Effects of Dietary Fiber on Oocyte Quality in Replacement Gilts and the Underlying Mechanisms: Postprint

Authors: Shi Jiankai, Shi Xiaolin, Zhang Pan, Wu Xiaoling, Wu De, Xu Shengyu

Date: 2017-11-07T00:00:00+00:00

Abstract

Oocyte quality constitutes a critical factor determining reproductive performance in female mammals. Studies have demonstrated that the addition of fiber to the diet can modulate oocyte quality by affecting hormones and metabolites in replacement gilts, among other mechanisms. This review examines the effects of dietary fiber on oocyte quality in replacement gilts and explores its possible mechanisms of action.

Full Text

Preamble

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

SHI Jiankai[1], SHI Xiaolin[2], ZHANG Pan[1], WU Xiaoling[1], WU De[1], XU Shengyu[1]*

(1. Institute of Animal Nutrition, Sichuan Agricultural University, Chengdu 611130, China; 2. Taishanshi Shengfeng Agriculture Co., Ltd., Taishan 529200, China)

*Corresponding author: Associate Professor, E-mail: shengyuxu@sicau.edu.cn

Abstract: Oocyte quality is a key determinant of reproductive performance in female mammals. Studies have confirmed that dietary fiber supplementation can regulate gilt oocyte quality by influencing hormones and metabolic products. This paper reviews the effects of dietary fiber on gilt oocyte quality and its potential 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 reaches as high as 20%-30% [1], and poor oocyte quality is a critical factor contributing to this elevated culling rate. Oocyte quality directly affects fertilization rates, cleavage rates, early embryo survival, uterine implantation and maintenance, fetal development, litter size, and even the long-term health of offspring [2]. As production systems become increasingly standardized and gilt rearing conditions and growth patterns converge, nutrition has emerged as a crucial factor influencing gilt development and maturation. The provision of different nutrients can significantly impact gilt oocyte quality [3]. Research has demonstrated that appropriate dietary fiber supplementation in 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 underlying mechanisms, aiming to draw scholarly attention to dietary fiber’ s role in regulating oocyte quality and provide a theoretical foundation for the rational application of dietary fiber in sow production.

1 Oocyte Quality and Reproductive Performance in Gilts

In the swine industry, high litter size is essential for farm profitability. Increased litter size depends on post-fertilization embryo survival and fetal development during gestation, both of which are determined by oocyte quality [2,4,7]. Multiple methods exist for evaluating oocyte quality. In vitro culture systems commonly assess oocyte maturity and quality by the proportion reaching metaphase II (MII) of meiosis. Additionally, subsequent developmental competence—including fertilization rates, cleavage rates, blastocyst rates, and embryo survival—serves as important criteria for evaluating oocyte quality.

In mammals, preovulatory oocytes undergo prolonged growth and development to achieve both cytoplasmic and nuclear maturation, thereby acquiring fertilization capacity and embryonic developmental potential [2]. During the high-mortality implantation period, only better-developed embryos can adapt to uterine environmental changes and survive to term. Studies have shown that Meishan pigs produce larger litters due to higher early embryo survival rates, with more oocytes reaching MII stage 7 hours before ovulation [2]. This indicates that a higher proportion of MII-stage oocytes correlates with improved early pregnancy survival. Zak et al. [8] strongly supported this conclusion using a similar lactating sow model. These findings demonstrate that oocyte quality directly impacts sow litter size [8-9]. Therefore, improving oocyte quality represents an important pathway to increase litter size, enhance lifetime reproductive performance, and improve economic efficiency in sows.

2 Effects of Dietary Fiber on Gilt Oocyte Quality

Supplementing appropriate levels of crude fiber in gilt diets before mating can improve oocyte quality, enhance embryo survival, and ultimately increase piglet survival rates and weaned piglet numbers, thereby improving reproductive performance [4–6]. Various fiber sources can be added to diets, including soybean hulls, wheat bran, wheat straw, beet pulp, and lupins, though 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, reporting embryo survival rates of 80.3% and 76.4%, respectively. Arias-Álvarez et al. [11] supplemented diets with lignin fiber (insoluble fiber, 4.9% of dry matter) and high-lignin fiber (insoluble fiber, 15.8% of dry matter), finding increased numbers of oocytes reaching MII stage with the lower lignin level. Feeding high-fiber diets before mating improved gilt oocyte quality, increased embryo survival during gestation, and reduced the number of intrauterine growth-retarded embryos [12]. Ferguson et al. [5] found that adding beet pulp (50.0% of dry matter) to gilt diets increased luteinizing hormone (LH) pulse frequency and the number of oocytes reaching MII stage, improving oocyte maturation rates by 10%. Weaver et al. [6] reported that adding wheat bran (5.0% of dry matter) and lupin (3.5% of dry matter) to pre-mating diets improved gilt oocyte quality, with lupin showing particular benefits.

In summary, different fiber sources and supplementation levels produce varying effects on oocytes. Fiber can promote oocyte development and improve oocyte quality to varying degrees, thereby benefiting gilt production. However, due to the complexity of fiber sources, optimal fiber types and supplementation levels for improving gilt reproductive performance require further investigation.

3 Mechanisms of Dietary Fiber Regulation of Gilt Oocyte Quality

Fiber is primarily found in plant cell walls, with grains, vegetables, legumes, nuts, fruits, and seeds serving as important dietary fiber sources. Fiber exhibits properties including water-holding capacity, viscosity, fermentability, adsorption/chelation, and bulking effects. Dietary fiber supplementation in sow diets can reduce costs, improve economic efficiency, and increase numbers of live-born and weaned piglets, as well as birth and weaning weights [13–15]. However, dietary fiber level also significantly affects feed digestibility, with excessively high fiber levels reducing digestibility.

3.1 Metabolism of Dietary Fiber in Gilts

A primary characteristic of dietary fiber is its resistance to small intestinal digestion, followed by fermentation in the large intestine. Some fibers function as prebiotics, selectively promoting beneficial gut microbiota [16]. In the large intestine, anaerobic bacteria hydrolyze indigestible fiber into oligosaccharides and further into monosaccharides. Through glycolysis (for hexoses) and the pentose phosphate pathway (for pentoses), monosaccharides are converted to phosphoenolpyruvate, which is then fermented by microbiota into organic acids. Acetate, propionate, and butyrate are the main short-chain fatty acids (SCFAs) produced through fiber fermentation. Anguita et al. [17] fed pigs diets with low (77 g/kg), standard (160 g/kg), and high (240 g/kg) fiber levels, finding that high-fiber diets increased SCFA concentrations and produced more acetate, while low-fiber diets generated more butyrate compared to the other groups.

In pigs, fermented SCFAs can provide 7%-17% of the total energy required [17], with SCFA types closely related to the monosaccharide composition of fiber sources [18]. Depending on dietary fiber monosaccharide composition, different fibers produce different SCFA profiles. Fiber with high uronic acid content increases acetate concentration, glucose-rich fiber elevates propionate levels, and xylose-rich fiber promotes butyrate production [19]. Of the fermented SCFAs, approximately 70% of acetate is taken up by the liver and converted to acetyl-CoA for fatty acid synthesis [20]; propionate affects hepatic cholesterol metabolism, with 30%-50% of circulating propionate absorbed by the liver as a gluconeogenic precursor for energy supply [21]; and about 65% of butyrate serves as an energy source for intestinal cells through gluconeogenesis in the gut, regulating growth and death of epithelial and immune cells [22,23].

3.2 Regulation of Gilt Oocyte Quality Through Fiber Fermentation Metabolites

Butyrate, a well-studied fiber metabolite, promotes colonocyte division and improves health by regulating antioxidant-related gene and enzyme expression [24]. During oocyte development, histone modification is critical during meiosis. Covalent histone modifications extensively affect acetylation, methylation, phosphorylation, and ubiquitination processes [25], with acetylation influencing fundamental processes such as cell cycle arrest, differentiation, and apoptosis, which often follow increased histone acetylation. Sodium butyrate is a non-competitive histone deacetylase inhibitor [26]. Liu et al. [27] collected pig ovaries, isolated oocytes, and treated them with 0, 1.0, 5.0, and 10.0 mmol/L sodium butyrate for 44 hours. Results showed that compared to the other three groups, the 1.0 mmol/L sodium butyrate group had more oocytes (47.2%, n=30) reaching MII stage. These findings indicate that SCFAs produced through fiber fermentation in vivo can promote oocyte development.

3.3 Regulation of Gilt Oocyte Quality Through Hormonal Modulation by Dietary Fiber

During fiber consumption, gilts experience hormonal changes that affect oocyte quality. Diets with different energy levels and sources (fat, starch, and fiber) can influence circulating estradiol (E2) and progesterone levels, thereby affecting follicular development and oocyte quality [3-5].

Increased hypothalamic gonadotropin-releasing hormone (GnRH) secretion is considered a key indicator of estrus [28-30]. Kisspeptin is an endocrine peptide hormone encoded by the Kiss-1 gene. Kisspeptin plays a critical signaling role in GnRH secretion 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, triggering puberty onset in mice [34].

3.3.1 Regulation of Gilt Oocyte Quality Through Estrogen Modulation by Dietary Fiber

Fiber can reduce estrogen concentration by affecting cholesterol metabolism [35]. The beneficial effects of dietary fiber on oocytes may result from fiber' s adsorptive action in the intestine, which increases E2 excretion in feces and reduces its enterohepatic circulation [5,36]. Reduced estrogen concentration decreases negative feedback on GnRH, increases LH release, and thereby improves gilt oocyte quality.

In vitro studies have shown that propionate, an SCFA produced through fiber fermentation, can inhibit cholesterol synthesis. Since cholesterol is the fundamental precursor for steroid hormone synthesis including E2, reduced cholesterol synthesis would lower E2 production and improve gilt oocyte quality. In vivo experiments found that lupin fiber supplementation in gilt diets could be converted to fatty acids as an energy source to maintain blood glucose and insulin concentrations while increasing LH release frequency and affecting follicular and oocyte development [37]. Studies have also shown that high-fiber diets can promote LH release frequency in gilts, stimulating follicular and oocyte development [5]. However, Weaver et al. [6] reported no significant effect of high-fiber diets on LH concentration in gilts, possibly due to differences in fiber types and supplementation levels. These findings collectively indicate that dietary fiber intake can promote follicular and oocyte development by modulating estrogen concentrations.

3.3.2 Regulation of Gilt Oocyte Quality Through Leptin Modulation by Dietary Fiber

Leptin, an important adipose-secreted factor, plays a significant role in mediating energy metabolism, neuroendocrine axes, and reproductive processes. It acts on the hypothalamic-pituitary-gonadal axis, directly affecting Kiss-1 gene expression to promote Kisspeptin expression. Studies in animals and humans have found that high-dose soluble fiber intake can reduce blood leptin concentrations [38]. Research has also shown that compared to non-vegetarians, vegetarians with higher fiber intake have significantly lower serum leptin levels [39]. These results demonstrate that fiber can affect leptin concentration, thereby regulating Kisspeptin expression to improve follicular and oocyte development.

3.4 Regulation of Gilt Oocyte Quality Through Modulation of Metabolic Products by Dietary Fiber

Studies have shown that high-fiber diets can reduce glucose absorption by preventing digestive enzymes from degrading starch encapsulated within cell walls, thereby slowing starch hydrolysis to glucose [40–41]. Among fiber-rich diets, lupin and lupin hulls are rich in non-starch polysaccharides that can be digested in the small intestine and increase available fatty acid content as an energy source, helping maintain blood glucose and insulin concentrations [37]. Knudsen et al. [40] found that fiber primarily regulates glucose absorption by affecting gastric emptying rate in pigs. Johansen et al. [41] demonstrated that cellulose can reduce blood glucose concentration in pigs. Liu et al. [42] reported that high-fiber diets significantly reduced 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 blood free fatty acid levels [44], thereby decreasing insulin resistance. The mechanism may involve acetate oxidation in blood to provide energy for muscle activity, reducing fat mobilization and free fatty acid release. When acetate energy supply is limited, the body accelerates free fatty acid oxidation, further reducing serum free fatty acid concentration [45]. In summary, dietary fiber helps maintain stable blood glucose and insulin concentrations in sows. Stable glucose and insulin levels enable nutrient partitioning that favors follicular growth, oocyte maturation, and fetal development [46], thereby improving gilt oocyte quality.

In conclusion, fiber is a crucial factor affecting gilt oocyte quality. Dietary fiber influences gilt oocyte quality through its fermentation metabolites, modulation of hormone secretion and concentrations (indirectly affecting GnRH and Kisspeptin), and regulation of metabolic products, thereby impacting embryonic and fetal development and ultimately reproductive performance. Although numerous studies have demonstrated that dietary fiber can improve gilt oocyte quality and reproductive performance, optimal fiber types and requirements remain to be precisely defined. Further research is needed to provide more accurate theoretical guidance and practical recommendations for dietary fiber application in sow production.

References:

[1] TUMMARUK P, TANTASUPARUK W, TECHAKUMPHU M, et al. Age, body weight and backfat thickness at first observed oestrus in crossbred Landrace×Yorkshire gilts, seasonal variations and their influence on subsequence reproductive performance[J]. Animal Reproduction Science, 2007, 99(1/2): 167-181.

[2] HUNTER M G. Oocyte maturation and ovum quality in pigs[J]. Reviews of Reproduction, 2000, 5(2): 122-130.

[3] ZHOU D S, FANG Z F, WU D, et al. Dietary energy source and feeding levels during the rearing period affect ovarian follicular development and oocyte maturation gilts[J]. Theriogenology, 2010, 74(2): 202-211.

[4] FERGUSON E M, ASHWORTH C J, EDWARDS S A, et al. Effect of different nutritional regimens before ovulation on plasma concentrations of metabolic and reproductive hormones and oocyte maturation in gilts[J]. Reproduction, 2003, 126(1): 61-71.

[5] FERGUSON E M, SLEVIN J, HUNTER M G, et al. Beneficial effects of a

high fiber diet on oocyte maturity and embryo survival in gilts[J]. Reproduction, 2007, 133(2): 433–439.

[6] WEAVER A C, KELLY J M, KIND K L, et al. Oocyte maturation and embryo survival in nulliparous female pigs (gilts) improved by feeding a lupin-based high-fibre diet[J]. Reproduction, Fertility and Development, 2013, 25(8): 1216–1223.

[7] KRISHER R L. The effect of oocyte quality on development[J]. Journal of Animal Science, 2004, 82 E-Suppl: E14–E23.

[8] ZAK L J, COSGROVE J R, AHERNE F X, et al. Pattern of feed intake and associated metabolic and endocrine changes differentially affect postweaning fertility in primiparous lactating sows[J]. Journal of Animal Science, 1997, 75(1): 208–216.

[9] ZAK L J, XU X, HARDIN R T, et al. Impact of different patterns of feed intake during lactation in the primiparous sow on follicular development and oocyte maturation[J]. Journal of Reproduction and Fertility, 1997, 110(1): 99-106.

[10] RENTERIA-FLORES J A, JOHNSTON L J, SHURSON G C, et al. Effect of soluble and insoluble dietary fiber on embryo survival and sow performance[J]. Journal of Animal Science, 2008, 86(10): 2576–2584.

[11] ARIAS-ÁLVAREZ M, GARCÍA-GARCÍA R M, REBOLLAR P G, et al. Follicular, oocyte and embryo features related to metabolic status in primiparous lactating does fed with high-fiber rearing diets[J]. Reproduction in Domestic Animals, 2010, 45(5): e91–e100.

[12] FERGUSON E M, SLEVIN J, EDWARDS S A, et al. Effect of alterations in the quantity and composition of the pre-mating diet on embryo survival and foetal growth in the pig[J]. Animal Reproduction Science, 2006, 96(1/2): 89-103.

[13] FENG Dongdong. Effects of dietary fiber level on reproductive performance of pregnant sows[D]. Master's thesis. Chengdu: Sichuan Agricultural University, 2010.

[14] LIAN Hongxia, WANG Chengzhang, YANG Yuxin, et al. Effects of different alfalfa meal addition levels on performance of pregnant sows and their piglets[J]. Journal of Northwest A&F University: Natural Science Edition, 2004, 32(6): 35–40.

[15] ZHANG Jinzhi. Study on effects of dietary energy structure on reproductive and lactation performance of sows[D]. Doctoral dissertation. Hangzhou: Zhejiang University, 2009.

[16] MACFARLANE G T, STEED H, MACFARLANE S. Bacterial metabolism and health-related effects of galacto-oligosaccharides and other prebiotics[J]. Journal of Applied Microbiology, 2008, 104(2): 305–344.

[17] ANGUITA M, CANIBE N, PÉREZ J F, et al. Influence of the amount of dietary fiber on the available energy from hindgut fermentation in growing pigs: use of cannulated pigs and in vitro fermentation[J]. Journal of Animal Science, 2006, 84(10): 2766–2778.

[18] LIN B, GONG J H, WANG Q, et al. In-vitro assessment of the effects of dietary fibers on microbial fermentation and communities from large intestinal digesta of pigs[J]. Food Hydrocolloids, 2011, 25(2): 180–188.

[19] SALVADOR V, CHERBUT C, BARRY J L, et al. Sugar composition of dietary fibre and short-chain fatty acid production during in vitro fermentation by human bacteria[J]. British Journal of Nutrition, 1993, 70(1): 189–197.

[20] BLOEMEN J G, VENEMA K, VAN DE P M. Short chain fatty acids exchange across the gut and liver in humans measured at surgery[J]. Clinical Nutrition, 2009, 28(6): 657-661.

[21] ROY C C, KIEN C L, BOUTHILLIER L, et al. Short-chain fatty acids: ready for prime time?[J]. Nutrition in Clinical Practice, 2006, 21(4): 351–366.

[22] VADDER F, KOVATCHEVA-DATCHARY P, GONCALVES D, et al. Microbiota-generated metabolites promote metabolic benefits via gut-brain neural circuits[J]. Cell, 2014, 156(1/2): 84–96.

[23] PRYDE S E, DUNCAN S H, HOLD G L, et al. The microbiology of butyrate formation in the human colon[J]. FEMS Microbiology Letters, 2002, 217(2): 133–139.

[24] BINGHAM S A. Epidemiology and mechanisms relating diet to risk of colorectal cancer[J]. Nutrition Research Reviews, 1996, 9(1): 197–239.

[25] KOUZARIDES T. Chromatin modifications and their function[J]. Cell, 2007, 128(4): 693–705.

[26] COUSENS L S, GALLWITZ D, ALBERTS B M. Different accessibilities in chromatin to histone acetylase[J]. Journal of Biological Chemistry, 1979, 254(5): 1716–1723.

[27] LIU L M, SONG G Q, FEI G, et al. Transient exposure to sodium butyrate after germinal vesicle breakdown improves meiosis but not developmental competence in pig oocytes[J]. Cell Biology International, 2012, 36(5): 483–490.

[28] TENA-SEMPERE M, HUHTANIEMI I. Gonadotropins and gonadotropin receptors[M]. In: FAUSER B C J M. Reproductive medicine: molecular, cellular and genetic fundamentals. New York: Parthenon Publishing, 2003, 225–244.

[29] GRUMBACH M M. The neuroendocrinology of human puberty revisited[J]. Hormone Research, 2002, 57 Suppl 2: 2–14.

[30] PLANT T M, BARKER-GIBB M L. Neurobiological mechanisms of puberty in higher primates[J]. Human Reproduction Update, 2004, 10(1): 67–77.

[31] PLANT T M. The role of Kiss-1 in the regulation of puberty in higher primates[J]. European Journal of Endocrinology, 2006, 155 Suppl 1: S11-S16.

[32] TENA-SEMPERE M. GPR54 and kisspeptin in reproduction[J]. Human Reproduction Update, 2006, 12(5): 631-639.

[33] GOTTSCH M L, CLIFTON D K, STEINER R A. Kisspepeptin-GPR54 signaling in the neuroendocrine reproductive axis[J]. Molecular and Cellular Endocrinology, 2006, 254-255: 91-96.

[34] SMITH J T, POPA S M, CLIFTON D K, et al. Kiss1 neurons in the forebrain as central processors for generating the preovulatory luteinizing hormone surge[J]. Journal of Neuroscience, 2006, 26(25): 6687-6694.

[35] EASTWOOD M A. The physiological effect of dietary fiber: an update[J]. Annual Review of Nutrition, 1992, 12(1): 19-35.

[36] ARTS C J M, GOVERS C A R L, VAN DER BERG H, et al. In vitro binding of estrogens by dietary fiber and the in vivo apparent digestibility tested in pigs[J]. The Journal of Steroid Biochemistry and Molecular Biology, 1991, 38(5): 621-628.

[37] DE LEEUW J A, JONGBLOED A W, SPOOLDER H A M, et al. Effects of hindgut fermentation of non-starch polysaccharides on the stability of blood glucose and insulin levels and physical activity in empty sows[J]. Livestock Production Science, 2005, 96(2/3): 165-174.

[38] QUESNEL H, MEUNIER-SALAÜN M C, HAMARD A, et al. Dietary fiber for pregnant sows: influence on sow physiology and performance during lactation[J]. Journal of Animal Science, 2008, 87(2): 532-543.

[39] AMBROSZKIEWICZ J, LASKOWSKA-KLITA T, KLEMARCZYK W. Low serum leptin concentration in vegetarian prepubertal children[J]. Roczniki Akademii Medycznej W Bialymstoku, 2004, 49: 103-105.

[40] KNUDSEN K E, JENSEN B B, HANSEN I. Digestion of polysaccharides and other major components in the small and large intestine of pigs fed on diets consisting of oat fractions rich in -D-glucan[J]. British Journal of Nutrition, 1993, 70(2): 537-556.

[41] JOHANSEN H N, KNUDSEN K E B. Effects of reducing the starch content in oat-based diets with cellulose on jejunal flow and absorption of glucose over an isolated loop of jejunum in pigs[J]. British Journal of Nutrition, 1994, 72(5): 717-729.

[42] LIU Changzhong, HE Ruiguo, MAO Zonglin, et al. Effects of dietary crude fiber level on production performance, metabolic hormones and biochemical indices in geese[J]. Chinese Journal of Veterinary Science, 2007, 27(6): 914-918.

[43] KIM S P, CATALANO K J, HSU I R, et al. Nocturnal free fatty acids are uniquely elevated in the longitudinal development of diet-induced insulin resis-

tance and hyperinsulinemia[J]. American Journal of Physiology Endocrinology & Metabolism, 2007, 292(6): E1590-E1598.

[44] TARINI J, WOLEVER T M S. The fermentable fiber inulin increases postprandial serum short-chain fatty acids and reduces free-fatty acids and ghrelin in healthy subjects[J]. Applied Physiology, Nutrition, and Metabolism, 2010, 35(1): 9-16.

[45] FERNANDES J, VOGT J, WOLEVER T M S. Intravenous acetate elicits a greater free fatty acid rebound in normal than hyperinsulinaemic humans[J]. European Journal of Clinical Nutrition, 2012, 66(9): 1029-1234.

[46] DE LEEUW J A, JONGBLOED A W, VERSTEGEN M W A. Dietary fiber stabilizes blood glucose and insulin levels and reduces physical activity in sows (Sus scrofa)[J]. Journal of Nutrition, 2004, 134(6): 1481-1486.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.