

Relationship Between Polyunsaturated Fatty Acids and Animal Production: A Review

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Abstract

Polyunsaturated fatty acids (PUFAs) play important roles in maintaining normal physiological conditions and, consequently, in animal health. Two PUFAs families, n-6 and n-3 fatty acids (FAs), are physiologically and metabolically distinct. The focus on PUFAs has been gradually extended from the apparent properties of growth performance, antioxidant ability and immune function to the mechanism of molecular regulation and mechanism such as regulating the expression of related genes and the anticancer action mechanism, which strengthen the understanding of the theoretical basis and application of animal husbandry in a range of animal species. The present review focuses on current knowledge related to the origin, biological function and practical application of PUFAs in animal production.

Keywords: Polyunsaturated fatty acids, Biological function, Animal production, Application

Çoklu Doymamış Yağ Asitleri ve Hayvansal Üretim Arasındaki İlişki: Derleme

Öz

Çoklu doymamış yağ asitleri normal fizyolojik süreçlerin ve bunun sonucu olarak da hayvan sağlığının sağlanmasında önemli rol oynamaktadır. İki çoklu doymamış yağ asitleri ailesi olan n-6 ve n-3 yağ asitleri fizyolojik ve metabolik olarak önemlidir. Büyüme performansı, antioksidan kabiliyeti ve immun fonksiyonlarından moleküler regülasyon ve ilgili genlerin ekspresyonunun ve anti kanser mekanizmaları gibi mekanizmalardaki belirgin özellikleri nedeniyle çoklu doymamış yağ asitlerine ilgi artmıştır. Bu durum pek çok hayvan türünde yetiştiricilik konusunda teorik temellerin anlaşılmasına katkıda bulunmuştur. Bu derleme, çoklu doymamış yağ asitlerinin hayvansal üretimdeki yeri, biyolojik fonksiyonları ve pratik uygulamaları üzerine güncel bilgiye odaklanmıştır.

Anahtar sözcükler: Çoklu doymamış yağ asitleri, Biyolojik fonksiyon, Hayvansal üretim, Uygulama

INTRODUCTION

Feeding fat has nutritional and economic advantages to satisfy energy requirement and replace carbohydrates with inexpensive lipid sources. Fatty acids (FAs) are important ingredients and essential substances of fats and oils. Based on their chemical structure FA can be differentiated into three groups: saturated, monounsaturated and polyunsaturated fatty acids (PUFAs). The biological reactivity of FA is defined by the length of the carbon chain and by both the number and position of any double bonds present. While saturated fatty acids (SFAs) do not contain double bonds within the acyl chain, unsaturated fatty acids (UFAs) contain at least one double bond. When two or more

double bonds are present, these UFAs are referred to as polyunsaturated fatty acids (PUFAs). Dietary imbalance of the n-6/n-3 PUFAs ratio can affect human health, especially with high n-6/n-3 PUFAs ratios^[1].

FAs supplies have been demonstrated to alter immune cells function because FAs alter the composition of the cells' membrane phospholipids, which relates to the membrane lipid fluidity, signal transcription factors, and bioactive synthesis of lipid mediators^[2]. Several studies have documented that PUFAs not only play an important role in maintaining structure and function of cell membrane, enhancing immune function, promoting growth and development, regulating lipid metabolism and related gene



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expression, but also reducing thrombosis, reducing the incidence of cardiovascular diseases as well as resisting cancer [3]. With the reduction of production cost and continuous pursuit of high quality animal product, the application of PUFAs in animal production has been a subject of great public attention and concern. The focus on PUFAs has been gradually extended from the apparent properties of growth performance, antioxidant ability and immune function to the mechanism of molecular regulation and mechanism such as regulating the expression of related genes and the anticancer action mechanism, which strengthen the understanding of the theoretical basis and application of animal husbandry in a range of animal species. This paper briefly described the origin, biological function and practical application of PUFAs in animal production.

SOURCES OF PUFAs

Polyunsaturated fatty acids are mainly found in all natural foods in varying amounts, but fatty foods contain the most. Generally speaking, vegetable oils are the most concentrated sources of PUFAs in the Western diet and include sunflower oil, safflower oil, corn oil, flax oil, sesame seed oil, pumpkin seed oil and canola (or rapeseed) oil. The exceptions include plants that grow in tropical climates, such as the oils extracted from chocolate and coconuts. These oils are highly saturated, and so are very stable and undoubtedly safe and beneficial.

Table 1 illustrated the members and typical sources of the n-6 and n-3 PUFA families. Linoleic acid (LA) is the parent FA of the n-6 family, which occurs in almost every dietary fat and attains major proportions in some common vegetable oils. Due to its wide distribution and abundance in many

common dietary fats, many populations over-consume LA, and consequently the intake of n-3 FAs fatty acids is very often lower than ideal. γ -linolenic acid (18:3n-6 or GLA) is a trace constituent in some animal PLs and ruminant fats. It is more readily available from seed oils of evening primrose (8-10%), borage (20-25%) and blackcurrant (15-18%). Arachidonic acid (AA) is present in lean meat, especially in free-living animals, liver and egg lipids. It is rare in the plant kingdom, but it has been reported in marine algae and other aquatic plants.

Alpha-linolenic acid (ALA), the parent FA of the n-3 family, is primarily present in the plant kingdom. Among the common vegetable oils, it is readily available in canola (6-10%) and soybean (5-8%) oils. Marine fish such as mackerel, salmon, sardine, herring and smelt are excellent sources of eicosapentaenoic acid (EPA), docosapentaenoic acid (DPA) and docosahexaenoic acid (DHA). Fish oil (FO) containing 60% of EPA and DHA is usually sold as sources of these important n-3 PUFAs. Algal oils and single-cell oil sources of the long-chain PUFAs are now becoming available to provide EPA+DHA+AA. Furthermore, genetically modified oil sources are now being developed and will be widely available in the near future by the genetic manipulation of soy and other plants.

BIOLOGICAL FUNCTIONS OF PUFAs

Influence on Membrane Fluidity

Polyunsaturated fatty acids play an important role in the composition of all cell membranes where they maintain homeostasis for correct membrane protein function and influence membrane fluidity, thus regulating cell signaling processes, cellular functions and gene expression. The fluidity

Table 1. Typical sources of n-6 and n-3 PUFAs

| Family | Common Name | Systematic Name | Abbreviation | Typical Sources |
|------------|--------------------------------|---|-------------------|--|
| n-6 family | Linoleic acid | cis-9,cis-12-octadecadienoic | 18:2n-6 (LA) | most vegetable oils |
| | γ -Linolenic acid | cis-6,cis-9,cis-12-octadecatrienoic acid | 18:3n-6 (GLA) | evening primrose, borage and black currant seed oils |
| | Homo- γ -linolenic acid | cis-8,cis-11,cis-14-eicosatetrienoic acid | 20:3n-6 (DGLA) | very minor component in animal tissues |
| | Arachidonic acid | cis-5,cis-8,cis-11,cis-14-eicosatetraenoic acid | 20:4n-6 (AA) | animal fats, liver, egg lipids, fish |
| | Docosatetraenoic acid | cis-7,cis-10,cis-13,cis-16-docosapentaenoic acid | 22:4n-6 | very minor component in animal tissues |
| | Docosapentaenoic acid | cis-4,cis-7,cis-10,cis-13,cis-16-docosapentaenoic acid | 22:5n-6 | very minor component in animal tissues |
| n-3 family | α -Linolenic acid | cis-9,cis-12-cis-15-octadecatrienoic acid | 18:3n-3 (ALA) | flaxseed oil, perilla oil, canola oil, soybean oil |
| | Stearidonic acid | cis-6,cis-9,cis-12,cis-15-octadecatetraenoic acid | 18:4n-3 (SA) | fish oils, genetically enhanced soybean oil, blackcurrant seed oil, hemp oil |
| | Eicosapentaenoic acid | cis-5,cis-8,cis-11,cis-14,cis-17-eicosapentaenoic acid | 20:5n-3 (EPA) | fish, especially oily fish (salmon, herring, anchovy, smelt and mackerel) |
| | Docosapentaenoic acid | cis-7,cis-10,cis-13,cis-16, cis-19-docosapentaenoic acid | 22:5n-3 (n-3 DPA) | fish, especially oily fish (salmon, herring, anchovy, smelt and mackerel) |
| | Docosahexaenoic acid | cis-4,cis-7,cis-10,cis-13,cis-16,cis-19-docosapentaenoic acid | 22:6n-3 (DHA) | fish, especially oily fish (salmon, herring, anchovy, smelt and mackerel) |

of the membrane is dependent on the lipid composition of the membrane and among the significant components of cell membranes are the phospholipids. The types of FAs in the diet determine the types of FAs that are available to the composition of cell membranes. A phospholipid made from a saturated fat has a different structure and is less fluid than the one that incorporates an essential FA. PUFAs are important constituents of all cell membranes, which confer on membranes properties of fluidity, and thus determine and influence the behavior of membrane-bound enzymes and receptors^[4]. PUFAs had an inhibitory effect on cell proliferation/viability and strongly increased tumor cell lipid peroxidation in a dose-dependent manner^[5]. n-3 PUFAs supplementation can modify the membrane phospholipid fatty acid composition and modulate the second messenger signaling pathways in the adult cardiac myocytes. However, because the unsaturated double bonds of PUFAs are susceptible to the oxidation of free radicals, excessive intake of PUFAs can lead to the enhanced lipid peroxidation *in vivo* and reduce cell membrane fluidity. They are able to decrease the cholesterol level in the neuronal membrane, which would otherwise decrease membrane fluidity, which in turn would make it difficult for the cell to carry out its normal functions and increase the cell's susceptibility to injury and death. These consequences for cell function are not restricted to absolute levels of FAs alone; rather it appears that the relative amounts of n-3 PUFAs and n-6 PUFAs in the cell membranes are responsible for affecting cellular function. In addition, n-3 PUFAs had ameliorative effects on the oxidative tissue degeneration and inflammatory processes induced by CCl₄ treatment in rats^[6].

Polyunsaturated fatty acids are important components of phospholipid in neuronal membranes, which play important roles in signal transduction of cellular surface. DHA accounts for 10% of the brain phospholipids, and it also has a high content in the central nervous system, mainly distributing in acetylcholine, amino phospholipids and serine glycerol^[7]. DHA is instrumental in the function of brain cell membranes, which are important for the transmission of brain signals. By making cell membranes more fluid, n-3 PUFAs, especially DHA, improve communication between the brain cells and lack of n-3 PUFAs in the body can cause a communication breakdown in the brain. EPA and DHA could affect signal transduction in brain cells by activating peroxisomal proliferator-activated receptors (PPARs), inhibiting G-proteins and protein kinase C, as well as calcium, sodium, and potassium ion channels. In addition, DHA and EPA can affect the membrane structure of sperm cells, making the sperm membrane with good fluidity and participating in cell response mediated in protein, which could influence the production of lipid-mediated conductor, cell signal transduction as well as gene expression^[8].

Lipid Metabolism

Polyunsaturated fatty acids, particularly those of the n-3

family, play essential roles in the maintenance of energy balance and glucose metabolism. n-3 PUFAs, in addition to affecting general properties of cells as membrane components, play a role in modulating the production of both lipid (eicosanoids) and protein (cytokines) mediators. The n-3 family of PUFAs appear to have the unique ability to enhance thermogenesis and thereby reduce the efficiency of body fat deposition. PUFAs exert their effects on lipid metabolism and thermogenesis by upregulating the transcription of the mitochondrial uncoupling protein-3, and inducing genes encoding proteins involved in fatty acid oxidation (e.g. carnitine palmitoyltransferase and acyl-CoA oxidase) while simultaneously down-regulating the transcription of genes encoding proteins involved in lipid synthesis (e.g. fatty acid synthase). n-3 PUFAs can inhibit the activity of fatty acid synthase (FAS), diacylglycerol acylase and hydroxymethyl glutarate coenzyme A reductase to promote the oxidative decomposition of fatty acids, thus depress the synthesis of triglyceride (TG) and reduce the content of low density lipoprotein (LDL) receptor in the liver to inhibit total cholesterol (TC) synthesis and absorption, finally reducing the level of TG and TC in the serum^[9].

Lipid metabolism, inflammation, oxidative stress and endothelial function play important roles in the pathogenesis of cardiovascular disease (CVD), which may be affected by an imbalance in the n-6/n-3 PUFAs ratio^[10]. Low n-6/n-3 PUFAs ratio (1:1 and 5:1) had a beneficial effect on cardiovascular risk factors by enhancing favorable lipid profiles, having anti-inflammatory and anti-oxidative stress effects, and improving endothelial function. In contrast, a high n-6/n-3 PUFAs ratio (20:1) had adverse effects.

Regulation of Gene Expression

Supplementation of PUFAs has become an important dietary strategy to reduce hepatic lipogenesis in rodents and humans by inducing the regulation of gene expression. PUFAs can affect gene expression through various mechanisms including, but not limited to, changes in membrane composition, intracellular calcium levels, and eicosanoid production. Furthermore, PUFAs and their various metabolites can act at the level of the nucleus, in conjunction with nuclear receptors and transcription factors, to affect the transcription of a variety of genes. Several of these transcription mediators have been identified and include the nuclear receptors peroxisome proliferator-activated receptor (PPAR), hepatocyte nuclear factor (HNF)-4 α , and liver X receptor (LXR) and the transcription factors sterol-regulatory element binding protein (SREBP) and nuclear factor- κ B (NF κ B). Their interaction with PUFAs has been shown to be critical to the regulation of several key genes of lipid metabolism^[11].

The presence of high concentrations of n-3 PUFAs, or shifts in n-6/n-3 ratios may modulate the expression of genes known to be critical to inflammatory processes^[12]. The majority of studies examining PUFAs and gene expression

have been carried out in isolated cell systems and a few animal studies. Curtis et al.^[13] had shown that α -linolenic acid (LNA, 18:3, n-3), EPA, or DHA reduce the expression of genes for TNF α and IL-1 β in bovine chondrocytes. DHA played different regulating roles in lipid metabolism in different tissues to reduce body fat mass through regulating lipogenesis and lipolysis genes. In adipose tissue, DHA increased the expression of lipogenesis and lipolysis genes. In liver lipogenesis genes were decreased, but lipolysis genes were increased by DHA^[14]. Similarly, mice fed FO had decreased mRNA levels for numerous inflammatory cytokines including IL-1 β , IL-6, and TNF α in kidney, spleen, and peritoneal macrophages^[15]. Feeding 6% α -LA-enriched camelina meal to lactating dairy cows reduced expression of IL-1 β , IL-8, and TNF- α in peripheral blood mononuclear cells^[16].

Immune Function

The beneficial effects of PUFAs are of obvious therapeutic interest, they are believed to be preventive in various chronic diseases, including rheumatoid arthritis, coronary heart disease, and stroke, and certain types of cancer, including breast, prostate, and colorectal cancers. Preclinical studies in cell culture and rodent models show that the EPA and DHA acids are immunomodulatory and can influence both innate and adaptive immunity^[17]. EPA and DHA are usually used in the treatment of inflammatory diseases such as rheumatoid arthritis, psoriasis and ulcerative colitis. In the eye, deficiency of DHA is associated with abnormalities in the visual system, including retinitis pigmentosa, peroxisomal disorders and compromised growth and development in infants^[18]. Dietary PUFAs can modulate the immune system to improve growth performance and health. Research showed that milk replacer containing FO weakened acute phase responses and the effect was linear in response as the FO FA replacement increased from 5 to 10%^[19].

Various n-3 PUFAs have been reported to exert beneficial effects, such as protection against liver diseases, regulation of cholesterol, and reduction of blood pressure, which prevents cardiovascular diseases (CVDs)^[20]. n-3 PUFAs can modify B-cell activation, antigen presentation to helper T cells, antibody production, surface expression of select molecules, development in bone marrow, and the relative percentage or frequency of B cells in specific tissues^[21-23]. In addition, n-3 PUFAs can also exert immunomodulatory effects on lymphocytes by targeting plasma membrane molecular organization^[24]. Several studies have indicated that n-3 PUFAs exert anti-inflammatory effects by regulating the expression of peroxisome proliferator activated receptors (PPARs) and nuclear factor kappa B (NF- κ B)^[25-27]. The inflammatory response is triggered by activation of NF- κ B, which induces the expression of pro-inflammatory cytokines, adhesion molecules, chemokines, growth factors, and inducible enzymes, such as cyclooxygenase 2 (COX-2) and nitric oxide synthase (NOS)^[28].

APPLICATION OF PUFAs IN ANIMAL PRODUCTION

Application in Poultry Diets

Previous studies in broiler chickens have shown different relationships between the fatty acid contents of diets and tissues, especially for breast and thigh meat^[29,30]. Comparable levels of n-3 PUFAs in the meat can be achieved by only feeding the flaxseed oil diet in the last 3-4 weeks of the growth period^[31]. The growth performance of broilers fed on n-3 PUFA-enriched diets (linseed oil) was not different from those fed on a control diet^[32]. Dietary incorporation of linseed oil and pig lard during starter, grower and finisher phases can enrich broiler chickens meat with n-3 PUFAs^[33].

Eggs enriched with n-3 PUFAs can be used to increase the n-3 PUFAs content of the human diet. In recent decades, the consumption of chicken meat has steadily increased and many studies have focused on the use of dietary modifications to improve the quality of the poultry egg and meat. More specifically, enhancing the functional value of poultry egg and meat through dietary intervention appears to be the most justified, safe, and efficient method^[34]. The most efficient way of promoting the functional value of meat was to feed chickens a diet containing FO and rapeseed (10 g/L and 60 g/L diet, respectively) for the last three weeks before slaughter^[35]. Such a dietary intervention not only increased the share of long-chain PUFAs and decreased the PUFAs n-6/n-3 ratio of meat lipids, but also increased the content of EPA and DHA in the edible parts of the carcass. López-Ferrer et al.^[36] assessed the effect of a diet supplemented with FO on the FAs composition and quality of broiler meat. The results showed that high FO concentrations decreased the saturated and monoenoic FAs contents in the thigh samples. The amount of PUFAs (mainly as EPA, DPA and DHA) increased when FO added in the diets and the levels of total n-6 PUFAs resulted in slight changes, mostly in LA. The total egg yolk n-3 PUFAs was increased from 135.4 mg/egg to 344.5 mg/egg after 18-day feeding with the diet containing 15% Lin-PRO (flaxseed:pea = 1:1; wt/wt)^[37]. For EPA and DHA, but not for LA, the diet effect was more distinct in the extensor carpi radialis compared to *longissimus thoracis* and *biceps femoris*^[38]. The emulsified fat powder can improve serum SOD and GSH-Px the activity and decrease the content of MDA, improving the antioxidant performance of laying hens^[39,40]. The effectiveness of the canola oil on the some metabolites ostriches was evaluated and indicated that glucose and total protein levels increased significantly, whereas total immunoglobulins insulin, albumin, ALT and AST did not change^[41]. The main immune organs in poultry are the thymus, spleen, and bursa of *Fabricius*. During an immune response, mature lymphocytes and other immune cells interact with antigens in these tissues. Wang et al.^[42] observed that feeding laying chickens diets rich in

n-3 PUFAs promoted the growth of the thymus, spleen, and bursa up to 4 weeks of age. However, from the age of 4 weeks onward, immune tissue weights began to decline, and the bursa degenerated between 4 and 8 week of age. Dietary n-3 PUFAs could decrease phagocytosis and lymphocyte proliferation in broiler chickens, highlighting the need for the poultry industry to consider the health status of poultry when poultry meat is being enriched with FO^[43]. An increased ratio of membrane n-6 to n-3 is involved in the pathogenesis of depression and n-3 supplementation has shown positive effects in clinical trials^[44]. Typical formulated broiler diets are deficient in n-3 PUFAs due to widening n-6/n-3 PUFAs ratio which could greatly affect performance, immune system of birds and meat quality. Ibrahim et al.^[45] evaluated the effect of modifying dietary n-6 and n-3 PUFAs ratio from plant and animal oil sources on performance, behavior, cytokine mRNA expression, antioxidative status and meat FAs profile of broiler chickens. The results indicated that narrowing n-6/n-3 ratio through the addition of FO or LO improved growth performance and immune response of broilers and resulted in healthy chicken meat, enriched with long chain n-3 PUFAs.

The proportion of respective PUFAs in the chicken partly depends on diet and an increase in the proportion of n-3 PUFAs in the diet has been shown to improve fertility. Diet supplementation with linseed oil has capability to make the suitable changes in the lipid contents of sperm as well as the improvement in live percentage of sperms^[46]. Blesbois et al.^[47] measured the effects of dietary n-3 PUFAs supplementation on the reproductive capacity of adult male turkeys in industrial flocks. The FO diet very effectively increased the percentage of n-3 PUFAs (22:5n-3 and 22:6n-3) in spermatozoa and correspondingly decreased the percentage of n-6 PUFAs (20:4-6 and 22:4n-6). These changes did not affect the spermatozoa content of n-9 PUFAs, particularly of 22:3n-9 which is abundant in turkey spermatozoa (9-12% of the total FAs). The supplementation was effective in the middle as at the end of the reproductive period. The reproductive capacity of males was modified by the diet and the positive effect of the n-3 supplemented diet increased with age (increase in hatching rates of nearly 2 points at 48-58 weeks for males fed FO diet). These results indicated that n-3 PUFAs enrichment of the turkey diet induced changes in spermatozoa PUFAs, with an overall positive effect on the reproductive capacity of adult males, especially during the decreasing phase of the annual reproductive period.

Application in Swine Diets

Sow Nutrition: Addition of fat to the diets of sows during late gestation and (or) lactation can increase milk production and fat content of colostrum and milk. The maternal dietary fat during the perinatal period affected the type and quantity of the FAs in milk, which was one of the most important pathways to afford nutrition for

neonates^[48]. For sows, PUFAs can not only influence the composition of FAs in sows, but also affect the composition of FAs in the body tissues of piglets through the composition of FAs in colostrum and milk, which can provide plenty of FAs and energy supply for piglets with the aims to improve the survival rate and growth of piglets as well as the reproductive performance of sows. Supplementation of the maternal diet with FO or linseed oil increased the level of n-3 PUFAs of the piglets in a tissue-specific manner. The response of $\Delta 6$ -desaturase and $\Delta 5$ -desaturase protein expression in female piglets to the dietary manipulation was also tissue-specific, suggesting that the increase in n-3 PUFAs content in the progeny was related, at least partially, to the activation of $\Delta 6$ -desaturase and $\Delta 5$ -desaturase expression^[49].

The administration of different oils to sows during lactation can alter the FAs composition of the offspring piglets at weaning, although the type of FAs was not consistent^[50]. The percentage of solids in milk was greater for sows fed the tallow diet, due to an increase in the fat and ash content. Compared with percentages of FAs in milk of sows fed the control diet, the percentages of C10:0, C14:0, C16:0, C16:1, and C18:3 FAs were lower and the percentages of C18:0 and C18:1 FAs were higher in milk of sows fed tallow diets. Litter weaning weight was greater for pigs from sows fed tallow diets than for pigs from control sows. Pigs from tallow-fed sows had greater carcass fat weight and fat percentages and lower water and protein percentages. The diet containing 8% corn oil starting seven days before farrowing until weaning significantly increased the contents of serum-lipid-related indexes in the sows^[51]. Although the triglyceride content did not change, the C18:2n-6 content was higher in the colostrum and in the *longissimus thoracis* muscle of offspring pigs at both investigated stages. The total n-6 content and the ratio of n-6 to n-3 generally increased. These results demonstrated that maternal dietary fat during lactation affected the FAs' composition of the *longissimus thoracis* muscle of progeny at weaning and had persistent effects in later life.

Growing-Finishing Pigs Nutrition: Fatty acids' composition in the pig body is related to their composition in the diet. The deposition of n-3 PUFAs in the body depended on the source of fat in the diet and the increase of n-3 PUFAs intake increased their deposition in the pig body. Sobol et al.^[52] reported that loin and shoulder of pigs (with high intramuscular fat content) fed a diet enriched with the mixture of linseed, rapeseed, and FO meet the European Union recommendations for human nutrition for products considered as either PUFAs n-3 sources or products with high PUFAs n-3 content. Alvarez-Rodriguez et al.^[53] found out that total n-3 PUFAs content (mainly α -linolenic acid, ALA) was greater in organic than in conventional pork, probably due to ALA content from dietary vegetable oils. The source of n-3 PUFAs and dietary n-6/n-3 ratios allow for the favourable manipulation of the fatty acid composition

of pork, indicating that fatty acids composition in the pig body was related to their composition in the diet and the deposition of n-3 PUFAs in the body depended on the source of fat in the diet. However, increasing ALA and EPA + DHA intake enhances their deposition in the body, their net DE decreases^[54].

Boar Nutrition

Pig spermatozoa contains a significant amount of DHA. Intake of different types and sources of PUFA has been shown to change the fatty acid composition of animal sperm and affect sperm quality^[55]. FO (rich in n-3 PUFAs) has been shown to alter sperm structure and penetration resistance, and to increase sperm number and antioxidant capacity^[56]. In addition, semen quality was significantly affected by the dietary n-6/n-3 PUFAs ratio. It has previously been reported that diets with a n-6/n-3 FA ratio of 1.6:1 could increase the proportion of intact acrosome of the boar's spermatozoa. Oils that are rich in n-3 PUFAs also significantly increased sperm density and sperm number^[57]. Lin et al.^[58] determined the effects of different dietary n-6/n-3 ratios on the reproductive performance of breeding boars and found that proper n-6/n-3 PUFAs ratio in the diet of breeding boars enhanced the development of testis and accessory sex gland function, and improved sperm quality, which may be related to favorable hormone metabolism and antioxidant capacity.

Application in Ruminant Diets

Reproductive Performance: Different types of fats have been utilized in an attempt to improve reproductive function in ruminant animals. FAs derived from plants and oil seeds have exerted a major impact on reproductive performance, some of the most common sources include sunflower, linseed, cottonseed, rapeseed and soybean. Animal fat (tallow) and calcium salts of SFAs may escape in a significant percentage rumen hydrogenation to be incorporated into adipose tissue and milk. Fish by-products contain a high proportion of PUFAs and pass without being altered in the rumen exerting no effects on rumen fermentation. There is strong evidence linking consumption of diets high in n-3 PUFAs with reduced circulating peripheral inflammatory markers such as PGF₂α. Supplementation of n-3 PUFA enriched diet improves the pregnancy rate in the cow and buffalo^[59], which is explained by a reduction in the uterine PGF₂α secretion and/or decrease in the sensitivity of the CL to PGF₂α during critical stage of embryonic development, preventing the onset of luteolysis and facilitating the establishment of pregnancy. Inflammatory eicosanoids including PGF₂α, in particular, can significantly affect reproduction outcomes such as the onset of oestrus, embryo survival and parturition. Supplementation of EPA and DHA rich FO for about 10 weeks around the time of mating improved the number of POF and ovulation rate. The twinning and kidding were also enhanced in FO supplemented goats possibly by lowering the E2 and

PGFM concentration during the window of pregnancy recognition^[60].

Polyunsaturated fatty acids are critical nutrients which play an important role in maintaining the physical properties of the sperm membrane fluidity. In general, PUFAs are major component of the sperm cell membranes and thus the major mechanism that PUFAs can affect the sperm quality is associated with membrane physiological characteristics. Te incorporation of PUFAs into diet is able to cause alteration of fatty acid profile of sperm plasma membrane and results in improved sperm quality. Dietary supplementation with PUFAs can alter fluidity/permeability of sperm membrane and enhance reproductive performance in male ruminants thought improving testis development, spermatogenesis, motility and viability of sperm before and post freezing^[61]. There have been a lot of studies carried out in various ruminants species reports have been published (Table 2).

Growth Performance: Ponnampalam et al.^[71] investigated the effect of diets containing n-3 PUFAs on muscle long-chain n-3 FAs content in lambs fed low and medium-quality roughage diets. Fish meal (80 g DM) can increased the muscle long-chain n-3 PUFAs content and decreased the ratio of n-6/n-3 in lamb meat. Feeding soy meal (75g DM modestly increased both the long-chain n-3 and n-6 PUFAs content of meat, resulting in no difference in the n-6/n-3 ratio of meat. The protected canola seed (6% DM) diet did not have a major effect on muscle n-3 FA but resulted in an increase in n-6 and the n-6/n-3 ratio of meat. Demirel et al.^[72] reported that the lambs supplemented with FO plus linseed oil had greater concentrations of C14:0 in the polar lipid fraction of lamb musculus semimembranosus than lambs supplemented with a Ca salt of palm oil, but this was not the case for the neutral lipid fraction. Kim et al.^[73] determined the effect of modifying the n-6:n-3 PUFAs ratio in a concentrate-based diet on feed intake, apparent nutrient digestibility, plasma hormones, and long chain FA composition of the ruminal contents, liver, and muscle of lambs. The results indicated that increasing the n-3 PUFAs in the diet with select oil sources decreased the n-6 to n-3 ratio in ruminal digesta, liver, and fore-shank muscle of growing lambs fed high concentrate diets. This change would likely improve the suitability of lamb meat as a healthful food.

Lactation: Ruminal biohydrogenation, combined with mammary lipogenic and Δ-9 desaturation pathways, considerably modifies the profile of dietary FA and thus milk composition^[74]. Ruminal biohydrogenation of dietary unsaturated FAs are relatively constant, whereas secretion of these in milk is more variable absorbed. Dietary lipids are extensively hydrogenated by rumen micro-organisms, and the extent of this biohydrogenation is a major determinant of long-chain fatty acid profiles of animal products (milk, meat). Numerous studies demonstrated that marine oil supplementation could affect rumen lipid metabolism by altering the activity of specific ruminal bacteria involved in

Table 2. Effect of dietary PUFAs enriched fat sources on semen quality

| Reference | Species | Fat Source | Percent Inclusion | Effect |
|-----------------------------------|----------|---|------------------------------|---|
| Samadian et al. ^[62] | Ram | Fish oil | 3% | Increased the proportion of DHA in sperm fatty acid composition, improved sperm concentration and motility |
| Esmaeili et al. ^[57] | Ram | Palm oil, sunflower oil, fish oil | 35 g/d | Improved prefreezing semen characteristics after thawing, 35 days after the removal of fatty acid source, the percentage of C22:6 was highest in the fish oil treated group |
| Fair et al. ^[63] | Ram | Protected fish oil | 2% | Increased semen concentration but no effect on other semen quality parameters including semen volume, wave motion, and progressive linear motion |
| Radmanesh et al. ^[64] | Ram | Calcium salts of soybean oil | 4% | Improved the volume of semen and total sperm count in ejaculate |
| Dolatpanah et al. ^[65] | Goat | Fish oil and Vit. E | 2.5% and 0.3g/kg DM | Improved testes development enhanced the quality and quantity of goat semen |
| Adeel et al. ^[66] | Buffalo | Sunflower oil, sunflower seed | 1% | Improved the quality of sperm including motility and hypo-osmotic swelling of post-thawed sperm |
| Santos et al. ^[67] | Buffalo | Palm kernel cake | 1% | Improvement of sperm quality, with higher sperm motility and higher levels of spermatozoa with plasma membrane integrity |
| Brnsko et al. ^[68] | Stallion | Commercially available nutraceutical formulated | 250 g | Improved the motion characteristics of cool-stored stallion semen and the freezability of semen |
| Moallem et al. ^[69] | Bull | Flaxseed oil, fish oil | 450 g/d (84.2 g/d C18:3 n-3) | Changed in the characteristics of both fresh and frozen-thawed semen, increased motility and progressive motility of sperm |
| Khoshvaght et al. ^[70] | Bull | Fish oil | 1.2% DM | Improved fresh and post-thaw semen quality in Holstein bulls via alteration of sperm fatty acid composition |

bio-hydrogenation and isomerization of dietary PUFAs^[75]. With greater interest in increasing the n-3 PUFAs content of human diets, interest has also developed to increase these FAs in animal products. FO can modify ruminal or systemic functions, stimulating increased conversion of linoleic acid into transvaccenic and conjugated linoleic acids^[76]. Supplementing the diet of partially grazing cows with FO and sunflower oil increased the milk cis-9, trans-11 CLA content, and that increase remained relatively constant after one week of oil supplementation^[77]. Zhao et al.^[78] investigated the relationship of FAs composition with specific bacteria involved in hydrogenation of 18-carbon UFA in response to dietary oil sources. These results demonstrated that unprotected FO and sunflower oil affected ruminal fermentation and produced series of bio-hydrogenation intermediates. Alterations in ruminal bio-hydrogenation were associated with changes in the abundance of *B. proteoclasticus*, but *B. proteoclasticus* was not the dominant bacterium in producing C18:0.

CONCLUSIONS AND FUTURE PROSPECTS

Polyunsaturated fatty acids are critical nutrients for normal growth and development and play an important role in the composition of all cell membranes where they maintain homeostasis for correct membrane protein function and influence membrane fluidity, thus regulating cell signaling processes, cellular functions and gene expression. Dietary supplementation with PUFAs can alter fluidity/permeability of sperm membrane and enhance reproductive performance in ruminants thought improving testis development, spermatogenesis, motility and viability of sperm before and

post freezing. More important, n-3 PUFAs can significantly affect circulating peripheral inflammatory markers such as PGF2 α as well as a number of hormones and cytokines and these peripheral markers can have a significant effect on reproduction outcomes. In addition, the structure of fat tissue of monogastric animals (pigs, poultry) is very similar to the fat structure of the feedstuffs on which the animals are fed, which means that source and type of fat in an animal feed can greatly influence the composition of fatty tissue and deposits in the resultant carcasses. Since PUFAs give rise to a variety of biologically active compounds which all have important roles in pathological and physiological processes, a proper understanding is needed regarding the contribution these active compounds have on the coinciding increases in inflammatory diseases seen with the disruption of the balance in the ratio of n-6 to n-3 PUFAs. So, it is necessary to conduct further researches to make clear about the effect of optimum n-6 to n-3 PUFAs ratio on various animals and their different stages, thereby contribute to modifying their diets in practice and achieve maximum effect on reproduction.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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