Croatian Journal of Food Science and Technology

journal homepage: www.ptfos.unios.hr/cjfst/

Review paper *DOI: 10.17508/CJFST.2019.11.2.09*

Climate Change and Mycotoxins - The African Experience

STEPHEN O. FAPOHUNDA*, ANNABELLA A. ADEWUNMI

Department of Microbiology, Babcock University, Ilishan Remo Nigeria

ARTICLE INFO

Article history:
Received: February 22, 2019
Accepted: June 17, 2019

Keywords:
climate change,
mycotoxin, Africa,
agro-ecozones

ABSTRACT

The role of climate change on mycotoxin profile and activity was reviewed. The unprecedented spread and relocation experienced by some regulated mycotoxins on food and feed items were investigated. Aspergillus species and aflatoxin, originally associated with tropical and subtropical climate characteristics of Sub-Saharan Africa are now comfortable guests in temperate zones. The same applies to *Fusarium* and *Penicilium* species, earlier thought to be strictly specific to temperate regions of Europe, now encountered in tropical Africa, with their toxins like zearalenone and trichothecenes, particularly in recent surveillance studies. This review is an update on the unstable trend on a global mycotoxin map with reference to the obvious climatic dynamics, having Africa in view.

Introduction

Mycotoxins are a group of biochemicals that actively partner with pesticides in determining the food safety profile in African countries (Adewunmi and Fapohunda, 2018). The potential effects of climate change on mycotoxigenic fungi and mycotoxin contamination of food crops pre- and post- harvest have been extensively studied (Magan et al., 2011; Kovalsky, 2014; Medina et al., 2015a). A shift in mycotoxin pattern triggered by climate change is being observed globally, which is significant, since mycotoxin production is climate driven. Global warming due to large scale deforestation, burning of fossil fuels, accelerated industrialization and other human activities resulting in flooding, excessive heat, livestock migration, adaptations and 'new–niche' circumstances for toxigenic fungi is now becoming a characteristic in the food and mycotoxin discipline. Concentrations of methane, carbon dioxide, nitrogen dioxide and chlorofluorocarbons in the atmosphere have increased, leading to serious environmental warming. Mycotoxins are climate - dependent, hence this climate change, which is affecting both agricultural and natural ecosystems, may lead to a 'new age' of extinction and 'evolution' of new forms, or a redirection of the biochemistry of some mycotoxigenic fungi, in event that the temperature increases sufficiently in already hot regions such as in Africa, South Asia and central America. This will be a welcome benefit of climate change. It has also been observed that some previously native fungal species are being displaced by other more virulent and aggressive ones, and the geographical distribution is being distorted, as fungal species which were originally endemic to tropical climate are now being isolated in known temperate regions. According to Russel et al. (2009) several factors affect mycotoxin contamination, but climate change is the most important. Hence, when climate change occurs, mycotoxin production will be affected because its production depends on environmental factors such as temperature and availability of moisture pre- and post-harvest. Studies on the impact of climate change factors on growth and mycotoxin production in food crops such as carbon dioxide (CO_2), water activity (a_w), and temperature interactions showed that the range of these 3 factors for mycotoxin production is narrower than that for fungal growth (Medina et al., 2015b). Kovalsky (2014) stated that climatic indicators such as temperature and carbon dioxide levels have increased due to high variability in weather

*Corresponding author E-mail: oystak@yahoo.co.uk

conditions, including changes in precipitation patterns and frequent storms. Various global warming projections have also been reported in recent times, with the prediction that global temperatures may rise up to 4.8°C in year 2100 (IPCC report, 2014). It is also assumed that the current CO_2 level will potentially be doubled by 2050's and tripled around 2100's (Magan et al., 2003, Magan and Aldred, 2007). Accordingly, this is expected to affect agriculture, and geographical distribution, or life cycle of insects that promote fungal infections of crops. It has also been observed that some species of fungi are being displaced by other more virulent and aggressive ones in response to these changes. FAO (2008) for instance, reported on climate change and its implications on food safety and observed that in the temperate region of North America, *Fusarium culmorum* is being replaced by *F. graminearum,* a very virulent plant pathogen. Furthermore, in North America, changes have also been observed where a more toxigenic *Fusarium* species is replacing the normal non-toxigenic population. This indicates that new strains of *Fusarium* that are capable of forming unexpected toxins as a result of climate and environmental instabilities are emerging. In Minnesota, USA, a new *Fusarium* isolate known as "Northland population" has been identified, which does not produce the protein-synthesis-inhibiting trichothecenes, deoxynivalenol (DON) or nivalenol (NIV) (Kovalsky, 2014). The highest mycotoxin risks will be observed not only in countries with tropical climate like Africa, but also in countries with temperate climates such as Europe and North America, if there is rise in temperature, which favours the growth of *Aspergillus* species and attendant aflatoxin B1 production. It is not surprising that in 2003, Northern Italy experienced hot and dry episodes which encouraged *Aspergillus flavus* to colonize maturing maize, a key crop, by out-competing the then more common *Fusarium* spp. (Kovalsky, 2014). Traditional and normal fungal flora are fast giving way to a new set whose virulence status is still under investigation.

Climate change inconsistencies can cause changes in mycotoxin production and prevalence within the same fungal species. *Alternaria alternata* produces a variety of mycotoxins like alternariol (AOH), alternariol monomethyl ether (AME), and altenuene (AE). At 21 °C and $0.95a_w$, AOH is produced, while AME is produced at the same $0.95a_w$ levels, but at 35 °C, a much warmer temperature, with the possibility of a shift from AOH production to AME. Changes in water activity and temperature stress may impact *Aspergillus* section Nigri species, influencing ochratoxin A contamination of grapes and grape-based products (Astoreca et al., 2010). Added to the already established food safety concern is the noticeable increase in worldwide production of mycotoxins like fumonisin zearalenone and deoxylivanenol on matrices like corn, wheat, rice and soybean(Gos, 2018).

In Sub-Saharan Africa drought stress is important, especially in terms of food security. For example, maize has the capacity to replace stress-tolerant sorghum, because of the susceptibility of maize and peanuts to fungal infection during water stress. As a result, there is increased pre-harvest aflatoxin contamination of food with significant negative impact on the consumption or the ability to export. According to Magan and Aldred (2007) and Leong et al. (2011), xerophilic fungi, such as *Wallemia sebi*, *Xeromyces bisporus* and *Chrysosporium* spp., ordinarilly regarded as extraneous, could also become more important colonizers of food, as they can grow under dry conditions (0.65–0.74 water activity (a_w)). This is possible because at such dry regime, there is less competition from other mesophilic fungi. These fungi, particularly *W. sebi*, can produce metabolites such as walleminol and walleminone, both with toxigenic potentials to animals and humans (Pieckova and Kunova, 2002). The impact that climate change may have on plant breeding, plant diseases and mycotoxins in Europe, Australia and Africa has also been examined (Garrett et al., 2006; Boken et al., 2008; Chauhan et al., 2008; 2010; Miraglia et al., 2009; Paterson and Lima, 2010).

Geographical Spread

The occurrence of mycotoxins in food and animal feed often follows a geographic pattern (Fig. 1). *Aspergillus* species naturally grow optimally in the tropical and subtropical climate, hence aflatoxins are a major concern in these regions, especially in Sub-Saharan Africa. *Fusarium* and *Penicilium* species grow optimally in temperate climate, hence fusariotoxins such as ZEN or trichothecenes occur mainly in the temperate climate of North America and Europe (Paterson and Lima, 2011; Magan et al., 2011). However, in recent times, a shift in mycotoxin patterns, driven by climate change is being observed globally. Global warming due to large scale deforestation, burning of fossil fuels, industrialization, ozone depletion, and other human activities has been experienced in the current dispensation. Concentrations of methane, carbon dioxide, nitrogen dioxide and chlorofluorocarbons in the atmosphere have increased leading to serious environmental warming. Aflatoxin distribution is no longer a preserve of the tropical and sub-tropical climate, but has now spread all over the world. Fumonisins, hitherto a strict preserve of the temperate climate are also found in high numbers in the tropical climate of Africa (Kovalsky, 2014).

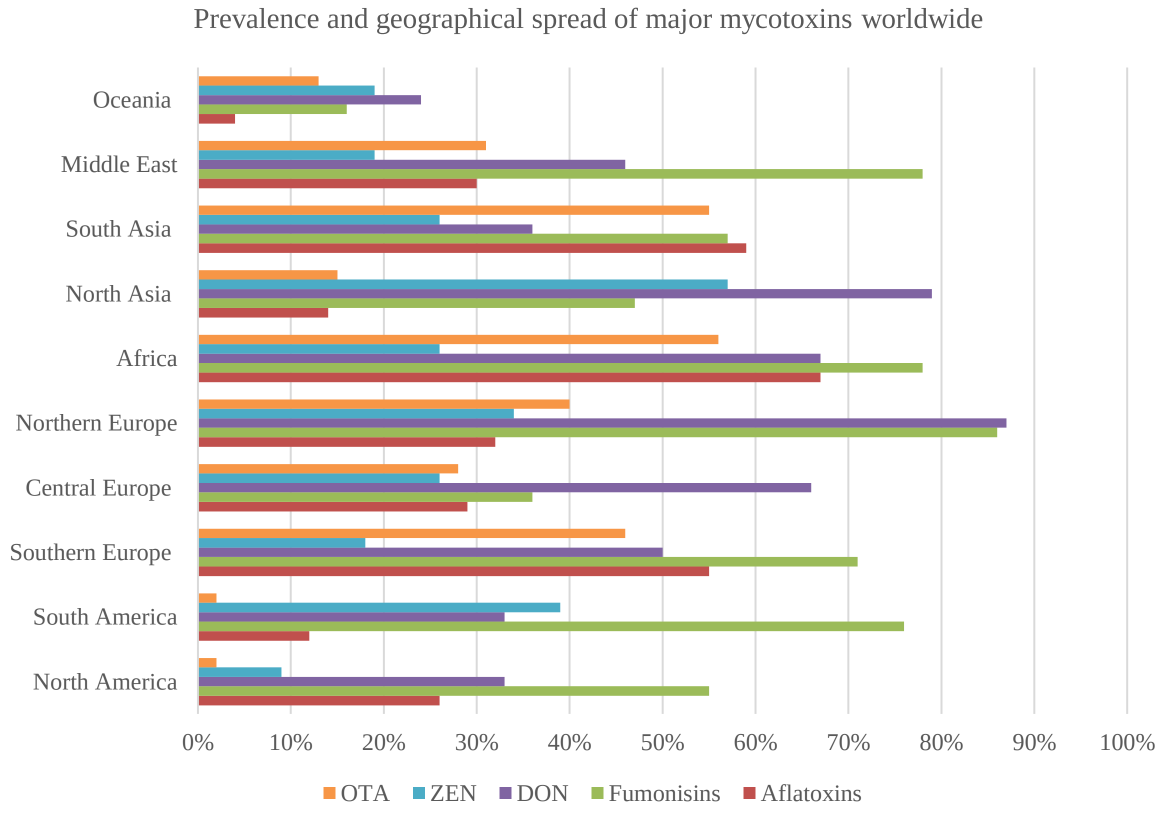

Fig 1. Global distribution of some regulated mycotoxin (adapted from Kovalsky, 2014).

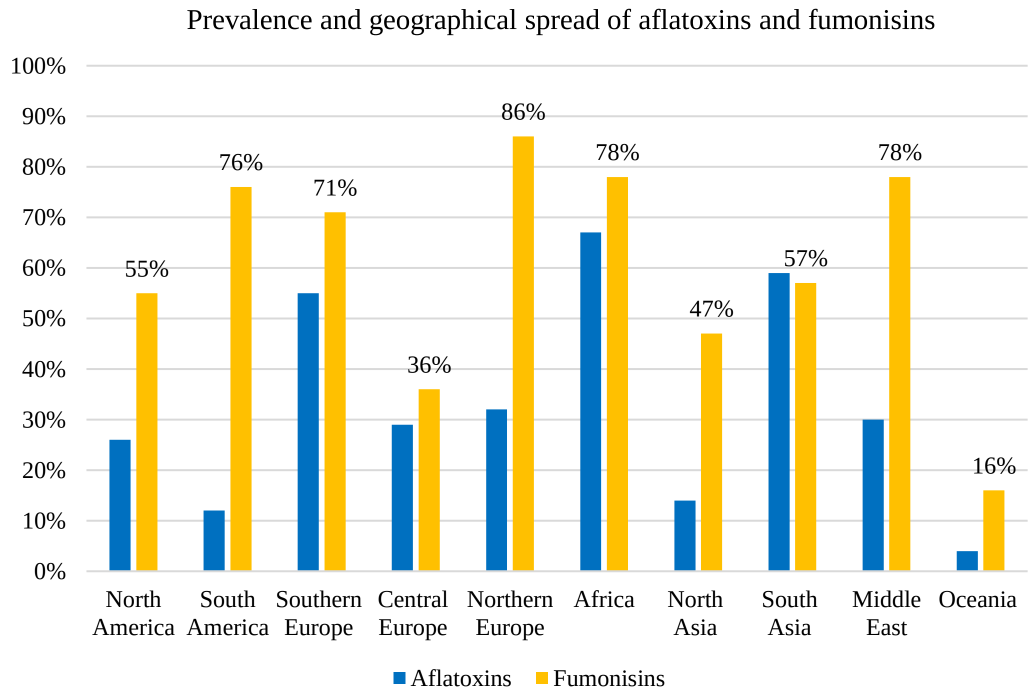

Fig 2. Global distribution of aflatoxins and fumonisins. Source: (adapted from Kovalsky, 2014).

Figures 1 and 2 show that, as in 2014, aflatoxins have a global spread covering the tropical and temperate regions of the world with 55% in Southern Europe. More interesting is the spread of fumonisins to the tropical climate of Africa, South Asia and Middle East where 78, 57 and 78%, were recorded respectively (Kovalsky, 2014). Other mycotoxins such as DON and OTA are now also predominant in the tropical regions of Africa with 67 and 56%, respectively. *Aspergillus* species, the producer of aflatoxins prefer the warm tropical and subtropical conditions, thus global warming, especially in the temperate climate, encourages the fungi and its toxin production. Crops that were initially resistant to *A. flavus* infections and subsequent mycotoxin production are now susceptible due to climate change, as the environmental conditions now favour fungal growth. In warm and humid subtropical and tropical conditions, maize ears are ideal for colonization and dominance of *A. flavus* and *A. parasiticus* with subsequent production of aflatoxins. Under drought conditions, groundnut pods can crack, so that *A. flavus* and *A. parasiticus* can ingress, resulting in high aflatoxin accumulation. Delayed harvest, late irrigation, rain and dew during warm periods are associated with increased aflatoxin levels. Exposure of peanuts to high temperatures during pod maturation and rainfall are additional factors for higher susceptibility (Milani, 2013). On the contrary, *Fusarium* species, the producer of fumonisins and trichothecenes, such as DON and ZEN, prefer the temperate climate. Maize grown in temperate region is an appropriate substrate for *F. liseola* and the production of fumonisins. *F. verticillioides* and *F. proliferatum* are important contaminants of maize in Southern Europe and in the North and South America (Sydenham et al., 1993; Sanchis et al., 1995) and in maize-based foods in different parts of the world (Doko and Visconti, 1994; Sanchis et al., 1994; Velluti et al., 2001). In the central Europe climate zone, ZEN has been found to play a role in food/feed deterioration (Conkova et al., 2003). The highest amount of ZEN produced by *Fusarium* was observed at 25 °C and 16% humidity. DON, a trichothecene mycotoxin is the more common one that may occur in warmer climates. DON impairs immune response in humans and animals and has been incriminated in outbreaks of acute gastrointestinal infections in Asia (WHO, 2002). In Africa, Ngoko et al. (2001) reported DON contamination of foods in the Cameroons. Maximum amounts of DON were produced at 0.997 water activity after 6 weeks at 30 °C (Maria et al 2006). Ochratoxin A is a mycotoxin produced by *A. ochraceus*, *P. verrucosum and A. carbonicus* (Frisvad and Thrane, 2002). In warm weather, such as in West and Central Africa, OTA is more commonly associated with *A. ochraceus* than with *P. verrucosum*, which often produces OTA in temperate climates of Northern Europe and Canada (Sweeney and Dobson, 1998; JECFA, 2001).

Generally, in Sub-Saharan Africa, the Sahel region has high temperatures and a high risk of drought stress, encouraging the growth of *A. flavus* over other grain fungi. The 'S' strain of *A. flavus* which has a higher aflatoxin production and toxicity occurs more in this zone (Cotty and Cardwell, 1999). Maize, in the Sahel region of both Benin and Nigeria, experienced a significantly higher risk of aflatoxin contamination after six months of storage than in the other zones.

Dry savannah region has dry climatic conditions with rainy season during which farmers introduce cotton, groundnut, and maize in their fields. All of these crops are prone to *A. flavus* and aflatoxin build-up and growing them together has the potential to increase contamination. However, in the dry savannah zone of Benin and Nigeria, overall toxin levels were low due to better crop husbandry and better climate (Udoh et al., 2000). In this zone, ear boring insects are known to increase aflatoxin contamination (Setamou et al., 1998).

The moist savannah, in contrast, has a bimodal rainy season and so farmers find it difficult to dry their first season crops before storage, resulting in insect infestation and deterioration in quality. The coastal savannah and humid rain forest regions have high humidity and warm temperatures and this increases the risk of fungal contamination of maize, but *A. flavus* being displaced by *Fusarium* and *Penicilium* spp. due to the cool climate found in this zone, has led to the dominance of fumonisins, DON and ZEN. These agro-ecological conditions exist across a large part of sub-Saharan Africa (Cardwell, 2000).In Africa, a very recent survey revealed that fumonisin, a *Fusarium* mycotoxin was found in 100% of samples analyzed at an average contamination level of 203ppb with a maximum of 3374ppb(Biomin, 2019).

Standards and legislations

Mycotoxins are regulated in foods and feeds due to health concerns. Mycotoxins such as aflatoxins, DON and ZEN are known to have carcinogenic, immunotoxic and environmental estrogenic properties respectively and also cause immune suppression in young animals (Cardwell, 2000). In the developed countries of the world, human exposure, especially of children, to dietary mycotoxins is virtually non-existent because of regulatory standards. In developing countries, monitoring and enforcement of standards are almost non-existent, and the staple foods are often susceptible to mycotoxins. In Sub-Saharan

Africa people are exposed to unsafe levels of various multi-mycotoxins, with attendant serious public health consequences (Ezekiel et al., 2014) which have been ignored. However, issues on standards and regulations on mycotoxins are gradually progressing because all countries recognize that addressing mycotoxin contamination in food commodities and feeds will not only reduce public health issues and costs, but also offer gains with respect to export trade. Regulations in individual countries depend on the final use, with the strictest limits for human consumption and for export products and the lowest for industrial uses. The "safe" limit of aflatoxins for human consumption range is 4-20 mg/kg, however the EU standard is the strictest, with AF-B_1 and total AFs not greater than 2 mg/kg and 4 mg/kg, for products meant for direct human consumption and marketing respectively (EC 2007, EC 2010).

The United States regulations have also specified the maximum acceptable limit for total AFs at 20 mg/kg (Wu, 2006, FAO, 2004). A tolerable level of 30 mg/kg for aflatoxin in all foods has similarly been set for India. In Brazil, total aflatoxin limits in nuts have been set at 30 mg/kg (Freitas-Silva and Venancio, 2011) and limits of 10 mg/kg for cocoa beans and 5 mg/kg for commercialized cocoa products and chocolate, for both OTA and total AFs have also been set (Copetti et al., 2014). Likewise, in Australia and Switzerland, maximum levels of 0.05 mg/kg for milk, 0.25 mg/kg for cheese, and 0.02 mg/kg for butter are established.

Studies have shown that protective legislation on mycotoxins is still non-existent in many developing countries, especially in Sub-Saharan Africa, where traditional practices and diets contribute to potential health risks, and this is probably due to the lack of competence and resources to detect contamination and enforce regulations (Waliyar et al., 2015; Williams et al., 2004; Wild 2007; Wild and Gong, 2010). In spite of this, few of these developing countries have endeavoured to set their own regulatory limits based on the country's food regulations. For instance, Kenya adopted a maximum allowed level (MAL) of 10 mg/kg of AF-B_1 in groundnuts and several grain foods. In Nigeria, 1.0 mg/kg is fixed as the regulatory limited for AF-B_1 in milk (Iqbal et al., 2015), whilst South Africa presently allows up to 0.05 mg/kg of AF-M_1 in milk and milk products (Mulunda and Mike, 2014).

Climate change - food security relations

Recent developmental approach on the effect of climate change and mycotoxin production has been to try to incorporate effect of climate change conditions on both plant physiology and the mycotoxin-producing fungi such as *A. flavus* and *F. verticillioides.* Vaughan et al. (2014) studied the effect of elevated CO_2 on the interaction between maize and *Fusarium verticillioides,* and discovered that elevated CO_2 of about 800 ppm (double the current CO_2) increased maize susceptibility to *F. verticillioides* colonization. Nevertheless, fumonisin production was not impacted. This suggested that there were some physiological effects on maize agronomy under climate change treatments, which could impact the infection and contamination with mycotoxigenic fungi. Furthermore, similar physiological effects were also seen in the interaction of wheat with Fusarium Head Blight (FHB) and *Septoria tritici* blotch (STB) diseases when CO_2 was doubled (Vary et al., 2015). Medina et al. (2015a, b) posited that a key gene in fumonisin biosynthetic pathway (FUM 1) is significantly affected by changes in environmental factors.

Future projections indicate clearly that climate change factors will have a profound effect on both the growth of fungi and relative mycotoxin production and food security, whose key components are three key components are: (a) sufficient food availability, (b) access to this food and (c) quality and utilization of the food in terms of both nutritional and cultural perspectives (FAO, 1998, Medina et al., 2017). The biggest risk with regards to mycotoxins and climate change may be found in developed countries with temperate climates such as Europe and the United States of America (Russel et al., 2009). The climate of these region will become warmer reaching temperatures of 33 °C, which is optimal for aflatoxin production, especially if aflatoxin susceptible crops are grown (e.g. peanuts and maize), thus increasing the risks of aflatoxin in these regions (Paterson and Lima, 2010). Therefore, from a position where aflatoxins were not of any concern to indigenous crops, there is a possibility that they may become a significant risk. On the flip side, aflatoxin may not be of any significant concern in the countries with currently very cold climates (e.g. Norway, Canada, and Russia), where even global warming will not result in temperatures warm enough for *A. flavus* and *A. parasiticus* growth. Hot tropical climates such as the one occurring in Africa, Middle East and South Asia may face more serious problems if the temperature of these countries increases at the same rates, as food security may be adversely affected. If temperature reaches 40 °C, as has recently been experienced in some hitherto temperate countries, it can be assumed that fungal growth, mycotoxin production and food damage could be reduced. Fungi which thrive in high temperature regions may not survive in such thermophilic conditions and, as other organisms, may become extinct (Walsh, 2009). However, if the temperatures do not become extremely high and drought conditions become more recurrent, then these may stimulate aflatoxin contamination (Lewis, 2005). *Penicilium* and *Aspergillus* toxins such as Patulin and OTA may become less important in the currently temperate climates as the temperature range become too high for these fungi, since their toxins are associated with lower temperatures.

In Africa, certain aflatoxin producers are associated with hot, dry, 'agroecozones' with latitudinal shifts in climate influencing fungal community structure (Cardwell and Cotty, 2002). Importantly, as global warming and weather patterns become unpredictable, aflatoxin contamination may further restrict the areas over which crops may be grown profitably. Maize, a staple of the large population of people in the warm regions of Africa, Asia and the Americas, is vulnerable, particularly to the influences of climate as demonstrated by the experiences with lethal aflatoxicosis in Kenya (Lewis et al., 2005). Thus, in Africa with hotter tropical climates and longer periods of drought stress, there will be significant impact on food production and susceptibility to mycotoxin contamination. This will in turn directly impact food security through economic instability arising from unpredictable factors beyond human control (Wu and Mitchell, 2016). If such instability has been experienced in the United States of America (Wu et al., 2011), it is only fair for Africa to factor in climate change as part of the overall soup of pre-disposing elements in mycotoxin challenge. This will enhance the quality of any intervention project.

The biological control project rests on stability and consistency with respect to fungal location and productivity. For example, the aflasafe and AF36 biopesticides are confirmed to have a future due to the deployment of native non-toxigenic *Aspergillus flavus*. With climate change, everything about this species may change, including genetic stability and infectivity, culminating in uncertainties in biological interventions

Conclusion

Hitherto native major mycotoxins are no longer restricted to certain regions of the world due to the effect of global warming and climate change. Climatic condition is one of the parameters which determines fungal colonization and mycotoxin production. Mycotoxins are a critical group of contaminants in African foods and feeds. A probe into the subcellular analysis of fungal strain in order to understand the ability to survive through various adaptations, must be updated. Many of the fungi are now extremophiles, making the issue of detection, distribution and intervention now cumbersome and unpredictable. More insight on tolerance of mycotoxigenic fungi to changes in CO_2, temperature and water activity conditions in order to improve predictions of mycotoxin risk is required. Legislations on mycotoxins will be inconclusive and ineffective without a reliable information on climate change.

References

Adewunmi, A. A, Fapohunda, S. O. (2018) Pesticides and food safety in Africa. *Eur. J. Biol. Res.* 8 (2), 70-83. http://dx.doi.org/10.5281/zenodo.1237542

Astoreca A. L., Magnoli, C. E., Dalcero, A. M. (2010) Ecophysiology of Aspergillus Section Nigri Species Potential Ochratoxin A Producers. *Toxins* 2, 2593-2605. https://dx.doi.org/10.3390%2Ftoxins2112593

Biomin (2019) BIOMIN Mycotoxin Survey Q1 2019 Results. https://www.biomin.net/en/articles/biomin-mycotoxin-survey-q1-2019-results/. Accessed September 16, 2019.

Boken, V. K., Hoogenboom, G., Williams, J. H., Diarra, B., Dione, S., Easson, G. L. (2008): Monitoring peanut contamination in Mali (Africa) using the AVHRR satellite data and a crop simulation model. *Int. J. Remote Sensing* 29, 117–129. https://doi.org/10.1080/01431160701264250

Cardwell, K. F. (2000): Mycotoxin contamination of Foods in Africa: Anti-nutritional factors. *Fd. Nut Bull.* 21(4), 488–492.

Cardwell, K. F., Cotty, P. J. (2002): Distribution of Aspergillus section flavi among field soils from the four agro ecological zones of the republic of Benin, West Africa. *Pl. Dis*. 86(4), 434–439. https://doi.org/10.1094/PDIS.2002.86.4.434

Chauhan, Y. S., Wright, G. C., Rachaputi, N.C. (2008): Modelling Climatic Risks of aflatoxin contamination in maize. *Austr. J. Exp. Agric*. 48, 358–366. https://doi.org/10.1071/EA06101

Chauhan, Y. S., Wright, G. C., Rachaputi, N.C. (2010): Application of a model to assess aflatoxin risk in peanuts. *J. Agric. Sci*. 148, 341–351. https://doi.org/10.1017/S002185961000002X

Chin, J. P., Megaw, J., Magill, C. L. (2010): Solutes determine the temperature windows for microbial survival and growth. *Proc. Nat. Acad. Sci. USA* 107, 7835 -7840. https://doi.org/10.1073/pnas.1000557107

Conkova, E., Laciakova, A., Kovac, G., Seidel, H. (2003): Fusarial toxins and their role in animal diseases. *Vet J.* 165, 214–220. https://doi.org/10.1016/S1090-0233(02)00127-2

Copetti, M.V., Iamanaka, B.T., Pitt, J. I., Taniwaki, M. H. (2014): Fungi and mycotoxins in cocoa: From farm to chocolate. *Int. J. Fd. Microbiol*. 178, 13-20. https://doi.org/10.1016/j.ijfoodmicro.2014.02.023

Cotty, P. J., Cardwell, K. F. (1999): Divergence of West African and North American communities of Aspergillus section Flavi. *Appl. Env. Microbiol.* 65, 2264 –2266.

Doko, M. B., Visconti, A. (1994): Occurrence of fumonisins B1 and B2 in corn and corn based human foods tuffs in Italy. *Fd. Addit. Contam.* 11, 433–439. https://doi.org/10.1080/02652039409374245

European Commission (2007): Adapting to Climate Change in Europe – Options for EU Action. Green Paper from the commission to the council, the European Parliament, the European Economic and Social Committee of the Regions, SEC (2007) 849. Brussels, Belgium: European Commission COM (2007) 354 final.

European Commission (2010): Commission regulation (EU) no. 165/2010 of 26 Feb. 2010, Amending regulation (EC) no. 1881/2006 setting maximum levels for certain contaminants in foodstuffs as regards aflatoxin. *Official Journal of the European Union*. 8–12, L50.

Ezekiel, C. N., Atehnkeng, J., Odebode, A. C., Bandyppadhyay, R. (2014): Distribution of aflatoxigenic Aspergillus section Flavi in commercial poultry feed in Nigeria. *Int. J. Fd. Microbiol.* 189, 18–25.

Food and Agriculture Organization (2004): Worldwide regulations for mycotoxins in food and feed in 2003. FAO Food & Nutrition. Paper No. 81, Rome, Italy.

Food and Agriculture Organization (2008): Climate Change and food security. A framework Document. Rome, Italy.

Freitas Silva, O., Venancio, A. (2011): Brazil nuts: Benefits and risks associated with contamination by fungi and mycotoxins. *Fd. Res. Inter.* 44, 1434 – 1440. https://doi.org/10.1016/j.foodres.2011.02.047

Frisvad, J.C., Thrane, U. (2002): Mycotoxin production by common filamentous fungi. In: Introduction to Food and Airborne Fungi, Samson R. A., Hoekstra E.S., Frisvad, J.C., Filtenborg, O. (eds.): 6th ed. Central bureau voor Schimmel cultures. Pp. 383.

Garrett, K.A., Dendy, S.P., Frank, E.E., Rouie, M.N., Travers, S.E. (2006): Climate change effects on plant disease: genomes to ecosystems. *Ann Rev Phytopathol.* 44, 489–509. https://doi.org/10.1146/annurev.phyto.44.070505.143420

Gos, A. Regional Results of Global Mycotoxin Occurrence through June 2018 https://www.biomin.net/en/blog-posts/regional-results-of-global-mycotoxin-occurrence-through-june-2018/. Accessed September 16, 2019

IPCC: The Intergovernmental Panel on Climate Change report (2014): Climate Change 2013. In: Synthesis report, Geneva, pp. 52

Iqbal, S. Z., Jinap, S., Pirouz, A.A., Ahmad-Faisal, A. R. (2015): Aflatoxin M1 in milk and dairy products, occurrence, and recent challenges: A review. *Trends Fd. Sci. Technol.* 46, 110–119.

JECFA (2001): Safety evaluation of certain mycotoxins in food. FAO Food and Nutrition Paper 74/WHO. *Fd. Addit. Series.* 47, 281–415. https://www.fao.org/3/a-bc528e.pdf

Kovalsky, P. (2014): Climate change and mycotoxin prevalence. Broadening Horizon no. 8 Feedipedia files on the web. http://www.feedipedia.org. Accessed September 10, 2018.

Leong, S., Pettersson, O. V., Rice, T., Hocking, A. D., Schnurer, J. (2011): The extreme xerophilic mould, *Xeromyces bisporus* – growth and competition at various water activities. *Int. J. Fd. Microbiol.* 145(1), 57–63. https://doi.org/10.1016/j.ijfoodmicro.2010.11.025

Lewis, L., Onsongo, M., Njapau, H., Schurz-Rogers, H., Luber, G., Kieszak, S., Nyamongo,J., Backer, L., Dahire, A.M., Misore, A., DeCock, K., Rubin, C., Kenya Aflatoxicosis Investigation Group (2005): Aflatoxin contamination of commercial maize products during an outbreak of acute aflatoxicosis in eastern and central Kenya. *Environ. Health. Persp.* 113(12), 1763–1767. https://doi.org/10.1289/ehp.7998

Magan, N., Medina, A., Aldred, D. (2011): Possible climate-change effects on mycotoxin contamination of food crops pre- and postharvest. *Plant Pathol.* 60,150–163. https://doi.org/10.1111/j.1365-3059.2010.02412.x

Magan, N., Aldred, D. (2007): Environmental fluxes and fungal interactions*:* maintaining acompetitive edge. In: Stress in Yeast and Filamentous Fungi. Van West, P., Avery, S., Stratford, M. (eds.) Amsterdam, The Netherlands: Elsevier Ltd. pp. 19–35.

Magan, N., Hope, R., Cairns, V., Aldred, D. (2003: Post-harvest fungal ecology: Impact of fungal growth and mycotoxin accumulation in stored grain. *Eur. J. Plant Pathol.* 109(7), 723–730. https://doi.org/10.1023/A:1026082425177

Maria, L., Ramirez, V., Chulze, S., Magan, N. (2006): Temperature and water activity effects ongrowth and temporal deoxynivalenol production by two Argentinean strains of *Fusarium graminearum* on irradiated wheat grain. *Inter. J. Fd. Microbiol.* 106, 291–296.

Medina A., Akbar, A., Baazeem, A., Rodriguez, A., Magan, N. (2017): Climate change, food security and mycotoxins: do we know enough? Fungal Biology Reviews 31 (3) 143-154. https://doi.org/10.1016/j.fbr.2017.04.002

Medina, A., Rodriguez, A., Magan, N. (2015a): Climate change and mycotoxigenic fungi: Impacts on mycotoxin production. *Curr. Opinion. Fd. Sci.* 5, 1-6. https://doi.org/10.1016/j.cofs.2015.11.002.

Medina, A., Rodrıguez, A., Sultan, Y., Magan, N. (2015b): Climate change factors and A. flavus: effects on gene expression, growth and aflatoxin production. *World Mycot. J.* 8, 171–178. https://doi.org/10.3920/WMJ2014.1726

Milani, J. M. (2013): Ecological conditions affecting mycotoxin production in cereals: A review. *Vet Medic*. 38 (8), 405–411.

Miraglia, M., Marvin, H.J.P., Kleter, G. A. (2009): Climate change and food safety: an emerging issue with special focus on Europe. *Fd. Chem. Toxicol.* 47, 1009–1021. https://doi.org/10.1016/j.fct.2009.02.005

Mulunda, M., Mike, D. (2014): Occurrence of Aflatoxin M1 from rural subsistence and commercial farms from selected areas of South Africa. *Fd. Cont*. 39, 92–96. https://doi.org/10.1016/j.foodcont.2013.11.011

Mycotoxin occurrence on the web. 2014. Biomin. http://www.biomin.net/at/science-and-solutions-magazine/#.U2M1Jvl_tVI. Accessed October 21, 2018.

Ngoko, Z., Marasas, W.F.O., Rheeder, J.P., Shephard, G. S., Wingfield, M.J., Cardwell, K.F. (2001): Fungal infection and mycotoxin contamination of maize in the humid forest and western highlands of Cameroon. *Phytoparasitica.* 29, 352–360. http://www.phytoparasitica.org posting July 19

Paterson, R.R M., Lima, N. (2010): How will climate change affect mycotoxins in Food? *Fd. Res. Int.* 43, 1902 – 1914. https://doi.org/10.1016/j.foodres.2009.07.010

Paterson, R. R. M., Lima, N. (2011): Further mycotoxin effects from climate change. *Fd. Res. Int.* 44, 2555–2566. https://doi.org/10.1016/j.foodres.211.05.038

Pieckova, E. Kunova, Z. (2002): Indoor fungi ad their ciliostatic metabolites. *Ann. Agric. Environ. Med.* 9, 59-63. https://www.ncbi.nlm.nih.gov/pubmed/12088399

Russel, L. M., Bahadur, R., Hawkins, L. N., Allan, J., Baumgardner, D., Quinn, P.K., Bates, T.S. (2009): Organic aerosol characterization by complementary measurements of chemical bonds and molecular fragments. *Atmos. Envir*. 43, 6100–6105. https://doi.org/10.1016/j.atmosenv.2009.09.036

Sanchis, V., Abadias, M., Oncins, L., Sala, N., Canela, I.V.R. (1994): Occurrence of Fumonisins B1 and B2 in corn based products from the Spanish market. *Appl. Envir. Microbiol.* 60, 2147–2148.

Sanchis, V., Abadias, M., Oncins, L., Sala, N., Canela, R., Vinas, I. (1995): Fumonisins B1 and B2 and toxigenic Fusarium strains in feeds from the Spanish market. *Int. J. Fd. Microbiol.* 27, 37–44. https://doi.org/10.1016/0168-1605(94)00151-u

Setamou, M., Cardwell, K.F., Schulthess, F., Hell, K. (1998): Effect of insect damage to maize ears, with special reference to *Mussidia nigrivenella* (Lepidoptera;Pyralidae), on *Aspergillus flavus* (Deuteromycetes; Monoliales) infection and aflatoxin production in maize before harvest inthe Republic of Benin. *J. Econ. Entomol*. 91, 433–438. https://doi.org/10.1093/jee/91.2.433

Sweeney, M. J., Dobson, A.D.W. (1998): Mycotoxin production by *Aspergillus*, *Fusarium*, and *Pencillium* species. *Int. J. Fd. Microbiol.* 43, 141– 158. https://doi.org/10.1016/s0168-1605(98)00112-3

Sydenham, E.W., Shephard, G.S., Thiel, P.G., Marasas, W.F.O., Rheeder, J.P., Sanhueza, C.E.,Gonzalez, H.H., Resnik, S.L. (1993): Fumonisins in Argentinian field trial corn. *J. Agri. Fd. Chem.* 41, 891–895.

Udoh, J. M., Cardwell, K.F., Ikotun, T. (2000): Storage structures and aflatoxin content of maize in five agro-ecological zones of Nigeria. *J. Stored Prod. Res.* 36, 187–201.

Vary, Z., Mullins, E., Mcelwain, J.C., Doohan, F. (2015): The severity of wheat diseases increases when plants and pathogens are acclimatized to elevated carbon dioxide. *Glob. Change Biol.* 21, 2661–2669. https://doi.org/10.1111/gcb.12899

Vaughan, M. M., Huffaker, A., Schmelz, E. A., Dafoe, N. J., Christensen, S., Sims, J. (2014): Effects of elevated CO_2 on maize defense against mycotoxigenic *Fusarium verticillioides*. *Plant Cell Environ.* http://dx.doi.org/10.1111/pce.12337

Velluti, A., Marin, S., Sanchis, V., Ramos, A. J. (2001): Occurrence of fumonisin B1 in Spanish corn based foods for animal and human consumption. *Fd. Sci. Technol Int.* 7, 433–437. https://doi.org/10.1106/5FK9-5JCW-7MTK-RKUT

Waliyar, F., Umeh, V.C., Traore, A. O., Osiru, M., Ntare, B. R., Diarra, B. (2015): Prevalence and Distribution of aflatoxin contamination in groundnut (*Arachis hypogaea L.*) in Mali, West Africa. *Crop Prot.* 70, 1–7. http://dx.doi.org/10.1016/j.cropro.2014.12.007

WHO (2002): Evaluation of certain mycotoxins in foods. Fifty sixth report of the Joint FAO/WHO Expert Committee on Food Additives, Technical Report Series. No. 906. WHO, New York.

Wild, C. P. (2007): The aflatoxin exposure in developing countries: the critical interface of agriculture and health. *Fd. Nutr. Bull*. 28, 372 –380. https://doi.org/10.1177/15648265070282S217

Wild, C. P., Gong, Y. Y. (2010): Mycotoxins and human disease: A largely ignored global health issue. *Carcinogenesis* 31, 71–82. https://doi.org/10.1093/carcin/bgp264

William, J. H., Philips, T. D., Jolly, P.E., Stilos, J.K., Jolly, C.M., Aggaroval, D. (2004): Human aflatoxicosis in developing countries: A review of toxicology, exposure, potential health consequences, and interventions. *Amer. J. Clin. Nutr.* 80(5), 1106 – 1122. https://doi.org/10.1093/ajcn/80.5.1106

Walsh, B. (2009): The New Age of Extinction. Time, April 13, pp. 31–39.

Wu, F. (2006): Mycotoxin reduction in Bt corn: Potential economic, health and regulatory impacts. Transgenic Res. 2006 Jun;15(3):277-89. https://doi.org/10.1007/s11248-005-5237-1

Wu, F., Mitchell N. J (2016): How climate change and regulations can affect the economics of mycotoxins. *World Mycot. J.* 9 (5), 653 – 663. https://doi.org/10.3920/WMJ2015.2015

Wu, F., Bhatnagar, D., Bui-Klimke, T., Carbone, I., Hellmich, R. L., Munkvold, G.P., Payne, P.G., Tackle, E. S. (2011): Climate Change impacts on mycotoxin risks in US maize. *World Mycot. J.* 4, 79-93; https://doi.org/10.3920/WMJ2010.1246