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Assessing the implications of mycotoxins on productive efficiency of broilers and growing pigs

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ABSTRACT: The effects of mycotoxins on the productive performance of growing pigs and broilers were evaluated using meta-analytical approach. Two databases were constructed: (1) Broilers, with information collected from 51,497 birds and published in 158 scientific papers from 1980 to 2016; and (2) Pigs, with information collected from 7,743 animals and published in 72 scientific papers from 1980 to 2015. The meta-analyses were performed independently for each specie, following three sequential analyses: graphical, correlation, and variance-covariance. Broilers and pigs challenged by mycotoxins reduced ($p < 0.05$) feed intake by 9 and 6 %, weight gain by 15 and 11 %, and feed efficiency by 6 and 4 % compared with non-challenged animals, respectively. Aflatoxins were the most studied mycotoxins in both databases. Birds and pigs challenged by aflatoxins reduced ($p < 0.05$) feed intake by 10 and 8 %, growth by 15 and 11 %, and feed efficiency by 6 and 7 % compared to non-challenged animals, respectively. In both databases, variation on growth performance due to mycotoxins showed a linear relationship ($p < 0.05$) with the feed intake variation caused by the challenge. The intercepts of the regression-based equations were different from zero and negative, which may indicate that mycotoxins altered the maintenance requirements in challenged animals. In conclusion, both broilers and growing pigs show losses in performance responses and worse nutritional efficiency when challenged by mycotoxins.

Keywords: aflatoxins, deoxynivalenol, nutrition, poultry, piglet

Introduction

Fungal contamination in grains is a serious issue for modern animal production. Mold growth is associated with decreased nutrient content in animal feedstuff (Vieira, 2003). Furthermore, the development of fungi under specific conditions may lead to another major threat: mycotoxin production. In past decades, over one quarter of the world's food crop production was estimated to be contaminated with mycotoxins (CAST, 2003).

Mycotoxins are secondary fungal metabolites with diverse structures and toxicological properties for humans and animals. Non-ruminant animals are cited as the most sensitive species to mycotoxins (Akande et al., 2006; Grenier and Applegate, 2013; Hussein and Brasel, 2001). The impact of mycotoxins on the production of poultry and pigs is considerable, but hardly quantified. Each mycotoxin has an action mechanism with different clinical manifestations, according to the ingested dose (Coulombe Jr., 1993; Hussein and Brasel, 2001). Furthermore, mycotoxin-related effects observed in animals vary highly and seem to be modulated by several factors; such as species, sex, age, and nutritional status (Andretta et al., 2011; D'Mello and MacDonald, 1997).

Quantifying the detrimental impacts of mycotoxins on animal performance as well as their effects on the efficiency that nutrients of diets are converted into food products is essential to understand such complex challenge. However, many of these effects are difficult to assess and quantify in conventional experimental designs, mainly due to ethical limitations and multiple interactions between influencing factors. In this context, a meta-analytical study was performed to investigate the effects of mycotoxins on the productive performance of broilers and growing pigs.

Materials and Methods

This study is a complementary approach to previously published meta-analyses (Andretta et al., 2011; Andretta et al., 2012) in which new responses are assessed using updated databases.

Scientific papers presenting experimental results of broilers and pigs challenged by mycotoxins were searched in different online data sources (Google Scholar, ScienceDirect, Scopus, Scielo, and PubMed) using the keywords: mycotoxin and performance, in addition to pig or broiler. References cited in the retrieved publications were also reviewed to identify additional articles considered relevant. After identification, the studies were critically evaluated in terms of their relevance and quality in order to answer all the questions raised using the meta-analysis approach. Abstracts were examined by coauthors and a record was only removed from the database when there was mutual agreement. In this step, a set of information about each selected study was analyzed through a checklist. Thus, the criteria for publication selection were: (a) complete research articles reporting (b) experimental *in vivo* studies assessing the effects of dietary intake of mycotoxins on (c) productive performance responses of (d) broilers (from 1 to 42 d old) or pigs (from post-weaning to finishing phases). After selecting the papers, information related to the proposed theoretical model and other additional variables were transferred to two electronic spreadsheets.

The methodology used for database construction and for data encoding followed the propositions described in the literature (Lovatto et al., 2007; Sauvant et al., 2008). Some codes were used with qualitative grouping criteria in the analytical models. Under this item, the main codes were applied for the presence of challenge (control or contaminated treatments) and mycotoxin type (broiler database: aflatoxins, deoxynivalenol, T2 toxin, and ochratoxin. Pig database: aflatoxins, deoxynivalenol, fumonisins, ochratoxins, zearalenone, T2 toxin, and nivalenol). Other codes were used as moderating variables in the analysis to consider the variability of the compiled trials (e.g.: effect of study or trial).

The analyzed variables were experimental characteristics (mycotoxin type and its concentration in diets) and performance responses (feed intake, weight gain, and calculated feed efficiency ratio). The meta-analyses were performed independently for each species, following three sequential analyses: graphical, correlation, and variance-covariance. The relationships between predetermined variables (experimental characteristics: animal age or body weight, mycotoxin concentration in diets; and animal performance: feed intake, body weight gain) were accessed using scatter charts. This procedure was performed to evaluate database quality and observe biological coherence of data. Unusual information or patterns were revised in the database. Outliers were not removed, as they may represent pathological responses (high variability may be expected in the performance of challenged animals). The Pearson correlation was accessed between variables, and significant results ($p < 0.05$) were used to identify related factors. Then, the analyses of variance were performed using the General Linear Model procedure to compare the treatments and obtain the prediction equations.

Equations were used to study the relation between feed intake and weight gain. For that purpose, the performance responses of challenged treatments were relativized to the respective control (non-challenged) treatment and expressed as percentage of variation (Δ). This procedure was adopted because it reduces considerably the variation effect between studies in the database. Relative data were used to generate equations that estimated the relationship between the variation in weight gain (ΔG) and in feed intake (ΔFI). The intercepts of the equations were empirically associated with the maintenance requirements, while the slopes were interpreted as an indication of changes associated with feed efficiency. The partition between these two effects was calculated considering the corrected ΔG (obtained using the equations) and the average ΔFI observed in the database. Similar interpretation was applied in previous studies on health challenges (Andretta et al., 2016; Pastorelli et al., 2012; Remus et al., 2014).

The effect of the dietary mycotoxin concentration on the animal productive performance was also studied using prediction equations. Relative performance data (ΔFI and ΔG) and dietary mycotoxin doses were used in this analysis.

The codes of the study effect were considered in all analytical models (variance and regression analysis) as a random effect. Linear and quadratic fits were tested in the regression analysis, but only equations in which all components were significant ($p < 0.05$) are presented in this paper. All analyses were performed using Minitab software (Minitab Inc., version 17).

Results

Description of the databases

The database containing broiler information occupied 1,349 lines on the electronic spreadsheet. Each line of the database referred to a treatment in the original publication. However, some treatments occupied more than one line when the measures were taken repeatedly over time. Data was obtained from 158 research papers published from 1980 to 2016. Poultry Science (27 % of the papers), International Journal of Poultry Science (4 %), and The Journal of Applied Poultry Research (3 %) were the journals with greater participation in the database. Most of the studies were conducted in the United States (20 % of the studies), Iran (12 %), Brazil (11 %), India (11 %), and China (8 %). The studies included in the database totaled 51,497 broilers, most of which were Ross (39 % of the treatments with genetic line information) and Cobb (19 %). Most of the papers used male broilers (63 %), while 4 % used females, 17 % used unsexed birds, and 16 % did not describe the gender. Average mycotoxin concentrations tested were 0.63 ppm of aflatoxins (ranging from 0 to 5 ppm), 3.40 ppm of deoxynivalenol (0 to 15 ppm), 2.23 ppm of T2 toxin (0 to 13.5 ppm), 0.71 ppm of ochratoxins (0 to 4.18 ppm), and 106.9 ppm of fumonisins (0 to 400 ppm). Mycotoxin concentration in the experimental diets was verified by laboratory analyses in 64 % of the studies that composed the broiler database.

The database constructed using pig information occupied 669 lines on the electronic spreadsheet. Data from 72 papers published from 1980 to 2015 were used in this database. The Journal of Animal Science (25 %) and Animal Feed Science and Technology (6 %) had the greater participation in the database. Most of the studies were developed in the United States (24 % of the studies), France (19 %), Canada (13 %), Brazil (8 %), and China (7 %). The studies used in this database totaled 7,743 pigs, from which 80 % were in the post-weaning phase. Most of the papers used mixed-sex groups (49 %), while 21 % used males, 15 % used females, and others did not describe the pig gender in the study. Average mycotoxin concentrations were 0.57 ppm of aflatoxins (ranging from 0 to 3 ppm), 3.49 ppm of deoxynivalenol (0 to 16.6 ppm), 1.36 ppm of zearalenone (0 to 3 ppm), and 25.12 ppm of fumonisins (0 to 120 ppm). The mycotoxin concentration in the experimental diets was verified by laboratory analyses in 57 % of the studies that composed the pig database.

Performance responses

Broilers fed diets containing mycotoxins reduced (p < 0.05) feed intake by 9 %, weight gain by 15 % and feed efficiency ratio by 6 % (Table 1), compared to control treatments. The mycotoxins with the greatest impact on feed intake were aflatoxins and T2 toxin, both with a 10 % reduction (p < 0.05) compared to non-challenged animals. Reduction (p < 0.05) in feed intake was also observed in broilers that were fed diets with ochratoxins (Δ = −7 %). Birds fed diets containing ochratoxins or T2 toxin presented the greatest impact (Δ = −21 %, p < 0.05) on daily weight gain, but growth reduction (p < 0.05) was also observed in challenges by aflatoxin (Δ = −15 %) and deoxynivalenol (Δ = −11 %). Feed efficiency ratio was reduced (p < 0.05) in broilers that received diets with ochratoxins (Δ = −11 %), aflatoxins (Δ = −6 %), and T2 toxin (Δ = −2 %) in relation to the respective control groups.

Mycotoxin challenges in pigs reduced (p < 0.05) feed intake by 6 %, weight gain by 11 %, and feed efficiency ratio by 4 %, compared to control groups (Table 2). Feed intake reduction (p < 0.05) was observed in pigs that consumed diets containing aflatoxins (Δ = −8 %) and deoxynivalenol (Δ = −10 %). Growth response was reduced (p < 0.05) in pigs receiving diets containing aflatoxins (Δ = −11 %), deoxynivalenol (Δ = −10 %), and fumonisins (Δ = −13 %). The feed efficiency ratio was reduced (p < 0.05) in pigs fed diets containing fumonisins (Δ = −10 %), deoxynivalenol (Δ = −8 %), and aflatoxins (Δ = −7 %) in relation to non-challenged groups.

Effect of dietary mycotoxin concentration

Dietary concentrations of mycotoxins were correlated with the variation in feed intake (ΔFI) and in weight gain (ΔG) in challenged broilers and pigs. The aflatoxin level in diets showed negative correlation with ΔFI (broilers: -0.389, pigs: -0.496; p < 0.001) and ΔG responses (broilers: -0.266, pigs: -0.327; p < 0.001).

ΔFI of 16 % in broiler was estimated for each dietary ppm of aflatoxins, while this response was estimated at 6 % for each ppm of aflatoxins in the pig diet (Figure 1). When aflatoxins were included in diets combined with other mycotoxins, ΔFI associated to each ppm of dietary aflatoxins increased to 74 % in broilers and 27 % in pigs. In addition, ΔFI of 3 % was observed per ppm of T2 toxins in broilers, while a reduction of 9 % was observed in the birds per each dietary ppm of ochratoxins. ΔFI of pigs challenged by deoxynivalenol was also estimated at 4 % per each dietary ppm.

ΔG of 16 % in broilers and 36 % in pigs was expected for each ppm of isolated aflatoxin in diets, while 41 % for broilers and 45 % for pigs (Figure 2) was estimated for each ppm of aflatoxin when combined with other mycotoxins in diets. Likewise, the estimated ΔG per ppm of deoxynivalenol was 4 %, while a reduction of 0.48 % was estimated per ppm of dietary fumonisins. The estimated ΔG in broilers was 0.82 % per ppm of deoxynivalenol, 6 % per ppm of T2 toxins, and 11 % per ppm of ochratoxins in the diets.

Table 1 – Performance (mean ± standard error) of broilers challenged by mycotoxins (MYC), aflatoxins (AFLA), deoxynivalenol (DON), toxin T2 (T2), ochratoxins (OCHR), fumonisins (FMN), or zearalenone (ZEA).

Variables	MYC	AFLA	DON	T2	OCHR	FMN	ZEA
n	1345	887	143	136	127	117	55
Daily feed intake, kg d^{-1}							
Control	0.0797 ± 0.0012	0.0809 ± 0.0014	0.1004 ± 0.0072	0.0733 ± 0.0025	0.0704 ± 0.0025	0.0666 ± 0.0022	0.1106 ± 0.0034
Challenged	0.0723 ± 0.0011	0.0727 ± 0.0013	0.0961 ± 0.0064	0.0659 ± 0.0022	0.0652 ± 0.0022	0.0632 ± 0.0017	0.1065 ± 0.0028
R^2	0.84	0.83	0.79	0.93	0.89	0.96	0.98
Age	19.9	20.2	23.6	18.1	20.7	16.4	27.6
p	< 0.001	< 0.001	0.562	0.017	0.028	0.146	0.222
Daily weight gain, kg d^{-1}							
Control	0.0450 ± 0.0006	0.0457 ± 0.0007	0.0540 ± 0.0028	0.0431 ± 0.0029	0.0383 ± 0.0018	0.0387 ± 0.0026	0.0615 ± 0.0023
Challenged	0.0383 ± 0.0006	0.0387 ± 0.0007	0.0480 ± 0.0025	0.0343 ± 0.0026	0.0303 ± 0.0017	0.0362 ± 0.0020	0.0597 ± 0.0019
R^2	0.79	0.78	0.80	0.73	0.80	0.83	0.97
Age	18.5	19.0	22.3	17.3	17.9	14.9	27.6
p	< 0.001	< 0.001	0.042	0.011	< 0.01	0.346	0.416
Feed efficiency, kg kg^{-1}							
Control	0.610 ± 0.007	0.604 ± 0.006	0.617 ± 0.059	0.587 ± 0.011	0.601 ± 0.030	0.632 ± 0.016	0.600 ± 0.020
Challenged	0.574 ± 0.006	0.566 ± 0.006	0.601 ± 0.053	0.578 ± 0.009	0.532 ± 0.027	0.618 ± 0.012	0.605 ± 0.016
R^2	0.59	0.70	0.29	0.84	0.46	0.86	0.67
Age	19.6	19.9	23.6	17.8	18.5	16.2	27.6
p	< 0.001	< 0.001	0.061	0.048	0.046	0.443	0.764

n = Number of treatments considered in each analysis; R^2 = Coefficient of determination; Age = Mean age, in days, considered as covariate in the analytical model (p < 0.01 for all responses); p = Probability of challenge effect. Models also considered the effect of studies (p < 0.001 for all responses).

Table 2 – Performance (mean ± standard error) of pigs challenged by mycotoxins (MYC), aflatoxins (AFLA), deoxynivalenol (DON), fumonisins (FMN), or zearalenone (ZEA).

Variables	MYC	AFLA	DON	FMN	ZEA
n	669	200	318	113	116
Daily feed intake, kg d^{-1}					
Control	1.264 ± 0.276	1.382 ± 0.384	1.207 ± 0.044	1.064 ± 0.034	0.952 ± 0.042
Challenged	1.183 ± 0.110	1.276 ± 0.370	1.092 ± 0.040	1.076 ± 0.029	0.851 ± 0.036
R^2	0.248	0.97	0.93	0.96	0.90
BW	27.2	21.9	28.5	28.4	22.8
p	< 0.001	0.025	0.027	0.740	0.051
Daily weight gain, kg d^{-1}					
Control	0.560 ± 0.012	0.530 ± 0.223	0.527 ± 0.021	0.541 ± 0.033	0.526 ± 0.021
Challenged	0.500 ± 0.011	0.474 ± 0.214	0.447 ± 0.019	0.472 ± 0.029	0.464 ± 0.019
R^2	0.71	0.50	0.81	0.71	0.73
BW	26.3	21.9	28.0	27.1	22.3
p	< 0.001	0.022	0.002	0.044	0.058
Feed efficiency, kg kg^{-1}					
Control	0.630 ± 0.008	0.603 ± 0.009	0.532 ± 0.020	0.599 ± 0.023	0.628 ± 0.025
Challenged	0.605 ± 0.007	0.560 ± 0.009	0.488 ± 0.018	0.542 ± 0.021	0.607 ± 0.022
R^2	0.97	0.92	0.61	0.74	0.98
BW	27.2	21.9	28.5	28.4	28.8
p	0.014	0.045	0.040	0.031	0.505

n = Number of treatments considered in each analysis; R^2 = Coefficient of determination; BW = Mean body weight, in kg, considered as covariate in the analytical model ($p < 0.01$ for all responses); *p* = Probability of challenge effect. Models also considered the effect of studies ($p < 0.001$ for all responses).

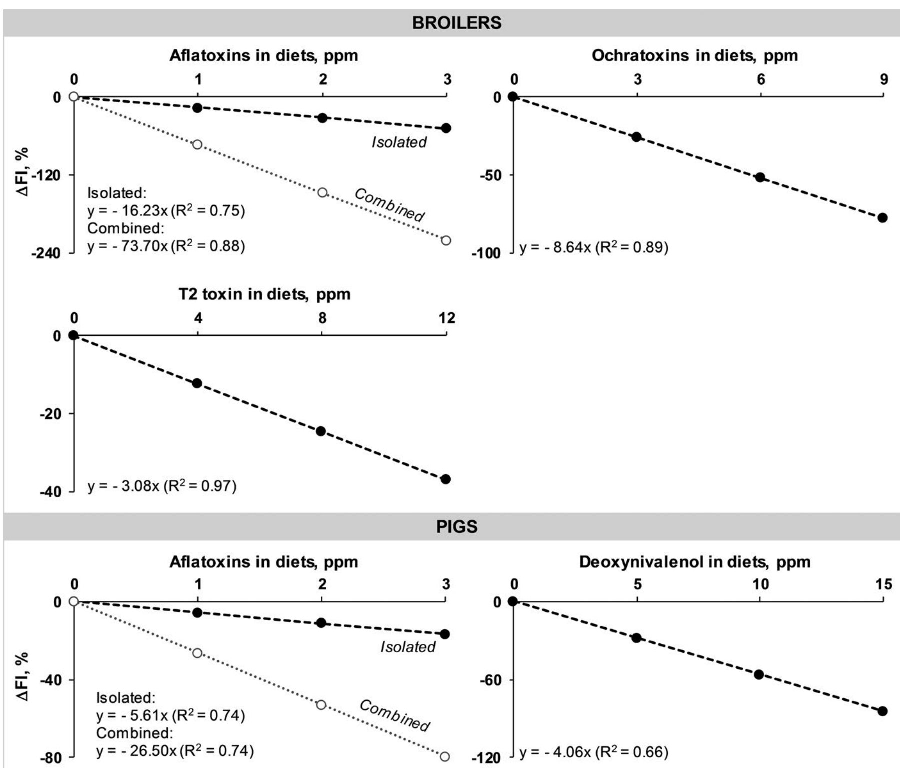

Figure 1 – Feed intake variation (ΔFI) in broilers and pigs challenged by aflatoxins, deoxynivalenol, T2 toxin, or ochratoxins relative to mycotoxin concentration in diets.

Quadratic fit was also applied to assess the effect of dietary mycotoxin levels on the performance reduction in broilers and pigs. The quadratic term was not significant, neither assessing ΔFI in pigs and broilers, nor ΔG in pigs. However, a quadratic fit was found assessing the effect of mycotoxin concentrations on broilers ΔG. Both equations (linear and quadratic, Figure 2) showed very similar coefficient of determination and exhibited

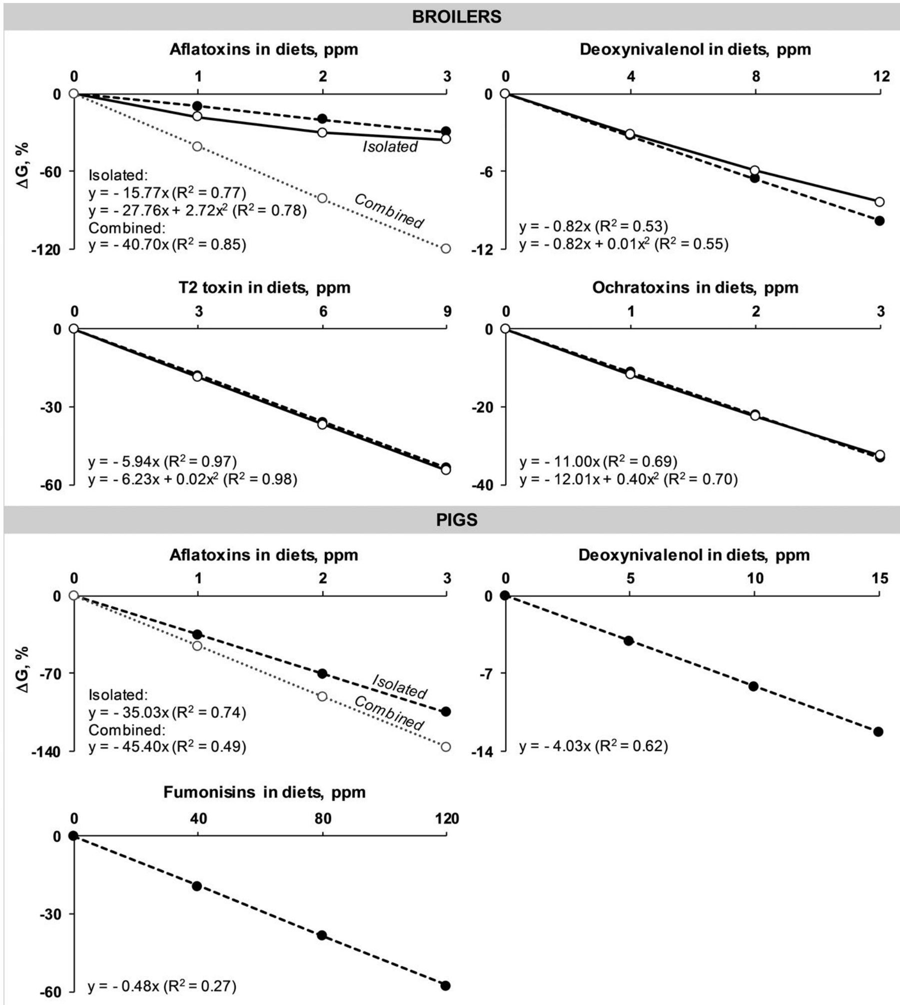

Figure 2 – Weight gain variation (ΔG) in broilers and pigs challenged by aflatoxins, deoxynivalenol, T2 toxin, ochratoxins, or fumonisins relative to mycotoxin concentration in diets.

comparable patterns. The low availability of results obtained in challenges with higher mycotoxin concentrations may partially explain this condition.

Feed efficiency in challenged animals

The correlation between ΔG and ΔFI was 0.686 ($p < 0.001$) for broiler and 0.389 ($p < 0.001$) for pigs in the overall database. Higher correlation values (0.739 for broilers and 0.825 for pigs, $p < 0.001$) were found when assessing only aflatoxin challenges.

ΔG showed a linear relationship with ΔFI in both databases (Figure 3). The intercepts of the equations were different from zero and negative in both challenges. The condition was observed for broilers (−7.73 % for overall database, −9.10 % for aflatoxins) and pigs (−8.18 % for overall database, -4.18 % for aflatoxins). In these equations, the intercept may be interpreted as the reduction on weight gain (ΔG) that is expected when no effect on feed intake is observed (i.e., ΔFI = 0). The partition of the effects on ΔG corrected for average ΔFI is presented in Figure 4. Considering the overall database, 48 % and 26 % of ΔG in broilers and pigs, respectively, was related with changes in feed efficiency. Otherwise, in the aflatoxin challenges, the fraction of ΔG related with changes in feed efficiency was estimated at 39 % in broilers and 62 % in pigs.

Discussion

General overview of the databases

Pigs are extremely sensitive to mycotoxins (Hussein and Brasel, 2001). However, the systematic literature review performed in this study found more publications assessing poultry mycotoxicoses (158) than papers dealing with this disease in pigs (72). A similar scenario is found for other research topics. In addition, the number of publications does not indicate by itself the quality, importance or refinement of the research in the field.

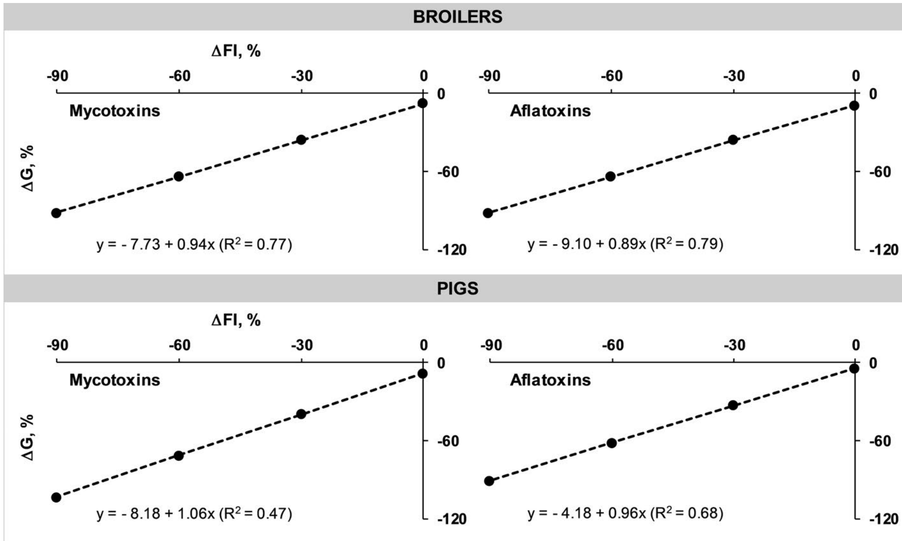

Figure 3 – Relationship between weight gain variation (Δ) and feed intake variation of broilers and pigs fed diets containing mycotoxins.

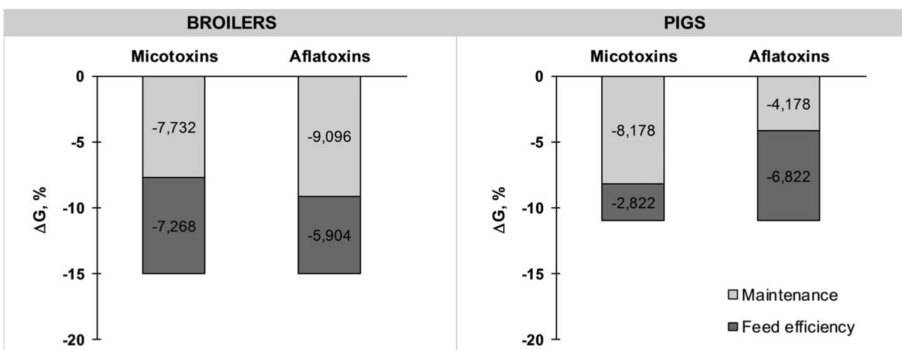

Figure 4 – Partitioning of weight gain variation (corrected Δ) between the fraction due to the change in maintenance requirement or in feed efficiency of broilers fed diets containing mycotoxins.

As expected, the concentrations tested in the studies varied greatly among mycotoxins, which is in agreement with the large variation in the mycotoxin concentration in feeds and ingredients throughout the year and between geographical distinct regions. Differences were also observed when comparing the same mycotoxin between the databases (i.e. between species). In general, the trials with broilers tested higher concentrations of mycotoxins (e.g. average level of aflatoxins and fumonisins were respectively 10 and 77 % higher in relation to pig trials). As most trials used controlled challenges (i.e. induced, not natural contaminations), the lower mycotoxin concentrations tested in pig feeds reflect the greater sensibility of this species to the toxic effects (Hussein and Brasel, 2001).

Considering that the databases used in our study encompassed an important part of the research in this field, it is appropriate to use these data to identify opportunities for future research projects. Some are listed here, also to point out limitations of the current research field.

Most information used in the databases was collected in male animals, especially in the broiler dataset. The influence of sex on the animal sensitivity to mycotoxins had already been reported in birds (Bryden et al., 1980) and pigs (Andretta et al., 2012; Marin et al., 2006). However, very little information is available to clarify the sex-related effects of mycotoxins on animal performance. Another topic that remain unclear is the effect of feeding programs or nutritional status on the responses of pigs and broilers to the mycotoxin challenge. Previous research already showed that some dietary approaches (additives, antioxidant components, nutrients, among others) may play an important role during the mycotoxicoses (Andretta et al., 2011; Andretta et al., 2012; Galvano et al., 2001; Guilford and Hope, 2014). Although closely related, nutritional aspects are neglected by several researchers, as some papers included in the database did not even properly described the nutritional composition of the diets used in the trials. A table describing feed composition was found only in 41 % of the papers in the broiler database and in 58 % of the papers in the pig database. Due to the lack of information available, this relationship is difficult to evaluate using a systematic review or meta-analysis.

Performance responses

As expected, deleterious effects of most mycotoxins on productive performance were observed in the current study. Databases encompassed several scenarios (experimental diversity of the original studies) and, therefore, the results obtained in this study may be useful in models to simulate animal performance during mycotoxin challenges.

The effects on animal performance varied between species and differed between mycotoxins. Each substance has a diverse mechanism of action by which can affect animal performance. In some cases, these mechanisms are still not fully known. Reduction in feed intake (in many animal species, particularly in pigs) may be attributed to organoleptic changes due to the fungal growth in feed naturally contaminated (Akande et al., 2006). Oral lesions or other discomfort signals caused by mycotoxins are also reasons by which feed intake is depressed in challenged animals (Forbes, 2007). Food refuse was reported even when the toxin is intraperitoneally infused (Prelusky, 1997), suggesting that other mechanisms unrelated to palatability (e.g. neuroendocrine factors and innate immune response) may contribute in manifestation of anorexia during mycotoxicosis (Flannery et al., 2011).

The negative interference of mycotoxins on nutrient absorption and protein synthesis may explain the reduction on weight gain of challenged animals (Coulombe Jr., 1993; D´Mello et al., 1999; Hussein and Brasel, 2001; Verma et al., 2002). In addition, direct effects of mycotoxins on target organs, disturbances in important metabolic pathways, and changes in nutrient balance are relevant to explain growth reduction in animals fed diets containing mycotoxins (Coulombe Jr., 1993; Hussein and Brasel, 2001).

The results of this study confirmed that growth suppression in challenged animals resulted largely from the capacity of mycotoxins to inhibit feed intake, but it cannot be explained only by this inhibition. This is important since the effects are difficult to quantify in conventional experimental designs. The approach used in our study evaluated the relationship between ΔFI and ΔG. When ΔFI was set to zero in the equations (i.e. simulating a scenario without changes in feed intake), ΔG was estimated at -8 % in broilers and -8 % in pigs challenged by mycotoxins. In the same simulation, broiler challenged by aflatoxins showed ΔG -9 % and with a reduction of 4 % in pigs. These values may indicate an increase in maintenance requirements when animals were challenged (Andretta et al., 2016; Pastorelli et al., 2012; Remus et al., 2014). Further evaluation of the effects shows that an important part of ΔG (48 % and 26 % in overall challenges; 39 % and 62 % in the aflatoxin challenges for broilers and pigs, respectively) may be related to a decrease in feed efficiency, which highlight the importance of better understanding the mechanisms by which the mycotoxins interfere on the metabolism of animals. Thus, studies using pair-feeding methods should be encouraged in this research field.

Factors affecting performance responses

Most toxicity mechanisms are specific for each type of mycotoxin. The metabolites derived from aflatoxins react with cellular macromolecules such as DNA and RNA, interfering with the functional properties of the liver and protein synthesis (Coulombe Jr., 1993; D'Mello and MacDonald, 1997). Inhibition of protein synthesis is also an important mechanism of ochratoxins and trichothecenes, such as deoxynivalenol (D'Mello and MacDonald, 1997; D´Mello et al., 1999). Estrogenic effects and interferences in reproductive functions are the main manifestations related to zearalenone (Zinedine et al., 2007). On the other hand, the proposed action mode of fumonisins relates its toxicity to interferences on sphingolipid biosynthesis (Marin et al., 2006).

In addition to the type of mycotoxin in the challenge, its dietary concentration was an important factor to explain the reduction on the productive performance of challenged animals. Dietary concentrations of mycotoxins were correlated to Δ FI and ΔG in challenged broilers and pigs. Although significant, these correlations were low, which indicates that other factors may also interfere on the performance of broilers and pigs during mycotoxicosis.

Equations with a good fit were obtained to predict the implication of dietary mycotoxin concentrations on ΔFI and ΔG of broilers and pigs. These empirical models can be used as decision-supporting tools in feed industries. However, these models were generated using experimental data and may not fully reflect a field condition. In this scenario, the complexity of factors affecting animal performance may interfere in the precision of the equation to predict the performance of challenged animals.

Mycotoxins can cause immunosuppression, resulting in many disease outbreaks, vaccination failures, and poor antibody titers (Awad et al., 2013; Murugesan et al., 2015). These failures may be observed even at concentration levels lower than those causing clinical mycotoxicoses. These problems may be related to outbreaks of other diseases and consequent reduction of productive performance. Despite their importance to the livestock industry, these indirect effects of mycotoxicoses could not be measured in this study due to their complexity and the lack of information available on particular interactions.

Another important factor interfering in the effect of mycotoxin concentrations on ΔFI and ΔG is the incidence of combined mycotoxins in the same diet. This is a very common problem in the feed industry because several mycotoxins may be produced concomitantly in a given substrate and ingredients may be cross-contaminated in feed mills (Grenier and Oswald, 2011; Speijers and Speijers, 2004). Interactions between mycotoxins are complex and may result from the association of individual toxic properties or additive effects (Speijers and Speijers, 2004). Some of these interactions were studied in this research and the results confirmed that the same concentration of mycotoxin may cause worse performance responses when animals are challenged by combined mycotoxins.

Mycotoxins are important in poultry and pig industries due to severe damages to animal health, affecting profitability of productive systems. This exploratory study allowed addressing and quantifying systematically the association of mycotoxins with animal performance. Current results also indicated some fields that need to be focused in future studies.

Authors' Contributions

Conceptualization: Kipper, M.; Andretta, I. Data acquisition: Kipper, M.; Andretta, I.; Ribeiro, A.M.L.; Pires, P.G.; Franceschina, C.S.; Cardinal, K.M.; Moraes, P.O.; Schroeder, B. Design of methodology: Kipper, M.; Andretta, I. Writing and editing: Kipper, M.; Andretta, I.; Ribeiro, A.M.L.; Pires, P.G.; Franceschina, C.S.; Cardinal, K.M.; Moraes, P.O.; Schroeder, B.

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