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

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Abstract

Zearalenone is highly toxic and commonly present in main feedstuffs. In practice, mycotoxin adsorbents are frequently employed to mitigate the toxic effects of zearalenone on animals, achieving certain efficacy. This review summarizes the effects of zearalenone on porcine reproductive function, immune function, and piglet growth performance, along with their underlying mechanisms, and discusses recent advances in the adsorption-based detoxification of zearalenone.

Full Text

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

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Abstract: Zearalenone (ZEN) is a highly toxic mycotoxin commonly found in animal feed. Mycotoxin adsorbents are routinely used in production to mitigate ZEN' s toxic effects on animals, with demonstrated effectiveness. This review synthesizes current research on ZEN' s impacts on swine reproductive function, immune capacity, and piglet growth performance, elucidates the underlying mechanisms, and discusses advances in detoxification through adsorption methods.

Keywords: zearalenone; mechanism; adsorbent; swine

A 2002 survey by the Food and Agriculture Organization (FAO) revealed that approximately 25% of global grain supplies are contaminated with mycotoxins to varying degrees, with zearalenone (ZEN) contamination representing a particularly serious concern [1]. ZEN was first isolated from corn infected with

Gibberella ear rot [2] and is primarily produced as a secondary metabolite by *Fusarium graminearum*. This mycotoxin exhibits strong toxicity and exists in multiple derivatives including zearalenol, 7-dehydrozearalenone, and 8-hydroxyzearalenone [3]. ZEN is widely present in grains, food products, and compound feeds, causing reduced appetite, growth retardation, and immunosuppression in livestock. Chronic exposure compromises reproductive function in female animals, while males exhibit feminization. Acute toxicity can damage the nervous system and vital organs including the heart and liver [4-5]. Crops become contaminated with *F. graminearum* during growth, and improper temperature and humidity control during storage can promote fungal proliferation and increased toxin production, making ZEN contamination difficult to avoid. Consequently, controlling ZEN contamination in grains and animal feed represents a major global challenge.

Traditional ZEN detoxification methods include physical approaches (high temperature, irradiation) and chemical methods (alkaline treatment, ammoniation), which suffer from significant nutrient loss, inconsistent efficacy, and limited scalability. Researchers have also explored microbial degradation of feed mycotoxins, but practical applications remain limited due to issues with degradation instability, strain degeneration, prolonged reaction times, and narrow toxin specificity [6-8]. Currently, the primary strategy for addressing feed mycotoxin contamination involves adding mycotoxin adsorbents. ZEN is reported to pose the greatest threat to swine, becoming the second most damaging factor in pig production [9-10]. However, comprehensive reviews systematically detailing ZEN' s effects on swine production performance remain scarce. To facilitate a thorough understanding of ZEN' s hazards to pig production, this article examines its impacts on reproduction, growth, and immunity, discusses the efficacy of common mycotoxin adsorbents against ZEN, identifies current limitations in adsorbent application, and proposes recommendations for future development to help livestock producers effectively manage mycotoxin contamination.

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

China' s Feed Hygiene Standard stipulates that ZEN content in feed and feed ingredients must not exceed 500 g/kg. International reports indicate that pigs are most sensitive to ZEN, exhibiting clinical symptoms when dietary levels reach 1-5 mg/kg [9]. Research demonstrates that 1-10 nmol/L ZEN can activate estrogen receptors and trigger transcription, leading to reduced feed intake, slow growth, immunosuppression, and reproductive disorders that cause substantial economic losses for pig operations [10].

1.1. Effects on Reproductive Function

ZEN' s structural similarity to endogenous estrogen allows it to competitively bind estrogen receptors, activate estrogen response elements, induce receptor

dimerization, and trigger estrogen-mimetic effects that disrupt reproductive hormones and ultimately damage the porcine reproductive system [11]. The primary manifestation of ZEN toxicity in sows is "estrogenic syndrome." Numerous studies show that sows consuming ZEN-contaminated feed develop vulvar swelling, ovarian atrophy, prolonged estrus intervals, false estrus, abortion, infertility, and stillbirth [12-13]. Due to its estrogenic activity, ZEN inhibits follicle-stimulating hormone secretion and release, thereby suppressing early follicle maturation and causing persistent estrus without normal ovulation [14]. ZEN-induced stillbirth may result from altered uterine morphology that disrupts the fetal development environment, as well as direct transplacental transfer of ZEN to the fetus [15].

Obremski et al. [16] administered 0.2 and 0.4 mg ZEN/kg body weight to sows for 7 consecutive days, observing follicular atresia and granulosa cell apoptosis. High ZEN concentrations inhibit granulosa cell proliferation, induce mitochondrial membrane potential loss, elevate reactive oxygen species levels, and increase apoptosis and necrosis [17]. ZEN and α-zearalenol (α-ZOL) reduce maturation rates of metaphase-stage oocytes in culture while abnormally increasing chromatin numbers, with higher doses markedly decreasing oocyte maturation [18]. Hydroxysteroid dehydrogenases (HSD) play crucial 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 that inhibit 3α-HSD reduction, a key factor in follicular development, and can also interfere with HSD through estrogen receptor signaling, thereby affecting reproductive function [19].

Gajecka et al. [20] fed 2-month-old gilts diets containing 20 and 40 g/kg ZEN for 48 days. Low-dose exposure caused endometrial congestion, glandular atrophy, and uterine wall hyperplasia, while high doses induced hyaline degeneration of uterine connective tissue and transparent degeneration with necrosis of myometrial cells. The mechanism likely involves α-ZOL' s high affinity for uterine estrogen receptors, competing with estrogen for target cell receptors and promoting DNA, RNA, and protein synthesis that triggers estrogen hyperactivity [21]. Additionally, ZEN can alter meiotic spindle formation, causing insufficient nourishment to oocytes and polyploid embryos, thereby impairing normal uterine physiology.

ZEN also compromises boar reproductive function. Studies show that boars continuously fed ZEN-contaminated diets develop feminization symptoms including enlarged nipples, mammary gland hypertrophy, preputial edema, and testicular atrophy [22-23]. Minervini et al. [24] demonstrated that feeding boars 9 mg/kg ZEN caused testicular atrophy and significantly reduced semen density. After 32 days of ZEN exposure, ejaculate volume decreased by 40.8% compared to normal, with sperm counts declining significantly within one week and semen quality deteriorating markedly [25]. Sambuu et al. [26] reported that feeding weaned boars 1 mg/kg ZEN significantly reduced reproductive organ indices. The mech-

anism for reduced spermatogenesis likely involves ZEN and α-ZOL' s significant inhibition of chorionic gonadotropin-induced testosterone secretion, downregulation of 3β-HSD-1 and cytochrome P450scc, and suppression of steroidogenic regulatory protein transcription, thereby decreasing testosterone synthesis [19]. Furthermore, ZEN and α-ZOL impair sperm-zona pellucida binding capacity and damage sperm chromatin integrity, adversely affecting fertilization and embryonic development [27]. ZEN also correlates with boar fertility parameters, as α-ZOL reduces motile sperm percentage and fertilization rates [28].

1.2. Effects on Piglet Growth Performance

ZEN affects visceral organ development in piglets. Dietary supplementation with 1-3 mg/kg ZEN significantly increased liver, kidney, and spleen weights ($P<0.05$) without significantly impacting digestive tract, heart, or lung development ($P>0.05$) [29]. Research findings on ZEN' s effects on feed intake and daily gain remain inconsistent. Šperanda et al. [30] observed no significant changes in average daily feed intake, average daily gain, or feed efficiency in weaned piglets fed 3 mg/kg ZEN. Zhao et al. [26] administered 1, 2, and 3 mg ZEN/kg body weight to piglets without significantly affecting average daily gain or feed-to-gain ratio. Powell-Jones et al. [31] suggested potential growth-promoting properties based on ZEN' s chemical structure. Zearalanol, the hydrogenated derivative of ZEN, has been commercialized as a growth promoter in ruminants, and ZEN and its metabolites exhibit anabolic activity in primates, rodents, and pigs [32]. Conversely, Swamy et al. [33] reported significantly reduced feed intake and daily gain in weaned piglets fed naturally ZEN-contaminated diets. This discrepancy likely arises because naturally contaminated feeds contain multiple mycotoxins, and interactions between ZEN and other toxins may impair growth performance. Additionally, ZEN requires accumulation to toxic levels before adversely affecting feed efficiency, potentially explaining initial growth improvements. Therefore, ZEN' s effects on piglet feed intake and daily gain require further investigation.

1.3. Effects on Immune Function

ZEN and its derivatives affect critical innate immune parameters including interleukin-8 and neutrophils, significantly reducing serum immunoglobulin A (IgA), IgM, and IgG levels [34]. Jiang [35] reported that 1.0 mg/kg ZEN in weaned piglet diets significantly decreased serum IgG, hemoglobin, and CSF antibody levels at 21 days. In contrast, Zhao et al. [29] found that feeding piglets 1-3 mg/kg ZEN for 18 days significantly increased serum IgM and IgG, white blood cell counts, and lymphocyte proportions. ZEN inhibits phytohemagglutinin-stimulated human peripheral blood lymphocyte proliferation and suppresses lymphocyte B and T cell formation induced by concanavalin A and pokeweed mitogen [10]. Vlata et al. [32] also observed that high ZEN concentrations inhibit lymphocyte T and B cell proliferation by stimulating lectins and mitogens.

Jiang [35] demonstrated that 2.0 mg/kg ZEN altered spleen histology and sig-

nificantly reduced spleen organ index, whereas Zhao et al. [29] found that 1-3 mg/kg ZEN significantly increased thymus and spleen indices. These inconsistent results suggest that ZEN' s effects on immune function depend on exposure duration, as trial periods may influence conclusions. Additionally, host resistance, management practices, and environmental conditions contribute to these variations.

2. Prevention and Adsorption of ZEN

Mycotoxin contamination in compound feeds and feed ingredients has intensified in recent years. Gong et al. [36] analyzed 245 feed and ingredient samples from Northeast China, Guangxi, Hunan, and other regions in 2014, finding ZEN detection rates approaching 90% in feed ingredients with 3.3% exceeding standards, reaching maximum levels of 1,920.2 g/kg. In corn and corn byproducts, detection rates were 84.4% and 100.0%, with exceedance rates of 3.1% and 6.8%, and maximum concentrations of 1,064.7 and 1,920.2 g/kg, respectively. Ji et al. [37] collected 612 feed and ingredient samples nationwide in 2014, revealing 100% positive detection rates for both ZEN and deoxynivalenol, with maximum levels of 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 feeds and ingredients.

2.1. Prevention of ZEN

Preventing ZEN production must begin with crop cultivation by providing optimal growth conditions and ensuring adequate, clean water supply. Drought stress reduces crop resistance to fungi, increasing infection risk. Inoculating crops with non-toxigenic ZEN strains during growth creates competitive inhibition against toxigenic strains, reducing infection probability. Pitt et al. [38] demonstrated that field inoculation with non-toxigenic *Aspergillus flavus* strains reduced aflatoxin contamination in peanuts by over 95%, though similar applications for ZEN remain underexplored and warrant future research.

Mold proliferation occurs optimally at 20-30°C with 80-90% relative humidity, and fungi readily multiply when feed moisture reaches 17-18%. ZEN is frequently detected in high-moisture corn (22-25% water content), caked feed, and moldy hay [39]. Therefore, strict quality control during storage is essential: maintain low moisture content, ensure warehouse ventilation and dryness, conduct regular inspections and turning of ingredients, promptly remove moldy materials, and rigorously control moisture and temperature during transport and processing to prevent contamination from rain, humidity, and heat. Biological preservatives may be added when necessary [40], and processing methods must adhere strictly to established protocols.

2.2. Adsorption of ZEN by Mycotoxin Adsorbents

Adsorption mechanisms rely primarily on electrostatic forces and intermolecular interactions to bind mycotoxins into inactive complexes before intestinal absorption, with adsorbents tightly binding toxins within the gastrointestinal tract to reduce bioavailability. Common adsorbents include activated carbon, clay-based adsorbents, yeast cell extracts, and composite mycotoxin adsorbents (e.g., processed aluminum silicates and yeast cell wall extracts). Activated carbon is rarely used commercially due to feed discoloration and cost concerns.

Clay structures consist primarily of silicates or aluminosilicates (bentonite, zeolite, montmorillonite, phyllosilicates, and hydrated sodium aluminosilicates). These natural adsorbents contain abundant inorganic porous materials within their silicate tetrahedral structures, where each silicon ion is surrounded by four oxygen ions forming sheet-like structures that attract and adsorb mycotoxins through charge interactions. Avantaggiato et al. [41] simulated ZEN absorption in the small intestine using a gastrointestinal model, finding that 2% adsorbent addition (cholestyramine and activated carbon) reduced ZEN bioavailability from approximately 32% to 16% and 5%, respectively. AFRIYIE-GYAWU et al. [42] demonstrated that hectorite and montmorillonite clays effectively reduced ZEN levels in moldy feed, while Wang et al. [43] reported improved feed intake, milk yield, and standardized milk production in dairy cows fed 0.5% montmorillonite. However, clay adsorbents require high inclusion rates, bind only limited mycotoxin types, and pose environmental risks through non-degradable fecal excretion.

Yeast cell extracts, specifically yeast cell walls, are porous carbohydrates whose active component is inner-wall glucomannan (GM). This high-molecular-weight polysaccharide adsorbs mycotoxins through ionic bonds, hydrogen bonds, and hydrophobic interactions across pH 3-8, causing minimal nutrient destruction in the digestive tract. GM functions effectively in the gastrointestinal pH of most livestock and requires low inclusion rates. Zhang et al. [44] reported that brewer' s yeast β-D-glucan could adsorb up to 2.29 g ZEN/mg, while Xu et al. [45] synthesized cross-linked carboxymethyl modified glucan with enhanced adsorption capacity reaching 18.64 g ZEN/mg.

Esterified glucomannan (EGM), formed through GM esterification, is a natural adsorbent with high surface area and numerous micropores that effectively binds ZEN. Broiler diets supplemented with 0.05% EGM improved feed intake, average daily gain, and feed efficiency while adsorbing ZEN [46]. Chang et al. [47] found that 0.20% EGM addition effectively adsorbed ZEN in moldy feed, enhanced piglet performance, reduced blood toxin residues, alleviated oxidative damage, and improved peripheral blood lymphocyte transformation rates and CSF antibody levels. Qi et al. [48] added three EGM concentrations (0.05%, 0.10%, and 0.15%) to culture media containing 5 g/mL ZEN, observing significant improvements in ZEN-induced reductions of lymphocyte transformation rates, increased malondialdehyde (MDA) content, and decreased superoxide dis-

mutase (SOD) activity.

Composite mycotoxin adsorbents are increasingly used for their broad-spectrum capabilities, combining multiple single adsorbent properties to bind various mycotoxins effectively [49]. Wang [50] compared hydrated aluminosilicates, EGM, and composite adsorbents in moldy feed, finding all reduced ZEN toxicity with composite adsorbents showing superior efficacy. Zhang et al. [51] demonstrated that a self-developed composite adsorbent (containing bentonite, yeast cell wall, and EGM) reversed mycotoxin-induced oxidative damage and immunotoxicity while improving vaccine efficacy in broilers.

ZEN' s potent toxicity severely impairs swine reproductive function, reduces piglet growth performance, and compromises immune capacity, establishing it as the second most damaging factor in pig production. Mycotoxin adsorbents effectively mitigate ZEN toxicity, as confirmed by numerous studies. However, single adsorbents may provide insufficient protection, and research on composite adsorbents remains limited. Production applications should combine different adsorbents at optimal ratios identified through in vitro screening and validated through in vivo trials. Composite adsorbents exhibit varying efficacy, requiring specific selection based on mycotoxin profiles. Long-term feeding of adsorbent-supplemented diets may affect essential nutrient absorption and utilization, necessitating investigation of safe inclusion levels and usage standards. Future research should explore interactions between adsorbents and feed additives such as acidifiers, enzymes, or probiotics to minimize nutrient loss and maximize feed utilization, thereby improving economic returns and promoting healthy, rapid development of China' s livestock industry.

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