Eur J Plant Pathol (2019) 155:381–392
https://doi.org/10.1007/s10658-019-01797-w

REVIEWS

Fungal contamination and mycotoxins associated with sorghum crop: its relevance today

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Accepted: 21 June 2019 / Published online: 28 June 2019

Abstract Sorghum grain is the fifth most produced cereal in the world. The dietary ingestion of sorghum along with other cereals is a way to take advantage of the grain's numerous benefits for human health. However, sorghum is now threatened by several fungal diseases that reduced crop yields and quality with substantial economic losses. Numerous fungal genera have been associated with the contamination of sorghum grains collected from different countries around the world, including the main mycotoxigenic genera. The main fungi that infect sorghum grains belong to *Aspergillus* and *Fusarium* genera, associated with the production of aflatoxins, fumonisins, zeralenone and deoxynivalenol, being the aflatoxins the main risk in this crop. Sorghum, unlike other cereals, does not yet have legislation that regulates the maximum content of mycotoxins in grains for its commercialization. As mycotoxins in food and feed are one of the main food safety problems worldwide, this work provides an in-depth examination into the occurrence of mycoflora and mycotoxins in sorghum. The current data compilation highlights the imperative need for sorghum-producing countries to strengthen surveillance and increase grain inspections to ensure the safety of this crop for human consumption as well as the need to establish regulations for mycotoxins or groups of mycotoxins in sorghum.

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Keywords Sorghum · Fungi · Mycotoxins · Food safety

Introduction

The origins of sorghum

Botanists, evolutionists, and archeologists alike have long debated the origins and domestication of cultivated sorghum. Sorghum is an ancient crop of African origin and especially important in the semiarid tropics of Africa and South Asia. Anthropological evidence suggests that hunter gatherers were exceedingly familiar with wild forms of sorghum as early as 8000 BC (Smith and Frederiksen 2000). Following its domestication around 4000 BC in the eastern Sudanese savannah, sorghum has been carried to over 100 different countries in a variety of environments and habitats and serves even now, as a staple all over the world (Venkateswaran et al. 2019).

Sorghum crop characteristics

Sorghum belongs to family *Poaceae*, tribe *Andropogoneae*, subtribe *Sorghinae*, and genus *Sorghum* Moench (Clayton and Renvoize 1986). This genus include about 28 species of grasses, but only one species—namely, *Sorghum bicolor* L.—is currently cultivated as grain for human being and animal consumption. This crop has several good agronomic characteristics: the time required to be harvested, the ability to

grow in arid regions, is photosynthetically efficient, and tolerates both drought and heat stresses, thus allowing a wide geographical distribution.

There are sorghum grains of many colors, white, yellow, red, brown, or black depending on the combination of the thickness and color of the pericarp, the color of the endosperm, the presence of a testa, and the expression of specific genes (*i. e.*, diffuser and intensification) involved in color generation. However, this has little or no correlation with the nutritional value. The main components in all grains are starch (~75%), protein (~12%), lipids (~4%), fiber (~3%), ash (~2%) and several minerals, vitamins, and amino acids in variable proportions (Paiva et al. 2017). Sorghum grain is also a rich source of a diverse array of polyphenolic compounds particularly phenolic acids and flavonoids present in the bran that have been shown to possess multiple health benefits (Althwab et al. 2015). Note that this crop contains higher levels of these compounds than most cereals and even some fruits and vegetables depending on the variety (Awika and Rooney 2004).

Use of sorghum grains

Low input cost and adaptability to a wide range of environments make sorghum a favorable potential candidate for various food and nonfood uses. Although it is a staple food crop for millions of people in parts of Africa and Asia, it was an underutilized resource in most developed countries, where it was being primarily used as animal feed. Even in developed countries of the Americas, Australia, and Europe, sorghum production is increasing in response to expanding market opportunities for use of the grain in industrial applications (Visarada and Aruna 2019).

More than 35% of the world sorghum production is grown directly for human consumption. Sorghum offers a number of functional and health benefits such as reduction of diabetes, cardiovascular, and celiac diseases, thus it has increased in recent years its use as an ingredient in a long list of healthy foods. The grain can be used as baked, extruded, and other cereal-based products (bread, cookies, expanded snacks, pasta, and breakfast cereals) as a partial or complete substitute for other cereals. It also can be boiled as for rice, cracked for porridge, malted for beer, baked into flatbreads, and even popped for snacks (Serna-Saldivar 2016).

Besides its food use, about 48% of global sorghum production has also been used an important feed as for ruminants, pigs, beef, cattle, fish and poultry. Thus, it can be incorporated into the rations in different quantities depending on the quality of the grain, the animal species and their growth stage (Peerzada et al. 2017). Sorghum is also grown for green forage and has great potential as a fodder resource due to its quick growth, high green fodder yield, and good quality. The whole plant is often used as hay and silage.

In recent years, sweet sorghum is emerging as an important biofuel, bioenergy, biogas, and bioethanol crop (Pontieri and Del Giudice 2016).

World trade and production

The international sorghum market recently announced a significant increase in the price of this grain, which it is characterized by being very volatile due to the influence of factors, such as climate, pests, diseases, trade -supply and demand- and macroeconomic variables as the type of change.

However, at the international level, total world imports also increased due to the high consumption of sorghum in China, −the main purchaser of sorghum- as its production is not sufficient to satisfy domestic demand and therefore becomes the first importer of sorghum grain. Other consuming countries are Mexico, Japan, Chile, Sudan and to a lesser extent, Kenya and South Africa. Whereas the five largest producers of sorghum in the world today, that satisfy that demand, are United States, Nigeria, Mexico, India and Sudan (Hansen et al. 2018) (Fig. 1).

As sorghum uses are increasing and more varied, the world production of sorghum has maintained an increasing tendency in the last years. The increase in the profitability of sorghum, in addition to the aforementioned qualities of the plant, has motivated the farmers to continue increasing the total area of cultivation (USDA 2015).

Fungal infection and associated mycotoxins

The good adaptation that the sorghum has to diverse conditions of climate and soil predisposes it to the attack of diverse pathogens such as bacteria, viruses, parasites, insects and/or fungi (Garba et al. 2017). Regardless of

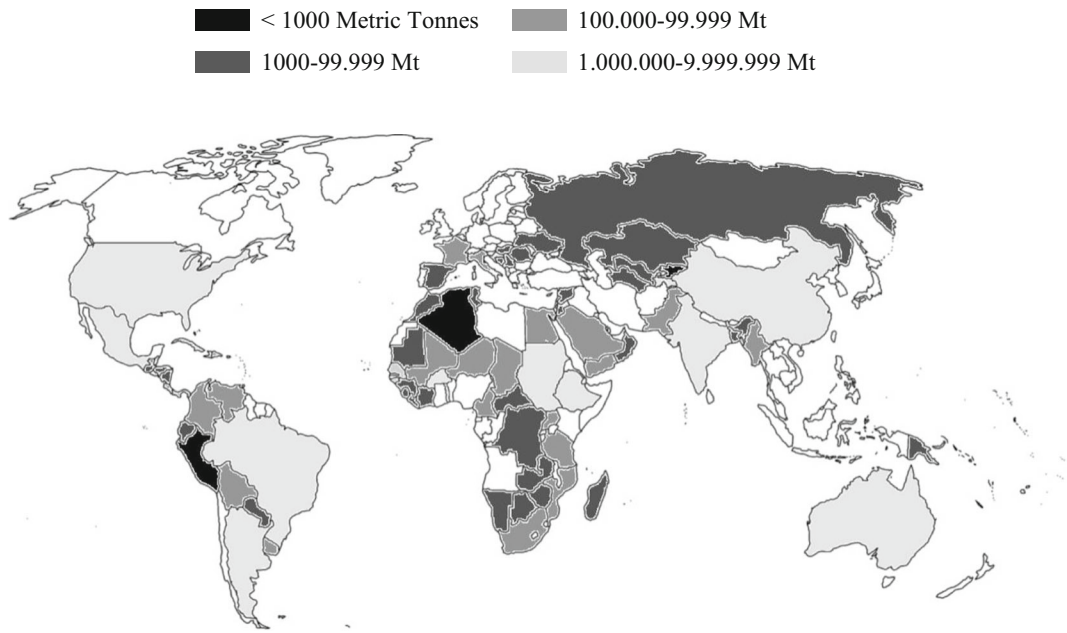

Fig. 1 Main countries producing-sorghum (2017–2018). Source: GRAMENE

its usual resistance to pests and microbes, fungal contamination constitutes a major biotic constraint to an increase in sorghum production worldwide. The pathogenic fungi are present externally or internally in plant tissues associated with the soil, the stems, the leaves and the panicle and it affect the growth and productivity of whole plants. Among the fungal diseases with high economic impact on sorghum explotation are cited: anthracnose (*Colletotrichum graminicola*), blight of the panicle (*Fusarium moniliforme*) and dry rot of the stem (*Macrophomina phaseolina)*. However, in the present article, focus will be given to fungal species that causes significant losses to sorghum production with the emphasis on mycotoxigenic fungi. The presence of these fungi in sorghum grains not only affects their nutritional and commercial value, but also represents a risk to the health of consumers due to the capacity to produce mycotoxins, substances whose interest has grown around the world for the significant economic losses that they cause.

An early report about sorghum under different storage conditions in India, shows the presence of aflatoxin-producing fungus for half a century ago (Mishra et al. 1969). Table 1 summarizes the main fungal species that infect sorghum according to the available bibliography. Sorghum is one of the staple foods for the poorest population in the world. This crop is carried out in small family farms that practice subsistence agriculture with scarce quality and safety food controls. Therefore in the African continent, sorghum is spread throughout the continent, and in Asia, mainly concentrated in China and India. For the same reason, there are also numerous research works in relation to the mycological and mycotoxicological quality of this substrate in these two continents where sorghum is mainly used for human consumption, as opposed to what happens in the developed countries of North America, where almost all of the production is used as feed. Note that there is no data from the European continent. This may be due to sorghum is cultivated in some small areas of France, Italy and Spain. While it concerns Oceania, only Australia is the only producer with little importance.

The presence of main potentially mycotoxigenic and pathogenic fungal species are widely reported in many of these papers, without finding predominance of any particular species according to the origin of the samples.

It can be observed that over the years, the characterization mode of the contaminating fungal species have been evolved; the first 30 years, the researches mention only morphological identification through the use of taxonomic keys or identification by visual comparison with reference strains while the articles of the last decade, show fungal identification through molecular techniques.

Contaminated sorghum grains with mycotoxins endanger human and animal health, animal production and

Table 1 Studies on mycoflora isolated from sorghum grains

Fungi isolated (Characterization mode)	Sample origin	References
Helminthosporium. Gloeocercospora, Curvularia, Aspergillus, and *Rhizopus* (Not mentioned)	India	Mishra et al. (1969)
Aspergillus, Penicillium, Fusarium, Alternaria, and *Curvularia* (Not mentioned)	Egypt	Moubasher et al. (1971)
ND	Nigeria	Salifu (1978)
Alternaria, Fusarium semitectum, Curvularia lunata and *C. protuberata, F. moniliforme,* and *Helminthosporium* (Not mentioned)	Southern and central Texas	Castor and Frederiksen (1980)
ND	United States	Shotwell et al. (1980)
Curvularia, Penicillium, Mucor, and *Aspergillus* (Not mentioned)	United States	Diener et al. (1981)
Aspergillus, Fusarium, Penicillium, Curvularia, Phoma, Alternaria, Chaetomium, and *Helminthsoporium* (Not mentioned)	Northern Nigeria	Elegbede et al. (1982)
ND	Georgia and Mississippi	McMillian et al. (1983)
Alternaria alternata, Fusarium moniliforme, F. equiseti, F. semitectum, Chaetomium, Cladosporium, Curvularia, Epicoccum, and *Helminthosporium* (Not mentioned)	Kansas and Texas	Seitz et al. (1983)
Rhizopus rhizopodiformis, R. oryzae, Aspergillus clavatus, A. flavus, Fusarium moniliforme, F. moniliforme var. subglutinans, F. chlamydosporum, and *Phoma sorghina* (Not mentioned)	Southern Africa	Rabie and Lübben (1984)
Aspergillus flavus, Curvularia lunata, and *Fusarium verticillioides* (Full research not available)	India	Reddy et al. (1985)
Aspergillus flavus, *A. niger*, *A. terreus*, *Fusarium*, *Curvularia clavata*, *C. lunata*, *Colletotrichum*, *Dreschslera australiensis*, *Eurotium chevalieri*, and *Penicillium* (Full research not available)	Venezuela	Mazzani (1988)
ND	Mexico	Garcia Aguirre and Martinez Flores (1991)
Aspergillus flavus, Curvularia lunata, Cladosporium dadosporioides, and *Fusarium moniliforme* (Morphological identification)	India	Kumar et al. (1992)
Fusarium moniliforme, F. equiseti, F. semitectum, F. nygamai, F. chlamydosporum, and *F. graminearum* (Morphological identification)	Nigeria, Lesotho and Zimbabwe	Onyike and Nelson (1992)
Aspergillus and *Fusarium* (Morphological identification)	India	Sashidhar et al. (1992)
Penicillium, Alternaria, F. moniliforme, Gibberella zeae, Colletotrichum graminicola, Helminthosporium, and *Cladosporium* (Not mentioned)	North America	Menkir et al. (1996)
Fusarium moniliforme, Alternaria alternata, Phoma sorghum, Penicillium funiculosum, and *Aspergillus flavus* (Morphological identification)	Argentine	Gonzalez et al. (1997)
ND	Egypt	Ibrahim et al. (1998)
Fusarium, Alternaria, Aspergillus, Phoma, and *Curvularia* (Morphological identification)	Argentine	Saubios et al. (1999)
Phoma, Aspergillus, Fusarium, and Rhizopus specie (Morphological identification)	Brazil	Da Silva et al. (2000)
Alternaria, Aspergillus, Curvularia, Cladosporium, Drechslera, Nigrospora oryzae, Trichoderma hamatum, Trichothecium roseum, Piptocephalis, Syncephalastrum racemosum, Fusarium moniliforme, F. subglutinans, Penicillium, and *Rhizopus* (Morphological identification)	Pakistan	Fakhrunnisa and Ghaffar (2006)
Alternaria alternata, Curvularia, Drechslera sorghicola, and *Fusarium* (Not mentioned)	South Africa	Tarekegn et al. (2006)
Fusarium, Curvularia lunata, Alternaria alternata, and *Phoma sorghina* (Not mentioned)	India	Thakur et al. (2006)
ND	Ethiopia	Ayalew et al. (2006)
ND	Tunisia	Ghali et al. (2008)
Aspergillus niger, Rhizopus oryzae, A. flavus, Chaetomium, Scopularia, Chrysosporium, Rhodoturula, and *Torula¨* (Morphological identification)	Nigeria	Hussaini et al. (2009)
ND	Tunisia	Ghali et al. (2009)
	Bangladesh	Islam et al. (2009)

Table 1 (continued)

Fungi isolated (Characterization mode)	Sample origin	References
Curvularia lunata, Fusarium moniliforme, Alternaria tenuis, Bipolaris sorghicola, Colletotrichum graminicola, Botrytis cinerea, Aspergillus niger, Penicillium oxalicum, and *A. flavus* (Morphological identification)		
Cladosporium, *Helminthosporium*, *Fusarium*, *Epicoccum*, *Mucor*, *Alternaria*, *Nigrospora*, *Aspergillus*, *Acremonium* and *Penicillium* species (Morphological identification)	Brazil	Dos Reis et al. (2010)
Rhizopus stolonifer, *Aspergillus niger, Penicillium funiculosum*, and *Fusarium semitectum* (Morphological identification)	Saudi Arabia	Yassin et al. (2010)
Fusarium proliferatum, F. thapsinum, F. equiseti, F. andiyazi and *F. sacchari* (Molecular identification: Through AFLP-based grouping of the isolates follow by sequencing part of α-elongation factor gene and comparing the sequences with the NCBI database)	India	Sharma et al. (2011)
Fusarium proliferatum, F. nelsonii, F. equiseti, F. thapsinum and F. sacchari (Molecular identification by comparing the sequence of the translation elongation factor 1 α gene against the database as well as using phylogenetic analyses)	India	Lincy et al. (2011)
Curvularia lunata, Rhizopus nigricans, Fusarium moniliforme, Drechslera longirostrata, Alternaria tenuis, Phytopthora, Aspergillus flavus, and *Alternaria alternata* (Morphological identification)	India	Panchal and Dhale (2011)
Helminthosporium, Aspergillus, Fusarium, Rhizoctonia, Penicillium, Sclerotium, and *Curvularia* (Morphological identification)	Nigeria	Abdulsalaam and Shenge (2011)
ND	Southern Africa	Matumba et al. (2011)
Alternaria, Aspergillus, Colletotrichum, Curvularia, Fusarium, Nigrospora, Macrophomina, Penicillium, Phoma, Claviceps, and *Bipolaris* (Morphological identification)	Southern Korea	Yago et al. (2011)
ND	Tunisia	Oueslati et al. (2012)
ND	India	Ratnavathi et al. (2012)
F. verticillioides, F. thapsina and *F.* cf. *incarnatum-equiseti* complex (Molecular identification by sequencing part of the Transcription Elongation Factor 1α gene)	India	Divakara et al. (2013)
ND	Sudan	Elbashir and Ali (2014)
Fusarium, Aspergillus, Penicillium, Alternaria, Rhizopus, and *Epicoccum* (Morphological identification)	Ethiopia	Chala et al. (2014)
Aspergillus candidus, A. flavus, A. niger, A. ustus, Fusarium verticilloides, Rhyzopus oligosporus, Scopulariopsis brevicaulis, and *Syncephalastrum racemosum* (Morphological identification)	Northeastern Nigeria	Jidda and Anaso (2014)
Fusarium moniliforme, Bipolaris sorghicola, Curvularia lunata, Colletotrichum graminicola and *Phoma sorghina* (Morphological identification)	Tanzania	Mamiro and Clement (2014)
ND	Tunisia	Oueslati et al. (2014)
Fusarium, Aspergillus, and *Alternaria* species (Molecular identification: *Aspergillus* species using specific primers, *Fusarium* isolates by partial sequencing of the Transcription Elongation Factor 1 α-gene and the β-tubulin and the other isolates by partial sequencing of the ITS region and the β-tubulin gene)	Tunisia and Egypt	Lahouar et al. (2015)
ND	Belgium and Germany	Ediage et al. (2015)
Aspergillus, Fusarium, and *Penicillium* species (Morphological identification)	Kenya	Kange et al. (2015)
Penicillium, *Aspergillus*, *Absidia*, *Fusarium*, *Paecilomyces, Alternaria, Cladosporium, Gliocadium* and *Mucor* species (Morphological identification).	Uruguay	Del Palacio et al. (2016)
ND	Mexico	Huerta-Trevino et al. (2016)
Aspergillus, Fusarium, Alternaria, Rhizopus, and *Penicillium* species (Morphological identification)	Ethiopia	Taye et al. (2016)
Aspergillus, Penicillium, Emericella, Fusarium, Curvularia, Rhizomucor, Phoma, and Paecilomyces species (Molecular identification by sequencing of the Transcription Elongation Factor 1 α-gene)	Nigeria	Garba et al. (2017)

ND Not determined

the economy of countries by the significant quantitative and qualitative reduction of yield for the agricultural sector (WHO 2006).

Despite the growing interest around the world for sorghum as food, for its nutritional and economic qualities, there are numerous articles about the presence of mycotoxins in cereals and food products derived from cereals but much less refer to the contamination of sorghum with this type of metabolites. In view of the adverse effects that these substances cause on different sectors of society, it is interesting to do an in-depth examination into the mycotoxins in sorghum. The Table 2 summarizes the maximum concentration, the incidences and the concentration average of the main four mycotoxins group that are frequently found in sorghum grains worldwide. The mycotoxigenic fungal species with higher incidence are *Aspergillus flavus* (aflatoxins producer), *Fusarium verticilloides* and *F. proliferatum* (main fumonisins producers), *F. equiseti* (type A trichothecene-producers), *F. semitectum* (zearalenone producer), *F. graminearum* (type B trichothecene-producers) and *Alternaria alternata* (alternariol, alternariol monomethyl ether, altenuene).

In this table, data on contamination by the main mycotoxins of sorghum collected from different countries is reported. Most of the presented samples were collected from African and Asian countries since this crop represents a basic cereal for food for millions of people of these regions and no data on samples collected in Oceania countries were available in the databases consulted.

Among the different types of mycotoxins, aflatoxins (AF) are the most frequently isolated from a wide variety of foods and feed products (Iqbal et al. 2015) and it are also predominant in sorghum grains. The natural occurrence of this group of mycotoxins in sorghum or sorghum-based beverages has been studied mainly in Asian continent (Abdulkadar et al. 2000; Cheraghali et al. 2007; Ghali et al. 2008, 2009). Aflatoxins can be produced by 21 species within sections *Flavi*, *Ochraceorosei*, and *Nidulantes* of *Aspergillus* genus. Aflatoxin is a carcinogenic and mutagenic mycotoxin that is confirmed as a class-1 agent. It contaminates the most of staple foods, affecting 25% of global crops (Niessen et al. 2018). Aflatoxins incidence (total and B_1) and its respective concentration reported in sorghum grain samples data since the 1980's to the present. Due to their high frequency and serious health effects, different countries and some international organizations have established strict regulations in order to control AFs contamination in food and feeds and also to prohibit trade of contaminated products (USFDA, 2000; EC, 2006; ANVISA, 2011). However, there is still no specific regulation of these mycotoxins for sorghum.

From all the publications consulted, some 61% reported higher aflatoxins concentrations than those allowed by the EU for other substrates and adopted for sorghum by many countries that produce and/or commercialize this crop (Apeh et al. 2016). The highest aflatoxin level (1164 μg Kg^{-1}) was found in a sample collected in Northern Nigeria by Hussaini et al. (2009) and only one paper reports a sorghum sample collected in southern Malawi with a maximum concentration of total aflatoxins (3 μg Kg^{-1}) lower than the limit established by the EU (Matumba et al. 2011).

Zearalenone is a nonsteroidal estrogenic mycotoxin produced by several species of *Fusarium* genera, being *Fusarium graminearum* (teleomorph *Gibberella zeae*) the main producer. It appears in corn, wheat, oats, barley, sorghum, millet, hay, silage and balanced foods. Zearalenone has major effects on reproduction in females, but it affects the male reproductive system as well. It is often associated with some trichothecenes since they are produced by the same fungal species (Gupta et al. 2018). Maximum limits for zearalenone (ZEN) in foods and feeds there are in various countries, however, only Colombia fixed a maximum limit of 1000 μg kg^{-1} specifically for grains sorghum (FAO 2004). In literature, only two authors reported concentrations greater than that limit, both manuscripts with similar incidence values (Hussaini et al. 2009; McMillian et al. 1983). In the most recent researches, the contamination levels with ZEN are very low, nevertheless it is important to consider that in many cases the ZEN presence could be indicative of the presence of other mycotoxins also produced by *Fusarium* spp. (Ayalew et al. 2006).

The other group of mycotoxins widely studied in this crop is fumonisins, due mainly to an outbreak of an acute disease transmitted by food contaminated by these toxins in southern India during 1995 that affected 1424 people by the consumption of sorghum and maize (Reddy and Raghavender 2008). This important fact forced both the authorities and the population in general to become aware of the serious risks posed by the presence of mycotoxins for food safety, mainly in a country where all the food products that are produced

there are consumed as human food without undergoing control analysis. Fumonisin is a mycotoxin produced by several species belonging to *Fusarium* genera, mainly by *Fusarium verticillioides* and *F. proliferatum*. It is most important in veterinary medicine as a cause of porcine pulmonary edema and equine leukoencephalomalacia. The clinical signs associated with fumonisin toxicity will vary significantly between species depending on their sensitivity and the primary target organ. Fumonisin B_1 (FB_1), the most predominant and well-studied isoform, have been classified as a Group 2B by the International Agency for Research on Cancer (IARC 2002) and regulated by the EU but not for sorghum grains (European Commission 2010). For total fumonisins, a maximum tolerable limits for non-processed maize, maize intended for direct human consumption and maize based breakfast cereals in 4000, 1000, and 800 μg Kg^{-1}, respectively, were recommended (EC, 2007). Extrapolating these recommendations to sorghum grains and also considering that the analyzed samples in the mentioned articles in Table 2 were intended for human consumption, it can be observed that two authors reported the presence of sorghum samples from Ethiopia that widely exceeds that limit (Ayalew et al. 2006; Taye et al. 2016).

Although deoxynivalenol (DON) would not represent a major problematic for sorghum grains considering that its incidence is lower than those mentioned above, it should be pay more attention since this trichothecene may be present in co-occurrence with other mycotoxins produced by the *Fusarium graminearum* complex and affect both human and animal health (Piacentini et al. 2019). With respect to chronic effects in animals, DON leads to decrease in feed intake (anorexia, decreased nutritional efficiency, reduced weight gain), immunosuppression (higher susceptibility to bacterial infections) and affect also the reproductive system in some animal species (reduced litter size) (CAST 2013). From acute toxicity studies in animals it seems plausible that DON might produce similar effects in humans (Pestka and Smolinski 2005). A few dozen countries have set regulatory or guideline limits for deoxynivalenol (DON) and nivalenol (NIV) in very few foods, generally for wheat in some countries and the majority for cereals in general. Both, the percentages of positive samples and the maximum concentrations found in mentioned articles were very variable, even between those carried out with sorghum samples obtained from the same country.

The present review focused on the four groups of mycotoxins that are found most frequently in sorghum, although in the last decade there has been an increase in the presence of other mycotoxins. According to a study carried out by Rychlik et al. (2016), contamination with tenuazonic acid (TeA) in foods based on sorghum indicates that this mycotoxin also represents a potential risk, especially for children's health. In general, the presence of this mycotoxin in feed and food has traditionally been associated with contamination by *Alternaria* and more recently associated with *Phoma sorghina* (at present *Epicoccum sorghinum*). According to Codex Committee on Contaminants in Foods (CCCF, 2012), more attention should be paid to the presence of *P. sorghina* and their toxins in sorghum grains since its incidence is reported from the early reports on sorghum grain (see Table 1) but it was never considered the fungal species responsible for producing TeA. Currently, it has been observed that *E. sorghinum* is an important producer of TeA and it is also considered one of the main components of the complex of fungal diseases that affect the sorghum grain (Oliveira et al. 2018). Furthermore, the occurrence of this mycotoxin in sorghum and derivatives has been demonstrated (Asam and Rychlik 2013; Oliveira et al. 2017).

Gliotoxin is another mycotoxin produced by *Aspergillus fumigatus,* a species also isolated from several sorghum samples. This mycotoxin has been found in sorghum pre- and post-fermented and extensively used for animal feeding because of the nutritional values. Keller et al. (2012) reported an incidence of around 50% of contaminated samples with variables levels of toxin, and therefore, its presence could probably affect animal productivity and health.

Conclusion

Although there are several worldwide regulations regarding all the previously mentioned mycotoxins for different human foods and animal feeds to preserve the public health and livestock production and to avoid trade barriers, there are no regulations or recommendations for any of these metabolites specifically for sorghum. Considering the ubiquitous nature of exposure to these metabolites worldwide (evidenced by the data collected in last years), this review highlight the urgent need to establish regulations that include more mycotoxins or groups of mycotoxins in foods such as sorghum that is emerging as a healthy alternative food.

Table 2 Occurrence of the main mycotoxins associated to sorghum grain

Mycotoxins	Maximum concentration ($\mu g\ Kg^{-1}$)	N° of positive samples/ N° of assayed samples (%)	Average ± SD ($\mu g\ Kg^{-1}$)	References
Aflatoxins	AFs: 56.0	4/197 (2)	19.8 ± 24.2	Shotwell et al. (1980)
	AFB_1: 90.0	36/64 (56)	70.0	McMillian et al. (1983)
	AFB_1: 40.0	2/150 (1.3)	Data not available	Sashidhar et al. (1992)
	AFB_1: 33.0	18/140 (12.8)	Data not available	Da Silva et al. (2000)
	AFB_1: 26.0	5/82 (6.1)	10.0	Ayalew et al. (2006)
	AFs: 67.0	13/17 (76.4)	22.3 ± 20.4	Ghali et al. (2008)
	AFs: 54.5	57/93 (62)	9.9 ± 11.5	Ghali et al. (2009)
	AFs: 1164.0	93/168 (55.3)	199.5 ± 259.9	Hussaini et al. (2009)
	AFs: 3.0	2/13 (15)	2.3 ± 0.9	Matumba et al. (2011)
	AFB_1: 79.9 AFG2: 52.4	2/3 (66.6) 3/3 (100)	46.7 ± 46.3 24.6 ± 11.8	Oueslati et al. (2012)
	AFs: 9.4	3/10 (30)	5.0 ± 3.9	Lutfullah and Hussain (2012)
	AFs: 263.9	1173/1606 (73)	Data not available	Ratnavathi et al. (2012)
	AFB_1: 62.5 AFB_2: 5.4	9/70 (12.9) 8/70 (11.4)	29.5 2.6	Chala et al. (2014)
	AFG_1: 61.5	3/70 (4.29)	29.7	
	AFG_2: 2.6	1/70 (1.43)	2.6 ± 0.0	
	AFB_1: 12.3 AFB_2: 5.1	17/60 (28.3) 6/60 (10)	Data not available	Elbashir and Ali (2014)
	AFB_1: 50.0	1/10 (10)	50.0 ± 0.0	Ediage et al. (2015)
	AFB_1: 10.8 AFB_2: 5.4	4/37 (10.8) 2/37 (5.4)	Data not available	Kange et al. (2015)
	AFG_1: 18.9	7/37 (18.9)		
	AFG_2: 32.4	12/37 (32.4)		
	AFB_1: 8.2 AFB_2: 0.8	23/60 (38) 1/60 (1.7)	1.5 0.8 ± 0.0	Oueslati et al. (2014)
	AFB_1: 14.0	2/275 (0.7)	7.5 ± 9.2	Del Palacio et al. (2016)
	AFs: 6.4	16/40 (40)	0.4	Huerta-Trevino et al. (2016)
	AFB_1: 33.1	90/90 (100)	Data not available	Taye et al. (2016)
Zearalenone	6900.0	56/197 (28)	Data not available	Shotwell et al. (1980)
	143.0	Data not available	121.5 ± 30.4	Elegbede et al. (1982)
	1468.0	20/64 (31)	Data not available	McMillian et al. (1983)
	32.0	2/29 (6.9)	25.5 ± 9.2	Ayalew et al. (2006)
	1454.0	62/168 (36.9)	184.7 ± 328.3	Hussaini et al. (2009)
	374.0	23/70 (33)	43.8	Chala et al. (2014)
	90.0	1/10 (10)	90.0 ± 0.0	Ediage et al. (2015)
	45.0	1/60 (1.6)	45.0 ± 0.0	Oueslati et al. (2014)
	199.5	40/40 (100)	171.7	Huerta-Trevino et al. (2016)
Fumonisins	FB_1: 0.1	104/140 (74.2)	Data not available	Da Silva et al. (2000)
	FBs: 2117.0	3/39 (4.5)	1713.3 ± 377.1	Ayalew et al. (2006)
	FB_1: 368.7	19/50 (38)	Data not available	Dos Reis et al. (2010)
	FB_1: 30.1 FB_2: 8.3	10/70 (14.3) 6/70 (8.6)	14.7 4.9	Chala et al. (2014)
	FB_3: 2.5	1/70 (1.4)	2.5 ± 0.0	
	FB_2: 16.2 FB_3: 45.9	2/60 (1.2)	16.2 ± 0.0 45.9 ± 0.0	Oueslati et al. (2014)
	FB_s: 97.0	4/10 (40)	63.0 ± 38.3	Ediage et al. (2015)
	FBs: 933.0	110/275 (40)	Data not available	Del Palacio et al. (2016)
	FBs: 182.0	25/40 (62.5)	168.7	Huerta-Trevino et al. (2016)

Table 2 (continued)

Mycotoxins	Maximum concentration (μg Kg^{-1})	N° of positive samples/ N° of assayed samples (%)	Average ± SD (μg Kg^{-1})	References
	FBs: 2041.0	64/90 (71.1)	Data not available	Taye et al. (2016)
Deoxynivalenol	2340.0	30/33 (90)	360.0	Ayalew et al. (2006)
	78.1	2/70 (2.86)	44.9	Chala et al. (2014)
	30.0	10/40 (25)	30.0	Huerta-Trevino et al. (2016)

SD Standard deviation, AFB_1 Aflatoxin B_1, AFB_2 Aflatoxin B_2, AFG_1 Aflatoxin G_1, AFG_2 Aflatoxin G_2, *AFBs* Total aflatoxins, FB_1 Fumonisin B_1, FB_2 Fumonisin B_2, FB_3 Fumonisin B_3, *FBs* Total fumonisins, *<LQ* Less than the limit of quantification, − A numerical value cannot be calculated

Therefore, further studies are necessary to estimate the daily intake of mycotoxins through sorghum for defining the norms that regulate these metabolites in order to protect the population health in relation this crop consumption.

Acknowledgements The authors acknowledge the financial support of the Consejo Nacional de Investigaciones Científicas y Tecnológicas (CONICET; Grant PIP 0819).

Compliance with ethical standards

Conflict of interest We have read the topics listed and confirm that there is no conflict of interest of any kind.

Research involving human participants and/or animals Does not correspond.

Informed consent We have carefully read everything concerning this point, and we give our consent to the veracity of the confirmed..

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