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Precision Nutrition Supply Models for Laying Hens: Divergence, Integration and Application Advances between Industrial Scaled Farms and Family Holdings

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Abstract: The two main forms of the world's egg industry are large-scale farms (LSFs) equipped with new technologies, and smallholder family farms (FFs) that have limited resources and different management. Precision nutrition has been introduced to the industrial system, but it has not yet been applied in family farms; therefore, this review will systematically compare the supply models of precision nutrition in the two systems across the five areas of calcium-phosphorus homeostasis, gut health modulation, housing environment interaction, energy-to-protein ratio optimisation, and integrative precision nutrition framework, and based on recent data (2021-2026), demonstrate that they are different. To meet the various nutritional requirements of plants in a new way, some new technologies have been introduced for LSF, such as real-time sensing, machine learning and automatic feeding ($R^2 > 0.90$). FFs are simple, low-cost decision tools that have only a few factorial coefficients and local additives, and their regulation of calcium and phosphorus is different from that of LSFs; therefore, FFs are used to express strain-specific transporters and vitamin D metabolites. FF is gradually introducing herbal ultrafine powders that have shown some improvement in gut health. Housing corrections are not all the same. Net Energy Systems can lower the feed cost of both types of systems by 3%-8%, but the way to achieve this is different; we will provide comparison tables showing the model architecture, validation results and economic threshold for each. Finally, there have been some convergences in the areas of open-source digital tools, transgenerational programming and the responsible nutrition framework. They can address the accuracy problem and consider the different conditions of different systems.

Keywords: Precision Nutrition; Laying Hens; Industrial Farms; Family Farms; Calcium-Phosphorus Metabolism; Gut Health; Net Energy; Machine Learning; Smallholder System

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1. Introduction: two worlds of egg production

World egg production is now over 95 million tonnes. It comes from the two very different farming systems; Large-Scale Farms (LSFs) have more than 50, 000 hens. Automated Feeding and Environmental Control will be employed to take care of the animals [1, 2]. Family farms (FFs) usually have between 500 and 5, 000 hens. They account for a relatively large proportion of the eggs in developing countries. However, they have insufficient funds and technology [3], so precise nutrition cannot meet the different demands of various groups or individual birds. The above way is now well-established in LSFs. Sensor Networks, Factorial Models and Machine Learning can be applied to solve this problem [4]. The same models are used for FFs but do not work well. Because it is high in cost, lacks data and has many types of management modes, this paper will examine the development of precision nutrition models in both systems. We will see where they are now and where they will go. The five subjects of the content are:

(i) Calcium-Phosphate regulation,

(ii) Gut Health and Intestinal Absorption.

(iii) Integration of Housing Environment.

(iv) Optimisation of the Energy-to-Protein Ratio.

(v) Combined Precision Frameworks.

Based on data and verification, we will decide at various times what modifications need to be made. Finally, we hope to find some good cooperation opportunities between the two systems.

2. Calcium and phosphorus homeostasis: from molecular targets to field application

Ca-P fluctuations in the eggs will directly affect eggshell quality and bone strength. Food plays a role in the quantity and quality of eggs laid by hens. For example, protein, energy and key amino acids such as methionine and lysine in the feed, calcium-to-phosphorus ratio and vitamin D are all necessary for the size and quality of eggs. During the peak laying period, the should have 16-18% crude protein and a calcium-to-phosphorus ratio of about 1.2:1. Feed additives can be added to improve the digestibility of feed, promote growth and increase egg production, and prevent or treat calcium and phosphorus deficiencies in lickits, osteoporosis and soft-shelled eggs, etc. Management matters too. The light, temperature and crowdedness of the chicken coop will affect the quantity and quality of eggs. For example, during the laying period, hens need 16-17 hours of light a day, the temperature should be kept at 18-23°C, and each hen should have 0.3-0.4 square meters of space to move around; the health of the hens is also a factor. The weight of the female, the age and health status of her reproductive system, any diseases such as salpingitis or Newcastle disease will reduce the number of eggs laid and their size; research has also been conducted on using microalgae (UG seaweed) as a calcium supplement. Seaweed is very rich in calcium; it is about 14 times more than eggs and about 5 times more than tofu, so it can provide natural calcium. All this research is really important for helping hens lay more healthy eggs, keep them healthy, develop better feed, and improve the way they are raised. By using precise nutrition, careful management, maintaining good health for the chickens, and employing science in production, we can increase egg production and improve the quality of the eggs.

Table 1. Contrasting CaP precision strategies in LSF vs. family farms

Aspect	Largescale farms (LSF)	Family farms (FF)	Key references
Monitoring tools	Automated eggshell breakage sensors, realtime feed intake, individual RFID	Manual egg quality scoring, periodic sampling, visual inspection	[5, 6]
Vitamin D metabolites	1αhydroxycholecalciferol, 25OHD$_3$ in premixes	Standard vitamin D$_3$, occasional use of commercial premix with D$_3$ only	[6, 8]
Phosphorus additives	Phytase + myoinositol, lowP diets with monitoring	Phytase inclusion but variable quality; limited myoinositol use	[7, 9]
Model type	Mechanistic + machine learning (RF, XGBoost) with realtime updates	Factorial tables with local ingredient coefficients	[4, 7]
Reduction in P excretion	20–25%	8–12% (when phytase used)	[6, 9]

3. Gut health modulation and intestinal nutrient absorption

Good gut health is closely related to the efficiency of nutrients and disease resistance; scientists at the Institute of Feed Science of the Chinese Academy of Agricultural Sciences have discovered an attractive secret. By adding a probiotic compound based on xylo-oligosaccharides to the feed, they have found that it can increase the laying performance of laying hens and reduce immune stress. Spoiler Alert: Just 0.2% of this compound can help hens lay more eggs, produce eggs with a good yolk, and even reduce the colour of the yolk! How? It is a “gut superhero” that helps to improve the intestinal barrier, reduce inflammation, and make the gut a microbial party with more good guys. Not when you add glycine! According to the above research, raising the amount of glycine in the low-protein diet (2.0% crude protein) by an additional 0.2% may increase the laying rate of laying hens. Eggs are heavier, feed efficiency has increased, and the quality of egg white is still excellent. Glycine is a good builder in the gut that promotes the growth of intestinal villi (increases the area for nutrient absorption) and strengthens the mucosal barrier to create a good environment for egg white production. It will also lower the feed-cost; win-win. A dream team led by Professor Lin Hai from Shandong Agricultural University and the University of Lomé in Togo has just achieved a remarkable victory, and their China-Africa Joint Laboratory for Poultry Nutrition and Gut Health has officially commenced! Their Mission? Heat Stress Crisis for Egg-Laying Hens in the Warming World. With advanced technology, they are building strong chicken production bases that can withstand high temperatures and have shown that science and teamwork can solve global problems.

Table 2. Gut health modulation approaches in LSF vs. family farms

Parameter	Largescale farms (LSF)	Family farms (FF)	Ref.
Primary additives	Commercial probiotics, xylanase, phytase, protected butyrate	Herbal ultrafine powders, fermented feeds, local plant extracts	[10, 11]
Dosing precision	Automated microdosing linked to feed intake	Manual mixing, batchwise	[10]
Intestinal barrier markers	Occludin, ZO1, claudin3 monitored in research trials	Field observation of fecal consistency, eggshell quality	[11, 12]
Microbiota modulation	Targeted SCFA profiles, metagenomic guided	Enrichment of Blautia, Faecalibacterium via CHUP	[11]
Cost/egg (USD)	0.012–0.018	0.005–0.009	[10, 11]

4. Housing environment integration into nutrient models

Environmental The environment (temperature, humidity, light, stocking density) affects how well the animals eat and are kept. LSF has a good climate control system that can be added to the thermal stress coefficients of the dynamic factorial model and is adjustable with a precision of $\pm 3\%$ [13]. FF has a relatively wide range of fluctuation but can be corrected with a simple factor. For example, according to the results of 12 Chinese FF studies, to increase the 6% feed efficiency by raising the temperature by 5°C above 22°C, adjust the lysine and methionine requirements by increasing them by 2.5% [14]. There will be different light-signal situations as well; LSF is fixed at a set amount of daylight hours to optimise feed intake, and FF is generally in the daytime with some artificial light, which may reduce the duration of egg laying. **Table 3** shows the different ways of environmental integration.

Table 3. Integration of housing environment in precision nutrition models

Environmental factor	Largescale farms (LSF)	Family farms (FF)	Ref.
Temperature monitoring	Continuous sensors (≥ 10 per house) + cloud analytics	Periodic thermometer, local weather data	[13, 14]
Nutrient adjustment algorithm	Dynamic ME and amino acid correction (R^2 > 0.92)	Simplified 2–3% per 5°C correction	[13, 14]
Lighting precision	LED dimming with intensity control, 16L:8D optimized	Fixed photoperiod or natural light extension	[15]
Stocking density consideration	Integrated into NE requirement (activity increment)	Rarely adjusted; usually fixed assumption	[13]
Model prediction error (FCR)	± 2.5%	± 7–10%	[14, 15]

5. Energytoprotein ratio optimization: net energy systems and application

The proportion of energy to protein is required for Feed Efficiency and carcass structure. Net-energy (NE) systems have been employed in the LSF, and as a result, the feed cost has dropped by 3%-8% compared with AME-based formulations [16-17]. Ban Zhibin and others built a new 12-chamber parallel open-flow respirometer system to determine the net energy required for the maintenance of Hy-Line Brown laying hens and Jilin Luhua chickens, which were 368.79kJ/(kgBW0.75d) and 449.24kJ/(kgBW0.75d), respectively. They also determined the apparent metabolizable energy (AME) and net energy (NE) of different types of corn in Hy-Line Br laying hens; they were between 15.06 - 16.19 MJ/kg and 11.29 - 12.57 MJ/kg, respectively, and newly harvested and properly matured corn was significantly better than aged corn. A 70-day trial of Jinghong-1 layers showed that NE-optimised diets maintained egg production and reduced abdominal fat by 13.6% [16]. Simplified NE prediction equations based on crude fibre, ether extract and crude protein have been verified for FF (R^2 = 0.76-0.82), so low-cost formulations can be realised without calorimetry [17]. **Table 4** shows the actual situation of E:P optimisation.

Table 4. Energytoprotein ratio optimization strategies

Parameter	Largescale farms (LSF)	Family farms (FF)	Ref.
Energy system	NE (net energy) with ingredientspecific values	AME (apparent metabolizable energy) or simplified NE prediction	[16, 17]
Data input	Indirect calorimetry, NIR analysis of ingredients	Local feed tables, crude fiber/fat content estimates	[16, 18]

Feed cost reduction	5–8%	3–5%	[16, 17]
FCR improvement	2.5–3.5%	2–3%	[16, 18]
Adoption barriers	Need for NIR and software	Lack of ingredient analysis, trust in formulas	[17, 18]

6. Integrative precision nutrition frameworks and model comparison

Based on the data from the sensor and model equations of the mechanism, a high-precision LSF model has been constructed. The hybrid framework of factorial sub-models and gradient boosting or LSTM networks has achieved an R^2 of more than 0.90 for the daily lysine and Ca requirements [19, 20]. An excess of dietary energy can decrease the efficiency of nutrient utilisation in chickens. When energy intake exceeds the requirement, the excess energy is stored as fat; therefore, there is too much carcass fat and reduced utilisation of feed ingredients. Based on extensive research, it has been determined that a diet with an appropriate low-energy level can promote the good growth and development of laying hens, improve production efficiency, etc. Research has found that the dietary energy requirements of hybrid chickens (Lohmann Brown $\times$ White Broiler-line laying hens and Langya chickens) are as low as 12.20MJ/kg in weeks 0-3, 12.00MJ/kg in weeks 4-6, and 12.57MJ/kg in weeks 7-9. The optimal AME level for the diet of Daw1 commercial egg chicks can be reduced to 11.81 MJ/kg; the suitable AME level for the growing period of Taihang chickens is 11.50MJ/kg; and an AME level of 11.70MJ/kg is suitable for the growing period (9-13 weeks old) of "Jinghong No.1" egg-type breeder chickens. Too much energy (12.10 MJ/kg) in the diet will reduce the average daily weight gain of Lushan Green-shelled egg chickens. The Dietary Energy Level for Jinghong laying hens in the late laying stage can be lowered to 9MJ/kg. Ren Xiyan and others have compared the strengths and weaknesses of the guaiacol method, tetrazolium salt staining method, and acid indicator method for determining the freshness, ripeness and adulteration of wheat, and at the same time, FF-adapted models are robust and require relatively little data. Recently, a tool based on a mobile application has been developed that uses a random forest model and only requires 5 input variables (age, egg weight, feed intake, temperature and housing type), and it has achieved a prediction error of less than 8% for Ca and lysine [20]. **Table 5** presents the Model Structure, Data Needs and Prediction Results.

Table 5. Comparison of integrative precision nutrition models for LSF vs. FF

Model feature	Largescale farms (LSF)	Family farms (FF)	Ref.
Data inputs (number)	15–25 (realtime BW, egg mass, FI, sensors, genetics)	5–8 (periodic BW, egg weight, ambient temp, manual FI)	[19, 20]
Algorithms	Hybrid mechanisticANN, XGBoost, LSTM, reinforcement learning	Factorial with corrections, linear regression, random forest	[4, 19, 20]
Prediction accuracy (R^2 for Lys)	0.91–0.94	0.82–0.88	[19, 20]
Model update frequency	Daily or weekly	Monthly or per phase	[4, 20]
Cost of implementation	High (sensors, software, training)	Lowmedium (mobile app, periodic training)	[20, 21]
Scalability across farms	Standardized within company	High adaptability with local calibration	[21]

7. Conclusions

The two ways to build the precision nutrition model of large-scale lay hen farms and family-operated farms are a high-complexity, data-intensive system and a low-cost, stable framework. There are many levels of control for CaP (molecular precision vs. local intervention), various types of gut health (synthetic vs. herbal), environments that combine different kinds (continuous vs. periodic), different energy systems (full NE vs. simplified), and all kinds of overall model architectures. However, with the recent changes, there have also been simplifications to the NE equation and the addition of new things, such as herbal gut health supplements, strain-specific mineral control and mobile decision-support systems. In the future, efforts should be made to build an open platform, introduce responsible nutrition indicators, and engage in participatory research to bridge the two worlds and improve both the productivity and sustainability of all stages in the egg production system.

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