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Effects of Dietary Fiber on Oocyte Quality in Replacement Gilts and Its Mechanism of Action: Postprint

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Abstract

Oocyte quality is a key determinant of reproductive performance in female mammals. Research has confirmed that dietary fiber supplementation can regulate oocyte quality through pathways such as influencing hormones and metabolites in replacement gilts. This article provides a review of the effects of dietary fiber on oocyte quality in replacement gilts and its potential mechanisms of action.

Full Text

Effects of Dietary Fiber on Oocyte Quality of Gilts and Its Mechanism

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Abstract: Oocyte quality is a key factor determining reproductive performance in female mammals. Evidence indicates that dietary fiber supplementation can regulate oocyte quality by influencing hormones and metabolites in gilts. This review examines the effects of dietary fiber on gilt oocyte quality and its possible mechanisms.

Keywords: dietary fiber; gilts; oocyte quality; effects; mechanism

In large-scale pig farms, the culling rate of replacement gilts due to anestrus or delayed estrus can be as high as 20%~30% [1], and poor oocyte quality is a key

factor leading to increased culling rates. Oocyte quality directly affects fertilization rate, cleavage rate, early embryo survival, implantation and maintenance of pregnancy, fetal development, litter size, and the health status of offspring in adulthood [2]. As production models become standardized, feeding conditions and growth patterns of replacement gilts tend to be consistent, making nutrition one of the important factors affecting gilt development and maturation. The supply of different nutrients can influence gilt oocyte quality to some extent [3]. Research has found that adding appropriate levels of fiber to sow diets can promote oocyte maturation and improve oocyte quality [4–6]. This review examines the effects of dietary fiber on gilt oocyte quality and its mechanisms, aiming to draw attention from researchers to the regulation of oocyte quality by dietary fiber and provide a theoretical basis for the rational use of dietary fiber in sows.

1. Oocyte Quality and Reproductive Performance of Gilts

In swine production, high litter size is key to farm profitability. Litter size is dependent on embryo survival after fertilization and fetal development during gestation, which is determined by oocyte quality [2,4,7]. Multiple methods are used to evaluate oocyte quality. In in vitro culture, the proportion of oocytes reaching metaphase II (MII) of meiosis is commonly used to assess oocyte maturation and quality. Additionally, subsequent developmental capacity, including fertilization rate, cleavage rate, blastocyst rate, and good embryo survival rate, are also used as criteria for evaluating oocyte quality.

In mammalian species, preovulatory oocytes undergo long-term growth and development to achieve cytoplasmic and nuclear maturation, thereby acquiring fertilization capacity and subsequent embryonic development ability [2]. During the implantation period, when embryo mortality is highest, only better-developed embryos can adapt to changes in the uterine environment and eventually become newborn offspring. Research has found that Meishan pigs have large litters due to high early embryo survival rates, with more oocytes reaching the MII stage 7 hours before ovulation [2], indicating that a higher proportion of oocytes reaching MII leads to higher survival rates in early pregnancy. Zak et al. [8] strongly demonstrated this view using the same lactating sow model. This shows that oocyte quality directly affects sow litter size [8–9]. Therefore, improving oocyte quality is an important way to increase litter size, enhance sow lifetime reproductive performance, and improve economic benefits.

2. Effects of Dietary Fiber on Gilt Oocyte Quality

Prior to breeding, supplementation with appropriate levels of dietary fiber to gilt diets can improve oocyte quality, thereby enhancing embryo survival and ultimately increasing newborn piglet survival and weaned piglet numbers, improving sow reproductive performance [4–6]. Various fiber sources may be incorporated into diets, such as soybean hulls, wheat bran, wheat straw, beet

pulp, and lupins; however, different fiber types exert differential effects on gilts. Renteria-Flores et al. [10] added 30% oat bran (soluble fiber) and 12% wheat straw (insoluble fiber) to sow diets, resulting in embryo survival rates of 80.3% and 76.4%, respectively. Arias-Álvarez et al. [11] added lignin fiber (insoluble fiber, 4.9% of diet DM) and high-lignin fiber (insoluble fiber, 15.8% of diet DM) to sow diets, with the former increasing the number of oocytes reaching MII. Feeding high-fiber diets before mating can improve gilt oocyte quality, increase embryo survival during gestation, and reduce the number of growth-retarded embryos in the uterus [12]. Ferguson et al. [5] found that adding beet pulp (50.0% of diet DM) to gilt diets increased luteinizing hormone (LH) pulse frequency and the number of oocytes reaching MII, improving oocyte maturation rate by 10%. Weaver et al. [6] found that adding wheat bran (5.0% of diet DM) and lupins (3.5% of diet DM) to pre-breeding diets improved gilt oocyte quality, with the latter showing particular benefits.

Collectively, different fiber sources and addition levels have different effects on oocytes. Fiber can promote oocyte development and improve oocyte quality to some extent, thus playing a role in gilt production applications. However, due to the complexity of fiber sources, the optimal fiber sources and addition levels for improving gilt production performance require further research verification.

3. Mechanism of Dietary Fiber Regulating Gilt Oocyte Quality

Dietary fiber is primarily found in plant cell walls, with large amounts present in grains, vegetables, legumes, nuts, fruits, and seeds, making these important sources of dietary fiber. Fiber has characteristics such as water-holding capacity, viscosity, fermentability, adsorption/chelation, and bulking effects. Adding fiber to sow diets can reduce costs, improve economic benefits, and increase the number of live-born and weaned piglets, as well as birth and weaning litter weights [13–15]. However, dietary fiber level is also an important factor affecting diet digestibility; excessively high dietary fiber levels can reduce diet digestibility.

3.1 Metabolism of Dietary Fiber in Gilts

A key characteristic of dietary fiber is that it is not digested in the small intestine but is fermented and broken down in the large intestine. Certain fibers can function as prebiotics in the gut and can be selectively fermented in directions beneficial to gut microorganisms [16]. In the large intestine, anaerobic bacteria can hydrolyze indigestible fiber into oligosaccharides and further into monosaccharides, which are metabolized through glycolysis (hexoses) and the pentose phosphate pathway (pentoses). Monosaccharides are converted to phosphoenolpyruvate, which is fermented by gut microbiota into organic acids, with acetate, propionate, and butyrate being the main short-chain fatty acids (SCFAs) produced by fiber fermentation. Anguita et al. [17] fed pigs diets with low

fiber (77 g/kg), standard fiber (160 g/kg), and high fiber levels (240 g/kg), reporting that high-fiber diets increased SCFA concentrations in pigs, producing more acetate, while low-fiber diets produced more butyrate than the other two groups.

In pigs, fermented SCFAs can provide effective energy equivalent to 7%~17% of the total energy required [17], and the types of SCFAs produced are closely related to the monosaccharide composition of the fiber source [18]. Based on differences in monosaccharide composition of dietary fiber, different fibers produce different SCFA types. Dietary fiber with high uronic acid content can increase acetate concentration in animals, fiber with high glucose content can increase propionate concentration, and fiber with high xylose content promotes butyrate production [19]. Of the fermented SCFAs, 70% of acetate is taken up by the liver and converted to acetyl-CoA for fatty acid synthesis [20]; propionate affects liver and cholesterol metabolism, with 30%~50% of propionate entering circulation being taken up by the liver as a gluconeogenic precursor for energy supply [21]; approximately 65% of butyrate is used as an energy source for intestinal cells through gluconeogenesis in the gut [22], regulating growth and death of epithelial and immune cells [23].

3.2 Regulation of Gilt Oocyte Quality Through Digestive Metabolites

Butyrate, a widely studied fiber metabolite, can promote colon cell division and improve health status by regulating expression of antioxidant-related genes and enzymes [24]. During oocyte development, histone modification is a critical step in the meiosis stage. Covalent histone modifications influence acetylation, methylation, phosphorylation, and ubiquitination processes [25]. Acetylation affects many fundamental processes, with cell cycle arrest, differentiation, and apoptosis often accompany increased histone acetylation. Sodium butyrate is a non-competitive histone deacetylase inhibitor [26]. Liu et al. [27] collected pig ovaries and isolated oocytes, treating them with 0, 1.0, 5.0, and 10.0 mmol/L sodium butyrate for 44 h. Results showed that compared with the other three groups, the 1.0 mmol/L sodium butyrate group had more oocytes (47.2%, n=30) reaching MII stage. This indicates that SCFAs produced by fiber fermentation in animals can promote oocyte development.

3.3 Regulation of Gilt Oocyte Quality Through Hormones

During dietary fiber consumption in sows, a series of hormonal changes occur that affect oocyte quality. Diets with different energy levels and sources (fat, starch, and fiber) can influence circulating estradiol (E2) and progesterone concentrations, thereby affecting follicular development and oocyte quality in gilts [3–5].

Research suggests that increased secretion of hypothalamic gonadotropin-releasing hormone (GnRH) is a key indicator of estrus in animals [28–30]. Kisspeptin is an endocrine peptide hormone encoded by the Kiss-1 gene (a

neuropeptide-encoding gene). Kisspeptin plays a key signaling role in the secretion of GnRH from hypothalamic neurons in rodents [31–33]. Steroid hormones such as E2, progesterone (P), and the energy metabolism hormone leptin can effectively increase Kisspeptin expression, inducing puberty onset in juvenile mice [34].

3.3.1 Through Estrogen Dietary fiber can reduce estrogen concentrations in the body by affecting cholesterol metabolism [35]. The beneficial effects of dietary fiber on oocytes may be due to fiber' s adsorption effect in the gut, resulting in E2 excretion with feces rather than entering systemic circulation [5,36]. Reduced estrogen concentrations decrease estrogen' s negative feedback on GnRH, increasing LH release and thereby improving gilt oocyte quality.

In vitro studies demonstrate that propionate, an SCFA produced by fiber fermentation, can inhibit cholesterol synthesis. Since cholesterol serves as the precursor for steroid hormone production such as E2 in animals, reduced cholesterol synthesis decreases E2 production, thereby improving gilt oocyte quality. In vivo studies indicate that adding lupin fiber to gilt diets can be metabolized to fatty acids in the body as an energy source to maintain blood glucose and insulin concentrations while increasing LH release frequency, affecting follicular and oocyte development [37]. Additional studies demonstrate that feeding high-fiber diets can promote LH release frequency in gilts, promoting follicular and oocyte development [5]. However, Weaver et al. [6] reported that feeding high-fiber diets had no significant effect on LH concentration in gilts, possibly due to different fiber types and addition levels leading to different results. The above studies indicate that dietary fiber intake can promote follicular and oocyte development in gilts by affecting estrogen concentration.

3.3.2 Through Leptin Leptin is an important adipokine that plays a critical role in mediating energy metabolism status, neuroendocrine axes, and reproductive processes. It acts on the hypothalamic-pituitary-gonadal axis, directly acting on the Kiss-1 gene to promote Kisspeptin expression. Studies in animals and humans have found that intake of high doses of soluble fiber can reduce blood leptin concentration [38]. Research also indicates that compared with non-vegetarians, vegetarians with increased fiber intake have significantly lower serum leptin concentrations [39]. This indicates that fiber can affect leptin concentration in the body, regulating Kisspeptin expression through leptin to improve follicular and oocyte development.

3.4 Regulation of Gilt Oocyte Quality Through Body Metabolites

Studies demonstrate that feeding high-fiber diets can reduce glucose absorption, prevent digestive enzymes from degrading starch encapsulated within cell walls, and slow the rate of starch conversion to glucose [40-41]. Lupins and lupin hulls, which are fiber-rich ingredients, contain abundant non-starch polysaccharides that resist digestion in the small intestine while increasing available fatty acid

content for energy, thereby helping maintain stable blood glucose and insulin concentrations [37]. Knudsen et al. [40] reported that fiber primarily regulates glucose absorption by influencing gastric emptying rate in pigs. Johansen et al. [41] demonstrated that cellulose effectively reduces blood glucose concentration in pigs. Liu Changzhong et al. [42] showed that high-fiber diets significantly decrease blood glucose concentration in geese.

Elevated free fatty acid concentration is one cause of insulin resistance [43], while acetate produced through fiber fermentation in the hindgut can reduce circulating free fatty acid concentrations [44], thereby mitigating insulin resistance. The proposed mechanism involves acetate produced via fermentation being oxidized in circulation to provide energy for muscle tissue activity, consequently reducing lipolysis and free fatty acid release. When acetate energy supply is limited, the body accelerates free fatty acid oxidation, further decreasing serum free fatty acid concentrations [45]. Collectively, dietary fiber helps maintain stable blood glucose and insulin concentrations in sows. Stable glucose and insulin levels enable nutrient partitioning in directions more favorable for follicular growth, oocyte maturation, and fetal development [46], thereby improving gilt oocyte quality.

In summary, dietary fiber represents a critical factor affecting gilt oocyte quality. Dietary fiber influences gilt ovarian oocyte quality through its digestive metabolites, regulation of related hormone secretion and concentrations, indirect effects on GnRH and Kisspeptin, and regulation of body metabolites, thereby affecting embryo and fetal development and ultimately gilt reproductive performance.

While numerous studies have demonstrated that dietary fiber can improve gilt oocyte quality and sow reproductive performance, optimal fiber types and requirements remain to be precisely defined. Further research is required to provide a more precise theoretical basis and practical guidance for dietary fiber use in production.

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