Literature review

rccp Revista Colombiana de Ciencias Pecuarias

Aflatoxin, deoxynivalenol, and zearalenone in swine diets: Predictions on growth performance¤

Aflatoxina, deoxynivalenol y zearalenona: predicciones sobre su impacto en el crecimiento de los cerdos

Aflatoxina, deoxinivalenol e zearalenona em dietas de porcos: predições de desempenho no crescimento

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(Received: March 11, 2013; accepted: October 21, 2013)

Summary

Dietary mycotoxins have been shown to cause detrimental effects in swine health and production. The objective of this study was to develop tools for predicting the effects of aflatoxin (AFL), deoxynivalenol (DON) and zearalenone (ZON) on feed intake (FI) and weight gain (WG) changes using a meta-analysis approach. A total of 80 and 63 observations were extracted from 18 experiments testing the effects of AFL on FI and WG, respectively, and the differences of AFL concentrations between the control and treatment groups ranged from 0.02 to 2.5 mg/kg. A total of 117 and 113 observations from 20 experiments were used for testing the effects of DON on FI and WG, respectively. The differences of DON concentrations between the control and treatment groups ranged from 0.5 to 10.5 mg/kg. A total of 16 and 17 observations from 18 experiments were used for testing the effects of ZON on FI and WG, respectively, and the differences of ZON concentrations between the control and treatment groups ranged from 0.2 to 9.0 mg/kg. Effects of experiment, initial body weight, and experimental period were not significant for developing prediction equations for the changes of FI and WG. The models developed for predicting FI and WG changes (ΔFI and ΔWG) as % by AFL concentrations as mg/kg were: $\Delta FI = -24.9 \times AFL - 1.7$ with $r^2 = 0.70$ and $p<0.001$; $\Delta FI = 0.4 - 51.6 \times (1 - e^{-0.947 \times AFL})$ with $r^2 = 0.79$ and $p<0.001$; $\Delta WG = -22.7 \times AFL - 4.0$ with $r^2 = 0.62$ and $p<0.001$; and $\Delta WG = -1.4 - 50.3 \times (1 - e^{-0.976 \times AFL})$ with $r^2 = 0.69$ and $p<0.001$. The equations for predicting ΔFI and ΔWG as % by DON concentrations as mg/kg were: $\Delta FI = -5.64 \times DON - 0.13$ with $r^2 = 0.60$ and $p<0.001$; and $\Delta WG = -6.49 \times DON + 0.93$ with $r^2 = 0.61$ and $p<0.001$. The feed consumption and growth rate of pigs decrease linearly and exponentially by the concentrations of AFL and linearly by the concentrations of DON. The equations provided herein may predict the effects of AFL and DON on swine production performance.

Key words: *feed intake, meta-analysis, mycotoxin, pig, weight gain.*

¤ To cite this article: Mok CH, Shin SY, Kim BG. Aflatoxin, deoxynivalenol, and zearalenone in swine diets: Predictions on growth performance. Rev Colomb Cienc Pecu 2013; 26:243-254.

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Resumen

Las micotoxinas presentes en los alimentos tienen efectos perjudiciales en la salud y la producción porcina. El objetivo de este estudio fue desarrollar herramientas para predecir los efectos de aflatoxinas (AFL), deoxinivalenol (DON) y zearalenona (ZON) sobre el consumo de alimento (FI) y ganancia de peso (WG) mediante un meta-análisis. Un total de 80 y 63 observaciones provenientes de 18 experimentos que evaluaron los efectos de la AFL sobre el FI y WG, respectivamente, fueron tenidas en cuenta. Se encontró que las diferencias de concentración de AFL entre los grupos control y tratados variaron desde 0,02 hasta 2,5 mg/kg. De otro lado, se utilizaron un total de 117 y 113 observaciones de 20 experimentos para probar los efectos de DON en FI y WG, respectivamente. Las diferencias de concentración de DON entre los grupos control y tratados variaron desde 0,5 hasta 10,5 mg/kg. Por último, un total de 16 y 17 observaciones de 18 experimentos se utilizaron para probar los efectos de ZON en FI y GT, respectivamente; las diferencias de concentración de ZON entre los grupos control y tratados variaron desde 0,2 hasta 9,0 mg/kg. Los efectos de Experimento, Peso corporal inicial, y Período experimental no fueron significativos para el desarrollo de las ecuaciones de predicción de cambios en FI y WG. Los modelos desarrollados para predecir cambios porcentuales en FI y WG (ΔFI y ΔWG) según la concentración de AFL (mg/kg) fueron: $\Delta FI = -24{,}9 \times AFL - 1{,}7$ con $r^2 = 0{,}70$ y $p<0{,}001$; $\Delta FI = 0{,}4-51{,}6 \times (1 - e^{-0.947 \times AFL})$ con $r^2 = 0{,}79$ y $p<0{,}001$; $\Delta WG = -22{,}7 \times AFL - 4{,}0$ con $r^2 = 0{,}62$ y $p<0{,}001$, y $\Delta WG = -1{,}4 - 50{,}3 \times (1 - e^{-0.976 \times AFL})$ con $r^2 = 0{,}69$ y $p<0{,}001$. Las ecuaciones para predecir ΔFI y ΔWG (como %) por las concentraciones de DON (mg/kg) fueron: $\Delta FI = -5{,}64 \times DON - 0{,}13$ con $r^2 = 0{,}60$ y $p<0{,}001$; y $\Delta WG = -6{,}49 + 0{,}93 \times DON$ con $r^2 = 0{,}61$ y $p<0{,}001$. El consumo de alimento y la tasa de crecimiento de cerdos disminuyen lineal y exponencialmente según la concentración de AFL; mientras que solamente se observa una disminución de tipo lineal en función de las concentraciones de DON. Las ecuaciones obtenidas en este trabajo podrían usarse para predecir los efectos de AFL y DON sobre el desempeño productivo del cerdo.

Palabras clave: *cerdo, consumo de alimento, ganancia de peso, meta-análisis, micotoxinas.*

Resumo

As micotoxinas presentes nos alimentos tem efeitos prejudiciais na saúde e na produção porcina. O objetivo deste estudo foi desenvolver ferramentas para a predição dos efeitos da aflatoxina (AFL), deoxinivalenol (DON) e zearalenona (ZON) sobre o consumo de alimento (FI) e ganho de peso (WG) mediante uma meta-análise. Um total de 80 e 63 observações extraídas de 18 experimentos que avaliaram os efeitos da AFL sobre o FI e WG, respectivamente, encontraram que as diferenças de concentração de AFL entre os grupos controle e tratados variaram desde 0,02 até 2,5 mg/kg. Por outro lado, foram utilizados um total de 117 e 113 observações de 20 experimentos para provar os efeitos de DON em FI e WG, respectivamente. As diferenças de concentração de DON entre os grupos controle e tratados variaram desde 0.5 até 10,5 mg/kg. Por fim, um total de 16 e 17 observações de 18 experimentos foram utilizados para provar os efeitos de ZON em FI e GT, respectivamente, e as diferenças de concentração de ZON entre os grupos controle e tratados variaram desde 0,2 até 9,0 mg/kg. Os efeitos de Experimento, Peso corporal inicial e Período experimental não foram significativos para o desenvolvimento das equações de predição de mudanças em FI e WG. Os modelos desenvolvidos para predizer mudanças percentuais em FI e WG (ΔFI e ΔWG) segundo a concentração de AFL (mg/kg) foram: $\Delta FI = -24{,}9 \times AFL - 1{,}7$ com $r^2 = 0{,}70$ e $p<0{,}001$; $\Delta FI = 0{,}4-51{,}6 \times (1 - e^{-0.947 \times AFL})$ com $r^2 = 0{,}79$ y $p<0{,}001$; $\Delta WG = -22{,}7 \times AFL - 4{,}0$ com $r^2 = 0{,}62$ e $p<0{,}001$, e $\Delta WG = -1{,}4 - 50{,}3 \times (1 - e^{-0.976 \times AFL})$ con $r^2 = 0{,}69$ e $p<0{,}001$. As equações para predizer ΔFI e ΔWG (como %) pelas concentrações de DON (mg/kg) foram: $\Delta FI = -5{,}64 \times DON - 0{,}13$ com $r^2 = 0{,}60$ e $p<0{,}001$; e $\Delta WG = -6{,}49 + 0{,}93 \times DON$ com $r^2 = 0{,}61$ e $p<0{,}001$. Conclusão: o consumo de alimento e a taxa de crescimento de porcos diminuem linearmente e exponencialmente segundo a concentração de AFL, e linearmente segundo a concentração de DON. As equações obtidas neste trabalho são de utilidade para predizer os efeitos de AFL e DON sobre o desempenho porcino.

Palavras chave: *consumo de alimento, ganho de peso, meta-análise, micotoxinas, porco.*

Introduction

Contamination of mycotoxin in feed causes problems in livestock production processes by reducing growth performance. Mycotoxins in swine feed generally cause feed intake (FI) and weight gain (WG) reductions (Lindemann *et al*., 1993). The detrimental effects of dietary mycotoxins result in significant economic losses (Shull and Cheeke, 1983). If a dietary mycotoxin causes growth retardation due to decreased FI, this production loss can be at least partially prevented by formulating diets with greater concentration of nutrients. The nutrient requirements for swine are based on the daily intake amount (NRC, 2012). Thus, an estimation of FI reduction based on the mycotoxin concentration is important.

The most frequently found mycotoxins in swine feedstuffs are Aflatoxin (AFL), deoxynivalenol (DON) and zearalenone (ZON). Many studies have investigated the influences of AFL, DON and ZON on growth performance of swine. However, responses reported in the literature vary considerably. The reasons for this variation are likely due to the differences of experimental conditions, such as pig age, concentration of mycotoxins, and type of feed, among others. Therefore, the present study was conducted to overview the effects of dietary mycotoxins on performance and physiological responses and to develop tools for predicting the effects of mycotoxins on FI and WG changes by integrating and summarizing the quantitative data were available. The information data in the literature.

Aflatoxin

Aflatoxins are toxic metabolites produced by *Aspergillus flavus-parasiticus* (Marin *et al*., 2002) and their effects on pig performance have been investigated in many studies. Most researchers concluded that dietary AFL affect FI and WG without affecting gain:feed or organ weight. In some studies, however, liver weight, liver-specific enzyme activity, and serum globulin patterns were influenced by dietary AFL (Table 1).

Table 1. Symptoms in pigs fed diets containing aflatoxin (AFL), deoxynivalenol (DON) or zearalenone (ZON).

Mycotoxin	References
Aflatoxin	
Increased liver weights	Southern and Clawson, 1979; Rustemeyer *et al*., 2010.
Increased kidney, spleen, and pancreas weights	Murthy *et al*., 1975; Shi *et al*., 2007.
Increased activity of liver-specific enzymes	Lindemann *et al*., 1993; Schell *et al*., 1993a.
Abnormal histology and altered serum globulin patterns	Southern and Clawson, 1979.
Increased serum alkaline phosphatase and γ-glutamyltransferase	Harvey *et al*., 1989, 1990.
Deoxynivalenol	
Vomiting	Pollmann *et al*., 1985; Rotter *et al*., 1996.
Found traces of DON in kidney, liver, spleen and heart tissues	Pollmann *et al*., 1985.
Reduced fetal weight and osmolality of the allantoic fluid	Friend *et al*., 1983.
Zearalenone	
Detected in bile of sows and piglets	Dänicke *et al*., 2007; Goyarts *et al*., 2007.
Swelling and redness of the vulvae in gilts with above 6 mg/kg of ZON	Young *et al*., 1981.
Increased uterine weight	Young *et al*., 1981.
Increased thickness of the vaginal epithelium	Young *et al*., 1981.
Decreased nutrient digestibility	Wang *et al*., 2012.
Increased oxidative stress	Wang *et al*., 2012.
Negative effects on growth performance	Wang *et al*., 2012.

For the compilation of data from the literature, experiments with growth data were selected. Data for dietary AFL concentrations, FI, and WG from the experiments were collected when the quantitative data were available. The information recorded included AFL concentration in diet, initial age, initial BW, final BW, sex, number of pigs, FI, WG, gain:feed, and experimental period. When possible, WG was calculated based on BW changes and gain:feed was calculated using FI and WG.

Data from 18 experiments were extracted and included 80 observations for FI and 63 observations for WG. The difference of AFL concentrations between the control diet and the treatment diets in these 18 experiments ranged from 0.02 to 2.5 mg/kg. The sources of AFL were rice (12 studies) and corn (9 studies). Purified AFL was used in 1 study. The source of AFL was unknown in 2 studies. In some studies multiple sources were used. Reductions of FI and WG were the major response to AFL. The changes (%) of WG, FI, and gain:feed by additional AFL relative to the control group were calculated from each treatment group (Table 2).

Table 2. Effects of dietary aflatoxin (AFL) on growth performance of pigs.

Reference	AFL concentration[1] (mg/kg)	IBW[2] (kg)	Experimental period (d)	Change rate (%)		
				WG: Weight gain[3]	FI[4]	Gain:feed
Hale and Wilson, 1979.	0.35	18.3	109	-5.3	2.4	-7.1
Southern and Clawson, 1979.	0.37	52.5	66	-13.0	-11.9	-1.3
	0.73	52.5	66	-26.0	-25.1	-1.2
	1.46	52.5	66	-46.8	-43.9	-5.1
Coffey *et al*., 1989.	0.18	7.2	28	-23.7	-17.7	-5.7
	0.18	7.2	28	0.0	-4.5	5.1
	0.18	7.2	28	-13.9	-9.4	-4.9
	0.18	7.2	28	-2.8	-1.6	-2.3
	0.18	7.2	28	-12.0	-6.1	-1.5
	0.18	7.2	28	-5.9	-8.9	-1.5
	0.18	7.2	28	4.1	3.1	0.5
	0.18	7.2	28	-2.0	-9.4	7.7
Harvey *et al*., 1990.	2.50	16.1	28	-54.6	-[5]	-
Lindemann *et al*., 1993.	0.42	10.5	49	-11.5	-15.9	4.4
	0.84	10.6	49	-46.2	-40.7	-19.6
	0.80	9.1	42	-35.9	-37.9	2.0
Schell *et al*., 1993a.	0.80	10.7	28	-25.0	-11.4	-14.6
	0.50	9.7	40	-30.3	-31.2	0.0
	0.80	9.9	28	-17.5	-20.9	4.1
Schell *et al*., 1993b.	0.92	8.8	42	-22.4	-20.0	-2.2
Harvey *et al*., 1995.	2.50	13.8	28	-38.1	-44.1	10.8
Marin *et al*., 2002.	0.14	11.4	22	0.0	-	-
	0.28	11.4	22	-37.5	-	-
	0.14	11.4	8	-15.5	-	-
	0.28	11.4	8	-28.7	-	-
Dilkin *et al*., 2003.	0.05	15.0	28	0.9	11.1	-9.2
Shi *et al*., 2005.	0.10	29.8	90	-12.9	-6.3	-7.0
Battacone *et al*., 2007.	0.02	110.0	28	-43.1	-0.4	-42.9
Meissonnier *et al*., 2007.	0.39	13.7	28	-9.6	-	-
	0.87	13.7	28	-17.7	-	-
	1.81	13.7	28	-46.8	-	-
Shi et al., 2007.	0.11	29.8	90	-12.9	-6.4	-7.0
Meissonnier *et al*., 2008.	0.39	-	-	-13.2	-	-
	0.87	-	-	-17.8	-	-
	1.81	-	-	-45.1	-	-
Thieu *et al*., 2008.	0.20	11.0	21	-22.8	-2.6	-22.7
	0.20	20.3	20	-21.6	-17.5	-6.9
Harper et al., 2010.	0.50	9.4	21	-27.5	-29.2	1.9
Rustemeyer *et al*., 2010.	0.25	14.2	21	-3.8	-8.0	4.6
	0.50	14.2	21	-6.0	-8.5	2.8
	0.25	26.7	49	-15.0	-19.3	5.3
	0.50	26.4	49	-33.4	-26.8	-9.0

[1]AFL concentration of the difference from the basal diet. [2]IBW = Initial body weight. [3]WG = Weight gain. [4]FI = Feed intake. [5]Data not available.

Collected data were analyzed using the REG and NLIN procedures of SAS (SAS Institute Inc., Cary, NC, USA). When values for REG procedures exceeded 0.20 in Cook's distance, data were considered as outliers and not used for further analysis. After excluding outliers, variations of FI and WG were predicted in equations by the REG procedures and regression equations by the NLIN procedures.

Effects of experiment, BW, and experimental period were not significant for developing prediction equations for the changes of FI and WG. The models developed for predicting FI and WG changes (ΔFI and ΔWG) as % by AFL concentrations as mg/kg were: $\Delta FI = -24.9 \times AFL - 1.7$ with $r^2 = 0.70$ and $p<0.001$; $\Delta FI = 0.4 - 51.6 \times (1 - e^{-0.947 \times AFL})$ with $r^2 = 0.79$ and $p<0.001$; $\Delta WG = -22.7 \times AFL - 4.0$ with $r^2 = 0.62$ and $p<0.001$; and $\Delta WG = -1.4 - 50.3 \times (1 - e^{-0.976 \times AFL})$ with $r^2 = 0.69$ and $p<0.001$ (Figure 1). Theoretically, the changes of FI and WG cannot be less than -100%, and thus, exponential models were also used. However, exponential models did not have large improvements in r-square compared with linear models. The linear response in WG changes was also reported by Andretta *et al*. (2012). However, they reported that the slope was -3.95 which was much less steeper than -22.7 in the present work. In our equation, if the negative intercept were forced to zero, the steepness of the slope would become even greater. The reason for the difference in the slopes is unknown.

In conclusion, feed consumption and growth rate of pigs decline linearly and exponentially with AFL concentration.

Deoxynivalenol

Deoxynivalenol is one of the secondary metabolites of *Fusarium* (Accensi *et al*., 2006). As dietary DON commonly causes vomiting in pigs, DON is often called vomitoxin. Deoxynivalenol mainly affects FI and WG in swine, and DON has been reported to accumulate in liver and kidney (Table 1). Also, dietary DON results in reduced fetal weight and osmolality of allantoic fluid.

As for AFL experimental data compilation, experiments with growth data were selected. Data for dietary DON concentrations, FI, and WG from the experiments were collected when quantitative data was available. The information recorded included DON concentration in diet, initial age, initial BW, final BW, sex, number of pigs, FI, WG, gain:feed, and experimental period. When possible, WG was calculated based on BW changes and gain:feed was calculated using FI and WG.

Data from 20 experiments were extracted and included 117 observations for FI and 113 observations for WG. The difference of DON concentrations between the control diet and the treatment diets in these 20 experiments ranged from 0.5 and 10.5 mg/kg (Table 3).

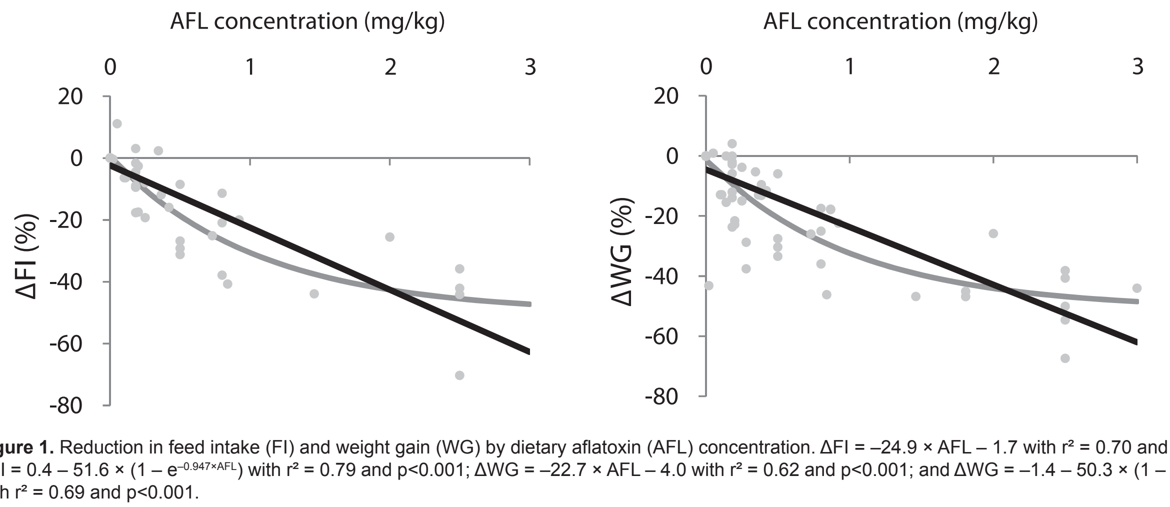

Figure 1. Reduction in feed intake (FI) and weight gain (WG) by dietary aflatoxin (AFL) concentration. $\Delta FI = -24.9 \times AFL - 1.7$ with $r^2 = 0.70$ and $p<0.001$; $\Delta FI = 0.4 - 51.6 \times (1 - e^{-0.947 \times AFL})$ with $r^2 = 0.79$ and $p<0.001$; $\Delta WG = -22.7 \times AFL - 4.0$ with $r^2 = 0.62$ and $p<0.001$; and $\Delta WG = -1.4 - 50.3 \times (1 - e^{-0.976 \times AFL})$ with $r^2 = 0.69$ and $p<0.001$.

Table 3. Effects of dietary deoxynivalenol (DON) on growth performance of pigs.

Reference	DON concentration, mg/kg[1]	IBW[2], kg	Experimental period, d	Change rate, %		
				WG[3]	FI[4]	Gain:feed
Friend *et al*., 1983.	2.0	123.0	51	-5.1	-3.8	-1.1
	4.0	119.0	51	-21.4	-18.2	-4.1
Young *et al*., 1983.	8.9	8.2	11	-72.2	-54.0	-39.6
	1.2	7.0	21	-23.5	-22.6	-3.1
	2.4	6.8	21	-44.1	-39.6	-13.9
	5.0	6.9	21	-64.7	-62.3	-15.4
	6.3	6.8	21	-67.7	-62.3	-18.5
	7.7	7.1	21	-76.5	-67.9	-47.7
	8.5	7.8	21	-61.8	-49.1	-23.1
	1.0	8.9	16	-15.6	-28.1	17.4
	1.0	8.9	36	-16.8	-28.1	15.6
Chavez, 1984.	0.8	6.8	56	0.0	-0.4	0.5
	1.7	6.9	56	-2.1	-2.4	0.5
	2.4	6.9	56	-18.1	-18.0	0.0
Cote *et al*., 1985.	2.4	10.0	35	-20.2	-[5]	-
	5.1	9.6	35	-17.5	-	-
Lun *et al*., 1985.	10.5	8.3	21	-50.0	-44.4	-9.4
Pollmann *et al*., 1985.	1.2	7.7	21	2.9	6.4	-3.3
	2.4	7.7	21	-17.1	-23.8	8.8
	3.6	7.7	21	-48.6	-34.9	-21.0
	1.2	8.3	14	5.7	0.0	0.0
	1.6	8.3	14	-2.9	-12.9	5.5
	2.0	8.3	14	0.0	-9.7	4.7
	0.9	60.5	42	-10.3	-14.4	4.8
	1.8	60.5	42	-18.4	-29.2	15.3
Foster *et al*., 1986.	4.7	27.5	49	-20.1	-17.9	-2.6
	4.9	27.5	49	-29.8	-34.2	6.6
	4.8	27.5	49	-34.4	-34.5	0.1
	5.1	27.5	49	-36.3	-39.9	6.0
	5.1	27.5	49	-25.6	-23.2	-3.2
	5.2	27.5	49	-37.5	-40.1	4.5
	4.7	27.5	49	-20.7	-16.4	-5.1
	4.2	27.5	49	-20.3	-20.1	-0.2
	4.7	27.5	49	-33.3	-36.7	5.4
	5.2	27.5	49	-29.8	-26.1	-5.0
	3.7	27.5	49	-17.8	-23.1	6.8
	4.6	27.5	49	-26.2	-23.7	-3.3
	3.3	27.5	49	-16.6	-13.0	-4.2
	3.6	27.5	49	-20.3	-14.9	-6.3
	2.1	27.5	49	-11.9	-10.5	-1.5
	2.8	27.5	49	-25.2	-23.1	-2.8
	3.8	27.5	49	-22.8	-22.6	-0.2

Continues

Table 3. Continued

Reference	DON concentration, mg/kg[1]	IBW[2], kg	Experimental period, d	Change rate, %		
				WG[3]	FI[4]	Gain:feed
Bergsjø *et al*., 1993.	0.7	20.9	94	-0.6	-0.5	-0.4
	1.7	21.5	96	-3.7	-7.9	5.1
	3.5	22.0	95	-17.6	-15.0	-3.5
He *et al*., 1993.	4.8	11.6	5	-56.7	-34.0	-81.5
Rotter *et al*., 1995.	4.0	17.9	7	-27.7	-25.2	-3.7
	4.0	17.9	42	-13.0	-20.0	9.3
Smith *et al*., 1997.	4.4	8.2	21	-34.9	-29.6	-7.9
	6.0	8.2	21	-39.8	-34.9	-9.5
	7.5	8.2	21	-49.4	-43.3	-11.1
	0.5	8.3	21	-2.2	1.3	0.0
	1.1	8.3	21	-16.7	-9.7	-5.7
	1.9	8.3	21	-7.8	-8.9	1.4
	2.2	8.2	21	-3.3	-1.3	1.4
	2.4	8.2	21	-4.4	-2.8	-1.4
	2.5	8.2	21	-12.2	-8.1	-2.9
Swamy *et al*., 2002.	3.8	10.0	7	-53.1	-33.5	-28.7
	3.8	10.0	14	-39.9	-32.2	-10.5
	3.8	10.0	21	-34.6	-32.7	-4.5
Döll *et al*., 2003.	0.6	12.4	36	3.6	1.3	2.0
	0.8	12.4	36	3.6	0.2	3.2
	1.7	12.4	36	-3.6	-5.1	1.5
	3.7	12.4	36	-19.2	-22.5	4.3
Dänicke *et al*., 2004.	2.3	28.0	14	-20.1	-13.8	-8.3
	4.6	28.0	14	-54.5	-40.5	-22.7
	1.4	55.2	42	-4.2	-5.9	2.0
	2.7	54.6	42	-1.5	-4.3	3.3
Dänicke *et al*., 2005.	3.8	12.3	21	-15.7	-15.3	-0.5
Goyarts *et al*., 2005.	6.4	26.0	77	-13.7	-14.8	1.5
Accensi *et al*., 2006.	2.8	11.2	28	-13.8	-3.2	-11.0
	5.6	11.2	28	-18.3	-14.8	-4.2
	8.4	11.2	28	-8.4	-3.9	-4.7
	2.8	28.0	28	-1.4	2.4	-3.6
	5.6	28.0	28	6.0	-0.6	6.7
	2.8	11.2	28	-5.7	0.3	-5.9
	5.6	11.2	28	-2.9	-5.8	3.1
Cheng *et al*., 2006.	1.0	8.9	16	-15.6	-28.1	17.4
	1.0	8.9	36	-16.8	-28.1	15.6
Gutzwiller *et al*., 2007.	3.1	10.0	35	-9.4	-10.1	0.8
Waché *et al*., 2009.	2.8	29.6	7	-56.3	-46.4	-18.7
	2.8	32.5	7	-5.9	7.0	-11.5
	2.8	39.3	7	-13.0	0.4	-14.2
	2.8	46.3	7	7.0	-8.9	17.7

[1]DON concentration of the difference from the basal diet. [2]IBW = Initial body weight. [3]WG = Weight gain. [4]FI = Feed intake. [5]Data not available.

Collected data were analyzed using the REG procedures and the NLIN procedures of SAS (SAS Institute Inc., Cary, NC, USA). Using the REG procedures, data were considered as outliers and not used for further analysis when values exceeded 0.20 in Cook's distance. After excluding outliers, variations of FI and WG were predicted in linear equations by the REG procedures.

The equations for predicting ΔFI and ΔWG (as %) by DON concentrations (as mg/kg) were: ΔFI = –5.64 × DON – 0.13 with $r^2 = 0.60$ and $p<0.001$; and ΔWG = –6.49 × DON + 0.93 with $r^2 = 0.61$ and $p<0.001$ (Figure 2). Exponential models were not significant perhaps due to concentrations of DON were not high enough to cause greater responses. Similarly to the AFL data, the steepness of the slope in the present study was greater than the slope reported by Andretta *et al*. (2012).

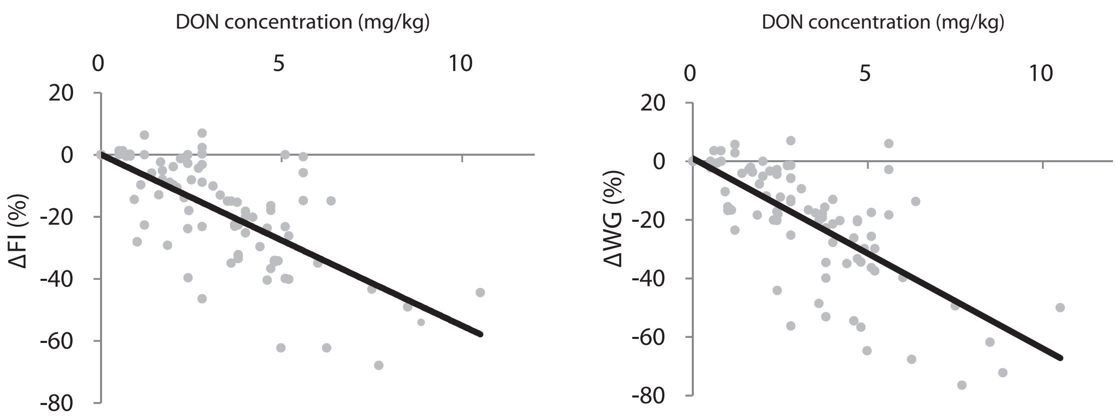

Figure 2. Reduction in feed intake (FI) and weight gain (WG) by dietary deoxynivalenol (DON) concentration. ΔFI = –5.64 × DON – 0.13 with $r^2 = 0.60$ and $p<0.001$; and ΔWG = –6.49 × DON + 0.93 with $r^2 = 0.61$ and $p<0.001$.

In conclusion, feed consumption and growth rate of pigs decline linearly with DON concentrations.

Zearalenone

Zearalenone was detected in bile of sows and piglets fed ZON contaminated diets (Dänicke *et al*., 2007; Goyarts *et al*., 2007). In a study by Young *et al*. (1981), when a diet containing ZON more than 6 mg/kg was fed to gilts, swelling and redness of the vulvae were observed (Table 1). With an increase of dietary ZON concentrations, uterine weight and the thickness of the vaginal epithelium increased (Young *et al*., 1981). Recently, Wang *et al.* (2012) reported that dietary ZON resulted in decreased nutrient digestibility, increased oxidative stress, and reduced growth rate of pigs.

In the present work, a meta-analysis for the effects of ZON on FI and WG was not conducted due to the lack of data reported in the literature. Available data to date are summarized in table 4. Detrimental effects of dietary ZON on growth performance of pigs are clear. Dietary ZON (mean 3.8 mg/kg in diet) resulted in 15.8% FI reductions and 28.8% WG reductions on average. However, more data are needed to develop a model for precise prediction of dose-dependent growth responses.

Table 4. Effects of dietary zearalenone (ZON) on growth performance of pigs.

Reference	ZON concentration, mg/kg[1]	IBW[2], kg	Experimental period, d	Change rate, %		
				WG[3]	FI[4]	Gain:feed
Young *et al*., 1981	3.0	63.6	21	-18.1	-9.9	-9.4
	6.0	63.8	21	-72.3	-57.6	-56.3
	9.0	62.6	21	-78.7	-43.1	-43.8
	3.0	6.3	21	-30.8	-9.9	-25.0
	6.0	6.3	21	-23.1	-24.7	10.0
	9.0	6.3	21	-53.9	-31.0	-35.0
	3.0	6.6	21	-25.0	-14.2	-12.3
	6.0	6.7	21	-28.1	3.3	-29.8
	9.0	6.2	21	-46.9	-37.5	-22.8
Williams and Blaney, 1994	0.7	40.0	14	-1.3	7.4	-8.1
	1.5	40.0	14	-37.5	-28.2	-12.9
	2.2	40.0	14	-43.8	-46.0	4.2
Šperanda *et al*., 2006	3.0	12.7	14	-11.5	-[5]	-
Jiang *et al*., 2012	1.0	8.8	22	0.0	1.3	-1.3
Wang *et al*., 2012	0.2	10.5	28	-3.3	12.1	-14.0
	0.4	9.7	28	-5.1	7.7	-12.2
	0.8	9.9	28	-9.6	6.0	-15.4

[1] ZON concentration of the difference from the basal diet. [2] IBW = Initial body weight. [3] WG = Weight gain. [4] FI = Feed intake. [5] Data not available.

Strategies to alleviate damages from mycotoxins

To avoid detrimental effects of mycotoxins, several decontamination or detoxification methods are available such as thermal inactivation and irradiating (physical methods), treatment with acid/base solutions, ozonation, and ammoniation (chemical methods), and degradation of toxins by microorganisms (biological methods) (Diaz and Smith, 2005). Supplementation with toxin-sequestering agents is the most frequently used method by the swine feed industry because of its economic feasibility and suitability from a nutritional perspective.

Mycotoxin sequestering agents available to the feed industry include silicate clays, activated carbons, and yeast-derived products (NRC, 2012). Zeolites, bentonites, and hydrated sodium calcium aluminosilicates (HSCAS) are representative types of silicate clays. These clays generally have high affinity for AFL, but have little sequestering effect on other mycotoxins (Diaz and Smith, 2005). While in some studies activated carbon reduced or eliminated the effects of AFL (Hatch *et al*., 1982; Dalvi and McGowan, 1984; Galvano *et al*., 1996), other researchers failed to find the effect of activated charcoal on animals fed mycotoxin-contaminated diets (Kubena *et al*., 1990; Edrington *et al*., 1997; Cabassi *et al*., 2005). Glucomannan polymers derived from yeast cell walls are also used as mycotoxin binders (NRC, 2012).

Several studies have been conducted to investigate the efficacy of sequestering agents to a single specific mycotoxin using *in vitro* and *in vivo* methods (Lindemann *et al*., 1993; Diaz *et al*., 2002, 2004; Marroquín-Cardona *et al*., 2009). However, swine diets could potentially be contaminated with multiple species of mycotoxins because those diets typically consist of a mixture of multiple ingredients (van Heugten, 2001). Nevertheless, to the best of our knowledge, no single sequestering agent is available that can effectively sequester multiple mycotoxins (i.e., AFL, DON, and ZON). Thus, a strategy to use multiple sequestering agents has been inevitably used. It is important to determine the sequestering efficiency of an agent for each toxin to obtain the optimum formula of sequestering agents.

Several *in vitro* methods are available to predict the *in vivo* efficacy of sequestering agents (Diaz *et al.*, 2002; Marroquín-Cardona *et al.*, 2009). However, these methods may not be applicable to the intestinal environment of pigs. Thus, research with a more precise *in vitro* method to mimic the digestive processes of pigs is needed.

In the present work, feed consumption and growth rate of pigs decline linearly and exponentially by the concentrations of AFL and linearly by the concentrations of DON. Detrimental effects of dietary ZON on growth performance of pigs are also clear. The equations provided herein may predict the effects of AFL and DON on swine production performance. Further experiments are warranted to confirm the accuracy of the models suggested in this work.

Acknowledgements

The authors are grateful for the support by the Rural Development Administration (Suwon, Republic of Korea; PJ008405).

References

Accensi F, Pinton P, Callu P, Abella-Bourges N, Guelfi JF, Grosjean F, Oswald IP. Ingestion of low doses of deoxynivalenol does not affect hematological, biochemical, or immune responses of piglets. J Anim Sci 2006; 84:1935-1942.

Andretta I, Kipper M, Lehnen CR, Hauschild L, Vale MM, Lovatto PA. Meta-analytical study of productive and nutritional interactions of mycotoxins in growing pigs. Animal 2012; 6:1476-1482.

Battacone G, Carboni GA, Nicolussi P, Ligios C, Pulina G. Use of a glucomannan polymer to reduce the effects of mycotoxin-contaminated diets in finishing pigs. Ital J Anim Sci 2007; 6:673-675.

Bergsjø B, Langseth W, Nafstad I, Jansen JH, Larsen HJ. The effects of naturally deoxynivalenol-contaminated oats on the clinical condition, blood parameters, performance and carcass composition of growing pigs. Vet Res Commun 1993; 17:283-294.

Cabassi E, Miduri F, Cantoni AM. Intoxication with fumonisin B1 (FB1) in piglets and supplementation with granulated activated carbon: Cellular-mediated immunoresponse. Vet Res Commun 2005; 29:225-227.

Chavez ER. Vomitoxin contaminated wheat in pig diets: Pregnant and lactating gilts and weaners. Can J Anim Sci 1984; 64:717-723.

Cheng YH, Weng CF, Chen BJ, Chang MH. Toxicity of different *Fusarium* mycotoxins on growth performance, immune responses and efficacy of a mycotoxin degrading enzyme in pigs. Anim Res 2006; 55:579-590.

Coffey MT, Hagler WM Jr, Cullen JM. Influence of dietary protein, fat or amino acids on the response of weanling swine to aflatoxin B_1. J Anim Sci 1989; 67:465-472.

Cote LM, Beasley VR, Bratich PM, Swanson SP, Shivaprasad HL, Buck WB. Sex-related reduced weight gains in growing swine fed diets containing deoxynivalenol. J Anim Sci 1985; 61:942-950.

Dalvi RR, McGowan C. Experimental induction of chronic aflatoxicosis in chickens by purified aflatoxin B_1 and its reversal by activated charcoal, phenobarbital and reduced glutathione. Poult Sci 1984; 63:485-491.

Dänicke S, Brüssow KP, Goyarts T, Valenta H, Ueberschär KH, Tiemann U. On the transfer of the *Fusarium* toxins deoxynivalenol (DON) and zearalenone (ZON) from the sow to the full-term piglet during the last third of gestation. Food Chem Toxicol 2007; 45:1565-1574.

Dänicke S, Valenta H, Gareis M, Lucht HW, Reichenbach H. On the effects of a hydrothermal treatment of deoxynivalenol (DON)-contaminated wheat in the presence of sodium metabisulfite ($Na_2S_2O_5$) on DON reduction and on piglet performance. Anim Feed Sci Technol 2005; 118:93-108.

Dänicke S, Valenta H, Klobasa F, Döll S, Ganter M, Flachowsky G. Effects of graded levels of Fusarium toxin contaminated wheat in diets for fattening pigs on growth performance, nutrient digestibility, deoxynivalenol balance and clinical serum characteristics. Arch Anim Nutr 2004; 58:1-17.

Diaz DE, Hagler WM Jr, Blackwelder JT, Eve JA, Hopkins BA, Anderson KL, Jones FT, Whitlow LW. Aflatoxin Binders II: Reduction of aflatoxin M1 in milk by sequestering agents of cows consuming aflatoxin in feed. Mycopathologia 2004; 157:233-241.

Diaz DE, Hagler WM Jr, Hopkins BA, Whitlow LW. Aflatoxin Binders I: *In vitro* binding assay for aflatoxin B1 by several potential sequestering agents. Mycopathologia 2002; 156:223-226.

Diaz DE, Smith TK. Mycotoxin sequestering agents: Practical tools for the neutralisation of mycotoxins. In: Diaz DE, editor. The Mycotoxin Blue Book. Nottingham: Nottingham university press; 2005. p.323-39.

Dilkin P, Zorzete P, Mallmann CA, Gomes JDF, Utiyama CE, Oetting LL, Corrêa B. Toxicological effects of chronic low doses of aflatoxin B_1 and fumonisin B_1-containing *Fusarium moniliforme* culture material in weaned piglets. Food Chem Toxicol 2003; 41:1345-1353.

Döll S, Dänicke S, Ueberschär K, Valenta H, Schnurrbusch U, Klobasa F, Flachowsky G. Effects of graded levels of *Fusarium* toxin contaminated maize in diets for female weaned piglets. Arch Anim Nutr 2003; 57:311-334.

Edrington TS, Kubena LF, Harvey RB, Rottinghaus GE. Influence of a superactivated charcoal on the toxic effects of aflatoxin or T-2 toxin in growing broilers. Poult Sci 1997; 76:1205-1211.

Foster BC, Trenholm HL, Friend DW, Thompson BK, Hartin KE. Evaluation of different sources of deoxynivalenol (vomitoxin) fed to swine. Can J Anim Sci 1986; 66:1149-1154.

Friend DW, Trenholm HL, Fiser PS, Thompson BK, Hartin KE. Effect on dam performance and fetal development of deoxynivalenol (vomitoxin) contaminated wheat in the diet of pregnant gilts. Can J Anim Sci 1983; 63:689-698.

Galvano F, Pietri A, Bertuzzi T, Fusconi G, Galvano M, Piva A, Piva G. Reduction of carryover of aflatoxin from cow feed to milk by addition of activated carbons. J Food Prot 1996; 59:551-554.

Goyarts T, Dänicke S, Brüssow KP, Valenta H, Ueberschär KH, Tiemann U. On the transfer of the *Fusarium* toxins deoxynivalenol (DON) and zearalenone (ZON) from sows to their fetuses during days 35–70 of gestation. Toxicol Lett 2007; 171:38-49.

Goyarts T, Dänicke S, Rothkötter HJ, Spilke J, Tiemann U, Schollenberger M. On the effects of a chronic deoxynivalenol intoxication on performance, haematological and serum parameters of pigs when diets are offered either for ad libitum consumption or fed restrictively. J Vet Med A Physiol Pathol Clin Med 2005; 52:305-314.

Gutzwiller A, Czegledi L, Stoll P, Bruckner L. Effects of Fusarium toxins on growth, humoral immune response and internal organs in weaner pigs, and the efficacy of apple pomace as an antidote. J Anim Physiol Anim Nutr 2007; 91:432-438.

Hale OM, Wilson DM. Performance of pigs on diets containing heated or unheated corn with or without aflatoxin. J Anim Sci 1979; 48:1394-1400.

Harper AF, Estienne MJ, Meldrum JB, Harrell RJ, Diaz DE. Assessment of a hydrated sodium calcium aluminosilicate agent and antioxidant blend for mitigation of aflatoxin-induced physiological alterations in pigs. J Swine Health Prod 2010; 18:282-289.

Harvey RB, Edrington TS, Kubena LF, Corrier DE, Elissalde MH. Influence of the antibiotics lincomycin and tylosin on aflatoxicosis when added to aflatoxin-contaminated diets of growing swine. J Vet Diagn Invest 1995; 7:374-379.

Harvey RB, Kubena LF, Huff WE, Corrier DE, Rottinghaus GE, Phillips TD. Effects of treatment of growing swine with aflatoxin and T-2 toxin. Am J Vet Res 1990; 51:1688-1693.

Harvey RB, Kubena LF, Phillips TD, Huff WE, Corrier DE. Prevention of aflatoxicosis by addition of hydrated sodium calcium aluminosilicate to the diets of growing barrows. Am J Vet Res 1989; 50:416-420.

Hatch RC, Clark JD, Jain AV, Weiss R. Induced acute aflatoxicosis in goats: treatment with activated charcoal or dual combinations of oxytetracycline, stanozolol and activated charcoal. Am J Vet Res 1982; 43:644-648.

He P, Young LG, Forsberg C. Microbially detoxified vomitoxin-contaminated corn for young pigs. J Anim Sci 1993; 71:963-967.

Jiang SZ, Yang ZB, Yang WR, Liu FX, Johnston LA, Chi F, Wang Y. Effect of purified zearalenone with or without modified montmorillonite on nutrient availability, genital organs and serum hormones in post-weaning piglets. Livestock Sci 2012; 144:110-118.

Kubena LF, Harvey RB, Phillips TD, Corrier DE, Huff WE. Diminution of aflatoxicosis in growing chickens by the dietary addition of a hydrated sodium calcium aluminosilicate. Poult Sci 1990; 69:727-735.

Lindemann MD, Blodgett DJ, Kornegay ET, Schurig GG. Potential ameliorators of aflatoxicosis in weanling/growing swine. J Anim Sci 1993; 71:171-178.

Lun AK, Young LG, Lumsden JH. The effects of vomitoxin and feed intake on the performance and blood characteristics of young pigs. J Anim Sci 1985; 61:1178-1185.

Marin DE, Taranu I, Bunaciu RP, Pascale F, Tudor DS, Avram N, Sarca M, Cureu I, Criste RD, Suta V, Oswald IP. Changes in performance, blood parameters, humoral and cellular immune responses in weanling piglets exposed to low doses of aflatoxin. J Anim Sci 2002; 80:1250-1257.

Marroquín-Cardona A, Deng Y, Taylor JF, Hallmark CT, Johnson NM, Phillips TD. *In vitro* and *in vivo* characterization of mycotoxin-binding additives used for animal feeds in Mexico. Food Addit Contam 2009; 26:733-743.

Meissonnier GM, Laffitte J, Loiseau N, Benoit E, Raymond I, Pinton P, Cossalter AM, Bertin G, Oswald IP, Galtier P. Selective impairment of drug-metabolizing enzymes in pig liver during subchronic dietary exposure to aflatoxin B1. Food Chem Toxicol 2007; 45:2145-2154.

Meissonnier GM, Pinton P, Laffitte J, Cossalter AM, Gong YY, Wild CP, Bertin G, Galtier P, Oswald IP. Immunotoxicity of aflatoxin B1: Impairment of the cell-mediated response to vaccine antigen and modulation of cytokine expression. Toxicol Appl Pharmacol 2008; 231:142-149.

Murthy TRK, Jemmali M, Henry Y, Frayssinet C. Aflatoxin residues in tissues of growing swine: effect of separate and mixed feeding of protein and protein-free portions of the diet. J Anim Sci 1975; 41:1339-1347.

NRC. Nutrient Requirements of Swine. 11th rev ed. Washington, DC: The Natl Acad Press; 2012.

Pollmann DS, Koch BA, Seitz LM, Mohr HE, Kennedy, GA. Deoxynivalenol-contaminated wheat in swine diets. J Anim Sci 1985; 60:239-247.

Rotter BA, Prelusky DB, Pestka JJ. Toxicology of deoxynivalenol (vomitoxin). J Toxicol Environ Health 1996; 48:1-34.

Rotter BA, Thompson BK, Lessard M. Effects of deoxynivalenol-contaminated diet on performance and blood parameters in growing swine. Can J Anim Sci 1995; 75:297-302.

Rustemeyer SM, Lamberson WR, Ledoux DR, Rottinghaus GE, Shaw DP, Cockrum RR, Kessler KL, Austin KJ, Cammack KM. Effects of dietary aflatoxin on the health and performance of growing barrows. J Anim Sci 2010; 88:3624-3630.

Schell TC, Lindemann MD, Kornegay ET, Blodgett DJ, Doerr JA. Effectiveness of different types of clay for reducing the detrimental effects of aflatoxin-contaminated diets on performance and serum profiles of weanling pigs. J Anim Sci 1993a; 71:1226-1231.

Schell TC, Lindemann MD, Kornegay ET, Blodgett DJ. Effects of feeding aflatoxin-contaminated diets with and without clay to weanling and growing pigs on performance, liver function, and mineral metabolism. J Anim Sci 1993b; 71:1209-1218.

Shi YH, Xu ZR, Feng JL, Xia MS, Hu CH. Effects of modified montmorillonite nanocomposite on growing/finishing pigs during aflatoxicosis. Asian Australas J Anim Sci 2005; 18:1305-1309.

Shi YH, Xu ZR, Wang CZ, Sun Y. Efficacy of two different types of montmorillonite to reduce the toxicity of aflatoxin in pigs. New Zeal J Agr Res 2007; 50:473-478.

Shull LR, Cheeke PR. Effects of synthetic and natural toxicants on livestock. J Anim Sci 1983; 57:330-354.

Smith TK, McMillan EG, Castillo JB. Effect of feeding blends of *Fusarium* mycotoxin-contaminated grains containing deoxynivalenol and fusaric acid on growth and feed consumption of immature swine. J Anim Sci 1997; 75:2184-2191.

Southern LL, Clawson AJ. Effects of aflatoxins on finishing swine. J Anim Sci 1979; 49:1006-1011.

Šperanda M, Liker B, Šperanda T, Šerić V, Antunović Z, Grabarević Ž, Senčić Đ, Grgurić D, Steiner Z. Haematological and biochemical parameters of weaned piglets fed on fodder mixture contaminated by zearalenone with addition of clinoptilolite. Acta Vet Beograd 2006; 56:121-136.

Swamy HVLN, Smith TK, MacDonald EJ, Boermans HJ, Squires EJ. 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 Anim Sci 2002; 80:3257-3267.

Thieu NQ, Ogle B, Pettersson H. Efficacy of bentonite clay in ameliorating aflatoxicosis in piglets fed aflatoxin contaminated diets. Trop Anim Health Prod 2008; 40:649-656.

van Heugten E. Mycotoxins and other antinutritional factors in swine feeds. In: Lewis AJ and Southern LL, editors. Swine Nutrition. 2nd ed. Washington, DC: CRC Press 2001. p. 563-83.

Waché YJ, Valat C, Postollec G, Bougeard S, Burel C, Oswald IP, Fravalo P. Impact of deoxynivalenol on the intestinal microflora of pigs. Int J Mol Sci 2009; 10:1-17.

Wang JP, Chi F, Kim IH. Effects of montmorillonite clay on growth performance, nutrient digestibility, vulva size, faecal microflora, and oxidative stress in weaning gilts challenged with zearalenone. Anim Feed Sci Technol 2012; 178:158-166.

Williams KC, Blaney BJ. Effect of the mycotoxins, nivalenol and zearalenone, in maize naturally infected with *Fusarium graminearum* on the performance of growing and pregnant pigs. Aust J Agric Res 1994; 45:1265-1279.

Young LG, McGirr L, Valli VE, Lumsden JH, Lun A. Vomitoxin in corn fed to young pigs. J Anim Sci 1983; 57:655-664.

Young LG, Vesonder RF, Funnell HS, Simons I, Wilcock B. Moldy corn in diets of swine. J Anim Sci 1981; 52:1312-1318.