

The Effect of Dietary Fatty Acids on the Nutritional Physiology of Swine

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Abstract. This review goes into the influence of fatty acids in diets upon the nutritional physiology of pigs, concentrating on saturated fatty acids, monounsaturated fatty acids, and polyunsaturated fatty acids. Different molecular pathways make each category play a crucial role in shaping growth performance, intestinal health, immune response, lipid metabolism as well as pork quality. And short-chain and medium-chain fatty acids enhance the intestinal morphology and immunity of weaned piglets, however, MUFA (monounsaturated fatty acids) has been verified to be quite crucial for the harmonizing of pork's flavor and the deposition of fat. PUFAs with biological activities like antioxidant and heart - protecting properties, especially the ω - 3 series of PUFAs that have an effect and the ω - 6/ ω - 3 ratio that can fine - tune systemic inflammation in pigs. Extended to the integrated action of fatty acids as nutrient signaling molecules and the phase - specific regulation methods. Several problems that are pointed out are the inconsistent results brought about by supplements, the elusive inter - generational transmission mechanism, and the relatively unclear interaction between fatty acids and other dietary components. This analysis has established a foundation for designing precise nutritional strategies in pig production.

Keywords: dietary fatty acids, swine, nutritional physiology, lipid metabolism, pork quality

1. Introduction

In the contemporary pig - raising production, the regulation of the diet nutrition is a crucial factor related to the production efficiency and the pork quality. Within this nutritional matrix, the fatty acids hold a central position and have a impact on various aspects of pig nutritional physiology as energy sources are at the core [1]. It is shown that saturated fatty acids having different chain lengths can change the growth of weaned piglets. To supplying energy, the fatty acids are indispensable for gut health that will regulate the integrity of the barrier, the balance of microorganisms, and the production of short-chain fatty acids, guiding the morphology of the gut and the proliferation, differentiation, and apoptosis of epithelial cells [2]. Their rules that cover the immune function and diverse metabolic processes actually have dietary fatty acids along with electrolyte balance which jointly work to control the intestinal epithelial function, the immune system, and the microbiota in piglets [2]. Fatty acids, as nutritional signaling molecules, can influence pig lipid metabolism by regulating the expressions of adipogenic genes like CEBP α , PPAR γ , SREBP1 and FABP4 [3,4].

According to their states of saturation the fatty acids in the diet are classified into three types saturated fatty acids SFAs monounsaturated fatty acids MUFAs as well as polyunsaturated fatty acids PUFAs [5]. Among the short-chain fatty acids the palmitic acid which is a C16 saturated fatty acid and the stearic acid which is a C18 saturated fatty acid are the most crucial ones. The fluctuations in the phospholipids of porcine muscle and liver tissues will bring about the changes in the oxidative stress states of these organs [6,7]. Monounsaturated fatty acids such as C18:1n9c and certain hexadecenoic acids. Such substances like palmitoleic acid and Sapienic acid crucial in various physiological and pathophysiological situations [8]. The PUFA family contains series of ω - 6 and ω - 3 series able to regulate the inflammatory responses and can also reduce the serum triglycerides and low - density lipoprotein cholesterol as well [9,10]. Different types of fatty acids exhibit distinctive differences in their biological characteristics. Supplementing ω - 3 polyunsaturated fatty acids can reduce the serum triglycerides, low - density lipoproteins and inflammatory markers of dialysis patients as is mentioned in [9], while conjugated linoleic acid (CLA) may affect the pork quality by regulating the intestinal flora and related metabolites as is noted in [10]. The inherent characteristics of fatty acids have laid the crucial foundation for implementing precise nutrition in pig production as is cited in [11].

2. Functions of saturated fatty acids

2.1. Effects and mechanisms of C16:0 (palmitic acid)

As the most abundant saturated fatty acid in plasma, palmitic acid, which has brought about a series of impacts on the nutritional physiology of pigs, as well. The experimental results show that adding it to the feed obviously changes the growth performance [12]. In the studies related to weaned piglets, the feed supplemented with palmitic acid can improve the intestinal morphology, regulate the proliferation and differentiation of epithelial cells, and thus enhance the feed conversion efficiency—nevertheless, these results rely on the chain length of the fatty acid. Potentially the mechanism might be that palmitic acid adjusts the intestinal function by changing the cell proliferation signaling pathway as mentioned in [1]. It changes lipid metabolism by regulating the liver's phospholipid metabolism and also reduces the accumulation of low - density lipoprotein cholesterol in muscle tissue as is mentioned in [13]. However, excessive intake of palmitic acid will increase the risk of cardiovascular diseases, including atherosclerosis. When it is compared with unsaturated fatty acids like oleic acid, it shows a stronger lipotoxicity, leading to more obvious cellular apoptosis and metabolic disorders. The activation of the unfolded protein response (UPR) caused by endoplasmic reticulum stress or mitochondrial dysfunction is a key mechanism; this process, which is induced by palmitic acid, will eventually result in DNA damage and cell death - particularly evident in adipocytes and muscles.

2.2. Effects and mechanisms of C18:0 (stearic acid)

The stearic acid that has unique biological characteristics in terms of pig nutrition. Compared with palmitic acid it has a more powerful inhibitory effect on cell growth and the mechanism in it is through the unfolded protein response (UPR) pathway to cause DNA damage as well as induce apoptosis [14]. Similar to palmitic acid its action might depend on those pathways of DNA damage. The caspase pathway is activated, resulting in problematic cell functions in the muscle tissues. Higher levels of stearic acid (specifically C18:0) can be detected in the muscles of immunoneutered pigs, which may change the metabolic state by having an impact on aspects like

the fluidity of membranes or receptor signaling. During the development of meat quality, the stearic acid which takes part in regulating the fatty acid composition within muscles. There is a connection between its accumulation and the increase of saturated fatty acids (SFAs), and it often occurs at the same time as the decrease of polyunsaturated fatty acids (PUFAs) [15]. For instance, in growing pigs, the increase in the proportion of stearic acid will lead to a high content of SFAs in the meat, thereby affecting its oxidative stability as well as its flavor characteristics. Like oleic acid which is a dietary unsaturated fatty acid, it can counteract the cell damage caused by stearic acid, and in the experiment regarding the ratio of unsaturated fatty acids to saturated fatty acids, this finding gets confirmed. Regarding the metabolic regulation, supplementing the weaned piglets with stearic acid can change the concentration of the plasma phospholipids and the state of the oxidative stress as well [6]. As for liver protection stearic acid just like palmitic acid is a long-chain saturated fatty acid and also demonstrates a protective effect in the model of chronic alcoholic liver disease [16]. The addition of stearic acid in the diet also affects the composition of polyunsaturated fatty acids of triglycerides and phospholipids in the muscles [7].

2.3. Effects and mechanisms of other SFAs

To palmitic acid and stearic acid, there are also other saturated fatty acids that have certain specific functions in respect of pig nutrition. As for weaned piglets, short-chain fatty acids like butyric acid can enhance intestinal health. By stimulating epithelial cell proliferation and differentiation and at the same time reducing cell apoptosis, improving growth. For instance, supplementing butyric acid can improve intestinal morphology. There are also fluffy structures and part is because of its dual role of being both an energy source and a signal molecule that regulates microbial fermentation. In the production of pigs, C12:0 acts as a feed additive for instance. These fatty acids optimize the intestinal environment through the action of direct bacteriostasis. To damage the cell membrane of bacteria and also regulate the production of short-chain fatty acids, thus relieving the stress of piglets [1]. From the perspective of molecular interactions there exist quite considerable differences in the binding mechanisms between β -lactoglobulin and saturated fatty acids of different chain lengths from C12:0 to C18:0 [17]. Moreover the differences in the chain lengths of saturated fatty acids will affect their biological effects the medium and short-chain fatty acids for example. The medium-chain type (lauric acid, C12:0) is more effective in improving the growth performance than the long-chain type. Just like palmitic acid this might be related to their rapid metabolism in the intestines; long-chain saturated fatty acids can bring about cardiovascular risks through lipotoxicity and inflammatory pathways. Activating the toll-like receptor or causing the unfolded protein response. The rise in the total consumption of saturated fatty acids usually reduces the PUFA/SFA ratio, thereby raising the risk index of atherosclerosis and thrombus formation. For instance, models of humans and pigs have demonstrated that a high-saturated-fat diet is associated with the risk of cardiovascular diseases, as well as fatty acids of different chain lengths. Well something like odd-chain fatty acids might have different kinds of functions you know. It is worth noting that there is a positive correlation between the total intake of saturated fatty acids and the risk of cardiovascular diseases, and saturated fatty acids with different chain lengths may produce different biological effects by affecting the integrity of the membranes [18] or the energy metabolism of the mitochondria [19]. When the formation of meat quality is taking place, the changes in the proportions of various saturated fatty acids will affect the release of free fatty acids in the muscles and the oxidative stability [7]. Generally speaking there are complex dual roles of saturated fatty acids in pig nutrition: the medium and short chain types that can assist intestinal health and growth

performance while the long chain types are not. Such saturated fatty acids like C16:0 and C18:0 are prone to induce lipotoxicity and bring about the risks of chronic diseases.

3. Functions of monounsaturated fatty acids

Oleic acid (C18:1n7) is one of the most important monounsaturated fatty acids plays various roles in the nutritional physiology of pigs with its mechanism of action being clear and also closely related to the production performance and product quality of pork. Meanwhile, the full - cycle nutrition strategy which is based on the characteristics of fatty acid metabolism needs to integrate the multi - dimensional regulation targets. Oleic acid plays a key role in different physiological stages and production links of pigs: in terms of reproduction, supplementing dietary fiber in the sow's diet can significantly increase the proportion of oleic acid in colostrum [20]; when forming the flavor of pork, oleic acid is an important related factor, for example, it is one of the main monounsaturated fatty acids in the longissimus dorsi muscle of Shaxiling pigs [21]. However, heat treatment can greatly reduce its content and then affect the flavor stability and quality of meat products; in regard to the regulation of fat metabolism, oleic acid is involved in the redistribution of fat, and it is discovered that leucine can increase the content of oleic acid in the longissimus dorsi by regulating related pathways [22]. Its physiological functions depend on clear molecular mechanisms: oleic acid which acts as an precursor for myelin synthesis participates in the synthesis of myelin peptides during the maturation of oligodendrocytes [23] which is quite crucial for the development of the nervous system; it affects fat deposition by regulating the expression of genes related to fat metabolism specifically by up-regulating the transcription levels of genes such as SCD and FAS [24]; meanwhile it can influence the fluidity of cell membranes playing a role in maintaining the stability of the structure and the integrity of the function of biological membranes [25]. Combined with the metabolic characteristics of fatty acids like oleic acid the whole - period nutritional strategy for pigs should specifically meet the special requirements of different physiological stages. The dietary fat level of sows during lactation directly affects the transcription of mammary lipid synthesis genes and the production of milk fatty acids [4] so the supply of functional fatty acids like oleic acid should be ensured to optimize the quality of colostrum. In the weaning piglet stage attention should be focused on the regulation of fatty acids on the intestinal barrier function and the improvement of fat absorption disorders laying a foundation for subsequent growth. In the fattening period special fatty acids like conjugated linoleic acid (CLA) can significantly improve meat quality by regulating the intestinal flora and lipid dynamics [10] forming a synergistic effect with the role of oleic acid in regulating flavor. From the perspective of the life cycle fatty acid nutrition should integrate three key dimensions: the metabolic crosstalk between the intestinal flora and the host. As for the difference between muscle tissue and adipose tissue there also exists the regulatory network of nutrition and epigenetics. After supplementing dietary fiber the content of nervonic acid (C24:1) in sows' colostrum will be increased and this change may be related to piglets' neural development maybe [20]. During the biofilm assembly, palmitoleic acid (C16:1) and heptadecenoic acid (C17:1) demonstrate different distributions, indicating that they are more widespread in biofilm cells in contrast to their planktonic equivalents [26]. Regarding the n - 7 series polyunsaturated fatty acids (C16:1n - 7 and C18:1n - 7), there is an obvious association with the growth performance of piglets [27]; these compounds can further regulate the overall fatty acid composition by regulating the activity of Δ - 9 desaturase, and the index of this enzyme in the offspring is itself affected by the parity of the mother [7]. The medium - chain fatty acid monoglyceride can enhance the resistance of weaned piglets to ETEC F18 infection [28]. Specific

monounsaturated fatty acids like C18:1(n-12) and C19:1(n-9)T will contribute to the formation of pork flavor [25].

4. Functions of polyunsaturated fatty acids

4.1. Effects and mechanisms of ω -6 PUFAs

The dual mechanisms of ω - 6 polyunsaturated fatty acids in the porcine nutritional physiology are being presented. These fatty acids, which might be related to their metabolic by-products, could potentially make disease progression worse by triggering inflammatory responses. Involvement in the synthesis of pro - inflammatory mediators is carried out by (arachidonic acid) [29]. The research shows that the level of ω - 6 polyunsaturated fatty acids in the birds infected with *Plasmodium* is obviously lower than that in the uninfected ones of the same kind, which indicates that the ω - 6 polyunsaturated fatty acids may have an impact on the susceptibility of the host to the pathogen. In the muscle tissue aspect, the accumulation situation of ω - 6 polyunsaturated fatty acids. The increase of triglyceride content in sows supplemented with linoleic acid (C18:2n - 6) and hydroxytyrosol is related [7,30]. It is worthy to note that the microbial synthesis of ω -6 polyunsaturated fatty acids still meets technical obstacles, which highlights its special status in terms of nutrition.

4.2. Effects and mechanisms of ω -3 PUFAs

ω -3 polyunsaturated fatty acids (ω -3 PUFAs) exhibit multiple protective effects in the porcine body, while nuclear receptors such as SREBP-1c and PPAR γ play core roles in the regulation of lipid metabolism and energy balance. Together, they constitute an important network for metabolic regulation in pigs, with specific mechanisms and effects as follows: The protective effects of ω -3 PUFAs span multiple systems: on the one hand, they trigger antioxidant responses by activating the NRF2 pathway, and simultaneously upregulate MDM2 expression to inhibit p53-mediated apoptosis, preventing cisplatin-induced myelosuppression; on the other hand, they exert triple effects of regulating lipid metabolism, inhibiting platelet aggregation, and suppressing inflammation, playing a cardiovascular protective role [29]. Studies using transgenic mouse models have confirmed that ω -3 PUFAs increase endogenous levels through the enzymatic conversion of ω -6 PUFAs, and this conversion capacity shows potential value in improving insulin secretion; compared with fibrils formed in a lipid-free environment, TTR fibrils formed by ω -3 PUFAs have different secondary structures and lower cytotoxicity. Multiple protective effects are exhibited by ω -3 polyunsaturated fatty acids (ω -3 PUFAs) within the porcine body. Their principal mechanisms involve the activation of the NRF2 pathway to initiate antioxidant responses while concurrently elevating MDM2 expression to suppress p53-mediated apoptosis, thereby effectively averting cisplatin-induced myelosuppression. For cardiovascular protection, ω -3 PUFAs—particularly EPA and DHA—deliver a triple action: they modulate lipid metabolism, hinder platelet aggregation, and quell inflammation [29]. Research confirms that endogenous ω -3 PUFA levels can be elevated through enzymatic conversion from ω -6 PUFAs; this conversion capability holds promise for enhancing insulin secretion. Furthermore, TTR fibrils formed in the presence of ω -3 PUFAs, when contrasted with those formed in lipid-free conditions, display distinct secondary structures and reduced cytotoxicity.

There exists an obvious regulatory network that connects the fatty acid signal transduction and the amino acid metabolism in a somewhat obvious manner. Supplementary glutamate can change

the monounsaturated fatty acids in the muscles and can also enhance the expression of lipogenic genes. Such a nutritional synergy provides a crucial molecular basis for precise nutritional intervention in pigs [11].

4.3. General effects and mechanisms of ω -6 and ω -3 series fatty acids

The balance of the fatty acids in the ω -6 and ω -3 series that has a systemic impact on the health of pigs is mainly realized by regulating the systemic inflammatory state. Actually, the change of this proportion directly impacts the inflammatory state of the body. There are examples to back up this point, in the birds in the natural habitat, the decrease of the ratio of ω -6/ ω -3 is found to be related to the infection of *Plasmodium* [30]. Regarding the aspect of muscle quality the reduction in the ratio of ω -6/ ω -3 often coexists with the decrease in the total content of polyunsaturated fatty acids which might damage the oxidative stability of meat products. In terms of metabolism the ω -3 series fatty acids will be further catalyzed and metabolized by the Δ -6 desaturase and the activity of this enzyme is greatly affected by the parity of sows as well as the level of vitamin E in the diet [7]. Both kinds of fatty acids can inhibit the aggregation of the TTR protein; however, the resulting fibril structure is notably different from that generated in a saturated fatty acid environment. From the clinical application aspect, although ω -3 polyunsaturated fatty acids have demonstrated effectiveness in enhancing cardiovascular risk factors, the determination of the optimal dietary ratio between them and ω -6 polyunsaturated fatty acids still needs to be further verified through randomized controlled trials.

5. Conclusion

5.1. Prospects or defects

There are still three main inconsistencies existing in the current research. First of all, although people have carried out a thorough examination regarding how long-chain fatty acids impact growing-finishing pigs, the outcomes of applying them are truly inconsistent. What is particularly unclear are the fundamental mechanisms that govern average daily gain and feed conversion ratio. Secondly, delving into the trans-stage transmission effects of fatty acids is insufficient. There exists a dearth of comprehensive evidence, such as on how the n-6:n-3 ratio in the maternal diet molds offspring immune programming across generations [2]. Thirdly, the interaction mechanism between fatty acids and the nutrients taken in together has not been completely figured out. For example, high dietary fiber will make endogenous fatty acids be consumed more intensely, and there also exist synergistic interactions between electrolyte balance and fatty acid metabolism as well [2]. The resolution of these gaps has quite practical significance in achieving precise pig nutrition as is mentioned in [11].

5.2. Main findings and implications

This review expounds the functions and mechanisms of dietary fatty acids which are classified into saturated fatty acids (SFAs), monounsaturated fatty acids (MUFAs), and polyunsaturated fatty acids (PUFAs) in pig nutritional physiology, points out the continuously existing knowledge gaps and their impacts on the application of precise nutrition. Short- and medium-chain types are produced by SFAs. Butyric acid and lauric acid and other substances by regulating the function of epithelial cells and the gut microbiota enhance the intestinal health growth and immunity of weaned piglets conversely long-chain saturated fatty acids affect lipid metabolism and may have a role in protecting

the liver yet if consumed in excessive amounts they will incur the risks of lipotoxicity inflammation and cardiovascular diseases. Centered around oleic acid (C18:1n9c) which are monounsaturated fatty acids that play various roles throughout the physiological stage, these fatty acids enhance the sow's colostrum quality, contribute to pork flavor, and also regulate fat deposition by upregulating genes such as SCD and FAS. Substances such as nervonic acid and palmitoleic acid are involved in neural development, membrane structures as well as antibacterial defense and so forth. Polyunsaturated fatty acids which are in multiple unsaturated fatty acid categories are divided into the ω - 6 and ω - 3 series. The ω - 6 polyunsaturated fatty acids may be able to intensify the inflammatory reaction via pro - inflammatory metabolites, whereas the ω 3 polyunsaturated fatty acids can bring about protective effects through such pathways as the NRF2MDM2p53 - including antioxidant, heart - protecting and anti - apoptosis activities, and also can be endogenously synthesized from the precursor substances of ω 6. Moreover, PUFAs and MUFAs both act as nutritional signaling molecules and play a role in controlling lipid metabolism through nuclear receptors such as the e part and others. This analysis brings to light three main research contradictions: the inconsistent growth results after adding long-chain polyunsaturated fatty acids (LCFA) in growing and finishing pigs; the insufficient evidence concerning the transgenerational transmission of fatty acids; and the unclear interaction mechanisms between fatty acids and auxiliary nutrients. To solve these problems is essential for formulating feeds for different stages with the aim of making use of the functional specificity of fatty acids so as to enhance the production performance, pork quality and nutritional value of pigs - these progresses ultimately contribute to human health.

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