Mycotoxins in Maize and Implications on Food Security: A Review

U.P. Chukwudi1,3, F.R. Kutu2, S. Mavengahama1

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 (Ismail 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?

1Food Security and Safety Niche Area Research Group, Faculty of Natural and Agricultural Sciences, North-West University P/Bag X2046, Mmabatho 2735, South Africa. 2School of Agricultural Sciences, University of Mpumalanga, Mbombela, South Africa. 3Department of Crop Science, University of Nigeria Nsukka, Enugu, Nigeria.

Corresponding Author: U.P. Chukwudi, Food Security and Safety Niche Area Research Group, Faculty of Natural and Agricultural Sciences, North-West University P/Bag X2046, Mmabatho 2735, South Africa. Email: uchechukwu.chukwudi@um.edu.ng

How to cite this article: Chukwudi, U.P., Kutu, F.R. and Mavengahama, S. (2021). Mycotoxins in Maize and Implications on Food Security: A Review. Agricultural Reviews. 42(1): 42-49. DOI: 10.18805/ag.R-140.

Submitted: 14-03-2020 Accepted: 15-12-2020 Online: 02-02-2021

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),...
Mycotoxins in Maize and Implications on Food Security: A Review

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 (Mishairabgwi 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. 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 (Mishairabgwi 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
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         | 49   | 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 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   |

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 |

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-Juboori and Juber, 2013). The latter is a more effective pathway for mycotoxin entry into maize kernel (Al-Juboori
Mycotoxins in Maize and Implications on Food Security: A Review

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 mycotoxinogenic 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; Mishairabgwii 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, hepatotoxicity 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, 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
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 nontoxicigenic 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 zeylanicium (Sumalan et al. 2013), lemon, grapefruit and Cymbopogon martinii (Perczak et al. 2016), garlic and Origanum vulgare (Ozcamak 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.

REFERENCES

Adékoya, I., Obadina, A., Adaku, C.C., De Boevere, M., Okoth, S., De Saeger, S. and Njohbe, P. (2018a). Mycobiota and co-occurrence of mycotoxins in South African maize-based opaque beer. International Journal of Food Microbiology. 270: 22-30.

Adékoya, I., Obadina, A., Phoku, J., De Boevere, M., De Saeger, S. and Njohbe, P. (2018b). Fungal and mycotoxin contamination of fermented foods from selected South African markets. Food Control. 90: 295-303.

Ahamed, S., Foster, J.S., Bukovsky, A. and Wimalasena, J. (2001). Signal transduction through the ras/Erk pathway is essential for the mycoestrogen zearalenone induced cell cycle progression in MCF 7 cells. Molecular Carcinogenesis: Published in cooperation with the University of Texas MD Anderson Cancer Center. 30: 88-98.

| Mycotoxin | European Union* | United States* | China** | South Africa* |
|-----------|-----------------|----------------|---------|---------------|
| Aflatoxins| 5 to 10         | 0.5 to 20      | 20      | 10            |
| Fumonisins| 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), *(Alshannahq and Yu, 2017), **(Anukul et al. 2013).
Mycotoxins in Maize and Implications on Food Security: A Review

Al-Juboori, H.H. and Juber, K.S. (2013). Efficiency of some inoculation methods of Fusarium proliferatum and F. verticilliodes on the systemic infection and seed transmission on maize under field conditions. Journal of North America. 4: 583-589.

Alshannaq, A. and Yu, J-H. (2017). Occurrence, toxicity and analysis of major mycotoxins in food. International Journal of Environmental Research and Public Health. 14: 632.

Ankul, N., Vangnai, K. and Mahakarnchanakul, W. (2013). Significance of regulation limits in mycotoxin contamination in Asia and risk management programs at the national level. Journal of Food and Drug Analysis. 21: 227-241.

Awad, W., Ghareeb, K., Böhm, J. and Zentek, J. (2013). The toxicological impacts of the Fusarium mycotoxin, deoxynivalenol, in poultry flocks with special reference to immunotoxicity. Toxins. 5: 912-925.

Bennett, J.W. and Klich, M. (2003). Mycotoxins. Clinical Microbiology Review. 16: 497-516. DOI: 10.1128/CMR.16.3.497-516.2003.

Berthiller, F., Crews, C., Dal’Asta, C., Saeger, S.D., Haesaert, G., Karlowsky, P., Oswald, I.P., Seefelder, W., Speijers, G. and Strøka, J. (2013). Masked mycotoxins: A review. Molecular Nutrition and Food Research. 57: 165-186.

Beukes, I., Rose, L.J., Shephard, G.S., Flett, B.C. and Viljoen, A. (2017). Mycotoxigenic Fusarium species associated with grain crops in South Africa: A review. South African Journal of Science. 113: 1-12.

Cheng, Q., Jiang, S.Z., Li, S.Q., Wang, Y.X., Zhang, C.Y. and Yang, W.R. (2017). Effects of low-dose zearealenone-contaminated diets with or without montmorillonite clay adsorbent on nutrient metabolic rates, serum enzyme activities and genital organs of growing-laying hens. The Journal of Applied Poultry Research. 26: 367-375.

Choudhury, D., Dobhal, P., Srivastava, S., Saha, S. and Kundu, S. (2018). Role of botanical plant extracts to control plant pathogens. Indian Journal of Agricultural Research. 52: 341-346. DOI: 10.18805/IJARe.A-5005

Chukwudi, U.P., Agbo, C.U., Echezona, B.C., Eze, E.I., Kutu, F.R. and Mavengahama, S. (2020). Variability in morphological, yield and nutritional attributes of ginger (Zingiber officinale) germplasm in Nigeria. Research on Crops. 21(3): 634-642. DOI: 10.31830/2348-7542.2020.099

Czembor, E., Waśkiewicz, A., Piechota, U., Puchta, M., Czembor, J.H. and Stepień, Ł. (2019). Differences in ear rot resistance and Fusarium verticillioides-produced fumonisint contamination between Polish currently and historically used maize inbred lines. Frontiers in Microbiology. 10: 449-449.

Eze, U.A. and Okonofua, F.E. (2015). High prevalence of male infertility in Africa: are mycotoxins to blame? African Journal of Reproductive Health. 19: 9-17.

Folcher, L., Delos, M., Marenque, E., Jarry, M., Weissenberger, A., Eychenne, N. and Regnaut-Roger, C. (2010). Lower mycotoxin levels in Bt maize grain. Agronomy for Sustainable Development. 30: 711-719.

Gratz, S.W. (2017). Do plant-bound masked mycotoxins contribute to toxicity? Toxins. 9: 85.

Hojnik, N., Cvelbar, U., Tavčar-Kalcher, G., Walsh, J.L. and Krizaj, I. (2017). Mycotoxin decontamination of food: Cold atmospheric pressure plasma versus “classic” decontamination. Toxins. 9: 151. doi: 10.3390/toxins9050151.

Human, U. (2018). Bimoin survey reveals global rise of mycotoxins. AFMA Matrix. 27: 49-53.

IARC (2012). Economics of mycotoxins: evaluating costs to society and cost-effectiveness of interventions. IARC Sci Publ: 119-129.

ITC [International Trade Centre] (2019) Available at https://www.trademap.org/ Country_SelfProductCountry.aspx.

Ismaiel, A. and Pappenbrock, J. (2015). Mycotoxins: producing fungi and mechanisms of phytotoxicity. Agriculture. 5: 492-537.

Janse van Rensburg, B., McLaren, N.W., Flett, B.C. and Schoeman, A. (2015). Fumonisins producing Fusarium spp and fumonisint contamination in commercial South African maize. European Journal of Plant Pathology. 141: 491-504.

Khatibi, P., McMaster, N. and Musser, R. (2014). Survey of mycotoxins in corn distillers’ dried grains with solubles from seventy-eight ethanol plants in twelve states in the US in 2011. Toxins. 6: 1155-1168.

Köppen, R., Koch, M., Siegel, D., Muel, R. and Nehls, I. (2010). Determination of mycotoxins in foods: current state of analytical methods and limitations. Applied Microbiology and Biotechnology. 86: 1595-1612.

Kovalsky, P., Kos, G., Nährer, K., Schwab, C., Jenkins, T., Schatzmayr, G., Sulyok, M. and Krška, R. (2016). Co-occurrence of regulated and masked emerging mycotoxins and secondary metabolites in finished feed and maize-An extensive survey. Toxins. 8: 363. doi: 10.3390/toxins8120363

Lavkor, I., Var, I., Saglam, S., Uckun, O., Tekin, A. and Savas, O. (2019). Presence of some mycotoxins in peanuts from harvest to storage. Legume Research. 42(6): 862-866. DOI: 10.18805/LR-446

Luo, Y., Liu, X. and Li, J. (2018). Updating techniques on controlling mycotoxins-A review. Food Control. 89: 123-132

Manna, M. and Kim, K.D. (2017). Influence of temperature and water activity on deleterious fungi and mycotoxin production during grain storage. Mycobiology. 45: 240-254.

Massart, F., Mesucci, V., Saggese, G. and Soldani, G. (2008). High growth rate of girls with precocious puberty exposed to estrogentic mycotoxins. The Journal of Pediatrics. 152: 690-695.

Medeiros, F.H.Vd., Martins, S.J., Zucchi, T.D., Melo, I.Sd., Batista, L.R. and Machado, Jd.C. (2012). Biological control of mycotoxin-producing molds. Ciência e Agrotecnologia. 36: 483-497.

Medina, Á., González-Jarín, J.M. and Sainz, M.J. (2017). Impact of global warming on mycotoxins. Current Opinion in Food Science. 18: 76-81.

Meyer, H., Skhosana, Z.D., Motlanthe, M., Louw, W. and Rohwer, E. (2019). Long term monitoring (2014-2018) of multi-mycotoxins in South African commercial maize and wheat with a locally developed and validated LC-MS/MS method. Toxins. 11: 271. doi.org/10.3390/toxins11050271.

Mishairabgwi, J., Ezekiel, C., Sulyok, M., Shephard, G. and Krška, R. (2017). Mycotoxin contamination of foods in Southern Africa: A 10-year review (2007-2016). Critical Reviews in Food Science and Nutrition. 59: 43-58.

Murillo-Williams, A. and Munkvold, G. (2008). Systemic infection by Fusarium verticillioides in maize plants grown under three temperature regimes. Plant Disease. 92: 1695-1700.
Mwanza, M., Ndou, R.V., Dzoma, B., Nyirenda, M. and Bakunzi, F. (2013). Canine aflatoxicosis outbreak in South Africa (2011): A possible multi-mycotoxins aetiology. Journal of the South African Veterinary Association. 84: 1-5.

Njobeh, P.B., Dutton, M.F., Åberg, A.T. and Haggblom, P. (2012). Estimation of multi-mycotoxin contamination in South African compound feeds. Toxins. 4: 836-848.

OECD/FAO (2018). OECD-FAO Agricultural Outlook 2018-2027. OECD Publishing/Food and Agriculture Organization of the United Nations.

Orina, I., Manley, M. and Williams, P.J. (2017). Non-destructive techniques for the detection of fungal infection in cereal grains. Food Research International. 100: 74-86.

Ozcakmak, S., Gul, O., Dervisoglu, M., Yilmaz, A., Sagdic, O. and Arici, M. (2017). Comparison of the effect of some essential oils on the growth of Penicillium verrucosum and its Ochratoxin a production. Journal of Food Processing and Preservation. 41: e13006.

Park, B.J., Takatori, K., Sugita-Konishi, Y., Kim, I.-H., Lee, M.-H., Han, D.-W., Chung, K.-H., Hyun, S.O. and Park, J.-C. (2007). Degradation of mycotoxins using microwave-induced argon plasma at atmospheric pressure. Surface and Coatings Technology. 201: 5733-5737.

Perczak, A., Juš, K., Marchwińska, K., Gwiazdowska, D., Wasikiewicz, A. and Golitiski, P. (2016). Degradation of zearalenone by essential oils under in vitro conditions. Frontiers in Microbiology. 7:1224. doi: 10.3389/fmicb.2016.01224.

Picot, A., Barreau, C., Caron, D., Lannou, C. and Richard-Forget, F. (2011). The dent stage of maize kernels is the most conducive for fumonisins biosynthesis under field conditions. Applied and Environmental Microbiology. 77: 8382-8390.

Pierron, A., Alassane-Kpembali, I. and Oswald, I.P. (2016). Impact of two mycotoxins deoxynivalenol and fumonisins on pig intestinal health. Porcine Health Management. 2: 21. DOI 10.1186/s40813-016-0041-2

Pietro, A.D., Madrid, M.P., Caracuel, Z., Delgado Jarana, J. and Roncero, M.I.G. (2003). Fusarium oxysporum, exploring the molecular arsenal of a vascular wilt fungus. Molecular Plant Pathology. 4: 315-325.

Pray, C.E., Rheeder, J.P., Gouse, M., Volkwyn, Y., Van Der Westhuizen, L. and Shephard, G.S. (2013). By maize and fumonisin reduction in South Africa: Potential health impacts. In: Genetically Modified Crops in Africa: Economic and Policy Lessons from Countries South of the Sahara. [Falck-Zepeda, J.B., GruA’te, G.P., Sithole-Niang, I., (eds)], International Food Policy Research Institute (IFPRI) p. 43-59.

Rheeder, J., Van der Westhuizen, L., Imrie, G. and Shephard, G. (2016). Fusarium species and fumonisins in subsistence maize in the former Transkei region, South Africa: a multi-year study in rural villages. Food Additives and Contaminants: Part B. 9: 176-184.

Robinson, A., Johnson, N.M., Strey, A., Taylor, J.F., Marroquin-Cardona, A., Mitchell, N., Afriyie-Gyawu, E., Ankrah, N-A., Williams, J.H. and Wang, J-S. (2012). Calcium montmorillonite clay reduces urinary biomarkers of fumonisin B1 exposure in rats and humans. Food Additives and Contaminants: Part A. 29: 809-818.

Russell, M., Paterson, R. and Lima, N. (2010). How will climate change affect mycotoxins in food? Food Research International. 43: 1902-1914.

SAGL (2018). South African Maize Crop Quality Report 2016/2017 Season, Pretoria, South Africa.

Santiago, R., Cao, A. and Butrón, A. (2015). Genetic factors involved in fumonisin accumulation in maize kernels and their implications in maize agronomic management and breeding. Toxins. 7: 3267-3296.

Shephard, G.S. (2008). Impact of mycotoxins on human health in developing countries. Food Additives and Contaminants. 25: 146-151.

Singh, S.D. and Chuturgoon, A.A. (2017). A comparative analysis of mycotoxin contamination of supermarket and premium brand pelleted dog food in Durban, South Africa. Journal of the South African Veterinary Association. 88: 1-6.

Sumsalan, R.-M., Alexa, E. and Poiana, M-A. (2013). Assessment of inhibitory potential of essential oils on natural mycophilia and Fusarium mycotoxins production in wheat. Chemistry Central Journal. 7: 32. doi: 10.1186/1752-153X-7-32.

Vaughan, M.M., Huffaker, A., Schmelz, E.A., Dafoe, N.J., Christensen, S., Sims, J., Martins, V.F., Swerbilow, J., Romero, M. and Alborn, H.T. (2014). Effects of elevated [CO] on maize defence against mycotoxigenic Fusarium verticillioides. Plant, Cell and Environment. 37: 2691-2706.

Wild, C.P., Miller, J.D. and Groopman, J.D. (2015). Mycotoxin control in low-and middle-income countries. International Agency for Research on Cancer Lyon, France.

Zain, M.E. (2011). Impact of mycotoxins on humans and animals. Journal of Saudi Chemical Society. 15: 129-144.