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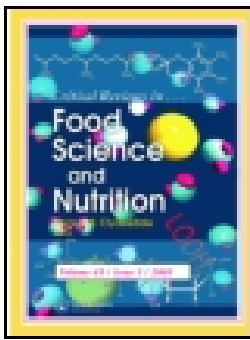
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Worldwide contamination of food-crops with mycotoxins: Validity of the widely cited 'FAO estimate' of 25%

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ABSTRACT

Prior to 1985 the Food and Agriculture Organization (FAO) estimated global food crop contamination with mycotoxins to be 25%. The origin of this statement is largely unknown. To assess the rationale for it, the relevant literature was reviewed and data of around 500,000 analyses from the European Food Safety Authority and large global survey for aflatoxins, fumonisins, deoxynivalenol, T-2 and HT-2 toxins, zearalenone and ochratoxin A in cereals and nuts were examined. Using different thresholds, i.e. limit of detection, the lower and upper regulatory limits of European Union (EU) legislation and Codex Alimentarius standards, the mycotoxin occurrence was estimated. Impact of different aspects on uncertainty of the occurrence estimates presented in literature and related to our results are critically discussed. Current mycotoxin occurrence above the EU and Codex limits appears to confirm the FAO 25% estimate, while this figure greatly underestimates the occurrence above the detectable levels (up to 60–80%). The high occurrence is likely explained by a combination of the improved sensitivity of analytical methods and impact of climate change. It is of immense importance that the detectable levels are not overlooked as through diets, humans are exposed to mycotoxin mixtures which can induce combined adverse health effects.

KEYWORDS



Chemical contaminant; occurrence; cereals; data; analysis; uncertainty

Introduction

Occurrence of mycotoxins is widespread throughout the world. Their acute and chronic dietary exposures can induce a variety of adverse health effects in humans and animals, making these chemically diverse substances highly relevant agricultural contaminants. They typically co-occur in agricultural crops and through diversified diets, exposure to mixtures of mycotoxins is common. Many fungal species produce them as a defense against their changing environmental growing conditions; *Aspergillus*, *Fusarium* and *Penicillium* regarded as the most important producers. Despite many years of research, and the introduction of good agricultural and manufacturing practices in the food chain, mycotoxin occurrence remains to be a global problem. Significant economic losses are associated with the impact of mycotoxins on human health, animal welfare and productivity, and both domestic and international trade (Pitt and Miller 2017; Wu and Mitchell 2016). Combined toxicological effects from the mycotoxin co-exposure are increasingly studied (Alassane-Kpembé et al. 2017; Grenier and Oswald 2011; EFSA 2016, 2017a, 2017b, 2017c, 2017d, 2018a, 2018b; JECFA 2011; Lee and Ryu 2017). Currently, aflatoxins (AFs), deoxynivalenol (DON), T-2 toxin (T-2),

HT-2 toxin (HT-2), zearalenone (ZEN), fumonisins (FBs), ochratoxin A (OTA), ergot alkaloids (EAs), patulin and citrinin are considered to be the mycotoxins of the greatest importance from food safety and regulatory viewpoints. This is evident not only because of the large number of published research, and the many international and national toxicity and exposure assessment reports, but also due to the extensive standards and legislation, which have been in place for many years to safeguard public and animal health at the world, European Union (EU) and national levels (Eskola et al. 2018; EUR-Lex 2018; WHO 2018).

AFs B1, B2, G1, G2 and M1 can be regarded as the most important mycotoxins owing to their genotoxic carcinogenic properties. In fact, AFs are amongst the most potent mutagenic and carcinogenic substances known. AFB1 is the most potent followed by AFG1 and AFM1 (JECFA 1999, 2017). The chronic AF-exposure induces liver cancer, infections and growth impairment in humans, while high exposures cause acute symptoms, even a death (EFSA 2004a, 2007, 2012a, 2018c; IARC 1993, 2002, 2012, 2015; JECFA 1997, 1998, 1999, 2002, 2008, 2017). Sterigmatocystin, a genotoxic-carcinogen, shares its biosynthetic pathway with aflatoxins and has the same target organ (liver) with AFB1 (JECFA

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2018). Cereals and different types of nuts and their products are the main exposure sources. The contribution of maize, peanuts, rice, sorghum and wheat each make more than 10% to the global exposure to AFs (JECFA 2017). The AFB1-metabolite AFM1 may be present in milk (EFSA 2004a, 2007; IARC 2002; JECFA 1997, 1999; Shephard 2008). Co-exposure to genotoxic AFB1 and FBs, which may induce regenerative cell proliferation, is of health concern, but due to the marked differences in their modes of action the combined effects are unlikely additive (IARC 2015; JECFA 2012, 2017). Of the FB-analogues, FB1 is the most predominant, comprising about 70% of the total FB-contamination. FB2 and FB3 co-occur with FB1 but with lower concentrations (IARC 2015; JECFA 2012, 2017). Oral exposure to FBs induces a wide range of adverse effects, with notable species differences (Deepa and Sreenivasa 2017; EFSA 2005a, 2014, 2018a; IARC 2002, 2015; JECFA 2001, 2002, 2012, 2017; WHO 2000). Liver is the target organ for FB-mediated toxicity in mice and kidney in rats, while in horses equine leukoencephalomalacia and in pigs porcine pulmonary edema with signs of liver toxicity can occur. FB1, FB2, FB3 and FB4 and their modified forms have similar toxicological profiles, but the potencies of the modified forms are lower (EFSA 2018a). FB1 is possibly carcinogenic to humans, and an association between chronic dietary exposure and human esophageal and liver cancer has been claimed, but causality has not been confirmed (EFSA 2018a; IARC 2002; JECFA 2001, 2012, 2017).

DON occurs in cereal grains alone or in combination with its most relevant forms 3-acetyl-DON, 15-acetyl-DON and DON-3-glucoside (10–20% of the DON-levels) (EFSA 2011, 2017d; JECFA 2001, 2011; McCormick et al. 2011; Nathanail et al. 2015; Vanheule et al. 2014). The exposure is mainly from cereals and cereal-based foods, wheat making the highest proportion (56–100%) (EFSA 2004b, 2011, 2017d; JECFA 2001, 2011). High exposure mediates acute gastrointestinal symptoms in humans (e.g. vomiting) but the effects from the chronic human exposure are unknown (EFSA 2004b, 2011, 2017d; IARC 1993; JECFA 2001, 2011; SCF 1999). Weight gain suppression and anorexia are the most common chronic effects in animals (JECFA 2001, 2011; EFSA 2017d). T-2 and HT-2 are also regularly found in cereal grains, but with lower frequency and levels than DON. Their chronic exposure induces general toxicity, hemato- and immunotoxicity and high exposure vomiting in animals (EFSA 2011, 2017b). Both DON and T-2 appear not to be carcinogenic (EFSA 2011, 2017b, 2017d; IARC 1993; JECFA 2002). ZEN is a common contaminant in maize and other grains making the cereal-based food its main source of exposure (EFSA 2011, 2014, 2016, 2017c; JECFA 2000; Nathanail et al. 2015; Vanheule et al. 2014). Female pigs are the most sensitive species (including human) towards its estrogenic activity (EFSA 2011, 2014, 2016, 2017c; IARC 1993; JECFA 2000; SCF 2000a). Relative estrogenic potencies show that some modified ZEN forms are markedly more estrogenic than ZEN itself (EFSA 2016). No definite link of a high ZEN-exposure with negative health effects in humans has been concluded. Nor ZEN was classifiable as to its

carcinogenicity in humans, although some data are available (EFSA 2011, 2017c; IARC 1993).

Although OTA is present in variety of foods (e.g. cereals, pulses, coffee beans, grapes, cacao beans, nuts, spices and animal-based foods), 60% of its total exposure is from cereals (EFSA 2006; IARC 1983, 1993; JECFA 1996, 2001, 2007, 2008; Marin et al., 2013). Kidney is the main target, OTA exposure exhibiting nephrotoxicity in animals (EFSA 2006; IARC 1983, 1993; JECFA 1996, 2001, 2007, 2008). Species-differences exist and pigs, poultry and dogs seem to be the most sensitive (EFSA 2004c, 2006; JECFA 1996, 2001, 2002, 2007, 2008). The causality of OTA inducing human nephropathy remains unclear but OTA appears to be one cause of the endemic Balkan nephropathy (Bui-Klimke and Wu 2014; EFSA 2006, 2010; JECFA 1996, 2001, 2002, 2007, 2008; Stiborová et al. 2016). In rodents OTA is a potent renal carcinogen, and it is possibly carcinogenic to humans (IARC 1993). Other regulated mycotoxins are patulin, EAs and citrinin, but based on the published assessments and other relevant data they appear to be less relevant from the food safety viewpoint (Diana Di Mavungu et al. 2011; EC 2006a; EFSA 2005b, 2012b, 2012c, 2017e; FDA 2001a; IARC 1986; Iqbal et al. 2018; JECFA 1996; Krska and Crews 2008; López Sánchez et al. 2017; Mornar et al. 2013; Pleadin et al. 2018; Puel et al. 2010; SCF 2000b; SCOOP 2002; Topi et al. 2017; WHO 1990). There are also several mycotoxins not included in any legislation or standards due to their apparent minor relevance (Eskola et al. 2018; JECFA 2017; WHO 1990). These mycotoxins are excluded from this paper.

Widely cited estimate of 25% world's food crops contaminated with mycotoxins

Over the years, published mycotoxin papers and reports have aimed at estimating the overall global prevalence of mycotoxins in agricultural crops. In this context, authors have often referred to an estimate of 25%, supposedly by Food and Agriculture Organization (FAO), published by Park and coauthors in the FAO Food, Nutrition and Agriculture Journal, number 23 in 1999. The second sentence states that 'According to FAO, at least 25 percent of the world's food crops are contaminated with mycotoxins, at a time when the production of agricultural commodities is barely sustaining the increasing population (Boutrif and Canet 1998)'. However, further evidence of the background for the figure of 25% is not provided by Park et al. (1999). Looking more in detail into the paper by Boutrif and Canet (1998) published in *Revue de médecine vétérinaire*, to which Park et al. (1999) refers, no figure or mention of 25% of food crops contaminated with mycotoxins can be found in this paper. It is also noted that on 28 February 1985 in the journal of *New Scientist*, Mannon and Johnson write in their article on mycotoxin contamination that according to the FAO, mycotoxins contaminate some 25% of the world's food crop, and later in the article they state that 'FAO has estimated that 25% of the world's food crops are ruined by mycotoxins' (Mannon and Johnson 1985). The authors do

not give any other references, except FAO, to the information of 25% contamination rate.

Thus, to best of our knowledge, it seems that there is no accurate published reference available for the figure of 25% world's food crop mycotoxin-contaminated. Nor there is any information on which dataset this estimate was based on or how it was calculated. Following the exchange of views with the FAO officials in spring 2017, it turned out that neither them were able to trace back the origin of the estimate. However, it could be reasonable to presume that the estimate of FAO stems from the proportion of the mycotoxin-contaminated food crops exceeding the Codex standards in place at the time, rather than from the contaminated food crops above the limits of detection (LODs)/limits of quantification (LOQs) of the analytical methods used back then. The estimate of 25% presented in the FAO journal back in 1999 has been widely cited since then in many publications. Over the years it has therefore become 'THE' reference value for the mycotoxin incidence in food crops at the global level. This can be evidenced for example by carrying out a search for key words 'FAO 25%, mycotoxins' through the Google search engine (19 August 2019) resulting in thousands of citations varying from the citations in the documents of the public national and international food safety organizations (including FAO) to the citations in research papers and in industry documents. For these aforementioned reasons, it is therefore highly important to discuss where this decades old FAO estimate for the world's mycotoxin-contaminated food crops stands today.

Notably in the recent past, data on large surveys on mycotoxin occurrence across the world have been released suggesting higher mycotoxin prevalence than 25% stated by FAO. Streit et al. (2013) reported that overall 72% of the around 17,300 feed samples origin from different parts of the world collected over eight years contained mycotoxins. Also, Kovalsky et al. (2016) reported that mycotoxin contamination in feeds could be up to 79% or even above in about 2000 samples from 52 countries. The authors noted that the observed frequency is considerably higher than FAO's 25% and concluded that the outcome of their study is a starting point for a more detailed investigation of mycotoxin contamination rates at the global level. They further emphasized that more data should be included in such an investigation. Similar high frequencies of mycotoxins in feed were recently published by Biomin (2017) (see also below) in a large survey comprising 72 countries across the globe. Although in these surveys mainly animal feed samples have been studied, they point to the direction that the prevalence of mycotoxin-contaminated food crops could also be higher than the 25%-estimation of FAO.

The aim of this paper is to provide a compilation of the most recent and most relevant published information on the estimated global prevalence of mycotoxins in food crops, in particular. Mainly food-grade cereals and nuts are considered. However, no large harmonized global-level mycotoxin occurrence surveys for food crops were identified in the literature, while for feed they are accessible. Therefore, the relevant data on mycotoxin-contaminated feed are also noted in this paper

although in general prevalence is assumed to be higher in feed crops than in food crops. Only those mycotoxins which are included in the standards of Codex Alimentarius and/or in the regulations of the EU are addressed in this review.

The World Health Organization (WHO) collects global food occurrence data on mycotoxins from the published literature and through its call for data. As these data are carefully scrutinized and cleaned by the WHO/FAO experts, the authors considered that the risk assessments of the Joint FAO/WHO Expert Committee on Food Additives (JECFA) represent currently the best available literature source for the global-level estimates of mycotoxin prevalence in food crops. Therefore, the estimates calculated by JECFA for mycotoxin-contaminated food crops are presented in this paper. In addition, the global estimates of prevalence from those individual research papers, which were considered of providing added value, were included. Furthermore, mycotoxin prevalence was assessed by the authors using two large datasets. The first one comprised the occurrence data on food collected in 2010–2015 by European Food Safety Authority (EFSA) from the EU Member States. These data were requested from EFSA through the application of the EU-regulation No 1049/2001 on public access to documents (EP and Council 2001). The second dataset on mycotoxins in feed was from Biomin Inc., Austria. Aspects causing variability in the occurrence data and impacting the uncertainty of the estimated mycotoxin prevalence are also discussed.

Variability and uncertainties associated with prevalence estimates of mycotoxins in food-crops

Many aspects cause variability in the data and therefore impact the uncertainty of the estimated frequencies of mycotoxin-contamination. This should be kept in mind when estimating the prevalence of mycotoxins in food and feed crops at the global level. Therefore, it is clear that the estimate for the overall mycotoxin-contaminated crops at the global level, based on the currently available data, can at its best be an indicative rather than an exact figure. Before an accurate estimate can be provided, statistically relevant amount of high-quality data should be made available. Therefore, large occurrence data surveys on mycotoxin contamination in food-crops, with harmonized sampling strategies and analytical performance criteria, across the world over several growing seasons should be conducted.

Different regulatory levels and standards impact the reported mycotoxin prevalence

The applied regulatory levels and standards of mycotoxins vary in the different regions of the world. At the global level, the Codex Alimentarius Commission of the Food, the joint inter-governmental body of FAO and WHO, is the main operator in standard setting. The Codex standard CXS 193-1995 establishes maximum levels (MLs) for AFs (sum of AFB1, AFB2, AFG1 and AFG2, and, separately, AFM1 in milk), DON, FBs (sum of FB1 and FB2) and OTA for different foods (Codex Alimentarius 1995). The Codex standard

Table 1. Maximum levels for most often regulated mycotoxins in food crops.

Mycotoxin	Food crop	Established levels (µg/kg)	
Codex Alimentarius standard			
Aflatoxins	Almonds, Brazil nuts, hazelnuts, peanuts, pistachios for processing	AFB1	Total
	Almonds, Brazil nuts, hazelnuts, pistachios for direct human consumption	—	15
Fumonisin B1 + B2	Unprocessed maize	4000	10
Deoxynivalenol	Cereal grains (wheat, maize and barley) for processing	2000	
Ochratoxin A	Unprocessed wheat, barley, rye	5	
European Union maximum and guidance levels			
Aflatoxins	Groundnuts (peanuts), hazelnut, Brazil nuts, other oilseeds for processing	AFB1	Total
	Almonds, pistachios, apricot kernels for processing	8	15
	Tree nuts, other than the tree nuts above for processing	12	15
	Groundnuts (peanuts), other oilseeds, other three nuts below for direct human consumption	5	10
	Almonds, pistachios, apricot kernels for direct human consumption	2	4
	Hazelnuts and Brazil nuts for direct human consumption	8	10
	All cereals except maize and rice	5	10
	Maize and rice for processing	2	4
Fumonisin B1 + B2	Unprocessed maize	5	10
	Maize intended for direct human consumption	4000	
Deoxynivalenol	Unprocessed cereals other than durum wheat, oats, maize	1000	
	Unprocessed durum wheat, oats, maize	1250	
Ochratoxin A	Unprocessed cereals	1750	
	Cereals intended for direct human consumption	5	
Zearalenone	Unprocessed cereals other than maize	3	
	Unprocessed maize	100	
T-2 + HT-2	Cereals intended for direct human consumption	350	
	Maize intended for direct human consumption	75	
	<i>Unprocessed barley and maize</i>	100	200
	<i>Unprocessed oats</i>		1000
	<i>Unprocessed wheat, rye and other cereals</i>		100
	<i>Maize intended for direct human consumption</i>		100
Aflatoxin B1	<i>Oats intended for direct human consumption</i>		200
	<i>Other cereals intended for direct human consumption</i>		50
USA: Action and guidance levels			
Aflatoxin B1	All food crops	20	
Fumonisin FB1 + FB2 + FB3	Maize		4000
Canada: Maximum and guidance levels			
Aflatoxins	Nuts	15	
Deoxynivalenol	Unprocessed soft wheat		2000
Australia: Maximum levels			
Aflatoxins	Peanuts, tree nuts	15	
Japan: Maximum and provisional maximum levels			
Aflatoxin B1	All food crops	10	
Deoxynivalenol	Wheat	1100 ^a	
China: Maximum and guidance levels			
Aflatoxin B1	Maize	20	
	Rice (brown rice)	10	
	Wheat, barley, other cereals	5	
	Peanuts	20	
Deoxynivalenol	Maize, barley, wheat, other cereals		1000
Ochratoxin A	Cereals	5	
	Beans	5	
Zearalenone	Wheat and maize		60

The guidance levels (the term may vary in legislation from country to country) are indicated in italics.

AFB1, aflatoxin B1; Total, total aflatoxins (sum of AFB1, AFB2, AFG1 and AFG2).

^aProvisional maximum level.

also defines sampling plans and analytical method performance criteria for the mycotoxins (Codex Alimentarius 1995). The standards issued by Codex are voluntarily applied by the Codex member countries. They are considered as neutral and generally accepted as global standards, and national mycotoxin legislation in many countries are based on them. The Codex MLs for food-crops are presented in Table 1.

The EU has its own established MLs for mycotoxins in foods and feeds. The EU-legislation comprises several legally binding regulations, and recommendations which are not binding but give a guidance for risk management. Since 1999 harmonized ML for AFs have been in place in the EU.

The enforceable MLs for AFs (AFB1 alone, sum of AFB1, AFB2, AFG1 and AFG2, and separately for AFM1), OTA, DON, ZEN, FBs (sum of FB1 and FB2) in various foods are stipulated in the Commission Regulation (EC) No 1881/2006 and in its amendments (EC 2006a). The EU MLs for food-crops are listed in Table 1. For the sum of T-2 and HT-2, the EC prescribes indicative levels for cereals and cereal products (EC 2013) (Table 1). Furthermore, the EC recognizes the need for simultaneous analysis of *Fusarium*-toxins (EC 2013). As an analog to the Codex standards, also the EC specifies sampling methods and performance criteria for the analytical methods (EC 2006b). While the Codex

standard CXS 193-1995 specifies that its MLs are for feeds only when the mycotoxins transfer to animal-derived foods and are relevant for the public health, the EU Directive 2002/32/EC regulates mycotoxin levels in animal feed (EP and Council 2002). However, only MLs for AFB1 in feeds have been set. The acceptable guidance levels for DON, ZEN, OTA, T-2 and HT-2 and the sum of FB1 and FB2 in feeds are covered by the Commission Recommendations 2006/576/EC and 2013/165/EU (EC 2006c, 2013). Although several parts of the EU mycotoxin-legislation have been harmonized with the Codex standards, the EU-legislation appears to be more detailed and the MLs more stringent than the corresponding Codex ones.

In addition to the Codex standards and EU-legislation, many world countries have their own national mycotoxin legislations. For example, in USA, the US Food and Drug Administration (US FDA) has issued Compliance Policy Guides on regulatory MLs for AFB1 and AFM1, and Guidance for Industry (non-binding) for guidance MLs of DON and sum of FB1, FB2 and FB3 in certain foods and feeds (FDA 1980a, 1980b, 1982, 1983, 2001a, 2001b, 2010). In Canada, legislated MLs have been established for AFs, and guidelines for DON and HT-2 in some foods and feeds (RG-8 Regulatory Guidance, CFIA 2017). Recommended levels Canada has set for T-2, ZEN and OTA in many feeds (CFIA 2017). In Australia, statutory MLs for AFs in nuts are in force (FSANZ 2017). Japan has established regulatory MLs for AFB1 in all foods and a provisional ML for DON in wheat (FAMIC 2011; Personal Communication, Ministry of Health, Labor and Welfare, Japan 2018). Regulatory ML and advisory levels for AFB1, DON and ZEN for feeds are also in place in Japan (FAMIC 2015). China has established statutory MLs for AFB1, AFM1 and OTA in many foods, while for DON and ZEN guidance levels have been prescribed (GB 2017). The regulatory MLs and guidance levels in food-crops for these selected countries are presented in Table 1.

Because only the compliance of the mycotoxin concentrations in food and feed with the regulatory MLs allows the food and feed business operators to place the commodities on the market, it is apparent that a large amount of the analytical occurrence data is generated for this purpose. The mycotoxin MLs and guidance levels established for food-crops by Codex Alimentarius, EU and some selected individual countries differ as seen in Table 1. Therefore, when considering the prevalence of mycotoxins across the globe, the different MLs and guidance levels in place in the different geographical regions undoubtedly influence the outcome of this consideration.

Sampling, monitoring and performance of the analytical methods

Across the world, the occurrence of mycotoxins in foods and feeds is actively monitored by food and feed business operators, official control laboratories and research organizations either to determine the regulatory compliance or the quality of foods and feeds. Analytical methods are generally

well established for many mycotoxins; currently liquid chromatography (LC) based methods coupled to tandem mass spectrometry (MS) are probably the most widely applied and preferred techniques (as also shown from the analyzed datasets below). The current trend in mycotoxin analysis seems to be on the one hand to reach ever lower concentration levels and multi-mycotoxin and full metabolite profiles (Arroyo-Manzanares et al. 2018; Brouwer-Brolsma et al. 2017; de Lourdes Mendes de Souza et al. 2013; Doppler et al. 2016; Adekoya et al. 2019; Malachová et al. 2014, 2018; Njumbe Ediage et al. 2015; Monbaliu et al. 2010; Rofiat et al. 2015; Shephard et al. 2013; Simader et al. 2015; Uhlig et al. 2013; Varga et al. 2013; Warth et al. 2012; 2015), and on the other hand to determine the compliance at the statutory levels by fast on-site techniques (Dorokhin et al. 2011; EC 2006b; Ediage et al. 2012; Joshi et al. 2016; Peters et al. 2017; Sieger et al. 2017). The current multi-analyte and multi-class analytical methods are capable of a high throughput of samples making larger amounts of results available than ever before in a short period of time. Today's analytical methods generally have lower LODs and LOQs than the methods a decade or two ago. For example for the determination of DON in foods, while the typical LODs for a range of different methods were within 5–1600 µg/kg as reported by JECFA in 2001, they were within 1–60 µg/kg for the MS-based methods (mainly used) as reported by JECFA 10 years later in 2011 (JECFA 2001, 2011). This, no doubt has a direct impact on the presently reported apparently higher mycotoxin-contamination rates than during earlier years. Most importantly, the higher amount of available data and more stringent analytical data quality requirements decrease variability in the currently estimated mycotoxin frequencies, thus justifying an update of occurrence data.

The analysis at the low concentrations requires not only advanced (and expensive) techniques but also experienced human resources and time. These reasons typically limit the routine control laboratories to analyze mycotoxins at their lowest possible LODs/LOQs the method is capable to. They rather operate with pragmatic fit-for-purpose methods in the region of the legal mycotoxin MLs. Thus, the adjusted sensitivity of the methods by the laboratories also affects the found prevalence of mycotoxins and causes variability in the reported frequencies. It is also clear that between-laboratory variation occurs independently from the approach of the laboratory to generate the analytical results at the lowest capable level of LOD/LOQ or at the level of MLs. Furthermore, the general practice how to report the positive results varies. The prevalence can be expressed either considering the mycotoxin results (quantifiable) above the LOD or above the LOQ of the respective laboratory. Thus, depending on the published report, the samples either above LODs or LOQs are considered positive or sometimes a distinction between the two is not made, leading to an increased variability of the reported data on frequencies of mycotoxin contamination. Even in the extensive mycotoxin reports of JECFA and EFSA, it is not always clear whether the indicated mycotoxin-incidence is based on > LOD or > LOQ.

It is very obvious that sampling influences the reported mycotoxin-incidence values. Different sampling strategies e.g. targeted and random, generate completely different outcomes. Sampling schemes can also alter, for example depending on the exporting destination of the food crops. Another sampling plan can be used when exporting to the EU with stringent mycotoxin regulations than when exporting to countries with more liberal requirements (JECFA 2008). This certainly impacts the observed incidence data on mycotoxins. For the prevalence data presented in this paper, it is expected that results from targeted sampling have been omitted by the authors when reporting their observations on mycotoxin incidences.

Amount of occurrence data varies across the world

While generally a large quantities of mycotoxin occurrence data are currently available, there are still many geographical regions in the world from where the data are limited or lacking. Typically, these are developing countries or countries with ongoing crisis events. This lack of data is evident only by looking into the many international mycotoxin assessments issued by JECFA and IARC or the WHO Global Environment Monitoring System (GEMS)/Food contaminants database on mycotoxin occurrence data collected by WHO, where majority of the data are from Europe, Americas and Western Pacific (WHO 2018). It is clear that limited and absence of data on mycotoxins lead to high uncertainties in the prevalence estimates or entirely prevents their calculations.

Contrary to the limited government and publicly available data, a wealth of mycotoxin occurrence data is assumed to be in the possession of the food and feed companies. To produce safe and high-quality food and feed commodities from agricultural crops, and to comply with the statutory levels, it is apparent that the largest amount of occurrence data is generated by the private food and feed business sector. Of these data, only a fraction is available for estimating the worldwide mycotoxin contamination rates as most of the companies do not publish their data or submit them to the organizations like WHO, FAO or EFSA. The occurrence data used by these international food safety bodies are from the official control laboratories and from research organizations. It is apparent that at the stage of the official food control, the food business operators have already applied their in-house control systems and discarded the most contaminated lots. Therefore, largely the data from the official controls represent the mycotoxin-results which are compliant with the MLs. This leads to a skewness of the dataset and a lower prevalence of mycotoxins than it likely would be in the crops at the farm level. For example, majority of the EFSA data are from the national control programs organized by the EU Member States (Eskola et al. 2018).

Climate influences mycotoxin prevalence

It is common knowledge that different mycotoxin producing fungal species favor different climate conditions making

mycotoxin prevalence highly variable across the world. Mycotoxins, such as trichothecenes, are typically regarded as toxins of the regions with temperate climate, while the presence of others, such as aflatoxins, are associated with tropical and subtropical climate areas. A large amount of information is available in the literature on the environmental factors impacting the presence of mycotoxins in food and feed crops (e.g. Van der Fels-Klerx et al. 2012a, 2012b; 2016; Battilani et al. 2012, 2013, 2016; Paterson and Lima 2017). A year-to-year variation occurs. While on the other years high mycotoxin contamination rates are observed, on the other years the prevalence of mycotoxins is low (Edwards and Jennings 2018; Kos et al. 2013; Meyer et al. 2019). Climate change is further believed to affect fungal growth and agricultural practices and, subsequently to the mycotoxin incidences and levels on the agricultural crops (Battilani et al. 2013; Paterson and Lima 2017; Van der Fels-Klerx et al. 2012a, 2012b, 2016). It is also projected that changes in climate will shift the geographic distributions of mycotoxin-producing fungi and hence the patterns of mycotoxin occurrence in the world. The amount of mycotoxin-contaminated crops are generally anticipated to increase with the global warming, but at the same time major variations in mycotoxin contamination are also expected as well as decreased occurrences of mycotoxins (Battilani et al. 2013; Paterson and Lima 2017; Van der Fels-Klerx et al. 2012a, 2012b, 2016). Furthermore, most of the mycotoxins are known to be chemically stable, with pre- and post-harvest mitigation strategies, such as with food and feed processing, only eliminating them to a certain extent (Leslie and Logrieco 2014).

Impact of global trade on mycotoxin prevalence data

Cereals are the core of human nutrition and their use for food and feed production will only increase during the coming decades (FAO 2015). World cereal production in 2017/2018 was estimated to be 2094 million tonnes by EC (EC 2018a). Globally, food remains as the most important use of cereals but due to the higher demand for protein-based foods, the need of cereals for feed materials will increase. Global food and feed trade has grown rapidly in the recent decades and is only expected to grow (FAO 2015). The countries in every region of the world have become more involved in the global trade than ever before, either as exporters or importers or both. For example, during the past decades the EU-imports from developing countries have increased sharply (Bureau and Swinnen 2018). Currently, the EU exports mainly wheat and barley, approximately 20% of the EU's wheat crop is exported annually, while large amounts of food-grade rice and feed (e.g. maize) are imported by the EU (EC 2018b). A country like Japan, where less than 40% of consumed foods were domestic in 2016, relies heavily on imported foods, agricultural foods comprising about 70% (MHLW 2018). As agricultural food and feed crops are widely internationally traded, the estimates of mycotoxin occurrence and prevalence reported in the literature for specific country or

region likely comprise results for both domestic and imported crops.

Previously reported global incidences for the regulated mycotoxins

While JECFA did not provide global estimates for AF-contaminated foods in its reports, IARC (2012) reported that it can vary from a few percent to 30% or more depending on the food product and geographical region. JECFA (2008), however, suggests that about 20% of tree nuts from different regions are contaminated. According to EFSA the prevalence in nuts for total AF (sum of AF B1, B2, G1 and G2) above LOD varied from 10% in cashew nuts to 40% in pistachio and Brazil nuts (EFSA 2009). Total AF contamination above LOD/LOQ was 45% in dried figs (EFSA 2012a) and 13% in cereals (EFSA 2013). Recently, Lee and Ryu (2017) assessed the incidence of AFs in unprocessed food-grade cereals (barley, maize, wheat, rice, and other cereals e.g. oats) in Africa, America, Asia and Europe compiling data from papers published over 10 years since 2006. Total AF-prevalence in these regions was 55%, varying from 15% in the American continent to 63% in Asia. Similar global contamination rates from 16% up to 33% for AFs over eight years were reported for 17,300 feed samples mainly from America (15%), Asia (40%) and Europe (38%) in 2013 (Streit et al. 2013). Amongst the around 14,400 globally collected feed samples in 2016–2017, the highest AF-incidence of 23% was found in nearly 7000 samples from North America (Biomim 2017).

In 2001, JECFA reported that over 60% of the data on maize and maize-derived foods from nine different world countries were FB-contaminated (above LOD) (JECFA 2001). In 2012, it reported that 70% of the results for maize samples worldwide were above the LOD or LOQ for FB1 (JECFA 2012). In 2017, the maize and maize-based foods had the highest occurrence of FB1, with the frequency close to 50% exceeding the LOQ (data from Europe, Canada and Japan) (JECFA 2017). A similar global prevalence of 61% for FBs was calculated by Lee and Ryu (2017) for unprocessed food-grade barley, maize, wheat, rice, and other cereals from the published data from 10 years since 2006. The total incidence varied from 39% of Europe to 95% of America (Lee and Ryu 2017). For FBs during a 8-year period, the prevalence was 50–63% in the 17,300 feed samples collected from America (15%), Asia (40%) and Europe (38%) (Streit et al. 2013). Within nearly 12,800 global feed-samples from 2016 to 2017, 85% of about 2500 Asian samples were contaminated with FBs, 75% of 5500 South American samples and 63% of about 450 African samples (Biomim 2017).

JECFA (2011) reported that worldwide 50% of oats results, 70% of barley, wheat and rice results and 90% of maize exceeded the LODs for DON. In its earlier evaluation (JECFA 2001), DON-contamination in cereal grains varied from 30% in rice to 60% in wheat and barley up to 70% in oats (levels above LOQs). A global DON-incidence of nearly 60% was reported by Lee and Ryu (2017) for unprocessed food-grade barley, maize, wheat, rice, and other cereals based on the published data in 10 years since 2006. The

prevalence varied from 50% in Asia to 76% in Africa (Lee and Ryu 2017). These percentages support the contamination rates of 46–64% from the eight years when 17,300 feed samples from America, Asia and Europe were analyzed (Streit et al. 2013). Biomim survey of around 15,100 feed samples sourced globally in 2016–2017 showed a lowest incidence of 65% for DON in about 4700 European samples, of 70% in about 650 Middle East and African samples and the highest DON-incidence of 82% in about 4800 South American samples (Biomim 2017). JECFA reported that the incidence of T-2 was 11% and of HT-2 14% in grain samples of barley, maize, oats, rice, rye and wheat for human consumption (mainly from Europe) (JECFA 2002). About 30% of the feed samples from Europe and South-America were positive for T-2, while only a few percentages were positive from other geographical regions in all nearly 8000 samples analyzed by Biomim (2017).

For the incidence of ZEN in contaminated food-crops across the world, JECFA (2000) reported a large variation (0–100%), suggesting roughly 30–40% of contamination. In unprocessed food-grade cereals (barley, maize, wheat, rice and other cereals) an incidence of 46% of ZEN across the globe was estimated based on the data published in 2006–2016 (Lee and Ryu 2017). The ZEN-incidence in cereals was the lowest in Asia (15%) and the highest (59%) in Africa (Lee and Ryu 2017). The range of 31–43% for ZEN-positive feed samples over the 8-year period in 17,300 samples primarily from Asia, America and Europe (Streit et al. 2013) was similar to those of JECFA (2000) and Lee and Ryu (2017). The global data of around 15,600 feed samples indicated that the ZEN-incidence was at the region of 40–50% (Biomim 2017).

Based on the worldwide data, an incidence of OTA-positive samples varied depending on the type of food crop but was generally lower than 50% for cereals (JECFA 2001, 2007, 2008). Similar incidences, varying from 20% in Europe to 42% in America, in unprocessed food-grade barley, maize, wheat, rice, and other cereals were reported by Lee and Ryu (2017) based on the published data from the 10 years. They estimated a global incidence of 29%. Only slightly lower prevalence of 17–28% for OTA was found in the 8-year-long study comprising 17,300 feed samples mainly from America, Asia and Europe (Streit et al. 2013). Similar prevalence of up to 27% was reported by Biomim (2017) for 6500 global feed samples. In the three largest sets of samples ($n = \sim 1500$ to ~ 2500), the OTA-contamination rates were 5% for North America, 24% for Europe and 27% for Asia (Biomim 2017).

Assessment of prevalence of mycotoxins in food crops by using EFSA and Biomim data

To assess mycotoxin occurrence frequency at different thresholds two data sets were investigated. The first set was obtained from EFSA with commodities destined for human consumption; the second set was commercial feed analysis data set provided by Biomim Inc. EFSA data were obtained through an access to information request (EFSA Ref. 17238686; PAD

Table 2. Summary statistics of the EFSA and Biomin data sets investigated for occurrence of six mycotoxin compounds, i.e. AFs (sum of AFB1, AFB2, AFG1 and AFG2), DON, ZEN, OTA, FBs (sum of FB1 and FB2) and the sum of T-2 and HT-2.

All samples and analyses	EFSA data	Biomin data
Total number of analyses	536,013 (single toxin)	1942 (multi-toxin)
Total number of samples	175,270	1942
Countries with three largest contributions (n analyses)	Germany (173,341) Netherlands (87,662) France (33,087)	Germany (348) South Africa (229) Austria (234)
Methods with 3 largest contributions (n analyses)	LC-MS (166,885) HPLC-FD (135,169) ELISA (36,200)	LC-MS (1942)
Years with 3 largest contributions (n analyses)	2013 (88,025) 2014 (126,419) 2015 (126,179)	2013 (139) 2014 (874) 2015 (837)
Grain samples only		
Number of grain analyses	74,696 (single-toxin)	560 (multi-toxin)
Number of grain samples	21,841	560
Countries with 3 largest contributions (n analyses)	Germany (25,367) Netherlands (10,878) Romania (9025)	Germany (224) Austria (143) Denmark (46)
Years with 3 largest contributions (n analyses)	2013 (13,428) 2014 (17,814) 2015 (16,220)	2013 (26) 2014 (227) 2015 (292)

2017 017) and was an extract of the EFSA chemical occurrence database concerning selected mycotoxin concentration data of all EU Member States. For the sampling years from 2010 to 2015 the following information was obtained from EFSA: (1) Year of sampling, (2) month of sampling, (3) country of origin of the sample, (3) commodity sampled, (4) method of analysis employed, (5) limit of detection of the method employed, and (6) co-occurring species with concentration levels. The data set contained 536,013 analyses from 175,270 samples of EU regulated mycotoxins with the ancillary data mentioned above. At the request of some national data providers, EFSA provided a replacement of the country name by the indication 'EU' due to 'a risk for indirect identification of economic operators, which may be country-specific and is to be considered as a commercial interest deserving protection' as specified by EFSA in its cover letter to the authors. In the dataset 31,651 samples were labeled as 'EU'. The EFSA occurrence data on food and feed were collected from the European markets but were not necessarily cultivated or originated from Europe. Owing to the fact that the FAO estimate is for food crops, to calculate the frequency of the contaminated samples in the EFSA dataset, results for processed food items were excluded and occurrence in raw materials only was evaluated.

The dataset obtained from Biomin was described in detail in an earlier report by Kovalsky et al. (2016). In brief, the original data set covered the years 2012–2015 for 1942 samples originating from 46 countries around the globe with a subset consisting of EU countries that was used for analysis. Samples were directly provided by farmers for analysis and commodities analyzed were primarily destined for use in animal feed, although the ultimate fate of the commodities remains unclear. Mycotoxin and metabolite concentrations were determined using a single multi-mycotoxin LC-MS method reported by Malachová et al. (2014). In the previous study by Kovalsky et al. focused on mycotoxin and metabolite concentrations (57 compounds) in three selected matrices with a focus on the co-occurrence of regulated mycotoxins with masked and

emerging toxins. In this study, we discuss outcomes of the statistical analysis of a very different subset, i.e. regulated mycotoxins and mycotoxins with guidance levels in grains of all kinds as reported to obtain an estimate of contamination frequencies and levels not provided previously. Table 2 provides a summary of the datasets and subsets investigated.

It should be noted that for analyses reported in the EFSA data set a large variety of methods was reported, including several methods classified as LC-MS (with and without the type of mass filter mentioned), high performance liquid chromatography (HPLC) with several detectors (e.g. fluorescence, diode array) and enzyme-linked immunosorbent assay (ELISA). Furthermore, complete method information was not always provided, such as no classification at all for 105,192 samples and 'HPLC with standard detection methods' for 40,336 samples. Incomplete method information was not a reason to exclude an analysis, although a very small number of erroneously reported samples analysis methods was removed prior to analysis, e.g. samples analyzed for mycotoxin concentrations using atomic absorption spectroscopy (AAS; $n = 149$). Because of this large number of different methods, an important consideration was to choose suitable LOD and LOQ values for statistical analysis. Regarding the analytical method employed the Biomin dataset was more consistent. Analysis was performed using a single LC-MS method by a single laboratory, thus eliminating a significant source of variability and allowing the use of a single LOD and LOQ value for a specific matrix.

Considering that the FAO 25% estimate was most likely calculated for samples exceeding the Codex MLs, one of the cutoff values for the data in this study was set at the current Codex MLs (Table 1) with the caveat that they might have changed from the (initial and unknown) levels, when the estimate of 25% was adopted over three decades ago. The percentages of mycotoxin contaminated samples above the current EU MLs and reported LODs/LOQs were also calculated from the EFSA and Biomin occurrence data.

Samples and mycotoxin concentrations in both data sets were of different origin and were chosen to serve different purposes for this study: The EFSA data set contained data primarily analyzed and submitted by public food safety and research organizations from samples of food crops destined for human consumption. The food crops likely underwent some form of prescreening by e.g., food business operators in their internal quality control prior to submission of sample for analysis. The Biomin dataset, on the other hand, provided data from samples submitted by farmers around the globe for investigation of mycotoxin occurrence and commodities were primarily intended to be used as animal feed. Consequently, results obtained from EFSA data likely provided a lower frequency cutoff for mycotoxin occurrence. The Biomin data, on the other hand, illustrated the upper threshold of mycotoxin occurrence in grains. Samples were intended for animal feed production and sampled directly

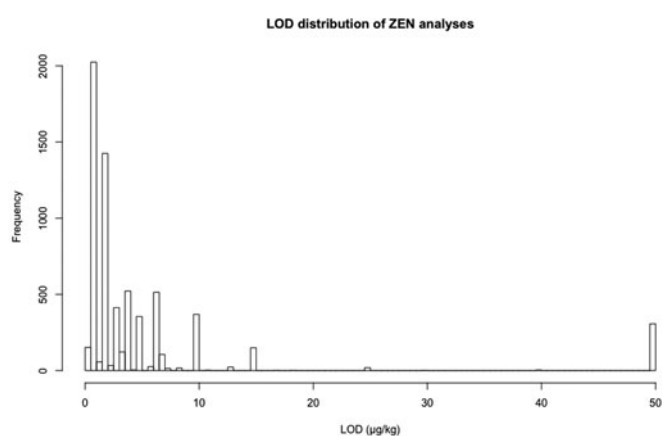


Figure 1. Histogram of reported LODs for ZEN in the EFSA grain subset.

from the field without further prescreening. Both datasets, therefore, provide a realistic range of mycotoxin occurrence from grain batches. For each of the samples selected above, subset by country and commodity, concentrations for the following toxins were determined for both EFSA and Biomin subsets: AFs (AFLAS, sum of AFB1, AFB2, AFG1 and AFG2), DON, ZEN, OTA, FBs (FUMS, sum of FB1 and FB2) and the sum of T-2 and HT-2 (T2HT2).

In order to find the percentage mycotoxin contamination and provide a detailed measure of contaminated grains in samples, several thresholds were defined and the percentage samples within each category was reported: (1) < LOD, (2) between LOD and lower legal ML/guidance level, (3) between lower and upper legal ML/guidance levels and (4) > upper legal ML/guidance level. While the definition of EU MLs/guidance levels and Codex MLs for the above categories was straightforward, the selection of a single LOD from the EFSA data posed some challenges. LODs for statistical analysis were, therefore, defined as follows in order to obtain a single value to be used for each toxin:

For the EFSA data sets a histogram of the different LODs from all analyses of a specific toxin in each grain subset was plotted. The LOD with the highest frequency was chosen for subsequent analysis and plotting. This approach taken was considered to be appropriate with the underlying rationale that the few laboratories reporting higher LODs did so to make the employed method suitable for the concentrations reported (i.e. fit for purpose) without assessing the method's full potential. Since other analyses showed lower LODs than the chosen value, reported results represent a conservative estimate regarding the frequency of mycotoxins detected. On the other hand, very few analyses had a higher than the chosen LOD, suggesting a marginal influence of the non-detects associated with higher LODs on the statistical analyses. Figure 1

Table 3. Thresholds employed for statistical analysis of EFSA and Biomin data.

	Codex level (µg/kg)	EU food level (µg/kg)	EU feed level (µg/kg)
Used for dataset	EFSA	EFSA	Biomin
Sum of AFs			
LOD	0.1	0.1	1.5
Lower legal level ^a	NA	2	5
Upper legal level ^a	NA	10	20
DON			
LOD	10	10	1.5
Lower legal level ^a	2000	1250	900
Upper legal level ^a	NA	1750	12,000
ZEN			
LOD	1	1	0.15
Lower legal level ^a	NA	75	100
Upper legal level ^a	NA	350	3000
Sum of T-2 and HT-2 toxins			
LOD	5	5	10
Lower legal level ^a	NA	50	50
Upper legal level ^a	NA	1000	2000
Sum of FBs			
LOD	20	20	4
Lower legal level ^a	4000	1000	5000
Upper legal level ^a	NA	4000	60,000
OTA			
LOD	0.1	0.1	1.5
Lower legal level ^a	5	3	100
Upper legal level ^a	NA	5	250

Sum of AFs was defined as the sum of AFB1, AFB2, AFG1 and AFG2; the sum of FBs was defined as the sum of FB1 and FB2. LODs were determined from reported data.

^aLegal level = EU ML or EU guidance level or Codex ML.

provides an example for ZEN with the final LOD chosen to be 1 µg/kg. For Biomin data, which were acquired employing a single analytical method in a single laboratory made the handling of the LOD straightforward. Table 3 provides a summary of the thresholds and limits employed for statistical analysis.

Determination of frequency of contaminated samples at different thresholds

Figure 2 shows an overview of the concentration distribution for the six investigated mycotoxins in grain samples from (a) EFSA and (b) Biomin samples. Means and medians were very low due to the fact that most of the results were found to be below the LOD. But there were occurrences of samples with high concentrations of especially DON and ZEN in both sample sets. While these numbers were to be expected for Biomin samples as they originated directly from the fields, samples without further prescreening, EFSA data submitted by the public organizations throughout the EU also showed an important number of samples with high DON and ZEN concentrations, despite assumed prescreening prior to analysis. The dense cluster of points with higher concentrations (often above the legal and guidance levels listed in Table 3) in the DON and ZEN boxplots suggested that an important number of samples featured high DON and ZEN concentrations, warranting further quantitative analysis.

Employing the thresholds from Table 3, plots were created with the percentage of samples for each toxin falling within one of the four categories: < LOD, between LOD and the lower limit, between the lower and upper limit and, finally above the upper limit. Limits were chosen to be EU MLs (for food) and guidance values (for feed) and Codex MLs. Figure 3 depicts results for EU food MLs applied to the EFSA subset for grains; Figure 4 shows the result obtained for the Biomin dataset and EU feed ML and guidance values.

Quantitative plots confirmed the initial assessment as shown in Figure 4. While most samples showed concentrations below the LOD (i.e. no toxin was detected), there is a certain percentage of samples that are contaminated (with concentrations between the LOD and the lower legal level) with DON and ZEN showing the highest occurrence. Very few samples were also found to contain elevated concentrations above the legal levels. Notable are the high frequencies of occurrence of DON, ZEN and FBs, with 40, 20 and 15% of samples, respectively, containing detectable concentrations, but below the EU lower ML (Figure 4a).

For the Codex MLs (Figure 3 b) applied to EFSA data it has to be noted that only one level is typically provided (Table 3), reducing the number of categories to three (< LOD, between LOD and the ML and above the ML). We assume that the calculated percentages reported here are appropriate for comparison with the 25% reported by FAO.

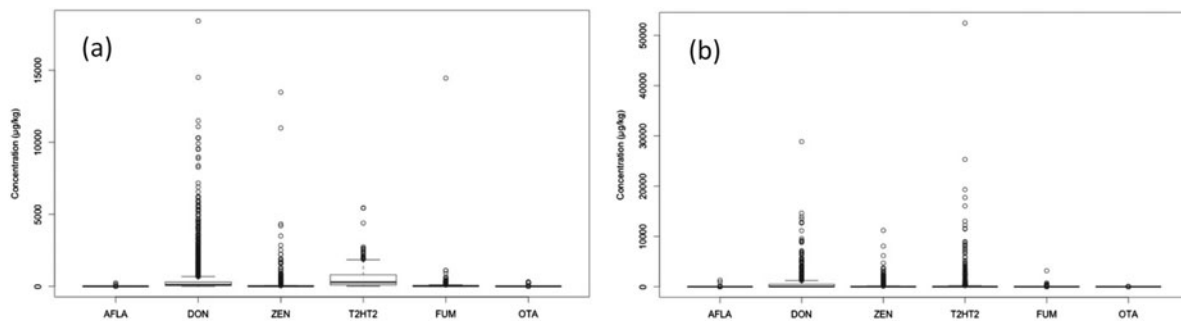


Figure 2. Boxplots of toxin concentration distribution in (a) EFSA and (b) Biomin grain samples.

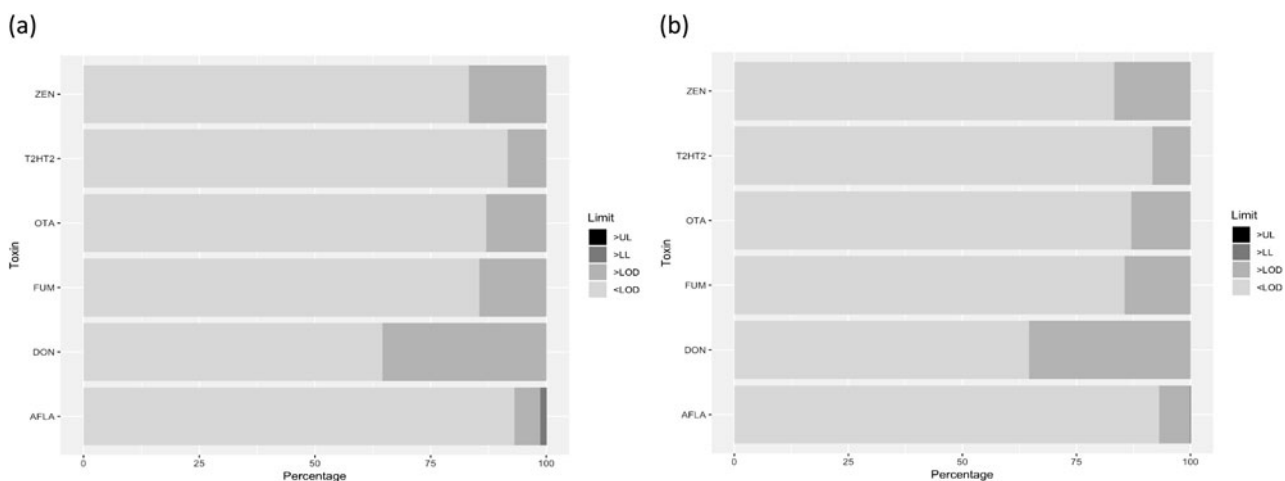


Figure 3. Percentage of EFSA grain samples falling within one of the four categories for each toxin as follows: (1) <LOD, (2) between LOD and lower legal level, (3) between lower and upper legal level and (4) above the upper legal level. (a) EU food MLs and (b) Codex MLs. For the respective limits see Table 3.

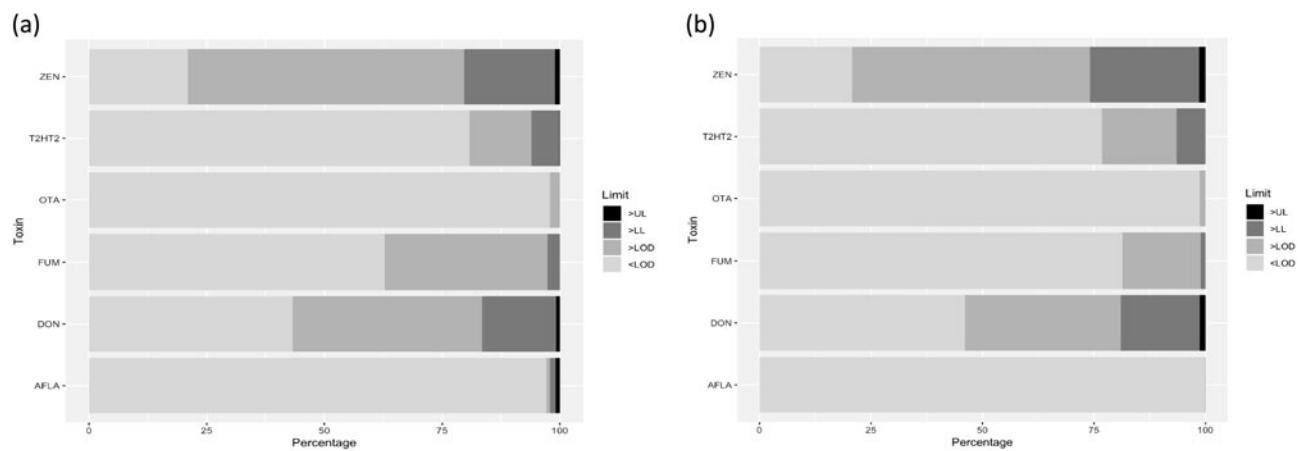


Figure 4. Percentage of Biomin grain samples falling within one of the four categories for each toxin as follows (from left to right): (1) <LOD, (2) between LOD and lower legal level, (3) between lower and upper legal level and (4) above the upper legal limit. (a) Samples of global origin with EU feed guidance values applied and (b) Samples of EU origin with EU feed guidance values applied. For limits see Table 3.

The calculated percentages in Figure 3a and b are very comparable and the percentages above the lower EU ML and the Codex ML are in the single digits, supporting the prescreening hypothesis.

Biomin data for samples originating directly from the field without further elimination of highly contaminated samples by prescreening shows an entirely different picture. Applied limits followed EU guidance values for feed. The application of EU and Codex food MLs were not considered appropriate since samples were preliminary destined for the production of animal feed. Furthermore, the MLs of DON and ZEN in feed, which showed the highest percentages of contamination above the lower legal/guidance level, are similar for food and feed (see Table 3), thus making percentage contamination data comparable for at least the most commonly found toxins.

Comparing plots for samples of (a) global and (b) EU origin show a high similarity, indicating that contamination percentages measured at the field levels are quite similar for mycotoxins commonly found in temperate climates, such as DON and ZEN. While established food safety systems are able to significantly reduce the risk of contaminated samples entering the food chain (as show in Figure 3 for EFSA data), the actual occurrence percentages (for EU countries presented in Figure 4 (b)) are significantly higher when looking at the data for feed. For ZEN the percentage of samples with detected mycotoxin concentrations reached about 80% with similar values for global and EU data from the Biomin dataset. Among these samples about 60% showed detected concentrations and while more than 20% of samples were found to be contaminated above the lower limit (lower EU guidance value for feed). The situation for DON was similar with 40% detected concentrations and slightly less than 20% contaminated above the lower limit.

Provided that the FAO 25% figure was established as percentage of samples above the Codex MLs and assuming that Codex MLs have not changed, the recent data for non-prescreened (i.e. feed) samples showed a similar level of contamination with around 20%. The percentage of samples with detected concentrations, on the other hand (> LOD,

but below the lower legal level or guidance value), was significantly higher. While no historical reference value for comparison was available for this category, its percentage has likely increased over the last decades. Method development progress has been significant, and sensitivity and selectivity of current state-of-the-art methods have greatly increased. These improvements provide the tools for further investigation of human and animal low-level exposures to mycotoxins, in particular exposures to mycotoxin-mixtures, and their contributions to the associated health risks. On the other hand, prevention strategies in the field and during storage would have helped to curb mycotoxin production over the last decades (Jard et al. 2011; Magan and Aldred 2007). The number of agricultural crops infected with toxigenic fungi is indeed quite high as the data > LOD clearly demonstrates with up to 80% of samples showing detectable concentrations of ZEN and 60% of samples showing detectable DON concentrations. This constitutes a large pool of infected crops potentially to produce even large quantities of mycotoxins in a warming climate. With climate change favoring fungal growth and toxin production the global mycotoxin problem is expected to worsen (Van der Fels-Klerx et al. 2012a, 2012b; 2016; Battilani et al. 2013; Paterson and Lima 2017).

Summary and conclusion

In this paper we strive to provide a rationale for a widely cited FAO estimate of 25% mycotoxin contamination in food crops around the globe. The exact origin and the basis for the estimate are unknown today and little details are available apart from secondary sources. The presented study provides a review of the occurrence of mycotoxins in grain from the literature with a focus on reports of JECFA. It has conducted extensive global reviews of the occurrence of known health-relevant and regulated mycotoxins, such as AFs, DON, ZEN, FBs, T-2 and HT-2 and OTA. Based on the literature data, the global mycotoxin prevalence in food crops varies largely depending on many factors, such as the mycotoxin of concern, used analytical methods and

reporting of the results, but it appears that the prevalence for the detected mycotoxins is up to 60–80%. Analyzing recent data on food grains for the years 2010–2015 provided by EFSA (from national food control programs and, therefore, most likely prescreened by the food business operators for quality before sampling) and Biomin Inc. (grains sampled at source at the farm-level) we found similar percentages in grain samples for DON (60%) and ZEN (80%), the two most prevalent mycotoxins in temperate climates. In addition to the detected mycotoxins, the analysis provides additional detail using different regulatory thresholds from the current EU legislation and Codex standards for food and feed. Results showed in the region of 20% of samples being contaminated above the lower regulatory EU and Codex level for materials sampled at source, but lower contamination levels (<10%) for food-grade grain samples. Comparing the FAO 25% estimate to values above EU and Codex limits (typically 20% for samples collected at source) would appear to confirm the original estimate. However, a comparison with the percentage of samples found to have mycotoxins present (in 60–80% of all samples for DON and ZEN alone) these figures greatly underestimate their occurrence. While progress in method development likely led to an increase in the percentage of detected mycotoxins (due to lower LODs), active mitigation strategies have most likely contributed to a reduction of high contamination batches, estimates that cannot be produced with the currently available data, but will need to be considered in future investigations. Climate change may have also had an impact on the higher incidence and will only serve to increase this level of contamination in future years. Before an accurate estimate can be provided, statistically relevant amount of high-quality data should be made available. Therefore, large occurrence data surveys on mycotoxin contamination in food-crops, with harmonized sampling strategies and analytical performance criteria, across the world over several growing seasons should be conducted. Humans and animals are typically exposed to mycotoxin mixtures which can induce combined adverse health effects. However, in those events where the concentration exceedance of the statutory limits (e.g. 20% or 25% of the samples) would lead to regular high dietary exposures to mycotoxins, and to their mixtures in particular, adverse health consequences can be expected. It is also of immense importance that the detectable levels (based on our estimation up to 60–80% of the samples) are not overlooked as through diets humans and animals are exposed to mixtures of different mycotoxins. Many of these possibly additive and synergistic effects are yet to be toxicologically investigated and their influence on the public health to be assessed by applying harmonized methodologies (EFSA 2019; Eskola et al. 2018).

Declaration of interest

The authors do not declare any conflict of interest.

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