Effects of Zearalenone on Swine Production and Study on Its Toxic Adsorption Postprint

Authors: Chen Jifa, Qu Xiangyong, Peng Canyang, Peng Yudong

Date: 2017-10-10T00:00:00+00:00

Abstract

Zearalenone exhibits high toxicity and is commonly present in staple feed ingredients. In practice, mycotoxin adsorbents are routinely employed to mitigate the toxic effects of zearalenone on animals, with demonstrated efficacy. This review comprehensively examines the impacts of zearalenone on porcine reproductive function, immune function, and piglet growth performance, elucidates the underlying mechanisms, and discusses recent advances in adsorption-based detoxification of zearalenone.

Full Text

Review on the Effects of Zearalenone on Swine Production and Its Toxicity Adsorption

CHEN Jifa, QU Xiangyong*, PENG Canyang, PENG Yudong
College of Animal Science and Technology, Hunan Agricultural University, Changsha 410128, China

Abstract: Zearalenone (ZEN) is highly toxic and commonly found in main feed ingredients. Mycotoxin adsorbents are routinely used in production to reduce the toxic effects of zearalenone on animals, achieving certain results. This review summarizes the effects of zearalenone on reproductive function, immune function, and growth performance of piglets in swine production, along with the underlying mechanisms. It also describes research progress on the removal of zearalenone toxicity through adsorption methods.

Keywords: zearalenone; mechanism; adsorbent; swine

A 2002 survey by the Food and Agriculture Organization (FAO) indicated that approximately one-quarter of global grain supplies are contaminated with mycotoxins to varying degrees, with zearalenone (ZEN) contamination being particu-

larly severe [1]. ZEN was first isolated from corn infected with gibberella ear rot [2] and is a secondary metabolite primarily produced by *Fusarium graminearum*. It exhibits strong toxicity and has multiple derivatives including zearalenol, 7-dehydrozearalenone, and 8-hydroxyzearalenone [3]. ZEN is widely present in grains, food products, and compound feeds. Livestock poisoned by ZEN show reduced appetite, growth retardation, and immunosuppression; chronic exposure damages reproductive function in females and causes "feminization" in males; acute poisoning can harm the nervous system and vital organs such as the heart and liver [4-5]. Crops become contaminated with *Fusarium graminearum* during growth, and improper temperature and humidity control during storage can lead to extensive proliferation of the fungus and increased toxin production. This makes it extremely difficult to prevent contamination of grains and feeds during storage, representing a major global challenge in controlling ZEN pollution in food and animal feed.

Traditional detoxification methods for ZEN include physical approaches such as high-temperature treatment and irradiation, and chemical methods such as alkaline treatment and ammoniation. However, these methods suffer from significant nutrient loss, unstable efficacy, and difficulty in large-scale application. Many researchers have attempted microbial degradation of mycotoxins in feed, but practical applications remain limited due to issues including unstable degradation, easy degradation of the microorganisms themselves, long reaction times, and narrow spectra of degradable mycotoxins. Currently, the primary measure to address mycotoxin contamination in feed is the addition of mycotoxin adsorbents. Foreign reports indicate that ZEN poses the greatest threat to swine and has become the second most damaging factor in pig production. However, systematic reviews on the effects of ZEN on swine production performance remain scarce. Therefore, to facilitate comprehensive understanding of ZEN' s hazards to pig production, this article examines its impacts on reproductive function, growth performance, and immune function in swine, along with the underlying mechanisms. Additionally, it discusses the detoxification efficacy of several common mycotoxin adsorbents against ZEN, identifies current limitations in adsorbent application, and offers recommendations and prospects for future development to help livestock producers effectively address mycotoxin contamination.

1. Effects of Zearalenone on Swine Production Performance and Its Mechanism

China' s *Feed Hygiene Standard* requires that ZEN content in feed and feed ingredients not exceed 500 g/kg. Foreign reports indicate that swine are most sensitive to ZEN, with clinical symptoms appearing when dietary ZEN reaches 1–5 mg/kg [6]. Studies have shown that 1–10 nmol/L ZEN can activate estrogen receptors and trigger transcription, leading to reduced feed intake, slow growth, immunosuppression, and reproductive disorders in livestock, causing substantial economic losses to pig farms [7].

1.1. Effects on Reproductive Function

ZEN' s structure closely resembles endogenous estrogen, allowing it to competitively bind estrogen receptors, activate estrogen response elements, cause receptor dimerization, and trigger a series of estrogen-mimicking effects that disrupt reproductive hormones and ultimately damage the reproductive system [8]. Sows develop "estrogenic syndrome" following ZEN poisoning, which represents the primary impact on reproductive performance. Numerous studies have shown that sows consuming ZEN-contaminated diets exhibit vulvar redness and swelling, ovarian atrophy, prolonged estrus intervals, false estrus, abortion, infertility, and stillbirth [9-10]. Due to its estrogenic effects, ZEN inhibits secretion and release of follicle-stimulating hormone, thereby suppressing early follicle maturation and causing sows to show continuous estrus without normal ovulation [11]. ZEN-induced stillbirth may result from altered uterine morphology that disrupts the environment for fetal development, as ZEN can also cross the placenta directly and affect fetal growth [12].

Obremski et al. [13] fed sows 0.2 and 0.4 mg ZEN per kg body weight for 7 consecutive days, observing follicular atresia and granulosa cell apoptosis. High ZEN concentrations inhibit granulosa cell proliferation, induce loss of mitochondrial membrane potential, and increase reactive oxygen species levels, thereby increasing the likelihood of granulosa cell apoptosis and necrosis [14]. ZEN and α-zearalenol (α-ZOL) reduce maturation rates of oocytes at metaphase during in vitro culture while abnormally increasing chromatin numbers; higher ZEN doses significantly decrease oocyte maturation rates [15]. Hydroxysteroid dehydrogenases (HSD) play important roles in estrogen and testosterone synthesis. ZEN serves as a substrate for 3α-HSD and 3β-HSD, which participate in gonadal steroid hormone biotransformation and synthesis of cytochrome P450 proteins and HSD. ZEN can accumulate active components and inhibit reduction of 3α-HSD, an important factor in follicle development, while also interfering with HSD through estrogen receptor action to affect reproductive function [16].

Gajecka et al. [17] fed 2-month-old gilts diets containing 20 and 40 g/kg ZEN for 48 consecutive days. The low-dose group showed endometrial congestion, uterine gland atrophy, and uterine wall hyperplasia, while the high-dose group exhibited hyaline degeneration of endometrial connective tissue and transparent degeneration and necrosis of uterine wall muscle cells. The mechanism of ZEN' s uterine effects may involve high affinity of α-ZOL for estrogen receptors in the sow endometrium, competing with estrogen for target tissue receptors and promoting synthesis of uterine DNA, RNA, and proteins, thereby inducing estrogen hyperactivity [18]. Additionally, ZEN can alter meiotic spindle formation, leading to insufficient nourishment of oocytes and polyploid embryos, which affects normal uterine physiological function.

ZEN also harms reproductive function in boars. Studies show that continuous consumption of ZEN-contaminated diets causes "feminization" symptoms including enlarged nipples, increased mammary tissue, preputial edema, and

testicular atrophy [19-20]. Minervini et al. [21] demonstrated that feeding boars a diet containing 9 mg/kg ZEN caused testicular atrophy and significantly reduced semen density. After 32 days of ZEN-contaminated diet, boars showed a 40.8% reduction in ejaculate volume, with significantly decreased sperm numbers and semen quality within one week post-treatment [22]. Sambuu et al. [23] reported that feeding weaned boars a diet containing 1 mg/kg ZEN significantly reduced reproductive organ indices. The mechanism by which ZEN and its metabolites reduce spermatogenesis may involve significant inhibition of chorionic gonadotropin-induced testosterone secretion. ZEN and α-ZOL decrease testosterone synthesis by downregulating 3β-HSD-1 and cytochrome P450scc and inhibiting transcription of steroidogenic regulatory proteins, thereby affecting spermatogenesis [16]. Additionally, ZEN and α-ZOL reduce boar sperm binding capacity to the zona pellucida and damage sperm chromatin integrity, adversely affecting fertilization capacity and embryonic development [24]. Furthermore, ZEN is closely associated with boar fertility-related sperm parameters, as α-ZOL can reduce the percentage of motile sperm and decrease fertilization rates [25].

1.2. Effects on Piglet Growth Performance

ZEN affects the development of internal organs in piglets. Dietary supplementation with 1–3 mg/kg ZEN significantly increased liver, kidney, and spleen weights ($P<0.05$) while showing no significant effects on digestive tract, heart, and lung development ($P>0.05$) [26]. Research conclusions on ZEN' s effects on piglet feed intake and daily weight gain remain inconsistent. Šperanda et al. [27] fed weaned piglets a diet containing 3 mg/kg ZEN and observed no significant changes in average daily feed intake, average daily gain, or feed conversion ratio. Zhao et al. [26] fed piglets 1, 2, and 3 mg ZEN per kg body weight and found no significant changes in average daily gain or feed-to-gain ratio ($P>0.05$). Powell-Jones et al. [28] analyzed ZEN' s chemical structure and suggested its potential growth-promoting effects. Zearalanol, formed through catalytic hydrogenation of ZEN, has been commercialized as a growth promoter in ruminant production as a hormone-like compound. Additionally, ZEN and its metabolites exhibit anabolic activity in primates, rodents, and swine [29]. However, Swamy et al. [30] fed weaned piglets naturally ZEN-contaminated diets and observed significantly reduced feed intake and daily gain. Comprehensive analysis suggests that naturally contaminated diets may contain multiple mycotoxins, and the growth performance decline may result from other toxins or interactions between ZEN and other toxins. Furthermore, ZEN must accumulate to certain levels before exerting toxic effects that reduce feed efficiency, so good growth performance may be observed initially. Therefore, the effects of ZEN on piglet feed intake and daily weight gain require further investigation.

1.3. Effects on Immune Function

Studies show that ZEN and its derivatives affect important innate immune parameters including interleukin-8 and neutrophils in swine, significantly reducing serum levels of immunoglobulin A (IgA), immunoglobulin M (IgM), and immunoglobulin G (IgG) [31]. Jiang [32] added 1.0 mg/kg ZEN to weaned piglet diets and found that serum IgG, hemoglobin content, and classical swine fever antibody levels at 21 days were significantly lower than in the control group ($P<0.05$). In contrast, Zhao et al. [26] fed piglets diets containing 1, 2, and 3 mg/kg ZEN for 18 days and observed significantly increased serum IgM and IgG content ($P<0.05$), increased white blood cell counts ($P<0.05$), and significantly elevated lymphocyte proportions ($P<0.05$). ZEN inhibits phytohemagglutinin-stimulated proliferation of human peripheral blood lymphocytes and suppresses lymphocyte B and T cell formation stimulated by concanavalin A and pokeweed mitogen [7]. Vlata et al. [29] also found that high ZEN concentrations inhibit proliferation of lymphocyte T and B cells by stimulating phytohemagglutinin and mitogens.

Jiang [32] demonstrated that feeding piglets a diet containing 2.0 mg/kg ZEN altered spleen tissue structure and significantly reduced spleen organ index ($P<0.05$), while Zhao et al. [26] found that feeding piglets diets with 1–3 mg/kg ZEN for 18 days significantly increased thymus and spleen indices ($P<0.05$). These inconsistent results suggest that ZEN' s effects on immune function require time to manifest, and experimental duration may be a factor influencing different conclusions. Additionally, animal resistance, feeding management levels, and environmental conditions may also contribute to these discrepancies.

2. Prevention and Adsorption of ZEN

In recent years, contamination of compound feeds and feed ingredients with mycotoxins has become increasingly severe. Gong et al. [33] measured and analyzed mycotoxin levels in Chinese feed and raw materials in 2014, testing 245 samples from Northeast China, Guangxi, Hunan, and other regions. Results showed ZEN detection rates in feed ingredients approaching 90%, with an excess rate of 3.3% and maximum content reaching 1,920.2 g/kg. In corn and corn by-products, ZEN detection and excess rates were 84.4% and 3.1%, and 100% and 6.8%, respectively, with maximum contents reaching 1,064.7 and 1,920.2 g/kg. Ji et al. [34] collected 612 feed and ingredient samples nationwide in 2014, with overall mycotoxin detection results showing 100% positive rates for both ZEN and deoxynivalenol, with maximum contents reaching 1,778.52 and 4,416.57 g/kg—far exceeding maximum limits (500 g/kg for ZEN and 1,000 g/kg for deoxynivalenol). Both toxins originated from corn protein feed, and ZEN, deoxynivalenol, and aflatoxin commonly coexisted in feed and feed ingredients.

2.1. Prevention of ZEN

Preventing ZEN production must begin with proactive measures starting at the crop growth stage. Providing suitable growing conditions with adequate and good-quality water is essential. Drought conditions reduce crop resistance to mold, increasing infection probability. Inoculating crops with non-toxigenic ZEN strains during growth creates competitive inhibition with toxigenic strains, reducing crop infection rates. Pitt et al. [35] inoculated non-toxigenic *Aspergillus flavus* strains in fields and reduced aflatoxin infection rates by over 95%; however, few studies have reported applications of non-toxigenic ZEN strain inoculation, representing a promising research direction.

The optimal temperature for mold proliferation is 20–30°C with relative humidity of 80%–90%, and mold readily reproduces when feed moisture content reaches 17%–18%. ZEN is commonly detected in high-moisture corn (22%–25% moisture), caked feed, and moldy hay [36]. Therefore, strict quality control during raw material storage is essential, including controlling moisture content, maintaining ventilated and dry warehouses, regularly inspecting and turning feed ingredients, and promptly removing moldy materials. Moisture and temperature must also be strictly controlled during transportation and processing to prevent mold caused by rain, humidity, and high temperatures. Biological preservatives may be added when necessary [37], and proper processing methods and strict adherence to technological procedures are crucial.

2.2. Adsorption of ZEN by Mycotoxin Adsorbents

The adsorption mechanism primarily involves electrostatic attraction and intermolecular forces. Effective adsorbents can bind mycotoxins before intestinal absorption, forming inactive complexes that remain tightly bound throughout the gastrointestinal tract, substantially reducing their bioavailability. Common adsorbents include activated carbon, clay-based adsorbents, yeast cell extracts, and composite mycotoxin adsorbents (such as processed aluminum silicates and yeast cell wall extracts).

Activated carbon is rarely used in production due to severe blackening of feed and increased costs. Clay-based adsorbents, primarily silicates or aluminosilicates (including bentonite, zeolite, montmorillonite, phyllosilicates, and hydrated sodium aluminosilicate), are natural adsorbents with numerous inorganic porous materials surrounding their silicate tetrahedra. Each silicon ion is surrounded by four oxygen ions, forming sheet-like structures that attract mycotoxins through charge and adsorb them within porous structures, achieving detoxification. Avantaggiato et al. [38] established a gastrointestinal model to simulate ZEN absorption in the small intestine, adding 2% adsorbent (cholestyramine and activated carbon) to simulate actual ZEN utilization. Before adsorbent addition, approximately 32% of ZEN was absorbed by the small intestine, which decreased to 16% (cholestyramine) and 5% (activated carbon) after addition, substantially reducing absorption. Afriyie-Gyawu et al. [39] demonstrated that

adding hectorite and montmorillonite clay to moldy feed effectively reduced ZEN content. Wang et al. [40] added 0.5% montmorillonite to dairy cow diets and observed significant improvements in average daily feed intake, milk yield, and 4% fat-corrected milk yield. However, clay-based adsorbents require high addition rates, can only adsorb limited mycotoxin types, are non-degradable, and pose environmental hazards when excreted in feces.

Yeast cell extracts—yeast cell walls—are porous carbohydrates whose active component is glucomannan (GM) from the inner cell wall. GM is a high-molecular-weight polysaccharide that adsorbs mycotoxins through ionic bonds, hydrogen bonds, and hydrophobic interactions across pH 3–8, causing minimal damage to digestive nutrients. It functions effectively in the pH environment of most livestock gastrointestinal tracts and requires low addition rates. Zhang et al. [41] used brewer' s yeast β-D-glucan to adsorb ZEN, finding maximum adsorption of 2.29 g/mg toxin. Xu et al. [42] synthesized cross-linked carboxymethyl composite modified glucan from yeast glucan, demonstrating maximum ZEN adsorption of 18.64 g/mg—superior to yeast glucan alone.

Esterified glucomannan (EGM) is formed through GM esterification. As a natural mycotoxin adsorbent with numerous surface pores and large surface area, EGM shows good ZEN adsorption capacity. Adding 0.05% EGM to broiler diets adsorbed ZEN and improved feed intake, average daily gain, and feed conversion ratio ($P>0.05$) [43]. Chang et al. [44] found that 0.20% EGM addition effectively adsorbed ZEN in moldy feed, significantly improving piglet performance while reducing blood toxin residues, alleviating oxidative damage, and increasing peripheral blood lymphocyte transformation rate and classical swine fever antibody levels ($P>0.05$). Qi et al. [45] added three EGM concentrations (0.05%, 0.10%, and 0.15%) to culture medium containing 5 g/mL ZEN, significantly mitigating ZEN-induced reductions in peripheral blood lymphocyte transformation rate, increased malondialdehyde (MDA) content, and decreased superoxide dismutase (SOD) activity.

Composite mycotoxin adsorbents are increasingly used to adsorb mycotoxins in feed, combining characteristics of multiple single adsorbents with broad adaptability and capacity to adsorb various mycotoxins [46]. Wang [47] added hydrated aluminosilicate, EGM, and composite mycotoxin adsorbents to moldy feed, showing all could reduce ZEN toxicity to some degree, with the composite adsorbent showing the best effect. Zhang et al. [48] used a self-developed composite mycotoxin adsorbent (mainly composed of bentonite, yeast cell wall, and EGM) to study its protective effects on broilers, finding it significantly reversed mycotoxin-induced oxidative damage and immunotoxicity while improving vaccine efficacy.

ZEN is highly toxic, severely affecting swine reproductive function while reducing piglet growth performance and immune function, making it the second most damaging factor in pig production. Mycotoxin adsorbents are commonly used to reduce ZEN toxicity, with numerous studies confirming their effectiveness. However, single adsorbents may have limited efficacy, and research on composite my-

cotoxin adsorbents remains relatively limited. In practice, different adsorbents can be mixed at specific ratios, with optimal combinations screened through in vitro adsorption tests and validated through in vivo experiments. Different composite adsorbents show varying efficacy, requiring specific selection based on mycotoxin types in practical applications. Additionally, long-term consumption of feed with adsorbents may affect absorption and utilization of essential nutrients, necessitating further investigation into safe limits and usage standards for mycotoxin adsorbents in feed. To minimize losses of original feed components and maximize nutrient utilization, acidifiers, enzymes, or probiotics could be added alongside adsorbents to explore interactive effects and improve economic benefits for livestock enterprises while promoting healthy, rapid development of China' s animal husbandry industry.

References

[1] Ji Cheng. Mycotoxins and Feed Food Safety[M]. Beijing: Chemical Industry Press, 2007.
[2] DESJARDINS E. *Fusarium*, mycotoxins: chemistry, genetics, and biology[M]. St. Paul, MN, USA: American Phytopathological Society, 2006: 1-260.
[3] Guan Shu. Infection Patterns of *Fusarium*, Formation and Regulation Mechanisms of Trichothecene Mycotoxins[J]. Feed Industry, 2011, 32(6): 44-48.
[4] Feng Yanzhong, Shen Wei, Wang Zhaoshan, et al. Research Progress on Mycotoxins[J]. Feed Industry, 2014, 35(4): 58-62.
[5] Chen Guangming, Liu Jianjun, Liu Guilan, et al. Research Progress on Mycotoxins[J]. Animal Husbandry and Feed Science, 2014, 35(12): 122-124.
[6] FITZPATRICK D W, PICKEN C A, MURPHY L C, et al. Measurement of the relative binding affinity of zearalenone, α-zearalenol and β-zearalenol for uterine and oviduct estrogen receptors in swine, rats and chickens: an indicator of estrogenic potencies[J]. Comparative Biochemistry and Physiology Part C: Comparative Pharmacology, 1989, 94(2): 691-694.
[7] Deng Youtian, Yuan Hui. Research Progress on Zearalenone Toxicity Mechanism[J]. Progress in Veterinary Medicine, 2007, 28(2): 89-92.
[8] He Xuejun, Qi Desheng. Research Progress on Zearalenone Toxicity[J]. China Feed, 2006(10): 2-5.
[9] Xiao Zhijun. Zearalenone Poisoning and Reproductive Disorders in Pigs[J]. China Animal Husbandry and Veterinary Medicine, 2005, 32(2): 45-46.
[10] Zhang Dinghua, Wang Yanfeng. Effects of *Fusarium* and Zearalenone on Livestock Reproductive Performance and Prevention[J]. Liaoning Animal Husbandry and Veterinary Medicine, 2004(7): 11-12.
[11] MINERVINI F, DELL' AQUILA M E. Zearalenone and reproductive function in farm animals[J]. International Journal of Molecular Sciences, 2008, 9(12): 2570-2584.
[12] SCHOEVERS E J, SANTOS R R, COLENBRANDER B, et al. Transgenerational toxicity of zearalenone in pigs[J]. Reproductive Toxicology, 2012, 34(1): 110-119.

[13] OBREMSKI K, GAJECKI M, ZWIERZCHOWSKI W, et al. The level of zearalenone and alpha-zearalenol in the blood of gilts with clinical symptoms of toxicosis, fed diets with a low zearalenone content[J]. Journal of Animal and Feed Sciences, 2003, 12(3): 529–538.
[14] ZHU L, YUAN H, GUO C Z, et al. Zearalenone induces apoptosis and necrosis in porcine granulosa cells via caspase-3- and caspase-9-dependent mitochondrial signaling pathway[J]. Journal of Cellular Physiology, 2012, 227(5): 1814–1820.
[15] TAKAGI M, MUKAI S, KURIYAGAWA T, et al. Detection of zearalenone and its metabolites in naturally contaminated follicular fluids by using LC/MS/MS and in vitro effects of zearalenone on oocyte maturation in cattle[J]. Reproductive Toxicology, 2008, 26(2): 164–169.
[16] YANG J Y, ZHANG Y F, WANG Y Q, et al. Toxic effects of zearalenone and alpha-zearalenol on regulation of steroidogenesis and testosterone production in mouse Leydig cells[J]. Toxicology in Vitro, 2007, 21(4): 558–565.
[17] GAJECKA M, RYBARCZYK L, JAKIMIUK E, et al. The effect of experimental long-term exposure to low-dose zearalenone on uterine histology in sexually immature gilts[J]. Experimental and Toxicologic Pathology, 2012, 64(6): 537–542.
[18] ALM H, GREISING T, BRÜSSOW K P, et al. The influence of the mycotoxins deoxynivalenol and zearalenol on in vitro maturation of pig oocytes and in vitro culture of pig zygotes[J]. Toxicology in Vitro, 2002, 16(6): 643–648.
[19] Shan Mei, Xu Zirong, Feng Jianlei. Effects of Zearalenone on Livestock Reproductive Performance and Human Health[J]. China Animal Health, 2005(7): 37–39.
[20] YANG J Y, WANG G X, LIU J L, et al. Toxic effects of zearalenone and its derivatives alpha-zearalenol on reproductive system in mice[J]. Reproductive Toxicology, 2007, 24(3/4): 381–287.
[21] MINERVINI F, DELL' AQUILA M E, MARITATO F, et al. Toxic effects of the mycotoxin zearalenone and its derivatives on in vitro maturation of bovine oocytes and 17β-estradiol levels in mural granulosa cell cultures[J]. Toxicology in Vitro, 2001, 15(4/5): 489–495.
[22] Kan Ning. Methods for Preventing Mold and Detoxifying Feed[J]. Sichuan Animal Husbandry and Veterinary Medicine, 2003, 30(7): 43.
[23] SAMBUU R, TAKAGI M, NAMULA Z, et al. Effects of exposure to zearalenone on porcine oocytes and sperm during maturation and fertilization in vitro[J]. Journal of Reproduction and Development, 2011, 57(4): 547–550.
[24] D' OCCHIO M J, HENGSTBERGER K J, JOHNSTON S D. Biology of sperm chromatin structure and relationship to male fertility and embryonic survival[J]. Animal Reproduction Science, 2007, 101(1/2): 1–17.
[25] TSAKMAKIDIS I A, LYMBEROPOULOS A G, KHALIFA T A A, et al. Evaluation of zearalenone and α-zearalenol toxicity on boar sperm DNA integrity[J]. Journal of Applied Toxicology, 2008, 28(5): 681–688.
[26] Zhao Hu, Yang Zaibin, Yang Weiren, et al. Study on Effects of Zearalenone on Piglet Performance and Visceral Organ Development[J]. Cereal and Feed

Industry, 2008(10): 37-38.
[27] ŠPERANDA M, LIKER B, ŠPERANDA T, et al. Haematological and biochemical parameters of weaned piglets fed on fodder mixture contaminated by zearalenone with addition of clinoptilolite[J]. Acta Veterinaria (Beograd), 2006, 56(2/3): 121-136.
[28] POWELL-JONES W, RAEFORD S, LUCIER G W. Binding properties of zearalenone mycotoxins to hepatic estrogen receptors[J]. Molecular Pharmacology, 1981, 20(1): 35-42.
[29] VLATA Z, PORICHIS F, TZANAKAKIS G, et al. A study of zearalenone cytotoxicity on human peripheral blood mononuclear cells[J]. Toxicology Letters, 2006, 165(3): 274-281.
[30] SWAMY H V L N, SMITH T K, MACDONALD E J, et al. Effects of feeding a blend of grains naturally contaminated with *Fusarium* mycotoxins on swine performance, brain regional neurochemistry, and serum chemistry, and the efficacy of a polymeric glucomannan mycotoxin adsorbent[J]. Journal of Animal Science, 2002, 80(12): 3257-3267.
[31] MARIN D E, TARANU I, BURLACU R, et al. Effects of zearalenone and its derivatives on porcine immune response[J]. Toxicology in Vitro, 2011, 25(8): 1981-1988.
[32] Jiang Shuzhen. Preliminary Study on Toxicity of Zearalenone to Weaned Piglets and Detoxification Effects of Modified Montmorillonite[D]. Doctoral Dissertation. Tai' an: Shandong Agricultural University, 2010.
[33] Gong Aqiong, Luo Jinling, Hu Junpeng. Determination and Analysis of Mycotoxin Content in Chinese Feed Raw Materials in 2014[J]. China Feed, 2015(7): 40-41.
[34] Ji Haixia, Su Yongteng. Analysis and Discussion of Feed Mycotoxins in 2014[J]. Swine Production, 2015(1): 17-19.
[35] PITT J I, HOCKING A D. Mycotoxins in Australia: biocontrol of aflatoxin in peanuts[J]. Mycopathologia, 2006, 162(3): 233-243.
[36] Wang Qing, Zhou Danchao, Zhao Yu, et al. Research Progress on Reproductive Toxicity of Zearalenone[J]. Journal of Animal Husbandry and Veterinary Medicine, 2014, 33(4): 32-35.
[37] Da Fulan, Xue Wanchao. Common Mycotoxins in Feed and Prevention[J]. Modern Animal Husbandry Science and Technology, 2015(1): 22-24.
[38] AVANTAGGIATO G, HAVENAAR R, VISCONTI A. Assessing the zearalenone binding activity of adsorbent materials during passage through a dynamic in vitro gastrointestinal model[J]. Food and Chemical Toxicology, 2003, 41(10): 1283-1290.
[39] AFRIYIE-GYAWU E, WILES M C, HUEBNER H J, et al. Prevention of zearalenone-induced hyperestrogenism in prepubertal mice[J]. Journal of Toxicology and Environmental Health, Part A: Current Issues, 2005, 68(5): 353-368.
[40] Wang Liwen, Ding Jian, Zhang Jiangang, et al. Effects of Mycotoxin Adsorbent Montmorillonite on Performance and Serum Biochemical Indices of Lactating Dairy Cows[J]. Chinese Journal of Animal Nutrition, 2013, 25(7): 1595-1602.

[41] Zhang Lixia, Xu Xueming. Study on Adsorption of Toxin Zearalenone (ZEA) by Brewer' s Yeast β-D-Glucan[J]. Food Science, 2006, 27(4): 75–78.
[42] Xu Xueming, Zhang Lixia. Synthesis of Cross-linked Carboxymethyl Composite Modified Glucan and Study on Its Adsorption of Zearalenone (ZEA)[J]. Food Science, 2006, 27(6): 139–143.
[43] ARAVIND K L, PATIL V S, DEVEGOWDA G, et al. Efficacy of esterified glucomannan to counteract mycotoxicosis in naturally contaminated feed on performance and serum biochemical and hematological parameters in broilers[J]. Poultry Science, 2003, 82(4): 571–576.
[44] Chang Shunhua, Zhu Lianqin, Zhu Fenghua, et al. Study on Esterified Glucomannan as Mycotoxin Adsorbent[J]. Feed Research, 2010(5): 48–50.
[45] Qi Juan, Zhu Fenghua, Chen Fu, et al. Protective Effect of EGM Adsorption of ZEN on Chicken Peripheral Blood Lymphocytes[J]. Feed Research, 2012(8): 1–3, 16.
[46] Ji Cheng, Zhao Lihong. Research and Prospects of Aflatoxin Biodegradation[J]. Chinese Journal of Animal Nutrition, 2010, 22(2): 241–245.
[47] Wang Huirong. Study on Detoxification Effects of Three Mycotoxin Adsorbents on Broilers with Combined Mycotoxicosis[D]. Master' s Thesis. Wuhan: Wuhan Polytechnic University, 2008.
[48] Zhang Ruixing, Huang Kai, Song Mingming, et al. Effects of Adding Composite Mycotoxin Adsorbent to Moldy Feed on Antioxidant and Immune Functions of Broilers[J]. Feed Industry, 2015, 36(9): 32–35.

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