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Mycotoxins in Maize and Implications on Food Security: A Review

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ABSTRACT

Mycotoxin poisoning is not restricted to pets and farm animals, it causes diseases and death in humans. Mycotoxin producing fungi are common components of the epiphytic and endophytic microflora in crops resulting in natural crop contamination in the field and during storage. The level of contamination is influenced by the genetics of the plant and fungi, management practices and prevailing climatic conditions. The Global movement of maize products necessitates global as well as country-specific surveys on mycotoxin occurrence. Significant differences in the concentrations of deoxynivalenol, fumonisins and zearalenone were found in commercial maize for the seven years under review but no significant difference was detected between white and yellow maize types with regards to fumonisins and zearalenone concentrations. The absence of Aflatoxins, Ochratoxin-A, T2-toxin and HT-2 toxin in the commercial maize samples from 2010/2011 to 2016/2017 seasons is a food safety advantage for South Africa maize producers.

Key words: Aflatoxin, Climate change, Deoxynivalenol, Fumonisins, Sub-saharan Africa, Zearalenone.

Maize (*Zea mays* L.) is the most important cereal crop in sub-Saharan Africa and plays key roles in many household diets, poverty reduction, food security, animal feed provision and foreign exchange. The importance of a plant depends on its identified benefits (Chukwudi *et al.* 2020). Maize supplies daily calories to millions of people and is used in the manufacturing of paper, paint, textiles, adhesives, biodiesel, medicine and food (Beukes *et al.* 2017). It is cultivated at both commercial and subsistence levels in South Africa with the surplus from the commercial sector exported to other countries. South Africa (SA) is the leading maize exporter in Africa and occupies 9th position in the global ranking. In 2018, SA exported maize to 75 countries with the top ten destinations being Vietnam, South Korea, Japan, Botswana, Italy, Namibia, Eswatini, China, Spain and Mozambique (ITC, 2019).

The movement of food and feed products across the world, including mycotoxin-contaminated products, highlights the importance of worldwide as well as country-specific surveys on mycotoxin occurrence (Meyer *et al*. 2019). This surveillance is important as mycotoxin entry into the food chain had been linked to maize or maize product consumption (Medina *et al.* 2017). Fungal activity and mycotoxin production reduce seed viability and vigour (Ismaiel and Papenbrock, 2015) as well as render grain useless for consumption. Hence, its presence in maize is a threat to food security. The unavailability of contaminated maize seeds for planting and grains for consumption as well as the high premium placed on the uncontaminated grains threaten the food security of millions of people that depend on maize for their daily calories. By 2027, maize consumption is projected to increase by 16% especially in sub-Saharan Africa where human and livestock populations are growing rapidly (OECD/FAO, 2018). Will this increase in maize consumption lead to an increase in exposure to mycotoxins?

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This article reviews mycotoxins including the entry into maize plant, factors influencing mycotoxins contaminations of grains and associated losses with mycotoxins contaminations in maize. It assesses the health implications of consuming mycotoxins contaminated foods, isolated mycotoxins in processed food, mycotoxins concentration levels across maize producing provinces in South Africa and proposes ways of reducing mycotoxin levels in the food chain to ensure food security.

What are mycotoxins?

Mycotoxins are low molecular weight natural products produced as secondary metabolites by filamentous fungi that can cause disease and death in human beings and other vertebrates (Zain, 2011). All mycotoxins are of fungal origin, but not all toxic compounds produced by fungi are called mycotoxins (Zain, 2011). Of the hundreds of mycotoxins identified, aflatoxins (AF), ochratoxins A (OTA),

trichothecenes (deoxynivalenol [DON], T-2 toxin and HT-2), zearalenone (ZEA) and fumonisins (FB) are mycotoxins of major public health concern and agro-economic significance (Eze and Okonofua, 2015; Luo *et al.* 2018; Misihairabgwi *et al.* 2017; Zain, 2011).

Mycotoxins are currently grouped as regulated, masked and emerging mycotoxins (Kovalsky *et al.* 2016). Regulated mycotoxins have legislations stating their acceptable limits while masked and emerging mycotoxins rarely have legislations stating their acceptable limits. Masked mycotoxins are covalently bound mycotoxin conjugates that are not detected by routine screening methods (Gratz, 2017) but are still harmful to vertebrates. Emerging mycotoxins are newly discovered fungi metabolites as a result of advanced screening techniques. This review will focus on regulated mycotoxins; however, more information on mycotoxin classification can be obtained from the following reports (Alshannaq and Yu, 2017; Bennett and Klich, 2003; Berthiller *et al.* 2013; Gratz, 2017; Kovalsky *et al.* 2016; Zain, 2011).

Mycotoxins isolated from animal feed

The best quality food products from developing countries are exported to countries with mycotoxin regulations resulting in poor quality food contaminated with high mycotoxin levels, being utilized domestically (Misihairabgwi *et al.* 2017). This leads to an abundance of mycotoxins in the domestic food chain. In Durban South Africa, Singh and Chuturgoon (2017) reported that irrespective of the brand or marketing channel, all 20 pet foods analyzed for mycotoxins were contaminated with fungi that are mainly *Aspergillus flavus, Aspergillus fumigatus and Aspergillus parasiticus* with AFs and FBs being the most prevalent.

Also, Mwanza *et al.* (2013) analyzed 60 dog food samples obtained from commercial outlets in South Africa and revealed that FBs, ZEA, AFs and OTA were present in 98%, 96%, 87% and 68% of the samples, respectively with some of the mycotoxins above the European Union and South African set levels.

Mycotoxins isolated from maize products destined for human consumption

The occurrence of these mycotoxins is not restricted to animal feeds as they have also been found in maize and maize products destined for human consumption in South Africa. Toxigenic fungi and a significant number of mycotoxins such as AFs, FBs and DON have been isolated from fermented maize products. Adekoya *et al.* (2018b) observed a low incidence of AFs and high levels of FBs in two locally processed maize products (*ogi* and *mahewu*) prepared for human consumption in SA.

In a study of 32 composite *umqombothi* samples, a traditionally brewed alcoholic beverage made principally from maize, Adekoya *et al.* (2018a) identified *Aspergillus, Penicillium, Saccharomyces and Phoma* genera as the predominant fungal species with a low occurrence of AFs, while T-2, HT-2, NIV, ZEA, 3- and 15-acetyl-DONs were not detected in the samples. Although the study suggested that the tested beer samples had safe levels of mycotoxins but were contaminated by at least two mycotoxins that could pose some additive or synergistic health effects among consumers. Results of the study thus revealed that the consumption of *umqombothi* can significantly enhance dietary exposure to multiple mycotoxins among consumers in SA.

Analysis of mycotoxin data from 2010/2011 to 2016/2017 cropping season

This study was performed at the Department of Crop Science, North West University, South Africa in 2020. In this review, multi-mycotoxin assessment reports were obtained from the Southern African Grain Laboratory (SAGL) database (https://sagl.co.za/maize/maize-reports/) from 2010/2011 to 2016/2017 cropping seasons. SAGL undertakes annual crop quality surveys of maize in South Africa to accumulate quality data on commercial crops at the national level from local production regions. SAGL collects maize samples during harvest from different silos across South Africa for quality evaluation. Sub-samples of both white and yellow maize collected every season are selected for multi-mycotoxin analyses to proportionally represent all the production regions. The number of white and yellow maize samples collected for the period under review is presented in Table 1.

The data set contained mycotoxins concentrations of DON, FB and ZEA according to maize type (white and yellow) harvested from Free State, Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, North West and Northern Cape provinces of South Africa. The mycotoxin data were analyzed using factorial design to show changes in mycotoxin concentration in the commercial maize samples from these provinces. The significant means were separated using Fisher's least significant difference at 5% probability level. In addition to the individual concentrations of DON, FB and ZEA, the percentage of samples that tested positive for one or two mycotoxins in each of the seven provinces was extracted from the SAGL database to show the mycotoxins trend.

Table 2 showed significant differences in the concentrations of DON, FB and ZEA across the seven provinces. The highest concentration of DON was identified in maize samples from Mpumalanga province followed by samples from North West and Free State provinces. The highest concentration of ZEA was found in Mpumalanga province followed by North West and KwaZulu-Natal provinces. The maize samples from Northern Cape province gave the highest concentration of FB followed by Free State and North West provinces. The lowest concentrations of DON, FB and ZEA were obtained in maize samples from Limpopo province.

Table 3 showed that the concentrations of FB and ZEA in the white and yellow maize were statistically similar while the DON concentration in the white maize was significantly higher than that of yellow maize. White maize from Mpumalanga province produced the highest concentration of DON that was statistically similar to white maize from North West, Gauteng, Free State and KwaZulu-Natal

provinces (Table 4). The obtained highest concentration of FB was from yellow maize samples in Northern Cape, which was statistically the same with yellow and white maize samples from Free State and North West provinces. White maize from North West province gave the highest ZEA concentration.

Table 1: The number of maize samples collected across South African silos for maize quality assessment.

Season	White maize	Yellow maize	Total
2010/2011	413	280	693
2011/2012	577	423	1000
2012/2013	508	492	1000
2013/2014	451	479	930
2014/2015	485	515	1000
2015/2016	415	505	920
2016/2017	549	451	1000

Source: Southern Africa Grain Laboratory (2018).

Table 2: Influence of province on DON, FB and ZEA mean concentration (µg/kg) on maize grain in South Africa.

Province	DON	FB	ZEA
Free State	362	605	29.0
Gauteng	330	315	25.1
KwaZulu Natal	265	271	34.6
Limpopo	59	231	0.0
Mpumalanga	402	350	59.8
North West	377	557	56.7
Northern Cape	174	719	19.6
F-LSD $_{(0.05)}$	169	279	29.9

Table 3: Mean concentrations (µg/kg) of DON, FB and ZEA on maize grain based on maize type in South Africa.

Maize type	DON	FB	ZEA
White	362	368	39.4
Yellow	200	503	24.8
F-LSD $_{(0.05)}$	90	ns	ns

ns=non-significant.

Table 4: Mean concentrations (µg/kg) of DON, FB and ZEA on maize grain based on maize type and province in South Africa.

Maize type	Province	DON	FB	ZEA
White	Free State	451	572	48.9
White	Gauteng	498	256	33.1
White	KwaZulu Natal	420	228	45.1
White	Limpopo	82	143	0,0
White	Mpumalanga	523	319	71.6
White	North West	494	558	77.1
White	Northern Cape	67	502	0.0
Yellow	Free State	273	637	9.1
Yellow	Gauteng	162	374	17.1
Yellow	KwaZulu Natal	110	314	24.0
Yellow	Limpopo	36	319	0.0
Yellow	Mpumalanga	280	381	48.0
Yellow	North West	259	555	36.3
Yellow	Northern Cape	282	936	39.3
F-LSD $_{(0.05)}$		239	395	42.3

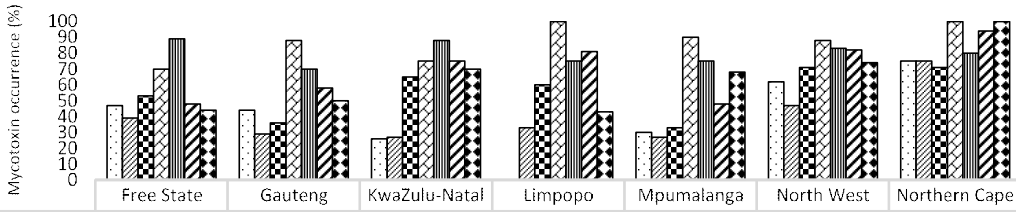
Fig 1 presents the percentage of maize samples that tested positive for one or two mycotoxins. These percentages ranged from 39-89% in Free State, 29-88% in Gauteng, 26-88% in KwaZulu-Natal, 0-100% in Limpopo, 27-90% in Mpumalanga, 47-88% in North West and 71-100% in Northern Cape provinces. The least percentages of mycotoxin in most provinces were recorded between the 2010/2011 and 2011/2012 seasons. The highest percentage of mycotoxin occurrences in each province were observed between the 2013/2014 and 2014/2015 seasons and subsequently started declining except in Northern Cape Province that rose to 100% in the 2016/2017 season.

The mean concentrations of FB, DON and ZEA in maize vary from season to season within and across the different South Africa production regions. SAGL (2018) postulated that certain climatic factors during the pre-harvest production period influence mycotoxin occurrence and concentration levels. Independent investigations in South Africa on mycotoxins contaminations of maize indicated that infection is common in commercial maize samples (Beukes *et al.* 2017; Janse van Rensburg *et al.* 2015). Janse van Rensburg *et al.* (2015) reported higher mycotoxin infection in the warmer, drier areas of North West, Northern Cape and Free State provinces where the average temperatures ranged from 29°C to 32°C. The presence of high mycotoxin levels in commercial maize could be attributed to the fact that commercial farmers still consider yield, not disease resistance, as the number one criteria when deciding on a variety to plant.

Though mycotoxins were found in different areas of South Africa, no AF, T-2 toxin, or OTA were found (Adekoya *et al.* 2018a; Njobeh *et al.* 2012). According to the 2017 Biomin Mycotoxin Survey, FB has been on the increase in almost all countries (Human, 2018). The absence of Aflatoxin B1, B2, G1, G2, OTA, T2-toxin and HT-2 toxin in the commercial maize samples from 2010/2011 to 2016/2017 seasons is a huge food and feed safety advantage for South Africa maize producers (SAGL, 2018).

Mechanism and effect of mycotoxins entry into maize plant

The fungi responsible for mycotoxins production are common components of the epiphytic and endophytic microflora in crops resulting in natural crop contamination in the field (Medina *et al.* 2017). Moniliformin, produced by several *Fusarium* species on the maize kernel, can survive for years in the soil (Zain, 2011). Maize contamination by aflatoxin B1 (AFB1) is increased by ploughing back contaminated stovers and grains of the previous crops into the soil as maize seedlings have the potential to absorb and translocate AFs from the roots to the stem and leaves (Ismaiel and Papenbrock, 2015). Mycotoxins can enter the maize plant through absorption from the soil, wound in the stalk, or direct contact with the exposed silk and husk leaves (Al-Juboory and Juber, 2013). The latter is a more effective pathway for mycotoxin entry into maize kernel (Al-Juboory



	Free State	Gauteng	KwaZulu-Natal	Limpopo	Mpumalanga	North West	Northern Cape
2010/2011	47	44	26	0	30	62	75
2011/2012	39	29	27	33	27	47	75
2012/2013	53	36	65	60	33	71	71
2013/2014	70	88	75	100	90	88	100
2014/2015	89	70	88	75	75	83	80
2015/2016	48	58	75	81	48	82	94
2016/2017	44	50	70	43	68	74	100

Fig 1: Mycotoxin occurrence (%) for maize producing provinces from 2010 to 2017 (Source: SAGL, 2018).

and Juber, 2013; Santiago *et al.* 2015). When a kernel is contaminated by mycotoxin, the spread is facilitated through the fungi hyphae (Köppen *et al.* 2010). Picot *et al.* (2011) identified the dent stage as the most conducive period for FB accumulation in maize kernels. There is no specific stage at which mycotoxins cannot contaminate grains. The contamination can occur in the field before harvest, at harvesting, or after harvest (Köppen *et al.* 2010).

Fusarium can colonize the xylem *via* the roots and the growing mycelium and results in the obstruction of vessels including the prevention of water transport to the aerial parts (Pietro *et al.* 2003). Mycotoxins can also damage the plant's immune system by inhibiting cell proliferation and protein synthesis (Human, 2018; Luo *et al.* 2018). Thus, resulting in a reduction in infected maize plant's dry weight (Al-Juboory and Juber, 2013).

Factors influencing mycotoxins contaminations of grains

Plant genotype and management practices

Maize cultivar, management practices and interaction of both influence the success or failure of grain colonization by fungi. Maize cultivars showed varying degrees of resistance to fungal infection under different environmental conditions (Janse van Rensburg *et al.* 2015; Vaughan *et al.* 2014). Less FB contamination was observed in Bt maize when compared with conventional hybrids and traditional maize seed in Northern KwaZulu-Natal Province of South Africa (Pray *et al.* 2013). A similar study in France showed that Bt maize decreased concentrations of FB by 90% and ZEA by 50% compared to its isogenic non-Bt counterpart (Folcher *et al.* 2010). Mycotoxin contamination of maize differs between genotypes (Czembor *et al.* 2019).

Poor management practices *i.e.* poor harvesting practices, improper storage, processing and less than optimal conditions during transport and marketing can also contribute to fungal growth and proliferation of mycotoxins (Santiago *et al.* 2015). Lavkor *et al.* (2019) reported an increase in aflatoxin levels during drying and storage compared to the pre-storage period.

Environmental factors

In addition to the genetic effects and management practices, climatic variables can also predispose maize grains to mycotoxin contamination. Climatic-related stresses *i.e.* drought, flooding, elevated CO_2 and extreme temperatures predispose maize plants to fungal infection. Drought conditions increased maize FB levels in South Africa (Rheeder *et al.* 2016). Flooding before maize harvest in Argentina has been reported to result in two out of three samples tested being above the mycotoxin risk threshold (Human, 2018). Prolonged drought under extreme temperatures can also favour the co-contamination of FB and AF in maize. Though not strongly established, the mean maximum temperature can influence FB contamination (Janse van Rensburg *et al.* 2015).

Mycotoxigenic fungi have their requirements of temperature and humidity for crop infection, as well as mycotoxin production and survival. A temperature range of 22-35°C has been reported as the minimal and supra-maximal temperatures for the growth of *F. verticillioides* with 30-32°C considered as the optimum (Murillo-Williams and Munkvold, 2008). Maize susceptibility to *F. verticillioides* colonization was reportedly increased under elevated CO_2 in a greenhouse study at the University of Florida, USA (Vaughan *et al.* 2014). High relative humidity and water availability during storage also contribute to maize infection by mycotoxigenic fungi and the production of mycotoxins (Mannaa and Kim, 2017).

Plants are vulnerable to infection under extreme weather conditions or fluctuations between wet and dry cycles (Human, 2018). Changes in temperature, rainfall and atmospheric CO_2 resulting from climate change are expected to have a wide range of impacts on plants' pathogen and mycotoxin concentrations in plants (Medina *et al.* 2017; Vaughan *et al.* 2014) as mycotoxigenic fungus can mutate in response to climate change (Russell *et al.* 2010). The geographical range and abundance of vectors are changing due to climate change. These alterations may result in some pathogens being transmitted by new vectors or an increase

in the feeding rate of many arthropod vectors under high temperature (Russell *et al.* 2010). Any of these changes will increase the exposure of crops to mycotoxigenic fungi and hence, the spread of mycotoxins.

Losses associated with mycotoxins contaminations in maize

Fungi infection of cereal grains is a global problem. Fungal species and their mycotoxins contaminate harvested seeds causing losses of agricultural commodities in many zones of the world (Choudhury *et al.* 2018; Ismaiel and Papenbrock, 2015). Maize grain can be colonized by different species of fungi which cause a reduction in yield, quality and nutritional value (Orina *et al.* 2017). These mycotoxins affect seed quality, germination, viability, seedling vigour, growth of root and coleoptile (Ismaiel and Papenbrock, 2015).

In addition to reducing the regenerating capacity of seeds, fungal activity and mycotoxin production can render grain useless for food as well as for feed. Nevertheless, the contaminated grains may be suitable for biofuel production (Russell *et al.* 2010). However, Khatibi *et al.* (2014) cautioned against channeling dried distillers' grain with solubles (DDGS) from biofuel production into animal feed as it can infect the animals due to the concentration of mycotoxins from the contaminated grains in the DDGS.

All mycotoxins in feed cost the agricultural industry over $1 billion each year in the USA (Human, 2018; Medeiros *et al.* 2012). The cost cuts across laboratory testing, decontamination cost, reduction in the market value of contaminated grains, total loss of value due to grain rejection, the veterinary cost for infected animals, the health-related cost for animal and human exposure to mycotoxins and in extreme cases, death resulting from consuming contaminated produces [International Agency for Research on Cancer, IARC (2012)]. Economically, mycotoxins affect the human society in two ways: (i) the direct market costs associated with lost trade or reduced revenues due to contaminated food or feed and (ii) the human health losses from adverse effects associated with mycotoxin consumption (IARC, 2012).

Health implications of consuming mycotoxins contaminated foods

Health implications for pets and farm animals

Contaminated maize grains rejected for human consumption are often channeled into feed formulations where they are widely reported to pose health risks to pets and farm animals (Bennett and Klich, 2003; Misihairabgwi *et al.* 2017; Singh and Chuturgoon, 2017). All mycotoxins in feed even at low levels, have a broad spectrum of effects on animal health that include immune dysfunction, digestive disorders, carcinogenicity, neurotoxicity, hepatoxicity and impaired reproduction (Beukes *et al.* 2017; Eze and Okonofua, 2015; Human, 2018).

Animal studies indicated that ZEA, DON, OTA and AFB1 can adversely affect fertility, through damage to sex organs, gametes and disruption of steroidogenesis. Ingestion of FB B_1 and DON in pigs disrupt the intestinal barrier leading to suppressed immune response as well as reduce feed intake and weight gain (Pierron *et al.* 2016). DON consumption had been reported to cause low feed conversion efficiency in livestock, anorexia in pigs and other monogastric animals (Beukes *et al.* 2017) while ruminants and poultry appear to be resistant to DON (Awad *et al.* 2013). However, diets containing low levels of DON (less than 5 mg DON/kg diet) have been reported to result in lower productivity, impaired immunity and higher susceptibility to infectious diseases in poultry (Awad *et al.* 2013). ZEA contaminated feeds on the other hand have been reported to significantly affect nutrient metabolic rates, serum enzyme activities and genital organs in growing-laying hens (Cheng *et al.* 2017). Continuous exposure of farm animals to mycotoxin contaminated feeds can induce clinical signs *i.e.* depression, anorexia, weakness, weight loss and sudden death (Singh and Chuturgoon, 2017).

Health implications for humans

Mycotoxin poisoning is not restricted to pets and farm animals, it can also cause diseases and death in humans. The conventional food processing temperature of 80-121°C will not affect most mycotoxins and modification of the chemical structures of mycotoxins by plant into conjugates (masked mycotoxins) enables them to escape detection by conventional analytical techniques (Berthiller *et al.* 2013), hence, their continuous entrance into the food chain. Currently, it may not be feasible to eliminate mycotoxins from the food chain due to their thermal and chemical properties and the losses associated with mycotoxin decontamination. Therefore, different regions of the world have permissive limits for different mycotoxins in the food chain (Table 5).

Nevertheless, constant consumption of low concentrations of mycotoxins below regulatory limits over a long period may instigate several diseases (Adekoya *et al.* 2018b; Medeiros *et al.* 2012; Wild *et al.* 2015). Also, exposures to multiple mycotoxins can be life-threatening to humans since combinations of mycotoxins could be agonistic, additive, or antagonistic in nature (Adekoya *et al.* 2018b; Eze and Okonofua, 2015). The severity of mycotoxin poisoning can be compounded by factors such as vitamin deficiency, caloric deprivation, alcohol abuse and infectious disease status (Bennett and Klich, 2003).

The consumption of FB contaminated foods has been linked to oesophageal cancer, abdominal pain, diarrhoea outbreaks and stunted growth particularly in children (IARC, 2012). High levels of FB in maize grain has been associated with leukoencephalomalacia, a fatal condition that causes the softening of brain tissue (Beukes *et al.* 2017). AFB1 has been linked to liver cancer, immune suppression, stunted growth, jaundice and in severe cases, it causes death (Shephard, 2008) while IARC (2012) similarly linked Balkan endemic nephropathy an endemic kidney disease, to

Table 5: Different regulation limits (µg/kg) of mycotoxins in maize destined for human consumption.

Mycotoxin	European Union*	United States±	China**	South Africa*
Aflatoxins	5 to 10	0.5 to 20	20	10
Fumonisin	200 to 4000	2000 to 4000	No limit yet	2000 to 4000
Deoxynivalenol	200 to 1750	1000	1000	1000 to 2000
Zearalenone	20 to 350	No limit yet	60	No limit yet
Ochratoxin A	3 to 5	No limit yet	5	No limit yet

Sources: *(SAGL, 2018), ±(Alshannaq and Yu, 2017), **(Anukul *et al.* 2013).

mycotoxin poisoning. In humans, ZEA has been linked to hypoestrogenic syndromes and is believed to be an eliciting factor for advanced puberty development in girls (Massart *et al.* 2008). The potential of ZEA to stimulate the growth of human breast cancer cells has also been demonstrated *in vitro* (Ahamed *et al.* 2001). In Africa, mycotoxins had been viewed as a contributory factor in increasing infertility in males (Eze and Okonofua, 2015).

Reducing mycotoxins in the food chain

Presently, it may not be feasible to eliminate mycotoxins from the food chain as the fungi producing them are common components of the epiphytic and endophytic microflora in crops resulting in natural crop contamination in the field. However, mycotoxin concentration levels in grains and their products could be reduced to the point where they pose no health risks to consumers.

Effective control of mycotoxins relies largely on preventive strategies *i.e.* use of resistant maize varieties (Czembor *et al.* 2019); good agricultural and processing practices and favorable storage practices that suppress the growth and development of the causative fungi. Early detection and possible exclusion of fungal contaminated grains are essential control measures for ensuring storage longevity and food safety (Lavkor *et al.* 2019; Orina *et al.* 2017). However, once mycotoxins contamination occurs, this approach might not eliminate mycotoxins thus necessitating the use of postharvest detoxification procedures.

Different species of yeasts, fungi and bacteria had been used as biocontrol agents for mycotoxigenic fungi (Medeiros *et al.* 2012). The use of biocontrol agents relies on competitive exclusion whereby large quantities of nontoxigenic inoculum are introduced into the soil around growing crops which compete with toxigenic strains for infection sites on the developing crop (Wild *et al.* 2015). Successful exclusion of the toxigenic fungi by the biocontrol agents at the infection sites results in reduced preharvest risk of mycotoxin contaminations.

The use of natural clay adsorbents such as phyllosilicate clay montmorillonite and dietary calcium montmorillonite has been demonstrated to decrease the bioavailability and associated toxicities of AFB and FB in the gastrointestinal tract of experimental animals and humans (Robinson *et al.* 2012).

Compared to other common mycotoxin-adsorption compounds, the natural essential oil has advantages as high efficiency, ecofriendly and low-drug-resistance tool (Luo *et al.* 2018). The inhibitory effects of some essential oils have been widely reported. *Melissa officinalis, Salvia officinalis, Coriandrum sativum, Thymus vulgaris, Mentha piperita* and *Cinnamomum zeylanicum* (Sumalan *et al.* 2013), lemon, grapefruit and *Cymbopogon martinii* (Perczak *et al.* 2016), garlic and *Origanum vulgare* (Ozcakmak *et al.* 2017) were reported as effective in either inhibiting or reducing the associated mycotoxins activities.

Cold atmospheric pressure plasma (CAPP) is a promising technology for removing mycotoxins from the food chain. It is efficient in degrading mycotoxins as well as being cost-effective and ecologically neutral (Hojnik *et al.* 2017). CAPP effectively decontaminated AFB1, DON and NIV and eliminated their cytotoxicity when tested on mouse macrophage RAW264.7 cells *in vitro* (Park *et al.* 2007). However, in-depth knowledge of the molecular mechanisms and kinetics of plasma-based mycotoxin decontamination is needed before commercializing the technology (Hojnik *et al.* 2017).

CONCLUSION

Mycotoxins naturally contaminate maize grains before harvest, at harvest and after harvest. The genetic make-up of the maize and mycotoxigenic fungi, crop management practices adopted and prevailing climatic factors influence mycotoxin contamination of maize. There is multi-mycotoxin contamination in the commercial maize which has been isolated from processed foods and feed in South Africa. The concentration of the mycotoxins can be reduced by using good agricultural practices and postharvest detoxification procedures. The absence of Aflatoxin B1, B2, G1, G2, OTA, T2-toxin and HT-2 toxin in the commercial maize samples from 2010/2011 to 2016/2017 seasons is a huge food and feed safety advantage for South Africa maize producers.

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