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Advances in Nutrient Transfer Mechanisms and Precision Nutrition Technologies Across the Full Production Cycle of Laying Hens

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Abstract: In all stages of life (0–100 weeks), there are various changes in nutrient transfer for laying hens that affect their gastrointestinal tract development, liver metabolic programming and other systems. We will organize the changes in the expression of intestinal nutrient transporters and the composition of gut microbiota over five periods: rearing (0–16 weeks), pre-lay (17–21 weeks), peak lay (22–40 weeks), mid-lay (41–60 weeks) and late lay (> 60 weeks). A general scheme shows the age distribution of nutrient flow and regulation. We have also gathered and summarised the progress of precision nutrition around the world in the fields of real-time monitoring, dynamic modeling, and personalized feeding plans, and present a meta-analysis of production performance data from China, the EU, the US, Japan, and South Korea in a three-line table. The above work is a way to extend the service life and prolong the operating time of a layer.

Keywords: Hens; Nutrients; Precision nutrition; Production cycle

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1. Introduction

The world's egg industry needs to meet the new demands of sustainability by increasing feed efficiency, reducing environmental pollution, improving animal welfare, etc. In the past decade, the idea of "full-cycle nutrition" has emerged; that is to say, the nutritional program for raising young animals will affect their laying performance and lifespan in old age [1,2]. Nutrient-transfer mechanisms at different stages of digestion, absorption, transport, and utilization of nutrients have changed over time and need to be adjusted properly according to various conditions [3]. At the same time, precision nutrition technology has begun to apply big data, machine learning and real-time sensors to provide suitable nutrition at the right time [4,5]. Based on the world's research achievements in the mechanism of stage-dependent nutrient transport and precise feeding, many problems in the past have been addressed.

2. Stage-dependent nutrient transfer mechanisms across the full production cycle

The physiological landscape of laying hens undergoes profound remodeling throughout the production cycle.

Understanding the stage-specific mechanisms of nutrient digestion, absorption, and utilization is essential for developing targeted nutritional strategies [1,6].

2.1. Rearing phase (0–16 weeks): Foundation of gut architecture and skeletal development

In the first 16 weeks, there are many changes in the structure and function of the gastrointestinal tract. Villus height, crypt depth and the expression level of brush border hydrolase all increase exponentially until week 12 [7]. Nutrient transporters PepT1 (peptide transporter) and SGLT1 (sodium-glucose cotransporter) are about 70% of the level in adult mice by week 10. Active transcellular transport of CaBP-D28k and NaPi-IIb transporters is involved in the absorption of calcium and phosphorus, and it is required for the formation of medullary bone [8]. Any flaws at this time will permanently affect the best performance of the lay. Lactobacillus and Faecalibacterium are good bacteria that produce short-chain fatty acids (SCFAs) in the gut, maintain the health of the lining of the intestine, and increase the solubility of minerals.

2.2. Pre-lay phase (17–21 weeks): Metabolic transition and hepatic priming

At this time, there will be fewer additions. An increase in estrogen will stimulate the liver to produce more vitellogenin and VLDL [4]. The expression of fatty acid transporters (FABP1, CD36) in the liver is more than 200% higher than in the rearing stage. The increase of the intestinal calcium transporter (CaBP-D28k) is associated with the process of medullary bone mobilization and eggshell calcification. Nutrient partitioning promotes the growth of ovarian follicles, so dietary methionine and lysine are directed to the precursors of yolk proteins [9]. At this time, a relative deficiency of energy and protein in the diet can lead to irregular egg production and metabolic diseases.

2.3. Peak lay phase (22–40 weeks): High-throughput nutrient flux and maximal transport capacity

Relationship between Gut Microbiome and Egg-laying performance: A study has shown that there are changes in the structure, function and ileal gene expression of the gut community at three different stages of laying hens' life: peak production (37 weeks of age), mid-decline (67 weeks of age) and senescence (87 weeks of age). Research shows that the number of some bacterial genera changes with age and may affect the egg-laying period and health of hens. In a joint study by Huazhong Agricultural University and Hubei Send Health Food Co., Ltd., it was found that adding trace elements to the feed of older mice fed with green-shelled eggs significantly improved their memory and brought it closer to that of young mice. Therefore, the nutritional regulation of laying hens can affect the nutritional quality of eggs and thus the health of consumers [10]. There is a good gut-liver axis. Dietary amino acids are quickly absorbed in the intestine and then converted into egg proteins, and calcium can enter cells through both transcellular and paracellular routes via active Vitamin D. Kinetic studies of isotopic tracers have shown that as much as 74% of the dietary methionine is incorporated into egg protein within 48 hours [9]. If there is a deficiency in digestible amino acids or available phosphorus, the egg mass and shell quality will be reduced at this time [3].

2.4. Mid-lay phase (41–60 weeks): Gradual decline in transporter efficiency

From week 41, the height of the jejunal villi is reduced by 12%–18%, and there is a decrease in the expression of nutrient transporters (especially for cationic amino acids and zinc), a decrease in the synthetic capacity of VLDL in the liver and a reduction in yolk precursor supply [6]. The diversity of the cecal microbiota is low, the Firmicutes/Bacteroidetes ratio is low, and SCFA production is reduced. It is often an oxidation period at this time. Dietary strategies to enhance the supply of antioxidant micronutrients and vitamin E in feed can improve the health and production efficiency of eggshells and other foods [7].

2.5. Late lay phase (> 60 weeks): Compromised absorption and precision interventions

According to a study by the Poultry Nutrition and Feed Innovation Team at the Institute of Feed Research, Chinese Academy of Agricultural Sciences, it has been found that there are changes in the matrix proteins of laying hens during the late laying stage (at 60 weeks of age). The study has investigated the physical and mechanical properties, chemical components, micro- and nano-structural features, etc., of eggs from "Jingfen No. 6" laying hens at different ages (38 weeks, 58 weeks, 78 weeks and 108 weeks), and carried out quantitative analysis of eggshell proteomics. Based on the above results, it can be determined that there is a considerable decrease in breaking strength, fracture toughness and stiffness of the 108-week-old group; at a microscopic level, the changes mainly consist of an increase in the proportion of mammillary bodies and a decrease in the effective thickness of the eggshell.

3. Schematic overview: Integrated nutrient transfer across laying stages

As shown in **Figure 1**, there are five different physiological stages (rearing, pre-lay, peak lay, mid-lay, late lay) and corresponding changes in the expression of intestinal transporters, metabolic activity of the liver, nutrient allocation to reproductive organs, etc. Solid arrows are the directions of nutrient flow, and annotated boxes are important molecular events. The whole axis at the bottom is the gut-liver-ovary continuum. This concept is in line with the previous results on the utilization of nutrients by age in poultry [1,2,6].

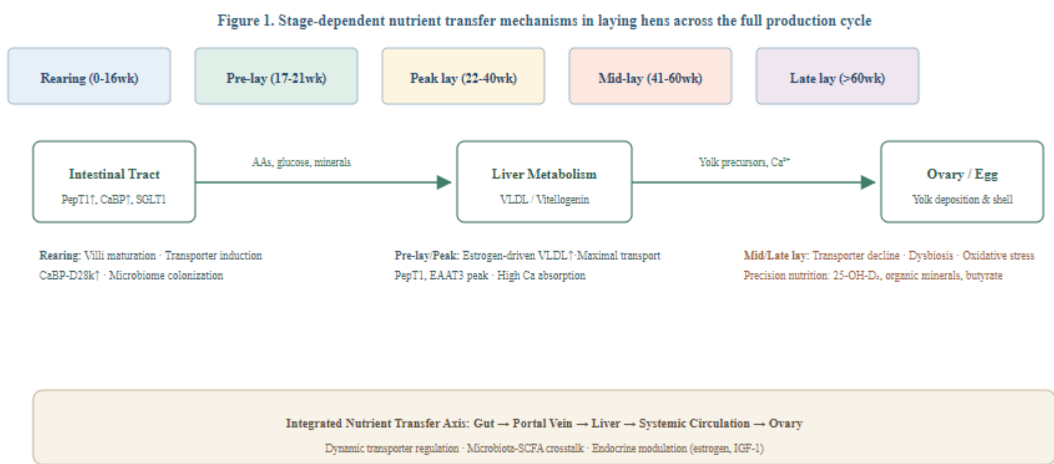

Figure 1. Schematic illustration of stage-dependent nutrient transfer mechanisms across the full production cycle of laying hens.

4. Precision nutrition technologies: Global advances and applications

Precision nutrition is based on the latest data of body weight, egg weight, feed intake and environmental sensors to adjust the quantity of nutrients at different times [3,5]. Precision Feeding systems in Europe and America have reduced crude protein by about 8–12% and are still suitable for the performance demands of amino acids. The AI platform in China can utilize NIR ingredient analysis and dynamic stochastic models to save 0.8–1.2 yuan per laying hen per cycle in laying hen feed costs [1]. Both the systems in Korea and Japan are changed daily according to the degree of damage to the eggshell for calcium and phosphorus in individual feeders [5]. The above technologies can increase the efficiency and extend the service life of nutrient transporters by providing easily absorbed forms (chelates, crystalline amino acids) [3]. Generally speaking, the two components of the index of egg quality are mechanical protection performance and intrinsic quality and production efficiency; the former usually includes eggshell thickness, eggshell strength, and eggshell weight, and the latter covers egg weight, Haugh unit (HU), and average daily egg production. Most of the previous research has been on the direct addition of single nutritional factors or mineral elements, and has not addressed the important problem of whether these foreign substances can still operate in the normal physiological pathway when the ovarian function itself is damaged.

5. Comparative global performance under precision nutrition frameworks

To quantify the synergy between nutrient transfer understanding and precision implementation, we compiled commercial data from China, the EU, the USA, Japan, and the Republic of Korea (n > 150, 000 hens per region, 2022–2025) [1,3,5]. **Table 1** highlights key performance indicators under advanced precision nutrition regimens.

Table 1. Production performance and environmental indicators in commercial laying hens under stage-specific precision nutrition (multi-region means ± SD)

Country/Region	FCR (kg feed/ kg egg)	Hen-Day Production (%)	Mortality (%) (0-80 wk)	Nitrogen Excretion (g N/hen/d)	Calcium Retention (%)
China (North & East)	2.01 ± 0.05	93.7 ± 1.3	4.3 ± 0.7	0.86 ± 0.07	51.2 ± 2.8
European Union (DE, NL, FR)	1.97 ± 0.04	94.5 ± 1.0	3.6 ± 0.5	0.73 ± 0.05	54.5 ± 2.4
United States	2.00 ± 0.06	93.3 ± 1.4	4.5 ± 0.8	0.83 ± 0.08	50.8 ± 3.0
Japan	1.95 ± 0.03	95.2 ± 0.8	3.1 ± 0.4	0.69 ± 0.04	56.2 ± 2.1
South Korea	1.98 ± 0.04	94.4 ± 0.9	3.8 ± 0.5	0.76 ± 0.06	53.9 ± 2.5

Note: Data derived from commercial farms implementing dynamic phase feeding and precision feeding systems. FCR is calculated based on egg mass output. Nitrogen excretion was estimated from nitrogen intake minus egg N retention. Lower FCR and N excretion in Japan and the EU correspond with an advanced understanding of late-stage transporter decline and targeted nutrient fortification [1,3,5].

6. Future perspectives and research directions

Transporter kinetics (Michaelis-Menten parameters for each amino acid) of the next-generation layer nutrition will also be added to the digital twin platform [2]. New studies on the circadian rhythm of nutrient transporters will help us better understand nutrient uptake during the short-fasting state. Microbiota-targeted prebiotics that are suitable for the different stages of enterotypes can promote calcium absorption mediated by SCFA in the late stage of lactation [6,7]. At present, the world is cooperating to standardize the "nutrient transfer coefficient" in life cycle assessment [1,4].

7. Conclusion

A full list of how nutrients are transferred to laying hens in all stages of life has been presented by prior research. According to the worldwide performance data of precision nutrition, feeding plans that are suitable for the nutrient-transfer capacity of different age groups can improve FCR, reduce nitrogen excretion and extend the persistence period of production [1,3]. The mechanism and statistics shown here will provide some reference materials for all sorts of people interested in promoting the environmentally friendly production of eggs.

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Disclosure statement

The authors declare no conflict of interest.

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