistic and dose-response models provide a biological basis for such estimates; for example, Sakomura et al. [73] estimated the SID leucine requirement for maintenance and modeled the egg-output response of laying hens to SID leucine intake. These models are not themselves artificial-intelligence systems but could serve as components of a broader decision-support pipeline in which differences between predicted and observed outcomes could be used to evaluate and recalibrate model parameters [69].

Automated Execution and System Integration

In the proposed framework, model-generated recommendations could be transmitted to feed-management software or automated feeding controllers if compatible system interfaces are available. Automated equipment may then adjust feed allocation, feeding time, or the proportions of preformulated diets; however, real-time reformulation should be regarded as a future integration target rather than an established commercial practice. Monitoring dashboards and cloud-based platforms can display key performance indicators and compare observed with expected performance to provide alerts or management feedback [74]. Practical adoption nonetheless depends on equipment reliability, usability, maintenance requirements, cost, and demonstrated commercial benefits; PLF should support rather than replace human oversight [72].

The Feedback Loop and Adaptive Management

A central feature of this framework is repeated feedback. Rather than evaluating a diet only after several weeks, production, intake, body-weight, and environmental data can be compared regularly with predicted outcomes. Deviations, such as reduced feed intake during heat stress, can then trigger alerts or recommendations to review nutrient density, environmental control, or flock health [69,70,74]. At present this is more appropriately described as AI-assisted decision support than as fully autonomous diet reformulation. Such feedback may be particularly valuable during extended laying cycles, in which small persistent deviations could become consequential over time; continuous monitoring can shorten the delay in detecting nutritional imbalances, though these long-term benefits require validation under commercial conditions [69,70,72].

Environmental and Economic Implications

Nitrogen and Ammonia Emission Reduction

A major environmental rationale for precision feeding is to reduce dietary nitrogen intake by aligning digestible amino acid supply more closely with the hens' physiological and productive requirements. Diets formulated primarily on the basis of crude protein may supply total nitrogen and some amino acids in excess of requirements, particularly when digestible amino acid balance is not adequately considered [6,47]. As described above, reduced-CP feeding supplemented with limiting amino acids lowers nitrogen excretion while maintaining most production traits; its effect on barn-level ammonia emission, however, is less consistent [47,48]. Excess amino acids cannot be stored as free amino acids and must instead be catabolized, with their nitrogen ultimately excreted predominantly as uric acid in poultry. Following excretion, microbial degradation of uric acid and other nitrogenous compounds contributes to ammonia formation. As a result, reducing unnecessary nitrogen intake and excretion may decrease the amount of substrate available for ammonia volatilization. The actual magnitude of ammonia emissions, however, also depends on manure pH, moisture, temperature, microbial activity, manure-management practices, and housing ventilation [5,6].

A recurring observation is that reductions in dietary and excreted nitrogen do not automatically translate into proportional reductions in ammonia emission. Wu-Haan et al. [75] reported that a reduced-emission diet combining 6.9% CaSO₄-zeolite with a modest reduction in dietary CP decreased NH₃ emissions by approximately 27–46%, depending on hen age, without adversely affecting productive performance. However, the treatment increased H₂S emissions, and the reduction in NH₃ cannot be attributed solely to the reduction in dietary CP because several dietary modifications were applied simultaneously.

Under commercial conditions, Burley et al. [76] reported that reduced-CP, amino acid-balanced diets maintained hen performance in a flock of 50,760 laying hens. Even so, manure nutrient concentrations and NH_3 flux did not differ significantly among the dietary treatments. These findings indicate that reduced-CP precision feeding can improve nitrogen-use efficiency and economic performance, but reductions in ammonia emissions are not guaranteed and depend on both dietary formulation and manure-management conditions. The divergence between these studies suggests that reduced dietary CP primarily lowers the quantity of nitrogen excreted, whereas the marked ammonia reduction reported by Wu-Haan et al. [75] likely reflected the acidifying and adsorptive action of the CaSO_4 -zeolite additive rather than CP reduction alone. Barn-level ammonia volatilization is therefore influenced not only by dietary CP concentration but also substantially by manure pH, moisture, ventilation, and manure-management conditions, indicating that reduced-CP formulation is most effective for ammonia mitigation when combined with appropriate manure-management practices.

Economic Feasibility

The economic rationale for precision feeding includes potential feed-cost savings from improved nutrient-use efficiency, whereas extending the laying cycle may reduce annual flock-replacement costs by distributing pullet, cleaning, and placement costs over a greater number of eggs.

In the same commercial study, the reduced-CP, amino acid-balanced diets were less costly and generated greater revenue than a high-CP control diet without adversely affecting most production and egg-quality variables [76]. The economic response to reduced-CP feeding, however, depends on ingredient prices, the cost of crystalline amino acids, flock performance, and the extent to which dietary CP can be reduced without impairing egg mass or body condition.

In a Canadian aviary/free-run case study, Traoré and Doyon [77] estimated that extending the production period from 51 to 64 weeks could increase annual producer EBITDA (earnings before interest, taxes, depreciation, and amortization) by approximately 5.8% over a 5-year planning horizon. The model also predicted an economically optimal production period of approximately 71 weeks under the price and production conditions evaluated. These estimates, though, were specific to the Canadian supply-management system and should not be extrapolated directly to other housing systems, markets, or 100-week production cycles.

Historical feeding studies indicate that reductions in dietary CP are often feasible when limiting amino acids are adequately supplemented. Keshavarz and Jackson [78] reported that hens receiving a phase-feeding sequence of 15%, 14%, and 13% CP supplemented with methionine and lysine maintained overall egg production and egg weight relative to hens fed higher-CP control diets, although egg mass and body weight were reduced. These findings demonstrate the need to evaluate economic savings together with potential changes in productive performance.

The economic viability of extended laying cycles depends on sustained egg production, commercially acceptable eggshell quality, mortality, the proportions of cracked and dirty eggs, feed

prices, and pullet-replacement costs. Phase-specific calcium and amino acid management can help support these outcomes, but nutritional management alone cannot guarantee the economic success of a 100-week production cycle.

Sustainability and the Triple Bottom Line

The integration of precision feeding with extended laying cycles may contribute to the three major dimensions of sustainability: environmental performance, economic viability, and animal health and welfare. Van de Braak [4] reviewed the broader biological, environmental, economic, and societal implications of extending the laying period. In parallel, Heidari et al. [79] proposed a regionalized, life cycle-based feed-formulation framework using weighted goal programming to balance nutritional, economic, and environmental objectives.

From an environmental perspective, reduced-CP diets supplemented with limiting amino acids can reduce nitrogen excretion when the amino acid profile is adequately balanced [47,48]. From an economic perspective, reduced feed costs and fewer flock replacements may improve profitability under suitable ingredient-price and production conditions [76,77]. From an animal-health perspective, phase-specific management of energy, amino acids, calcium, and phosphorus can support productive performance, liver health, eggshell formation, and skeletal integrity, although these outcomes depend on multiple nutritional, genetic, environmental, and management factors [13,14,19,30,61].

Precision feeding should therefore be regarded as a potentially important strategy for improving the sustainability of extended laying cycles rather than as a guarantee of regulatory compliance, economic feasibility, or animal welfare. Its practical value must be evaluated according to flock performance, housing system, feed prices, environmental objectives, equipment requirements, and local regulatory conditions.

Conclusion

The transition toward extended laying cycles of up to 100 weeks requires nutritional strategies that respond to age-related changes in feed intake, egg mass output, body condition, amino acid utilization, and eggshell formation. Feeding programs based on fixed crude protein concentrations cannot adequately address these changes.

Precision feeding based on the ideal protein concept and digestible amino acid specifications provides a scientifically grounded framework for aligning nutrient supply with flock requirements. Phase-specific adjustment of nutrient density, together with the strategic use of crystalline amino acids, can improve nitrogen-use efficiency and allow crude protein to be reduced while maintaining productive performance. This benefit depends on careful control of the reduction and its coordination with energy balance, calcium and phosphorus supply, calcium particle size, and feeding time. Even so, nutritional intervention alone cannot eliminate the physiological challenges associated with aging.

Overall, the ideal protein concept and phase-specific feeding are well-supported nutritional principles. Moderate reductions in dietary CP, when accompanied by adequate digestible amino acid supplementation, generally reduce nitrogen excretion while maintaining most production traits [47,48]. Several aspects, however, remain less certain. The precise amino acid ratios for each phase vary with breed, age, and assessment method [47]; the magnitude of ammonia mitigation varies considerably among studies; and fully autonomous data-driven feeding remains largely experimental [69-72].

Data-driven precision livestock farming technologies could further support this approach by enabling more frequent monitoring and more responsive management. The combination of precision feeding and extended laying cycles can contribute to environmental, economic, and animal-health objectives. Reduced-CP, amino acid-balanced diets can reduce nitrogen excretion under appropriate formulation conditions, although reductions in ammonia emissions depend on housing and manure-management factors. Improved nutrient-use efficiency and fewer flock replacements may also enhance economic performance, but the outcome remains dependent on ingredient prices, crystalline amino acid costs, flock productivity, eggshell quality, mortality, housing system, and market conditions.

Precision feeding should therefore be regarded as an increasingly important strategy for managing extended laying cycles rather than as a guarantee of environmental compliance, economic profitability, or animal welfare. Future research should focus on validating phase-specific nutrient recommendations, refining age-dependent digestibility values, evaluating long-term health and production outcomes, and determining the technical and economic feasibility of data-driven feeding systems under commercial conditions.

요약 (Korean Abstract)

산란계 산업에서는 자원을 효율적으로 이용하고 새로운 산란계를 들여와 기존 계군을 교체하는 비용을 더 많은 계란에 분산하기 위해 산란주기를 약 100 주령까지 연장하려는 관심이 증가하고 있다. 그러나 고정된 조단백질(crude protein, CP) 함량을 기준으로 한 기존 급이 프로그램은 닭의 주령이 증가하면서 나타나는 사료섭취량, 계란 생산량, 아미노산 이용성, 에너지 균형 및 난각 형성의 변화를 충분히 반영하지 못할 수 있다. 또한 산란기간이 길어질수록 간 건강, 뼈 건강 및 난각 품질을 유지하기 위한 관리가 더욱 중요해진다. 본 리뷰에서는 기초 회장 내인성 아미노산 손실을 보정한 표준회장소화율(standardized ileal digestibility, SID)과 필요한 아미노산의 균형을 맞추는 이상단백질 개념에 기반한 정밀급이 전략을 검토하였다. 산란 초기·중기·후기에 따라 영양소 공급을 조절하면 계란 생산량, 유지

요구량 및 사료섭취량의 변화에 맞추어 아미노산과 에너지를 보다 적절하게 공급할 수 있다. 결정형 아미노산을 보충하면 소화 가능한 아미노산의 균형을 유지하면서 사료의 CP 수준을 낮출 수 있다. 그러나 부족하기 쉬운 필수 아미노산이 충분히 공급되지 않은 상태에서 CP를 지나치게 낮추면 계란 생산량, 닭의 몸 상태 또는 생산성이 저하될 수 있다. 또한 본 리뷰에서는 정밀축산 기술과 정밀급이의 통합 가능성도 검토하였다. 센서를 이용한 모니터링, 영양 반응 예측 모델 및 인공지능 기반 의사결정 지원 기술은 닭 무리의 생산상태를 자주 확인하고 급이와 사육환경을 더욱 신속하게 조절하는 데 도움을 줄 수 있다고 나타났다. 다만 실시간 측정자료를 사료 재배합과 급이 시스템에 직접 연결하는 완전 자율형 시스템은 상업적 산란계 생산에서 아직 실험적인 단계에 있다. 종합하면, 생산단계별 정밀급이는 질소 이용 효율을 높이고 간 건강과 에너지 대사의 안정성을 유지하는 데 기여하며, 연장된 산란주기의 경제적·환경적 지속가능성을 향상시킬 가능성이 있다. 그러나 이러한 효과는 사료배합, 계군의 생산성, 원료 가격, 사육환경, 분뇨 관리 및 데이터 기반 기술의 신뢰성에 따라 달라질 수 있다.

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Tables and Figures

Table 1. Recommended standardized ileal digestible amino acid ratios relative to lysine for laying hens by production phase¹

Amino Acid	Early laying (18–24 wk)	Mid laying (25–47 wk)	Late laying (48+ wk)
Lysine	100	100	100
Met + Cys (TSAA)	92	91	90
Threonine	70	70	70
Valine	90	89	88
Isoleucine	82	81	80
Tryptophan	22	22	22

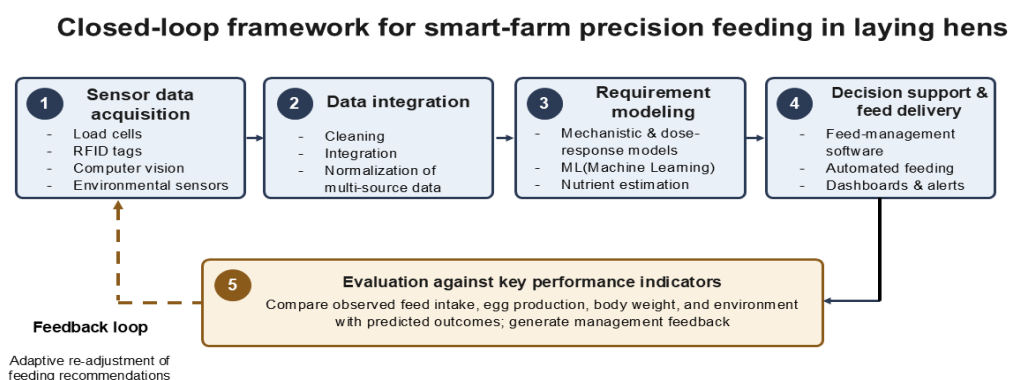
¹Values are expressed relative to lysine, which was assigned a value of 100. The ratios represent practical phase-specific reference values and should not be interpreted as absolute amino acid requirements. Bregendahl et al. [45] reported ratios on a true digestible basis and this study was used as an academic reference rather than as the direct source of all phase-specific values. The phase-specific ratios were derived primarily from the Hy-Line Brown ideal protein reference [52], with the peaking, layer-2, and layer-3 phases corresponding to the early-, mid-, and late-laying periods, respectively; Bregendahl et al. [45], Okazaki et al. [53], and Manoukas and Young [54] were used to provide experimental context.

Table 2. Summary of representative studies on reduced crude protein and split feeding strategies in laying hens

Study	Hens (strain, age)	Dietary CP strategy	Amino acids supplemented	Production performance	Nitrogen / ammonia outcome
Ji et al. [48]	Hy-Line W-36, 21–34 wk	CP reduced from 18.0 to 16.0% (graded)	Met, Thr, Ile, Val, Trp, Lys (ideal amino acid profile)	Egg production, egg mass, feed intake, and FCR maintained; egg weight reduced at lower CP	Nitrogen excretion reduced; blood ammonia unchanged
Horváth et al. [68]	Brown Nick, 28 wk; Hy-Line Brown, 47 wk	Split-feeding (morning/afternoon); CP reduced by about 2% (afternoon diet ~92% of control CP)	Lys, Met, and Met+Cys held constant ($\pm$ Thr, Val)	Laying rate maintained or increased; FCR improved; egg weight reduced	Nitrogen intake and excretion reduced; nitrogen emission reduced in one trial but unchanged in the low-CP split trial
Wu-Haan et al. [75]	Hy-Line W-36, 21/38/59 wk	6.9% CaSO ₄ -zeolite plus slight CP reduction (control 18.0/17.0/16.2%; reduced 17.0/15.5/15.6%)	Limiting amino acids	Egg production, egg weight, feed intake, and body weight unaffected	NH ₃ reduced by about 27–46% (by hen age); H ₂ S increased; multiple diet changes confound the CP effect
Burley et al. [76]	Lohmann LSL Lite, 50,760 hens, 18–51 wk	Low, intermediate, or high (control) CP, least-cost formulation	Limiting amino acids	Egg production, egg weight, egg quality, and body weight maintained; feed cost lower and revenue higher	Manure nitrogen and NH ₃ flux not significantly different

CP, crude protein; FCR, feed conversion ratio; NH₃, ammonia; H₂S, hydrogen sulfide. Bracketed numbers denote reference citation

Fig. 1. Conceptual closed-loop framework for smart-farm precision feeding in laying hens.



Fully autonomous linkage of sensor data to real-time diet reformulation remains largely conceptual in commercial laying-hen production.