Chapter 3

Preharvest Management Strategies and Their Impact on Mycotoxigenic Fungi and Associated Mycotoxins

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Abstract

Mycotoxigenic fungi that contaminate grain crops can lead to reduced grain quality, crop yield reduction and mycotoxicosis among humans and livestock. Preharvest management of fungi and mycotoxin contamination is considered among the most important mitigating strategies. Approaches include the breeding of resistant cultivars, use of microorganisms chemical control, production practises and the management of plant stressors. Resistant plants provide an effective and environmentally sound strategy to control mycotoxigenic fungi and mycotoxins; and have been documented. Their incorporation into commercial cultivars is, however, slow and complex. Therefore, emphasis should be placed on determining the resistance of cultivars and landraces currently used by producers. Chemical control has been successfully used for wheat; yet little to no research has been done on other important crops. Biological control strategies have focussed on *Aspergillus flavus* that produces aflatoxins and infects commercially important crops like maize and groundnuts. Commercial biological control products have been developed and field-tested in several African countries with promising results. The impacts of production practises are unclear under variable environmental conditions; but subsequent disease manifestation and mycotoxin contamination can be reduced. Each preharvest approaches contribute to managing mycotoxigenic fungi and their mycotoxins but integrating approaches may provide more effective management of fungal and mycotoxin contamination in crops.

Keywords: preharvest management, mycotoxins, tolerance, cereals, cultural practices

1. Introduction

The contamination of food and feed crops with mycotoxigenic fungi is a persistent problem contributing to food safety and security worldwide. The infection of crops by these fungal pathogens affects crop yield and quality but of greater concern are the secondary metabolites they produce, collectively known as mycotoxins. Ingestion of mycotoxin-contaminated products has been associated with a wide range of noxious effects on humans and livestock. The major food and feed crops affected by mycotoxigenic fungi and mycotoxins include rice, maize, wheat, soybean, sorghum and groundnut, although several other crops are also affected. The association of these crops with mycotoxigenic fungi is ubiquitous, and crops are affected wherever they are produced. Three major groups of mycotoxigenic fungi are associated with mycotoxin contamination namely *Aspergillus*, *Fusarium* and *Penicillium*. They each produce a number of mycotoxins, but six mycotoxins have been studied extensively and are considered among the most important and they include the aflatoxins (AF), fumonisins (FUM), trichothecenes (TCT), zearalenone (ZEA), ochratoxin (OT) and patulin (PAT). Mycotoxin contamination levels in food and feed crops have therefore elicited numerous countries to institute regulations regarding the maximum permissible levels of these mycotoxins in unprocessed and processed products.

More than 100 countries have established mycotoxin regulations, including 15 African countries [1–3]. The European Union and United States Food and Drug Administration established maximum allowable levels for certain food contaminants, including mycotoxins, with the aim to reduce their presence in foodstuffs to the lowest levels reasonably achievable by means of good manufacturing or agricultural practices [4]. Most of the countries have mycotoxin regulations for at least AFB1, produced predominantly by *Aspergillus* spp., to aid in minimising food safety concerns. Although fewer countries regulate *Fusarium* mycotoxins, a marked increase in the regulation of this mycotoxin has been observed recently. These regulations have globally significant implications for the importation and exportation of products. Regulatory infrastructure, however, does not enable inspection and enforcement [5], making the regulatory control of mycotoxins in Africa largely ineffective [6].

The management of mycotoxigenic fungi and their subsequent mycotoxins is therefore vital towards ensuring sustainable, safe food and feed production. Integrated management practises that reduce the incidence of mycotoxigenic fungi as well as the management of abiotic factors that contribute to mycotoxin contamination are required before and following harvest. However, preharvest management is considered the most important in limiting the overall contamination of crops. Therefore, the use of tolerant varieties is deemed the most proficient and environmentally sound approach to manage fungi and their toxins. In addition, several other management approaches such as optimal plant production, cultural practises, chemical control and the management of mycotoxigenic fungi by atoxigenic strains or bacteria could further reduce fungal incidence and subsequent mycotoxin contamination.

2. Management of mycotoxigenic fungi and their mycotoxins

Managing mycotoxigenic fungi and their mycotoxins in crop plants requires a proper understanding of the biology, epidemiology and genetics/genomics of the fungus and host plant. Major crops vary significantly in susceptibility to mycotoxigenic fungi and subsequent mycotoxin contamination. Maize is widely considered to be among the most susceptible of major crops to mycotoxins, while rice is considered among the least susceptible crop [7–9].

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2.1. Tolerance to mycotoxigenic fungi

Crops with resistance to numerous mycotoxigenic fungi have been documented [10–12], but none of these are immune. Resistance to mycotoxigenic fungi therefore appears to be quantitative rather than qualitative. Breeding programmes at both public and private institutions are initiating and expanding their efforts to develop disease-resistant inbred and hybrid materials [13]. A number of international institutions such as the International Maize and Wheat Improvement Centre (CIMMYT) and the International Institute of Tropical Agriculture (IITA) in African countries including Kenya and Nigeria have established breeding programmes with the primary focus on producing inbred lines with improved resistance to *A. flavus* and AF. The development of tolerant cultivars, however, has been slow due to the polygenic, quantitative nature of resistance to mycotoxigenic fungi [14–17], the unavailability of immune germplasm [11, 15] and the effect of the environment on disease development and mycotoxin production [18–20]. The development of tolerant varieties, therefore, may be a long (8–10 years) and costly process that needs to be conducted as effectively as possible. Little to no commercial plant crop, completely resistant to mycotoxigenic fungi and mycotoxins, has been produced by conventional breeding, with the exception of wheat [21–23].

2.2. Conventional breeding strategies

Diallel analysis to determine the general combinability (GC) and specific combinability (SC) of resistant genotypes has been reported for *Aspergillus* and *Fusarium*, mostly performed on maize [24–27] and wheat [28–30]. The response of an inbred line to *F. verticillioides* and FUM, and the corresponding GC in hybrids, was significantly correlated. This indicates that an efficient way to improve resistance to *F. verticillioides* and FUM in maize hybrids, specifically, is to first evaluate and select resistant inbred lines that can be used to develop resistant hybrids [24]. This was also demonstrated for breeding resistance to Fusarium head blight (FHB) of wheat [30]. Maize hybrid performance for resistance to *F. graminearum* could, however, not be predicted based on the GC of inbred line parents [27]. Therefore, this relationship needs to be determined for each crop and fungal pathogen, respectively.

Inbred lines with resistance to aflatoxin contamination were evaluated for GCA and SCA for resistance to fumonisin accumulation, and two lines with resistance to FUM and AF were registered [25]. That research demonstrated the ability to breed resistance to multiple mycotoxigenic fungi and/or their mycotoxins. Furthermore, improved resistance to *F. verticillioides* and FUM in inbred lines derived from cross-pollination of resistant and elite maize lines has been demonstrated [31]. The subsequent hybrids produced from the crossing of improved lines with elite lines, however, did not demonstrate an improved activity against Fusarium ear rot (FER) and FUM accumulation, although some improved lines performed well as an inbred line and as a component of a hybrid [31]. To date, little to no research is reported on the development of tolerant varieties using recurrent selection breeding methods. Considering that resistance to mycotoxigenic fungi is polygenic and quantitative, recurrent selection presents a feasible breeding strategy; however, time and cost involved in this breeding strategy may be strong deterrent factors.

Quantitative trait loci (QTL) associated with resistance to mycotoxigenic fungi has been mapped in maize and wheat and can be used for marker-assisted selection [15, 16, 32–36]. Some QTLs, however, displayed pleiotropic effects, sometimes resulting in resistance to both traits [15, 32, 37]. QTL analyses have also demonstrated pleiotropic effects for resistance to other mycotoxigenic fungi and/or their associated mycotoxins. In QTL studies involving multiple ear rot pathogens, maize resistant to FER and FUM accumulation was also resistant to *F. graminearum* and/or *A. flavus*, with common loci for ear rots and FUM, respectively [15, 37, 38]. Research revealed that some of the genes involved in resistance to FER and Aspergillus ear rot (AER) of maize caused by *A. flavus*, as well as their associated mycotoxins (FUM and AF, respectively), were identical or genetically linked [38]. These studies highlighted common genes and/or resistance mechanisms to multiple mycotoxigenic fungi, demonstrating the potential for breeding resistance to one type of mycotoxigenic fungus, and its mycotoxin may lead to similar responses among other mycotoxigenic fungi and associated mycotoxin. The value of marker-assisted selection for improving Fusarium head blight resistance in wheat has been confirmed by numerous researchers and success stories from breeding programmes implementing MAS [39–47].

2.3. Unconventional breeding strategies

2.3.1. Genetic modification

Genetically modified crops are plants of which the DNA has been altered through the introduction of a foreign gene to express a trait not inherent to the modified plant. Three transgene-mediated strategies have been proposed for the management of mycotoxigenic fungi and mycotoxins in maize [48]. These include (1) the reduction of fungal infection, (2) the degradation of mycotoxins and (3) interfering with the mycotoxin biosynthetic pathway. To reduce infection by the fungus, the incorporation of antifungal and/or resistance genes, as well as the overexpression of defence-related genes, is required. Catabolic enzymes from microbes have been used to detoxify certain mycotoxins both *in vitro* and *in situ*, before they accumulate in the plant [49–51]. Fumonisin esterase and amine oxidase genes encoding FUM-degrading enzymes have been identified in *Exophiala spinifera* de Hoog and Hasse [48]. None of these genes have, however, been successfully introduced into maize. Maize plants have, however, been genetically engineered to interfere with the biosynthesis of AF and TCT [52, 53]. The best-known example of using genetically modified maize for reducing FER and FUM contamination of grain is Bt maize [54, 55]. This is due to the close association between kernel damage by insects and infection by *F. verticillioides* [56]. Bt maize plants that prevent insect damage, therefore, also reduce FUM contamination of maize grain. Genetically modified maize is not authorised in all countries and, consequently, conventional breeding efforts are still commonly used.

2.3.2. Mutation breeding

Exposure of seeds or other heritable materials to chemicals or radiation with the purpose to induce DNA changes (mutations) is known as mutation breeding. Nuclear technology for crop improvement makes use of ionising radiation, which causes induced mutations with a

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high mutation frequency in plants [57]. These mutations might be beneficial and alter physiological characters of plants, including plant height, ear height and improved root architecture [58, 59]. The radiation of seeds may also cause genetic variability that enables breeders to select new genotypes with improved grain yield and quality [60]. Mutation breeding has been successfully used to generate genetic variation in cereal crops, including maize, for a number of aspects including enhanced yield and productivity, altered ear length, drought tolerance and enhanced stem structure [61–63]. It can thus potentially provide an attractive means for generating tolerance to mycotoxigenic fungi and their mycotoxins.

2.4. Host-plant resistance

The planting of disease-resistant plants is an effective, affordable and environmentally sound strategy to control ear rot diseases and mycotoxin accumulation [64]. Commercial hybrids differ in their ability to accumulate mycotoxins [64], while hybrids grown outside of their adapted range are more susceptible to mycotoxins than those grown within their adapted range [18]. Determining host-plant resistance to mycotoxigenic fungi and mycotoxin accumulation is a fundamental step towards developing commercially tolerant plant varieties. Several factors require careful consideration when screening materials for resistance to mycotoxigenic fungi and their mycotoxins. Inoculation technique significantly contributes to the efficacy of the screening protocol and should, therefore, be appropriate, produce consistent results and consider the disease cycle of the pathogen. Numerous studies relating to different crops report on the importance of screening for resistance under variable environmental conditions since genotype by environment interactions (GEI) plays such a vital role in disease development and mycotoxin contamination. Furthermore, GEI and stability indicators provide for the selection of material tolerant across a broad range of environments or alternatively exhibiting tolerance in specific environments.

Various countries have reported on the tolerance levels of maize and wheat cultivars to mycotoxigenic fungi and associated mycotoxins [65–67]. However, focus has been placed on the characterisation of inbred lines for the identification of appropriate breeding material towards resistance to mycotoxigenic fungi and their toxins [68–74]. Genetically modified maize, expressing *Bacillus thuringiensis* genes (BT maize), has been found to accumulate less FUM than its non-modified isolines [54].

2.5. Cultural preharvest management strategies

2.5.1. Planting recommendations

Adhering to planting dates and planting plants at lower or optimal densities reduces mycotoxin accumulation during production [75–77]. Plants should be planted at recommended row widths and densities to specifically reduce water stress [78] and ensure optimal nutrient availability. Maize ears should be harvested from the field as soon as possible because favourable conditions for ear rot and/or mycotoxin accumulation may occur if harvest is delayed, thus leading to elevated mycotoxin levels [79, 80].

2.5.2. Crop rotation

The primary objective of cultural control of mycotoxigenic fungi is to minimise factors that result in plant stress. Inoculum build-up on plant residues can be reduced by crop rotation practices, such as the rotation of maize with non-host crops [75, 81, 82]. Crop rotation with legumes, brassicas and potato could also significantly reduce *F. graminearum* contamination levels [83].

2.5.3. Tillage practises

Field preparation and cultivation practices play a central role in the management of *Fusarium* diseases and associated mycotoxins [84]. The burial of plant residues from a previous planting season by deep ploughing can reduce the primary inoculum that causes infections [85]. This is especially important when crops are affected by the same *Fusarium* species, such as *F. graminearum* on maize, wheat and sorghum grown in rotation [4]. While minimum tillage has significantly decreased stalk rot and increased grain yield of sorghum in South Africa [86], it has also increased inoculum build-up of mycotoxigenic fungi in maize cropping systems [84]. Alternate tillage practices, however, have had little effect on the incidence of FER in maize [87, 88].

2.5.4. Managing plant stressors

Limiting plant stress to increase plant vigour by adhering to optimum plant dates, preventing drought stress and the optimal use of fertilisers have reduced *Fusarium* infection in a number of grain crops [76, 89–91]. However, maize cultivated by means of organic agriculture does not accumulate less FUM than maize cultivated conventionally [92, 93]. Extended periods of heat and drought stress that lead to increased FUM levels could be managed with proper irrigation schedules [77, 94]. Managing plant stress conditions is also important as this is considered key in the symptomless endophytic relationship converting to a disease- and/or mycotoxin-producing interaction [95].

2.5.5. Chemical control

Fungicides have been shown to significantly reduce FHB and DON contamination of wheat grain. Triazole fungicides such as metconazole and tebuconazole have been shown to control FHB and DON contamination in wheat [96]. However, fungicides are neither effective in reducing *F. verticillioides* infection/FUM accumulation, nor *A. flavus* infection/AF accumulation in maize [97]. This may be due to the husks that cover maize kernels. FUM were, however, reduced by 95% *in vitro* when four fungicides and a biocontrol bacterium (Serenade, *B. subtilis*) were evaluated for the control of *F. verticillioides* and *A. flavus* [98]. No registered fungicides are available for the control of either *F. verticillioides* or *A. flavus* in any African country [98]. The use of insecticides can prevent insect wounds that contribute to fungal infection and mycotoxin accumulation in maize kernels [91].

Reduced FHB severity and mycotoxin contamination of wheat under field conditions using tannic acid and the botanicals, Chinese galls and buckthorn, have been shown [100]. These researchers also reported disease and mycotoxin reduction efficacy close to that observed with a synthetic fungicide, thereby demonstrating the potential use of natural compounds in managing mycotoxigenic fungi and their toxins. Furthermore, several studies report on a reduced fungal growth and mycotoxin contamination for *Aspergillus* and *Fusarium* using natural oils and phenolic compounds *in vitro*; however, the commercial value of such products has not been explored and may not be feasible [101, 102].

2.5.6. Managing mycotoxigenic fungi with other microorganisms

The use of biological control agents to manage mycotoxigenic fungi has been reported. Atoxigenic *F. verticillioides* strains competitively excluded FUM-producing strains and prevented them from producing FUM [103]. When these strains were applied by themselves through the silk channel, however, they resulted in high levels of FER. The effective control of toxigenic *F. verticillioides* and *F. proliferatum* by non-toxigenic *Fusarium* species in maize residues has also been observed [104]. Most success, however, has been achieved with the use of atoxigenic strains of *A. flavus* to control toxigenic *A. flavus* and *A. parasiticus*. When introduced into the soil, these atoxigenic strains reduced AF contamination of peanuts in the USA by 74.3–99.9% [105]. Atoxigenic *A. flavus* strains are now widely used to control AF in maize in several African countries (www.aflatoxinpartnership.org). Endophytic bacteria have been reported to control FUM-producing fungi by competitive exclusion [106], while *Trichoderma* strains controlled them through competition for nutrients and space, fungistasis, antibiosis, rhizosphere modification, mycoparasitism, biofertilisation and the stimulation of plant-defence mechanisms [107].

2.5.7. Prediction systems

An epidemic can be described as a 'change in disease intensity in a host population over time and space' [108]. Mathematical modelling of crop disease is a rapidly expanding discipline within plant pathology [109] with the first models developed by Van der Plank [110, 111]. In epidemiology, modelling aims to understand the main determinants of epidemic development in order to address disease management in a sustainable and efficient manner. It can, therefore, serve as an instrument to monitor and assess the risk of mycotoxin contamination in crops that would drive agronomic decisions during cultivation, in order to enhance management strategies [112].

Most research regarding disease forecasting of mycotoxigenic fungi has focussed on FHB of wheat. This disease is considered well suited for risk assessment modelling because of the severity of epidemics, compound losses resulting from mycotoxin contamination and relatively narrow time periods of pathogen sporulation, inoculum dispersal and host infection [113]. This can be seen from the online forecasting model FusaProg [114], which is a threshold-based tool to control *F. graminearum* with the optimised timing of fungicide applications and forecasts of DON content during flowering. DONCast is a prediction model from Canada that has been extensively validated and commercialised for wheat [112], while an adaption of this model has been proposed for maize. This model predicts the variation in mycotoxin levels associated with the year and agronomic effects from simple linear models using wheat samples from farmers. The DONCast model accounts for up to 80% of the variation in DON and is commercially employed for the past 10 years.

Field-based models to predict FUM B1 contamination in maize grain have been elusive, most probably due to the complexity of interactions between numerous abiotic and biotic disease factors [115]. The concentration and severity of FUM produced by *Fusarium* spp. varies with meteorological conditions, genotype and location [19]. In general, favourable conditions for *F. verticillioides* infection include high temperatures [56], drought stress [56, 116] and insect damage stress [56]. A mathematical simulation of the growth of *F. graminearum* and *F. verticillioides* in maize ears was developed; however, the model only simulates fungal growth and not mycotoxin accumulation [117]. A preliminary model developed in the Philippines and Argentina identified four weather periods near silking as critical to FUM accumulation at harvest [19]. This model accounted for 82% of the variability of total FUM across all locations in 2 years of study, but did not consider meteorological conditions during grain maturation when FUM are synthesised.

A risk assessment model (FUMAgrain) developed for FUM contamination of maize grain in Italy gives an initial risk alert at the end of flowering based on meteorological conditions [118]. A second alert follows at kernel maturation following assessments of grain moisture, European corn borer damage and FUM synthesis risk. FUMAgrain could simulate FUM synthesis in maize accounting for 70% of the variation for calibration and 71% for validation. The importance of meteorological conditions at flowering and the growth of *F. verticillioides* and FUM synthesis during grain maturation was emphasised as the most important factors contributing to FUM contamination [118]. Another model consistently identified mean maximum temperature and minimum humidity as driving variables in the colonisation of maize kernels by fumonisin-producing *Fusarium* spp [99]. Furthermore, *Fusarium* colonisation of grain and fumonisins were related to prevailing weather conditions during early post-flowering and dough stage of grain development, respectively [99]. A prediction model using variables such as cultivar, climate, management practice, soil type, phenological stages of the host plant and pathogen variation would be advantages in identifying areas with potentially dangerous levels of fungal contamination and associated mycotoxin production, enabling them to implement mycotoxin management strategies.

3. Conclusion

Food and feed crops are consistently threatened by mycotoxigenic fungi and compound their infection by depositing toxic metabolites, including mycotoxins. Preharvest management of mycotoxin contamination is vital to maintaining contamination levels below economically feasible and legislated thresholds. Planting genotypes with enhanced host resistance is considered the most practical, affordable and environmentally sound method of controlling mycotoxigenic fungi and their mycotoxins. However, integrating resistant varieties with good agricultural practises such as crop rotation, chemical/biological control and other strategies that optimise plant production by minimising stressors may further reduce the risks associated with mycotoxin contamination. Resistance to mycotoxigenic fungi exists and has been identified in appropriate breeding materials but such resistance needs to be introduced in high-yielding and locally adapted hybrids. To date, conventional breeding has not been able to introgress disease and/or mycotoxin resistance into important staple crops like maize. Therefore, further research is required into factors with a greater efficacy to reduce mycotoxigenic fungi and mycotoxins preharvest as resistant varieties are being developed.

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Conflict of interest

The authors declare no conflict of interest.

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References

[1] Van Egmond HP. Worldwide regulations for mycotoxins. Advances in Experimental Medicine and Biology. 2002;**504**:257-269

[2] Barug D, Van Egmond H, Lopez-Garcia R, Van Osenbruggen T, Visconti A. In: Meeting the Mycotoxins Menace. The Netherlands: Wageningen Academic Publishers; 2003

[3] Fellinger A. Worldwide mycotoxin regulations and analytical challenges. In: World Grain Summit: Foods and Beverages; 17-20 September. Vol. 2006. California, USA: San Francisco; 2006

[4] Beukes I, Rose LJ, Shephard GS, Flett BC, Viljoen A. Mycotoxigenic *Fusarium* species associated with grain crops in South Africa—A review. South African Journal of Science. 2017;**773**:3. DOI: 10.17159/sajs.2017/20160121

[5] Warburton ML, Williams WP. Aflatoxin resistance in maize: What have we learned lately? Advances in Botany. 2014;**2014**:10. Article ID: 352831. https://doi.org/10.1155/2014/352831

[6] Strosnider H, Azziz-Baumgartner E, Banziger M, Bhat RV, Breiman R, Brune MN, DeCock K, Dilley A, Groopman J, Hell K, Henry SH, Jeffers D, Jolly C, Jolly P, Kibata GN, Lewis L, Liu X, Luber G, McCoy L, Mensah P, Miraglia M, Misore A, Njapau H, Ong CN, Onsongo MT, Page SW, Park D, Patel M, Phillips T, Pineiro M, Pronczuk J, Rogers HS, Rubin C, Sabino M, Schaafsma A, Shephard G, Stroka J, Wild C, Williams JT, Wilson D. Health strategies for reducing Aflatoxin exposure in developing countries. A Workgroup Report. Environmental Health Perspectives. 2006;**12**:1898-1903

[7] Abbas HK, Cartwright RD, Windham GL, Xie W, Shier WT, Mirocha CJ. The presence of mycotoxins and fungi in rice and corn in the southern United States. Bulletin of the Institute for Comprehensive Agricultural Science, Kinki University. 2000;**8**:21-34

[8] Abbas HK, Williams WP, Windham GL, Pringle Jr JC, Xie W, Shier WT. Aflatoxin and Fumonisin contamination of commercial corn (*Zea mays*) hybrids in Mississippi. Journal of Agricultural Food Chemistry. 2002;**50**:5246-5254

[9] Reddy KRN, Abbas HK, Abel CA, Muralidharan K. Mycotoxigenic fungi, mycotoxins, and management of rice grains. Toxin Reviews. 2008;**27**:287-317

[10] Nankam C, Pataky KK. Resistance to kernel infection by *Fusarium moniliforme* in the sweet corn inbred IL 125b. Plant Disease. 1996;**80**:593-598

[11] Clements MJ, Maragos CM, Pataky JK, White DG. Sources of resistance to fumonisin accumulation in grain and Fusarium ear and kernel rot of corn. Phytopathology. 2004;**94**:251-260

[12] He X, Singh PK, Duveiller E, Schlang N, Dreisigacker S, Singh RP. Identification and characterization of international Fusarium head blight screening nurseries of wheat at CIMMYT, Mexico. European Journal of Plant Pathology. 2013;**136**:123-134

[13] Mesterhazy A, Lemmens M, Reid LM. Breeding for resistance to ear rots caused by *Fusarium* spp. in maize—A review. Plant Breeding. 2012;**131**:1-19

[14] Hart LP, Gendloff E, Rossman EC. Effect of corn genotypes on ear rot infection by *Gibberella zeae*. Plant Disease. 1984;**68**:296-298

[15] Pérez-Brito D, Jeffers D, González-de-León D, Khairallah M, Cortés-Cruz M, Velázquez-Cardelas G, Azpíroz-Rivero S, Srinivasan G. QTL mapping of *Fusarium moniliforme* ear rot resistance in highland maize. México. Agrociencia. 2001;**35**:181-196

[16] Robertson-Hoyt LA, Jines MP, Balint-Kurti PJ, Kleinschmidt CE, White DG, Payne GA, Maragos CM, Molnár TL, Holland JB. QTL mapping for Fusarium ear rot and fumonisin contamination resistance in two maize populations. Crop Science. 2006;**46**:1734-1743

[17] Reid LM, Zhu CX, Parker CA, Yan CW. Increased resistance to *Ustilago zeae* and *Fusarium verticillioides* in maize inbred lines bred for *Fusarium graminearum* resistance. Euphytica. 2009;**165**:567-578

[18] Shelby R, White DG, Burke EM. Differential fumonisin production in maize hybrids. Plant Disease. 1994;**78**:582-584

[19] de la Campa R, Hooker DC, Miller JD, Schaafsma AW, Hammond BG. Modeling effects of environment, insect damage, and Bt genotypes on fumonisin accumulation in maize in Argentina and the Philippines. Mycopathologia 2005;**159**:539-552

[20] Cao A, Santiago R, Ramos AJ, Souto XC, Aquin O, Malvar RA, Butron A. Critical environmental and genotypic factors for *Fusarium verticillioides* infection, fungal growth and fumonisin contamination in maize grown in northwestern Spain. International Journal of Food Microbiology. 2014;**177**:63-71

[21] Clements MJ, White DG. Identifying sources of resistance to aflatoxin and fumonisin contamination in corn grain. Journal of Toxicology-Toxin Reviews. 2004;**23**:381-396

[22] Eller M, Robertson-Hoyt LA, Payne GA, Holland JB. Grain yield and Fusarium ear rot of maize hybrids developed from lines with varying levels of resistance. Maydica. 2008;**53**:231-237

[23] Steiner B, Buerstmayr M, Michel S, Schweiger W, Lemmens M, Buerstmayr H. Breeding strategies and advances in line selection for Fusarium head blight resistance in wheat. Tropical Plant Pathology. 2017;**42**:165-174

[24] Hung H-Y, Holland JB. Diallel analysis of resistance to Fusarium ear rot and fumonisin contamination in maize. Crop Science. 2012;**52**:2173-2181

[25] Henry WB, Williams WP, Windham GL, Hawkins LK. Evaluation of maize inbred lines for resistance to Aspergillus and Fusarium ear rot and mycotoxin accumulation. Agronomy Journal. 2009;**101**:1219-1226

[26] Naidoo G, Forbes AM, Paul C, White DG, Rocheford TR. Resistance to *Aspergillus* ear rot and aflatoxin accumulation in maize F1 hybrids. Crop Science. 2002;**42**:360-364

[27] Reid LM, Bolton AT, Hamilton RI, Woldemariam T, Mather DE. Effect of silk age on resistance of maize to *Fusarium graminearum*. Canadian Journal of Plant Pathology. 1992;**14**:293-298

[28] Malla S, Ibrahim AMH, Glover KD. Diallel analysis of Fusarium head blight resistance in wheat. Journal of Crop Improvement. 2009;**23**:213-234

[29] Malla S, Ibrahim AMH, Glover KD, Berzonsky WA. Combining ability for fusarium head blight resistance in wheat (*Triticum aestivum* L.) Communications in Biometry and Crop Science. 2010;**5**(2):116-126

[30] Mardi M, Buerstmayr H, Ghareyazie B, Lemmens M, Moshrefzadeh N, Ruckenbauer P. Combining ability analysis of resistance to head blight caused by Fusarium graminearum in spring wheat. Euphytica. 2004;**139**(1):45-50

[31] Eller MS, Payne GA, Holland JB. Selection for reduced Fusarium ear rot and fumonisin content in advanced backcross maize lines and their topcross hybrids. Crop Science. 2010;**50**:2249-2260

[32] Ding J-Q, Wang X, Chander S, Yan J, Li J. QTL mapping of resistance to Fusarium ear rot using a RIL population in maize. Molecular Breeding. 2008;**22**:395-403

[33] Li Z, Ding J, Wang R, Chen J, Sun X, Chen W, Song W, Dong H, Dai X, Xia Z, Wu J. A new QTL for resistance to Fusarium ear rot in maize. Journal of Applied Genetics. 2011;**52**:403-406

[34] Chen J, Ding J, Li H, Li Z, Sun X, Li J, Wang R, Dai X, Dong H, Song W, Chen W, Xia Z, Wu J. Detection and verification of quantitative trait loci for resistance to Fusarium ear rot in maize. Molecular Breeding. 2012;**30**:1649-1656

[35] Zila CT, Samayoa LF, Santiago R, Butron A, Holland JB. A genome-wide association study reveals genes associated with Fusarium ear rot resistance in a maize core diversity panel. Genes, Genomes, and Genetics. 2013;**3**:2095-2104

[36] Maschietto V, Colombi C, Pirona R, Pea G, Strozzi F, Marocco A, Rossini L, Lanubile A. QTL mapping and candidate genes for resistance to Fusarium ear rot and fumonisin contamination in maize. BMC Plant Biology. 2017;**17**:20

[37] Xiang K, Zhang ZM, Reid LM, Zhu XY, Yuan GS, Pan GT. A meta-analysis of QTL associated with ear rot resistance in maize. Maydica. 2010;**55**:281-290

[38] Robertson-Hoyt LA, Betran J, Payne GA, White DG, Isakeit T, Maragos CM, Molnar TL, Holland JB. Relationships among resistances to Fusarium and Aspergillus ear rots and contamination by fumonisin and aflatoxin in maize; 2007;**97**:311-317

[39] Del Blanco IA, Frohberg RC, Stack RW, Berzonsky WA, Kianian SF. Detection of QTL linked to Fusarium head blight resistance in Sumai 3-derived North Dakota bread wheat lines. Theoretical and Applied Genetics. 2003;**106**:1027-1031

[40] Zhou WC, Kolb FL, Bai GH, Domier LL, Boze LK, Smith NJ. Validation of a major QTL for scab resistance with SSRmarkers and use of marker-assisted selection in wheat. Plant Breeding. 2003;**122**:40-46

[41] Miedaner T, Wilde F, Steiner B, Buerstmayr H, Korzun V, Ebmeyer E. Stacking quantitative trait loci (QTL) for Fusarium head blight resistance from non-adapted sources in an European elite spring wheat background and assessing their effects on deoxynivalenol (DON) content and disease severity. Theoretical and Applied Genetics. 2006;**112**:562-569

[42] Anderson JA. Marker-assisted selection for Fusarium head blight resistance in wheat. International Journal of Food Microbiology. 2007;**119**:51-53

[43] Wilde F, Korzun V, Ebmeyer E, Geiger HH, Miedaner T. Comparison of phenotypic and marker-based selection for Fusarium head blight resistance and DON content in spring wheat. Molecular Breeding. 2007;**19**:357-370

[44] von der Ohe C, Ebmeyer E, Korzun V, Miedaner T. Agronomic and quality performance of winter wheat backcross populations carrying non-adapted Fusarium head blight resistance QTL. Crop Science 2010;**50**:2283-2290

[45] Salameh A, Buerstmayr M, Steiner B, Neumayer A, Lemmens M, Buerstmayr H. Effects of introgression of two QTL for Fusarium head blight resistance from Asian spring wheat by marker assisted backcrossing into European winter wheat on Fusarium head blight resistance, yield and quality traits. Molecular Breeding. 2011;**28**:485-494

[46] Agostinelli AM, Clark AJ, Brown-Guedira G, Van Sanford DA. Optimizing phenotypic and genotypic selection for Fusarium head blight resistance in wheat. Euphytica. 2012;**186**:115-126

[47] Balut AL, Clark AJ, Brown-Guedira G, Souza E, Van Sanford DA. Validation of Fhb1 and QFhsnau-2DL in several soft red winter wheat populations. Crop Science 2013;**53**:934-945

[48] Duvick J. Prospects for reducing fumonisin contamination of maize through genetic modification. Environmental Health Perspective. 2001;**109**:337-342

[49] Yoneyama K, Anzai H. Gene technological study on disease-control by the inactivation of pathogenic toxins in transgenic plants. Journal of Pesticide Science. 1991;**16**:291-299

[50] Lu G, Scelonge C, Wang L, Norian L, Mancl M, Parson M, Cole G, Yalpani N, Bao A, Hu X, Heller J, Kulisek E, Schmidt H, Tagliani L, Duvick J, Bidney DL. Expression of oxalate oxidase in sunflower to combat *Sclerotinia* disease. Proceedings of the 1998 International Sclerotinia workshop; Fargo; 1998. p. 43

[51] Zhang L, Xu J, Birch R. Engineered detoxification confers resistance against a pathogenic bacterium. Nature Biotechnology. 1999;**17**:1021-1024

[52] Brown RL, Chen ZY, Cleveland TE, Russin JS. Advances in the development of host resistance in corn to aflatoxin contamination by *Aspergillus flavus*. Phytopathology. 1999;**89**:113-117

[53] Okubara PA, Blechl AE, Mccormick SP, Alexander NA, Dill-Macky R, Hohn TM. Engineering deoxynivalenol metabolism in wheat through the expression of a fungal trichothecene acetyltransferase gene. Theoretical and Applied Genetics. 2002;**106**:74-83

[54] Munkvold GP, Hellmich RL, Rice LG. Comparison of fumonisin concentrations in kernels of transgenic Bt maize hybrids and nontransgenic hybrids. Plant Disease. 1999;**83**:130-138

[55] Abbas HK, Zablotowicz RM, Weaver MA, Shier WT, Bruns HA, Bellaloui N, Accinelli C, Abel CA. Implications of Bt traits on mycotoxin contamination in maize: Overview and recent experimental results in southern United States. Journal of Agricultural and Food Chemistry. 2013;**61**:11759-11770

[56] Munkvold GP. Epidemiology of *Fusarium* diseases and their mycotoxins in maize ears. European Journal of Plant Pathology. 2003a;**109**:705-713

[57] Yadav A, Singh B, Sharma DK, Ahuja S. Effects of gamma irradiation on germination and physiological parameters of maize (*Zea mays*) genotypes. Indian Journal of Agricultural Sciences. 2015;**85**:1148-1152

[58] Borzouei A, Kafi M, Khazaei H, Naseriyan B, Majdabadi A. Effects of gamma radiation germination and physiological aspects of wheat (*Triticum aestivum* L.) seedlings. Pakistan Journal of Botany. 2010;**42**:281-290

[59] Khawar A, Bhatti IA, Khan QM, Bhatti HN, Sheikh MA. A germination test: An easy approach to know the irradiation history of seeds. Pakistan Journal of Agricultural Science. 2010;**47**:279-285

[60] Noreen Z, Ashraf M. Changes in antioxidant enzymes and some key metabolites in some genetically diverse cultivars of radish (*Raphanus sativus* L.). Environmental Experimental Botany. 2009;**67**:395-402

[61] Mashev N, Vassilev G, Ivanov K. A study of N-allyl N-2 pyridyl thiourea and gamma radiation treatment on growth and quality of peas and wheat. Bulgarian Journal of Plant Physiology. 1995;**21**:56-63

[62] Jain SM. Mutagenesis in crop improvement under the climate change. Romanian Biotechnological Letters. 2010;**15**:88-106

[63] Tomlekova NB. Induced mutagenesis for crop improvement in Bulgaria. Plant Mutation Reports. 2010;**2**:4-27

[64] Munkvold GP, Desjardins AE. Fumonisins in maize: Can we reduce their occurrence? The American Phytopathology Society. 1997;**81**:556-565

[65] Rheeder JP, Marasas WFO, Van Wyk PS, Van Schalkwyk DJ. Reaction of south African maize cultivars to ear inoculation with *Fusarium moniliforme*, *F. graminearum* and *Diplodia maydis*. Phytophylactica 1990;**22**:213-218

[66] Janse van Rensburg B, Mclaren NW, Flett BC, Schoeman A. Fumonisin producing *Fusarium* spp. and fumonisin contamination in commercial south African maize. European Journal of Plant Pathology. 2015;**141**:491-504

[67] Schjøth JE, Tronsmo AM, Sundheim L. Resistance to *Fusarium verticillioides* in 20 Zambian Maize Hybrids. Journal of Phytopathology. 2008;**156**:470-479

[68] Afolabi CG, Ojiambo PS, Ekpo EJA, Menkir A, Bandyopadhyay R. Evaluation of maize inbred lines for resistance to Fusarium ear rot and fumonisin accumulation in grain in tropical Africa. Plant Disease. 2007;**91**:279-286

[69] Small IM, Flett BC, Marasas WFO, McLeod A, Stander MA, Viljoen A. Resistance in maize inbred lines to *Fusarium verticillioides* and fumonisin accumulation in South Africa. Plant Disease. 2012;**96**:881-888

[70] Balconi C, Berardo N, Locatelli S, Lanzanova C, Torri A, Redaelli R. Evaluation of ear rot (Fusarium verticillioides) resistance and fumonisin accumulation in Italian maize inbred lines. Phytopathologica Mediterranea. 2014;**53**:14-26

[71] Rose LJ, Mouton M, Beukes I, Flett BC, van der Vyver C, Viljoen A. Multi-environment evaluation of maize inbred lines for resistance to Fusarium ear rot and fumonisins. Plant Disease. 2016;**100**:2134-2144

[72] Rose LJ, Okoth S, Beukes I, Mouton M, Flett BC, Makumbi D, Viljoen A. Determining resistance to *Fusarium verticillioides* and fumonisin accumulation in maize inbred lines resistant to *Aspergillus flavus* and aflatoxins. Euphytica. 2017;**213**:93. DOI: 10.1007/s10681-017-1883-7

[73] Okoth S, Rose LJ, Ouko A, Beukes I, Sila H, Mouton M, Flett BC, Makumbi D, Viljoen A. Field evaluation of resistance to aflatoxin accumulation in maize inbred lines in Kenya and South Africa. Journal of Crop Improvement. 2017a;**31**:862-878. DOI: 10.1080/15427528.2017.1391915

[74] Okoth S, Rose LJ, Ouko A, Nakisani NEI, Sila H, Viljoen A. Assessing genotype by environment interactions in Aspergillus ear rot and preharvest aflatoxin accumulation in maize inbred lines. Agronomy. 2017b;**7**:86

[75] Munkvold GP. Cultural and genetic approaches to managing mycotoxins in maize. Annual Review of Phytopathology. 2003b;**41**:99-116

[76] Blandino M, Reyneri A, Vanara F. Effect of plant density on toxigenic fungal infection and mycotoxin contamination of maize kernels. Field Crops Research. 2008a;**106**:234-241

[77] Abbas HK, Mascagni Jr HJ, Bruns HA, Shier WT, Damann KE. Effect of planting density, irrigation regimes, and maize hybrids with varying ear size on yield and aflatoxin and fumonisin contamination levels. American Journal of Plant Sciences. 2012;**3**:1341-1354

[78] Mukanga M, Derera J, Tongoona P. Gene action and reciprocal effects for ear rot resistance in crosses derived from five tropical maize populations. Euphytica. 2011;**174**:293-301

[79] Chulze SN, Ramirez ML, Farnochi MC, Pascale M, Visconti A, March G. *Fusarium* and fumonisin occurrence in Argentina corn at different ear maturity stages. Journal of Agricultural and Food Chemistry. 1996;**44**:2797-2801

[80] Bush BJ, Carson ML, Cubeta MA, Hagler WM, Payne GA. Infection and fumonisin production by *Fusarium verticillioides* in developing maize kernels. Phytopathology. 2004;**94**:88-93

[81] Flett BC. The potential of crop rotation in the control of maize ear and stalk rots caused by *Stenocarpella maydis*. Phytophylactica. 1993;**25**:184

[82] Marocco A, Gavazzi C, Pietri A, Tabaglio V. On fumonisin incidence in monoculture maize under no-till, conventional tillage and two nitrogen fertilisation levels. Journal of the Science of Food and Agriculture. 2008;**88**:1217-1221

[83] Gilbert J, Tekauz A. Strategies for management of Fusarium head blight (FHB) in cereals prairie soils. Crops J. 2011;**4**:97-104

[84] Magan N, Olsen M. Mycotoxins in Food: Detection and Control. CRC Press. Woodhead Publishing Limited; 2004. DOI: 10.1201/9781439823361

[85] Blandino M, Pilati A, Reyneri A, Scudellari D. Effect of maize crop residue density on Fusarium head blight and on deoxynivalenol contamination of common wheat grains. Cereal Research Communications. 2010;**38**(4):550-559. DOI: 101556/CRC382010412

[86] Flett BC. Crop rotation and tillage effects on yield and the incidence of root and stalk rot in sorghum (*Sorghum bicolor*). South African Journal of Plant and Soil. 1996;**13**:136-138

[87] Flett BC, Wehner FC. Incidence of Stenocarpella and Fusarium cob rots in monoculture maize under different tillage systems. Journal of Phytopathology. 1991;**133**:327-333

[88] Flett BC, Mclaren NW, Wehner FC. Incidence of ear rot pathogens under alternating corn tillage practices. Plant Disease. 1998;**82**:781-784

[89] McMullen M. An integrated approach to cereal disease management. In: Proceedings of the Manitoba-North Dakota Zero Tillage Farmer's Association 24th Annual Meeting; Minot, North Dakota; 2002. 1-5 pp

[90] Blandino M, Reyneri A, Vanara F. Influence of nitrogen fertilization on mycotoxin contamination of maize kernels. Crop Protection. 2008b;**27**:222-230

[91] Parsons MW, Munkvold GP. Associations of planting date, drought stress, and insects with Fusarium ear rot and fumonisin B1 contamination in California maize. Food Additives Contaminants: Part A. 2010;**27**:591-607

[92] Arino A, Juan T, Estopanan G, Gonzalez-Cabo JF. Natural occurrence of *Fusarium* species, fumonisin production by toxigenic strains, and concentrations of fumonisins B-1 and B-2 in conventional and organic maize grown in Spain. Journal of Food Protection. 2007;**70**:151-156

[93] de Galarreta JIR, Butrón A, Ortiz-Barredo A, Malvar RA, Ordás A, Landa A, Revilla P. Mycotoxins in maize grains grown in organic and conventional agriculture. Food Control 2015;**52**:98-102

[94] Miller JD. Factors that affect the occurrence of fumonisin. Environmental Health Perspectives. 2001;**109**:321-241

[95] Abbas HK, Cartwright RD, Xie W, Shier WT. Aflatoxin and fumonisin contamination of corn (maize, *Zea mays*) hybrids in Arkansas. Crop Protection. 2006;**25**:1-9

[96] Edwards SG, Pirgozliev SR, Hare MC, Jenkinson P. Quantification of trichothecene-producing *Fusarium* species in harvested grain by competitive PCR to determine the efficacy of fungicides against Fusarium head blight of winter wheat. Applied and Environmental Microbiology. 2001;**67**:1575-1580

[97] Nel A, Krause M, Khelawanlall N. A guide for the control of plant diseases. National Department of Agriculture, Pretoria, South Africa. 2003;131 pp

[98] Formenti Magan N, Pietri A, Battilani P. In vitro impact on growth, fumonisins and aflatoxins production by Fusarium verticillioides and Aspergillus flavus using antifungal compounds and a biological control agent. Phytopathologia Mediterranea. 2012;**51**:247-256

[99] Janse van Rensburg B. Modelling the incidence of *Fusarium* and *Aspergillus* toxin producing species in maize and sorghum in South Africa [PhD thesis]. Bloemfontein, South Africa: University of the Free State; 2012

[100] Forrer HR, Hecker A, Musa T, Schwab F, Bucheli TD, Wettstein FE, Vogelgsang S. Fusarium head blight control and prevention of mycotoxin contamination in wheat with botanicals and tannic acid. Toxins. 2014;**6**:830-849. DOI: 10.3390/toxins6030830

[101] Kumar A, Shukla R, Singh P, Prasad CS, Dubey NK. Assessment of *Thymus vulgaris* L. essential oil as a safe botanical preservative against post-harvest fungal infestation of food commodities. Innovative Food Science and Emerging Technologies. 2008;**9**:575-580. DOI: 10.1016/j.ifset.2007.12.005

[102] Sampietro DA, Fauguel CM, Vattuone MA, Presello DA, Catalan CAN. Phenylpropanoids from maize pericarp: Resistance factors to kernel infection and fumonisin accumulation by *Fusarium verticillioides*. European Journal of Plant Pathology. 2013;**135**:105-113

[103] Desjardins AE, Plattner RD, Lu M, Claflin LE. Distribution of fumonisins in maize ears infected with strains of *Fusarium moniliforme* that differ in fumonisin production. Plant Disease. 1998;**82**:953-958

[104] Luongo L, Galli M, Corazza L, Meekes E, de Haas L, Van Der Plas C, Köhl J. Potential of fungal antagonists for biocontrol of *Fusarium* spp. in wheat and maize through competition in crop debris. Biocontrol Science and Technology 2005;**15**:229-242

[105] Dorner JW, Cole RJ, Blackenship PD. Effect of inoculum rate of biological control agents on preharvest aflatoxin contamination of peanuts. Biological Control. 1998;**12**:171-176

[106] Bacon CW, Yates IE, Hinton DM, Meredith F. Biological control of *Fusarium moniliforme* in maize. Environmental Health Perspectives. 2001;**109**:325-332

[107] Benítez T, Rincón MA, Limón MC, Codón CA. Biocontrol mechanisms of *Trichoderma* strains. International microbiology. 2004;**7**:249-260

[108] Madden LV, Hughes G, van den Bosch F. The Study of Plant Disease Epidemics. The American Phytopathological Society; 2007:33-61. DOI.org/10.1094/9780890545058.003

[109] Van Maanen A, Xu XM. Modelling plant disease epidemics. European Journal of Plant Pathology. 2003;**109**:669-682

[110] Van der Plank JE. Analysis of epidemics. In: Horsfall JG, Cowling EB, editors. Plant Pathology: An Advanced Treatise. New York, USA: Academic Press; 1960. pp. 229-289

[111] Van der Plank JE. Plant Diseases: Epidemics and Control. New York, USA: Academic Press; 1963

[112] Schaafsma AW, Hooker DC. Climatic models to predict occurrence of *Fusarium* toxins in wheat and maize. International Journal of Food Microbiology. 2007;**119**:116-125

[113] De Wolf ED, Madden LV, Lipps PE. Risk assessment models for wheat Fusarium head blight epidemics based on within-season weather data. Phytopathology. 2003;**93**:248-435

[114] Musa T, Hecker A, Vogelsang S, Forrer HR. Forecasting of Fusarium head blight and deoxynivalenol content in winter wheat with FusaProg. Bulletin OEPP/EPPO. 2007;**37**:283-289

[115] Parsons MW, Munkvold GP. Effects of planting date and environmental factors on Fusarium ear rot symptoms and fumonisin B1 accumulation in maize grown in six north American locations. Plant Pathology; 2012;**61**:1130-1142. DOI: 10.1111/j.1365-3059.2011.02590.x

[116] Logrieco A, Mule G, Moretti A, Bottalico A. Toxigenic *Fusarium* species and mycotoxins associated with maize ear rot in Europe. European Journal of Plant Pathology. 2002;**108**:597-609

[117] Stewart DW, Reid LM, Nicol RW, Schaafsma AW. A mathematical simulation of growth of *Fusarium* in maize ears after artificial inoculation. Phytopathology. 2002;**92**:534-541

[118] Maiorano A, Reyneri A, Sacco D, Magni D, Ramponi C. A dynamic risk assessment model (FUMAgrain) of fumonisin synthesis by *Fusarium verticillioides* in maize grain in Italy. Crop Protection. 2009;**28**:243-256