Effects of Polyunsaturated Fatty Acids on Reproductive Performance in Breeder Roosters and Their Mechanism of Action: Postprint

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Abstract

Polyunsaturated fatty acids (PUFA) are lipid substances with important biological functions. In addition to providing energy, they also regulate animal immune function, metabolism, and reproductive performance. This article briefly describes the effects of PUFA on the reproductive performance of breeding roosters and their mechanism of action, providing theoretical reference for the rational utilization of oil and fat resources in poultry diets and for improving the economic benefits of the poultry breeding industry.

Full Text

Title

Effects of Polyunsaturated Fatty Acids on Reproductive Performance of Breeder Roosters and Their Mechanisms of Action

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Abstract

Polyunsaturated fatty acids (PUFAs) are lipids with important biological functions. In addition to providing energy, they regulate immune function,

metabolism, and reproductive performance in animals. This paper briefly reviews the effects of PUFAs on the reproductive performance of breeder roosters and the underlying mechanisms, providing a theoretical reference for the rational utilization of oil resources in poultry diets and improving the economic benefits of the poultry breeding industry.

Keywords: polyunsaturated fatty acid; breeder rooster; reproductive performance; mechanism

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Introduction

With the rapid development of modernized and intensive livestock production, artificial insemination technology has become widely applied, leading to increasingly high demands for male livestock reproductive performance. In large-scale breeder chicken production, semen quality in roosters directly affects the reproductive performance of hens. Currently, declining reproductive performance in breeder roosters in China has resulted in low rates of qualified eggs and fertilization, poor hatchability of fertilized eggs, high mortality and culling rates, and poor chick quality, thereby affecting the development of the poultry breeding industry.

For a long time, the poultry breeding industry has focused primarily on genetics, environment, and disease control. In breeding practice, hens have been the dominant focus, with most technologies implemented to maximize their production potential, while roosters have been relegated to a subordinate position. However, from a genetic perspective, the genetic foundation, physical condition, and reproductive performance of breeder roosters are crucial for chick quality and overall production performance. As research has progressed, scholars have gradually recognized that nutritional regulation of breeder roosters plays a vital role in fully realizing the genetic potential of superior chicken breeds and improving production performance.

Polyunsaturated fatty acids (PUFAs) are lipids with important biological functions that significantly impact animal growth, development, and reproductive performance, making them a hot topic in recent research both domestically and internationally. PUFAs enhance immune function, alter sperm membrane phospholipid composition, and affect animal reproductive performance. Common n-3 PUFAs include -linolenic acid (-ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA). Current research on the effects of PUFAs on animal reproductive performance has focused primarily on semen quality in male animals; for example, n-3 PUFAs can increase sperm concentration and improve sperm quality. This paper briefly reviews the effects of PUFAs on rooster reproductive performance and elaborates on the mechanisms through which PUFAs influence animal reproductive performance from different perspectives, provid-

ing a theoretical reference for promoting the application of PUFAs in nutritional regulation of breeder roosters.

1. Effects of Dietary PUFA Supplementation on Reproductive Performance of Breeder Roosters

As lipids with important biological functions, PUFAs have been studied in poultry primarily for their effects on immune function, antioxidant activity, production performance, egg quality, and meat quality. Research has shown that PUFAs also exert beneficial effects on the reproductive performance of breeding poultry. In production practice, the widespread adoption of artificial insemination technology has led to stricter requirements for semen quality in breeder roosters. However, semen concentration in roosters declines with age, primarily due to increased lipid content in sperm and seminal plasma. The phospholipids in sperm and seminal plasma mainly include phosphatidylcholine and phosphatidylethanolamine; the former increases with age, while the latter decreases. The decline in phosphatidylethanolamine content is mainly caused by decreased n-6 PUFA levels. Studies have shown that semen rich in docosapentaenoic acid (DPA) or DHA can significantly improve rooster reproductive performance after artificial insemination, with this effect being more pronounced in young birds. Therefore, dietary PUFA supplementation can extend the semen production period of breeder roosters, thereby improving their utilization rate and reducing production costs [1].

Early reports showed that poultry developed deficiency symptoms when diets lacked linoleic acid (LA) and linolenic acid (ALA), including poor growth in chicks and reduced egg production and hatchability in adult birds; these symptoms disappeared when LA and ALA were added. As research has progressed, scholars have found that PUFAs from different sources and in different ratios also affect rooster reproductive performance. Adding fatty acids from different sources to diets can increase the proportion of n-3 PUFAs in rooster sperm phospholipids and significantly improve semen quality [2]. This may be because changes in the dietary n-3/n-6 PUFA ratio alter the composition of lipids and phospholipids in the sperm cell membrane [3]. When the n-3/n-6 PUFA ratio is 1:(6–9), rooster sperm contain the least amount of saturated fatty acids and achieve maximum reproductive performance [4]. When the n-3/n-6 PUFA ratio is 1.00:4.15, PUFAs have no significant effect on rooster testicular index, but significantly increase the spermatogenic cell layer and blood sex hormone levels such as gonadotropin-releasing hormone (GnRH), follicle-stimulating hormone (FSH), luteinizing hormone (LH), and testosterone (T) [5].

As unsaturated fatty acids, PUFAs are prone to oxidation; combining them with vitamin E can help maintain PUFA levels in diets to some extent. Studies have shown that dietary supplementation with fish oil and vitamin E increases DPA and DHA content in rooster sperm without changing total PUFA content, while improving sperm motility. Adding 300 mg/kg vitamin E to animal diets rich in n-3 PUFAs can optimize sperm quality [6-7]. However, dietary fish oil and

vitamin E supplementation in turkeys increased n-3 PUFA content in sperm and elevated the n-3/n-6 PUFA ratio but had no significant effect on reproductive performance [8]. These discrepancies may be related to differences in animal species and additive doses, and warrant further investigation.

2.1. PUFA and Semen Quality

PUFAs affect reproductive performance by altering semen quality in male animals. Sperm from pigs, cattle, sheep, chickens, ducks, and other animals contain large amounts of long-chain PUFAs, particularly in poultry semen, where arachidonic acid (AA) and docosatetraenoic acid content ranges from 5–9% and 15–21%, respectively.

Poultry cannot synthesize n-3 or n-6 PUFAs and must obtain them from their diet. Changing the type and amount of PUFAs in the diet can alter PUFA composition in sperm [4,6,9]. Dietary supplementation with different PUFA ratios can affect semen quality and libido, significantly increasing sperm density and motility while increasing ejaculate volume and total sperm count, prolonging ejaculation time, and benefiting testicular development and sperm morphological integrity [10-12]. The mechanisms through which PUFAs affect semen quality include: (1) PUFAs synthesize prostaglandins. Seminal prostaglandins include four main factors closely related to reproduction: prostaglandin E (PGE), prostaglandin F (PGF), 19-hydroxy-prostaglandin E (19-OH-PGE), and 19-hydroxy-prostaglandin F (19-OH-PGF). PGE and 19-OH-PGE, which account for 90% of total prostaglandins in semen, are associated with sperm motility [13]. C20 PUFAs are precursors for various bioactive substances, including prostaglandins, thromboxanes, and leukotrienes. EPA is ultimately converted to 3-series prostaglandins (3-series PGs) under the regulation of various enzymes. Studies have confirmed that exogenous prostaglandin F2 can affect boar sexual behavior and prolong ejaculation time [14]. (2) Dietary PUFAs participate in phospholipid synthesis and metabolism in animals and are converted into DHA, an essential bioactive factor that effectively maintains and improves sperm motility and male reproductive capacity. DHA content is positively correlated with superoxide dismutase (SOD) and catalase (CAT) activities. Peroxidases can catalyze hydrogen peroxide and amine compounds, eliminating the toxicity of both and maintaining sperm structural and functional integrity. Studies have shown that adding 3% fish oil rich in n-3 PUFAs significantly increases sperm concentration and DHA content in boar semen [9] and benefits the cryopreservation of quail sperm [15]. Adding n-3 PUFAs and 1% vitamin E to semen cryopreservation extenders for cattle and sheep significantly reduces sperm damage and improves sperm survival rate and acrosome integrity. Additionally, most DHA is located in the sperm tail, and higher DHA content in the tail facilitates flagellar movement and improves sperm motility [16]. (3) Increased eicosanoid concentrations may improve semen quality, as PUFAs and their derived eicosanoids interact under the regulation of the hypothalamic-pituitary axis and spermatogenesis hormones [17-18]. Studies have shown that simultaneous dietary supple-

mentation with soybean oil and linseed oil can improve semen quality in rats by promoting T secretion [10]. However, other studies have reported that fish oil supplementation in diets for different boar breeds had no significant effect on ejaculate volume or sperm density [19], and adding 10% AA (an n-6 PUFA) significantly reduced sperm concentration and motility in mice, with high n-6/n-3 PUFA ratios causing significant damage to sperm number and lipids [20]. These results indicate that different PUFA addition levels, types, and ratios have varying effects on semen quality in male animals, and the underlying reasons require further investigation.

2.2. PUFA and Sperm Cell Membrane

PUFAs are important components of cell membrane phospholipids, exhibit high affinity for membrane lipids, and are closely related to membrane fluidity and deformability while participating in lipid formation. Their deficiency can severely impair sperm fertilization capacity. Sperm cell membranes contain abundant PUFAs, and both n-3 and n-6 PUFAs are closely related to sperm fertility. Animals must obtain PUFAs from external sources to maintain sperm structural integrity. PUFAs with more than 20 carbons contain multiple double bonds that can alter the physical properties of cell membranes, such as membrane fluidity and raft structure [21], affecting sperm cell membrane structure and participating in protein-mediated cellular responses. The mechanism primarily involves altering cell membrane receptor expression, activity, and affinity or changing intracellular signal transduction mechanisms to affect cell signaling pathways, thereby altering transcription factor activity and gene expression [22-23]. Meanwhile, the high degree of unsaturation in PUFAs makes membrane lipids susceptible to peroxidation, causing changes in membrane receptors, enzymes, and ion channels that lead to cell dysfunction and affect membrane fluidity. Dietary fat sources can alter phospholipid quantity, fatty acid content, and n-3/n-6 PUFA ratios in cell membranes. Changing any of these factors can affect sperm cell membrane composition, fluidity, and sensitivity to oxidation, thereby influencing sperm fertilization capacity [24]. Studies have shown that adding a mixture of fish oil and antioxidants to boar diets allows dietary PUFAs to gradually incorporate into sperm cell membranes, significantly altering sperm plasma membrane elasticity and affecting flagellar movement [25]. Fish oil supplementation in diets for different boar breeds also significantly affects sperm morphology and plasma membrane [19]. Thus, PUFAs can affect semen quality and fertilization capacity by altering sperm cell membrane composition and fluidity.

2.3. PUFA and Sperm Oxidative Damage

Free radicals are essential for maintaining normal physiological status, and their continuous generation and elimination keep the body in a state of balance. During metabolic processes, reactive oxygen species (ROS) and lipid peroxidation reactions maintain homeostasis. When this balance is disrupted, metabolic dys-

function occurs, exacerbating the free radical chain reaction and causing severe oxidative damage to the body [26].

Research on PUFAs and sperm oxidative damage is relatively limited. Sperm cell membranes contain abundant PUFAs and are vulnerable to ROS attack, triggering lipid peroxidation cascade reactions that damage the sperm cell membrane, reduce sperm motility, disrupt normal sperm morphology and structure, and impair sperm penetration, thereby affecting sperm quality [27]. Therefore, improving antioxidant capacity in male animals and ensuring the structural and functional integrity of the body, particularly testicular tissue, is important for reproductive performance [28].

Antioxidant enzymes, as important antioxidants widely distributed in animals, can scavenge oxygen free radicals such as superoxide anions and hydroxyl radicals, protecting cell integrity [28]. Antioxidant enzymes are an important component of the seminal plasma antioxidant defense system, and increased activity can prevent sperm damage and maintain normal sperm fertility. Lipid peroxidation of cell membranes is a major factor causing decreased sperm quality. Mature sperm cell membranes are rich in unsaturated fatty acids, and sperm cytoplasm contains few antioxidant enzymes, making them susceptible to oxidation. Therefore, the antioxidant defense system in seminal plasma plays a critical role in sperm maturation [29]. Dietary supplementation with appropriate levels of PUFAs can significantly increase antioxidant enzyme activity and reduce lipid peroxidation product content, thereby enhancing the body' s antioxidant capacity [28,30-31]. Thus, dietary PUFA supplementation can improve animal reproductive performance by increasing antioxidant enzyme activity, reducing sperm oxidative damage, and maintaining sperm maturation.

2.4. PUFA and Reproductive Hormones

Research on PUFA regulation of reproductive hormones is limited, and the mechanisms remain unclear. Current reports focus on two main aspects: (1) PUFAs participate in prostaglandin synthesis. Prostaglandins are endogenous bioactive substances with extensive effects that regulate animal reproductive processes. PUFAs are precursors of eicosanoids that form AA and DHA in animals, which are then converted into different types of prostaglandins through cyclooxygenase and lipoxygenase catalysis [14]. (2) PUFAs affect reproductive performance by synthesizing steroid hormones. Adrenocortical hormones and gonadal hormones are steroid hormones, including T, estradiol, and progesterone. Steroid hormones not only promote the growth and differentiation of animal reproductive organs but also play important roles in maintaining fertility, such as promoting spermatogenesis, follicular development, and estrous behavior [32]. PUFAs can form triglycerides and cholesterol esters with glycerol and cholesterol. Cholesterol absorbed by intestinal mucosa forms chylomicrons with triglycerides and cholesterol esters, which transport triglycerides and cholesterol esters from the small intestine to the adrenal glands or gonads for conversion into various steroid hormones [33].

Sperm production is a continuous process of cell proliferation and differentiation that depends on hormonal regulation. FSH and LH secreted by the pituitary gland and T secreted by Leydig cells are regulatory hormones for spermatogenesis, mediated through interactions between Sertoli cells and germ cells [34]. T, stimulated by FSH and LH, is the primary hormonal regulator. T is a steroid hormone containing 19 carbon atoms synthesized from cholesterol in Leydig cells through a series of enzymatic reactions. After cholesterol enters cells, it is transferred from the outer to inner mitochondrial membrane by the steroidogenic acute regulatory protein (StAR) in the rate-limiting step of T synthesis [35]. It is then cleaved into pregnenolone by P450 cholesterol side-chain cleavage enzyme (P450scc), which is converted into T through the action of 3 -hydroxysteroid dehydrogenase, 17 /17,20-hydroxylase, and 17 -hydroxysteroid dehydrogenase. P450scc is the rate-limiting enzyme in T synthesis [36]. Studies have shown that enhancing StAR expression promotes T synthesis in mouse Leydig cells [37], while downregulating StAR expression inhibits T synthesis [38]. Similarly, enhancing P450scc activity promotes T production in rat Leydig cells [39], while reducing P450scc activity decreases T production [35]. Thus, the rate-limiting protein StAR and the key T synthesis enzyme P450scc play critical roles in T synthesis.

Over 90% of T in the body is synthesized and secreted by Leydig cells. T promotes testicular growth and development and stimulates spermatogonial proliferation [40], playing important roles in promoting spermatogenesis and maturation, maintaining normal libido, and preserving male secondary sexual characteristics [41-43]. T deficiency directly causes spermatogenesis disorders [44]. Therefore, T is considered essential for sperm production [41]. PUFAs promote sperm maturation in animals [45], and their deficiency can directly cause infertility [46]. Studies have shown that dietary fatty acid supplementation can alter T secretion in rats [47-48], PUFA supplementation can increase total and free T levels in rat plasma [49], and significantly enhance T secretion by rat Leydig cells [50]. Additionally, research has shown that increasing dietary linseed oil (rich in ALA) dosage significantly elevates serum T levels in male SD rats [13]. Feeding boars diets with different n-6/n-3 PUFA ratios increased serum T and prostaglandin E2 levels, with the highest levels observed at an n-6/n-3 PUFA ratio of 1:1 [51]. Thus, PUFAs significantly affect T secretion in male animals, though the mechanisms require further investigation.

Conclusion

Obtaining high-quality semen from breeder roosters can improve the economic efficiency of large-scale chicken farms and reduce production costs. The aforementioned studies demonstrate that dietary PUFA supplementation can extend the semen production period of breeder roosters, increase PUFA content in sperm cell membrane lipids and phospholipids, improve semen quality, and ultimately enhance reproductive performance. However, most studies have focused only on sperm quality and fatty acid composition, without providing reasonable

explanations or in-depth research on increased semen density, sperm number, or sperm maturation. Meanwhile, for male animals, reproductive hormones, particularly T, not only affect spermatogenesis, sperm maturation, and testicular development but also play extremely important roles in maintaining secondary sexual characteristics and increasing libido. PUFAs can increase T secretion in male animals, but the specific mechanisms remain unclear and require further investigation.

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