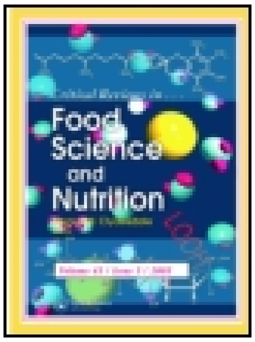

Critical Reviews in Food Science and Nutrition

ISSN: 1040-8398 (Print) 1549-7852 (Online) Journal homepage: http://www.tandfonline.com/loi/bfsn20

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CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
https://doi.org/10.1080/10408398.2018.1543252

REVIEW

Mycotoxin management in a developing country context: A critical review of strategies aimed at decreasing dietary exposure to mycotoxins in Zimbabwe

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ABSTRACT
Mycotoxins are unavoidable environmental contaminants, which are found throughout the food chain, particularly in cereals. Mycotoxin management is not effective in developing countries, such as Zimbabwe, due to resource constraints, yet human health risk is evident. Various practical mitigation strategies that can be employed to decrease human dietary exposure to mycotoxins as a means of preliminary steps towards risk management are discussed. These strategies were stratified into two categories. First, crop/commodity-centred strategies, mainly the pre-harvest actions of cultivar selection, bio-control, as well as good agricultural practices (GAP), and the post-harvest actions including timeous harvesting, appropriate drying and storage technologies, are elaborated making use of hazard analysis critical control points (HACCP) principles. The role of legislation is also explored as a crop/commodity centred mitigation strategy. Second, human-centred strategies anchored on dietary diversity and the use of socio-cultural approaches as a direct means of reducing mycotoxin exposure are discussed. Finally, an integrated science-based mycotoxin management strategy, encompassing targeted legislation on mycotoxins, consumer education and information sharing, human and institutional capacity building, training and financing, is suggested in addition to GAP, as a means of reducing human health risk associated with mycotoxin exposure in Zimbabwe.

Highlights

- Farm-to-fork HACCP-based mycotoxin management
- Human-centred mycotoxin management approaches are key
- Agronomy, technology and legislation critical in reducing mycotoxin exposure

KEYWORDS
cereals; exposure; HACCP; human health; mitigation strategies; Mycotoxin management

Introduction

Mycotoxins are toxic secondary metabolites of fungi (Battilani et al. 2008), occurring naturally in many agricultural commodities. Exposure to these environmental contaminants is often unavoidable, due to their ubiquitous natural occurrence in various elements of the food chain (Binder et al. 2007). Of high toxicological relevance are the aflatoxins, mainly aflatoxin B1 (AFB1) which is a known human carcinogen implicated in the aetiology of liver cancer (Williams et al. 2004, 2010, IARC 2011, 2015). Contamination of cereal crops is a critical human exposure route, since cereals are used as staple foods. Thus, human dietary exposure and risk assessment are necessary in this regard, particularly in developing countries where food and nutrition security are compromised, often leading to an over-reliance on cereal and cereal-based products in the diet. Human dietary exposure to mycotoxins and the related risk in Zimbabwe has been proven in various areas, particularly among subsistence farming communities (Hove et al. 2016; Murashiki et al. 2017). Though exposure is evident, the contrary is true with respect to mitigation efforts. It is therefore imperative that mycotoxin management measures are considered to reduce human dietary exposure to mycotoxins. Trends in dietary exposure assessments related to mycotoxins have alluded to the fact that high contamination in the various elements of the food basket is the causal agent (Chelule et al. 2001; de Nijs et al. 2016; Burger et al. 2010; Martin E. Kimanya et al. 2010; Ezekiel et al. 2014; Shirima et al. 2013; Lewis et al. 2005; Shephard et al. 2007; M. E. Kimanya et al. 2008). High mycotoxin contamination in food is positively correlated to high dietary exposure, but an exception to the rule has been proven within the Zimbabwean context (Hove et al. 2016). In Zimbabwe, high exposure is not a result of high mycotoxin contamination, particularly of the staple food, but rather an issue of high consumption of the staple food which contains low levels of mycotoxins (Hove et al. 2016). Maize is consumed daily in a majority of households, and is the primary source of complimentary foods given during weaning. Therefore,

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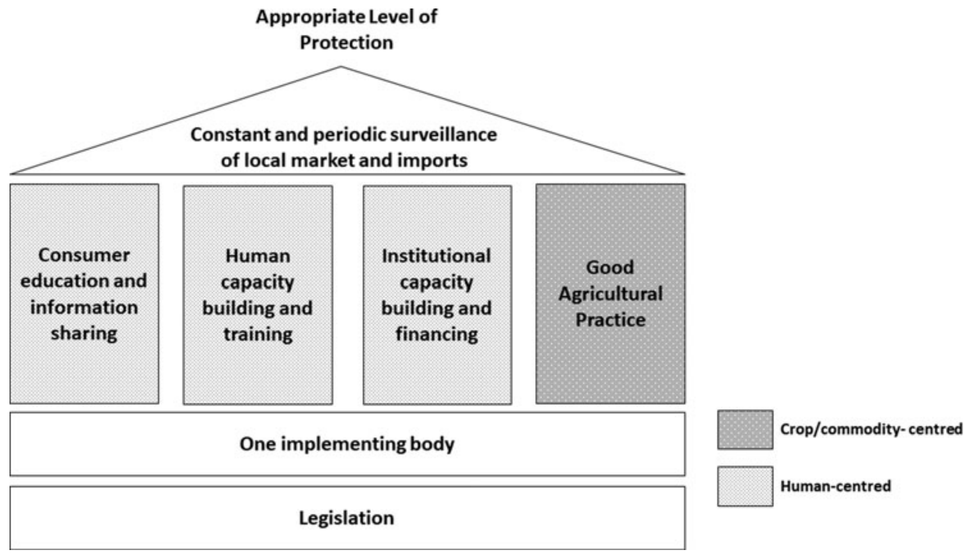

Figure 1. Proposed mycotoxin management strategy for Zimbabwe.

controlling exposure to mycotoxins from this staple crop is a first step towards mycotoxin mitigation efforts in Zimbabwe. Dietary diversity is another option to consider in the reduction of mycotoxin exposure within the Zimbabwean population. However, there is a possibility that other crops apart from maize in Zimbabwe may be prone to mycotoxin contamination as well. For example, there is evidence to show susceptibility of groundnuts grown in the southern part of Zimbabwe to *Aspergillus parasiticus* and *A. flavus* infection (Dube and Maphosa 2014). Given the appropriate conditions, aflatoxin production in groundnuts cannot be ruled out. In fact, varying levels of mycotoxins have also been detected in beans, groundnuts and bambara nuts (Maringe et al. 2017), which are typically consumed legumes in Zimbabwe. Other cereals cultivated in Zimbabwe, such as sorghum, have also been found to be contaminated with mycotoxins (Mupunga 2013). Therefore, this review focuses on the various farm-to-fork mitigation strategies that can be employed to decrease human dietary exposure to mycotoxins as a means of preliminary steps towards risk management. The aim of this review is to derive science-based recommendations to circumvent existing challenges in mycotoxin management in Zimbabwe such as to decrease dietary exposure to mycotoxins. Figure 1 is an illustrated summary of an integrated science-based mycotoxin management strategy, which if attempted, can lead to significant strides in reducing mycotoxin exposure in Zimbabwe.

This strategy is anchored on targeted legislation on mycotoxins and centralized enforcement of the same in Zimbabwe. The supporting pillars of the strategy are;

a. **Consumer education and information sharing;** All the proposed post-harvest interventions will be of non-effect if the farmers and consumers themselves do not see the value in modifying their current cultural dietary practices from monotonic diets towards more diverse and healthy diets.
b. **Human capacity building and training;** It is important to have a skilled human resource base executing all proposed mycotoxin management activities (monitoring, sampling, analytical work, risk assessment, research, reporting, etc).
c. **Institutional capacity building and financing;** It is imperative to set up centres of excellence where mycotoxin research can be carried out. These centres of excellence should be equipped with modern equipment capable of meeting the current minimum standards globally.
d. **Good agricultural practices (GAP);** it is imperative to educate subsistence farmers on the importance of employing GAP, employing bio-control and cultivating improved hybrids as a way of ensuring food safety and ultimately food security.

A critical analysis regarding mycotoxin mitigation actions that have yielded positive results and approaches to mirror these success stories in Zimbabwe, is presented. These mycotoxin reduction strategies can be grouped into two main categories, namely crop/commodity-centred strategies and human-centred strategies. The discussed elements can be used to contextually draw parallels to other developing countries.

Crop/commodity-centred interventions

A wealth of literature exists to describe crop/commodity-centred mycotoxin management strategies, and much emphasis is placed on the management of mycotoxins as food hazards based on the farm-to-fork ideology. The farm-to-fork principle aims at management and control measures being applied to a food source from the point of cultivation/rearing to the point of consumption. The aim is to eliminate or reduce the quantity of foodborne hazards to acceptable levels which pose no adverse effects to human health upon consumption. Food safety objectives (FSO), which are guidelines that aim to reduce foodborne hazards to a point where an appropriate level of health protection (ALOP) is guaranteed, have been used as an important tool in risk management. Regarding mycotoxin management in the food chain, the concept of FSO has been applied in the past, paying attention to decreasing exposure from cereal sources (Pitt, Taniwaki, and Cole 2013; García-Cela et al. 2012). For example, regarding fumonisin B1 (FB1) a widely occurring mycotoxin and pre-dominant in Zimbabwean maize, measures can be suggested to achieve the FSO, which include analysis and subsequent rejection of non-compliant lots, chemical decontamination procedures such as nixtamalization as well as milling (Pitt, Taniwaki, and Cole 2013). This typically crop/commodity-centred postulation of Pitt et al. (2013) mainly focuses on monitoring actions post-harvest, which when effectively applied are expected to decrease fumonisin levels in maize. Another example is that of aflatoxin B1, the most potent mycotoxin, being classified as a group 1 carcinogen by the International Agency for Research on Cancer (IARC) (IARC 2011). In Zimbabwe, AFB1 contamination is typical in legumes, particularly groundnuts (Dube and Maphosa 2014; Maringe et al. 2017). Measures suggested to achieve the FSO with respect to groundnuts include rapid drying of freshly harvested groundnuts followed by storage in well-designed silos which prevent moisture migration and a humid atmosphere (Pitt, Taniwaki, and Cole 2013). Hand sorting to remove visibly moulded and discoloured grain coupled with analysis and elimination of contaminated lots are foreseen to decrease mycotoxin contamination in groundnuts (Pitt, Taniwaki, and Cole 2013). Other impractical measures suggested to achieve the FSO include blanching and refrigerated storage at temperatures below 10 °C (Pitt, Taniwaki, and Cole 2013), a feat that would be difficult to achieve in Zimbabwe due to huge volumes of groundnuts and the possibility of intermittent power supply. Further, the applicability of these measures is subjective to the availability of technical capacity, a condition that is not necessarily fulfillable in most developing country contexts. When applying the FSO concept to mycotoxin reduction in maize and groundnuts, Pitt et al. (2013)'s theory is ideally applicable where mycotoxin contamination has been linked primarily to the occurrence levels of mycotoxins in the commodity as a result of agronomic practices. Such a scenario requires the formulation of mycotoxin management strategies that are anchored on GAP. It is known that certain cultivation practices can result in the creation of micro-climatic conditions that will favour the infection of crops by toxigenic fungi and the subsequent production of mycotoxins.

Other strategies aimed at the reduction of mycotoxin contamination of crops have been suggested in literature, which employ physical, cultural and genetic approaches. These strategies include the prevention of crop infection by toxigenic fungi by altering the conditions of the crop's growth, agronomic practices such as tillage, proper irrigation, crop rotation, better handling of grain during and post-harvest to prevent grain damage, thorough cleaning of storage facilities, and the cultivation of resistant hybrids (Munkvold 2003). However, physical strategies require a lot of manpower and the availability of manpower can influence the outcome of such a strategy in reducing contamination of the crop. For example, the timeous harvesting of crops, subsequent drying and storage can be delayed by shortage of manpower in a given setting such as in small-holder farming communities and/or subsistence farming households. As observed in Benin, for example, the timeous storage of maize was in some cases hampered by the shortage of manpower resulting in maize remaining in the field for longer periods than are necessary after maturity (Hell et al. 2000). When legumes are concerned, improper storage can have serious implications particularly related to aflatoxin production post-harvest (Neme and Mohammed 2017). In view of a plethora of possible mitigation activities, the most practical and feasible ones in developing country contexts, such as Zimbabwe, are further discussed.

Pre-harvest strategies

Several pre-harvest mycotoxins strategies centred around GAP have been discussed in literature (Wagacha and Muthomi 2008; Degraeve et al. 2016; Torres et al. 2014; Cleveland et al. 2003; Neme and Mohammed 2017; Matumba et al. 2017; Massimo Blandino, Reyneri, and Vanara 2008a). Most of these practices (crop rotation, removal of previous crop debris from the fields prior to cultivation, minimizing plant stress, among others) are mainly farmer-dependent, and are not easy to control especially in subsistence farming settings. Subsequently, the impact of these interventions is difficult to assess, requiring extensive fieldwork and monitoring over time. Pre-harvest interventions with the potential for great impact in low-resource settings include the use of optimised hybrids and/or the use of bio-control agents to decrease fungal infection and subsequent mycotoxin production. The pre-harvest selection of hybrids is important particularly for maize agronomy (Magan and Aldred 2007). Early maturing hybrids are preferred in minimising fungal infection of crops (Magan and Aldred 2007; Ndemera et al. 2018), probably because the vegetative period and time in the field is shorter, resulting in less chances for fungal colonisation (M. Blandino et al. 2008). Some suggestions on the use of transgenic approaches such as the cultivation of transgenic maize with resistance to insect injury could result in decreased mycotoxin contamination, since insect injury is positively correlated to fungal infection and mycotoxin contamination in grain (Munkvold 2003; Cleveland et al. 2003; Alberts et al. 2017). For example, the use of *Bacillus thuringiensis* (BT) cultivars which are resistant to insect infestation, minimizes insect damage (Pitt et al 2013), and lowers mycotoxin contamination (Cleveland et al. 2003). While insect damage pre-disposes grain to fungal infection, this may be viewed as secondary. Though complex, it is important to primarily develop hybrids that are resistant to fungal infection and toxin production through the careful selection of genes for resistance (Torres et al. 2014). It is important to note that risk assessments in terms of metabolic profiling are also necessary for these improved varieties to avoid long-term adverse public health consequences from the adoption of these technologies. Ecological assessments are also necessary to determine whether or not the genetically improved varieties will not affect the ecological balance in the areas where they are introduced.

Bio-control of mycotoxins in crops is yet another option in pre-harvest mycotoxin management. Bio-control is the method of introducing atoxigenic fungal strains in a cultivated area so that they out-compete toxigenic strains thereby limiting the production of secondary toxic metabolites such as mycotoxins (Cleveland et al. 2003; Torres et al. 2014). Methods of application vary from inoculating the soil with atoxigenic fungal strains prior to cultivation (Cleveland et al. 2003) to applying water-soluble granules containing atoxigenic fungi to plants (Lyn et al. 2009). In legumes, particularly groundnuts, bio-control strategies have been researched and applied in the control of aflatoxin production in this important cash crop (Joe W. Dorner 2004; Pitt and Hocking 2006; J. W. Dorner 2008). Also, a number of successes have been recorded with respect to aflatoxin management in maize using bio-control (Lyn et al. 2009; Torres et al. 2014; Cleveland et al. 2003). Commercial products such as Aflasafe™ and Afla-Guard® have been tried and tested in East and West Africa (Cleveland et al. 2003; Torres et al. 2014) proving to significantly lower aflatoxin production in crops. In groundnuts, atoxigenic strains of *A. parasiticus* and *A. flavus* have been reported to decrease aflatoxin contamination by up to 99% (Wagacha and Muthomi 2008). Limited data exists on the application of bio-control in other regions of Sub-Saharan Africa. The efficacy of bio-control may not necessarily be the same owing to differing environmental, ecological and bio-diversity factors. For example, climatically, vast areas in Southern Africa experience a tropical climate while East Africa mainly experiences an equatorial climate. The aetiology of fungal diseases and mycotoxin contamination is highly influenced by climate (Doohan, Brennan, and Cooke 2003; Magan and Aldred 2007; M. Blandino et al. 2008; Covarelli, Beccari, and Salvi 2011; Samsudin et al. 2017). There is need for more data on the efficacy of aflatoxin bio-control in other regions of Sub-Saharan Africa.

Bio-control of *Fusarium* fungi is still on-going research and commercial products are not yet available on the market. Studies on the control of *F. verticilloides* using *Bacillus spp.*, *Pseudomonas spp.* or *Azotobacter nigricans* containing microbial agents have been documented in literature (Martínez-Álvarez et al. 2016; Figueroa-López et al. 2016; Nagaraja et al. 2016). For example, inoculating maize with a powder containing a *Bacillus cereus sensu lato* strain (B25) resulted in the inhibition of *F. verticilloides in vitro* (Martínez-Álvarez et al. 2016; Figueroa-López et al. 2016). Other studies have shown that bacterial biocontrol agents have low efficacy particularly when applied to plants in field settings (Samsudin et al. 2017). Therefore, much work needs to be done to develop an effective biocontrol agent for the control of *Fusarium* infection and subsequent mycotoxin production in maize and other cereals. Furthermore, proposed bio-control agents must demonstrate viability and applicability in stressful climatic conditions (Wagacha and Muthomi 2008), for example sporadic droughts that occur in Zimbabwe from time to time.

Post-harvest strategies

Post-harvest management of crops can be segmented into post-harvest handling of the crops prior to storage and post-harvest handling during storage. In each segment, different processes can result in varied effects on final mycotoxin contamination of the crop. Depending on the type of processes the crop is subjected to during harvesting, soon after harvesting and during storage, it is expected that levels of mycotoxins may remain stagnant or increase. Much grain is lost due to poor post-harvest methods (Kumar and Kalita 2017). For example, poor post-harvest handling of maize by processes such as open air drying and field storage of harvested maize before it was transferred to the final storage area was found to pre-dispose the maize grain to insect infestation and fungal attack in a study carried out in Zambia (Kankolongo, Hell, and Nawa 2009). It is estimated that post-harvest losses in developing countries are in excess of 50% (World Food Preservation Centre 2014). This alarming fact is a signal for action. As a starting point, farmer education is imperative (Wagacha and Muthomi 2008) as it will result in more informed decision making and ultimately reduced post-harvest losses.

The Hazard Analysis and Critical Control Points (HACCP) approach can be applied to mycotoxin management particularly in maize. Prior to storage, the main critical control points (CCP) for fungal infection and mycotoxin contamination are harvesting and drying. The practice of early harvesting of crops and further subjecting crops to sun-drying is not uncommon. Reasons for this vary, and sometimes it is to avoid theft of agricultural produce while in the field (Matumba et al. 2017; Wagacha and Muthomi 2008; Neme and Mohammed 2017). Other times, and typically among subsistence farmers in Zimbabwe, the limited availability of manpower during specific times (school holidays, for example) restricts farmers to a particular time frame within which to harvest their crop. At times, the crops such as maize will not be mature enough to harvest with respect to moisture content. The disadvantage of harvesting maize too early is that it has been associated with increased proportions of damaged kernels, and kernels that have a high propensity for fungal growth due to very high moisture content (Kumar and Kalita 2017; Neme and Mohammed 2017). Timeous harvesting is key in ensuring that the maize crop is not pre-disposed to more fungal colonization (Neme and Mohammed 2017; Bankole and Adebanjo 2003; Magan and Aldred 2007; Wagacha and Muthomi 2008; Torres et al. 2014), as natural pre-harvest fungal colonization is expected. Harvesting maize at the appropriate moisture content (between 23 and 28% moisture content) will also ensure a shorter drying period of the maize post-harvest (Kumar and Kalita 2017). Traditionally in Zimbabwe, appropriate grain moisture content prior to harvesting maize is determined visually, and a variety of indicators are used. For example, subsistence farmers from

Zimbabwe who were part of a field survey on the investigation of maize agronomic practices (Hove et al. 2016) implied that their maize crop was ready for harvesting either when; the maize ear had turned over (faced downwards); the maize leaves were a golden-brown colour; or when the maize stalks were starting to fall to the ground. These methods lack scientific merit, and one might say that they are a gamble. The accurate determination of grain moisture content is of paramount importance (Magan and Aldred 2007), requiring the use of scientific apparatus such as dry weight balances or moisture probes. This equipment is beyond the reach of most subsistence farmers in Zimbabwe. However, if per se, it was possible to avail a moisture probe for each of the agriculture extension services personnel who are often in contact with the farmers, it would solve the problem. In this case, the extension service personnel would provide the service of accurately testing the grain moisture content so that the farmer can make a scientifically informed decision on when to start harvesting their maize. This communal approach can also be applied to alleviate labour challenges faced by subsistence farmers during harvesting by providing communal combine harvesters. Combine harvesters significantly shorten the harvesting time and this will reduce delays in removing crops from the fields. Delays in removing mature crops from the fields expose the crops to variable weather elements, pests and at times disease (Kumar and Kalita 2017; Magan and Aldred 2007), all of which are undesirable in mycotoxin prevention. The government can consider providing and managing the use of such equipment through various grassroots structures at ward, village or district level.

Crops are usually stored as shelled grain in Zimbabwe after a drying process. Open-air sun-drying is the commonly practised drying method. As in other developing countries, this method is not unique to Zimbabwe, being slow and risky as the drying crops are exposed to pests, dust and variable weather (Kankolongo, Hell, and Nawa 2009; Kumar and Kalita 2017; Bankole and Adebanjo 2003). Open-air sun-drying is a slow and uncontrolled activity, which may be affected by changes in weather parameters such as the degree of cloud cover or sporadic rainfall. The length of the drying period is also not fixable under such conditions, yet GAP, with respect to mycotoxins, denotes rapid drying of grain to less than 14% moisture content (Magan and Aldred 2007). Solar dryers are a technologically advanced alternative method to open-air sun-drying. Zimbabwe is strategically positioned to harness solar energy. Solar dryers require capital investment initially and regular maintenance thereafter. In the long term, they are a worthwhile investment as they can be employed in drying perishable commodities within a reasonable time and under controlled conditions. The drying parameters can be monitored and managed throughout the drying process (Kumar and Kalita 2017; Weiss and Buchinger 2012). A variety of solar dryers have been developed for use in a wide range of commodities. Weiss and Buchinger (2012) recommend an *in-house type solar crop dryer* for crops. This type of dryer has been used in Ghana, and is capable of drying up to 500 kg of maize at a time.

Figure 2. Typical traditional granary in Zimbabwe.

Generally, grain storage is usually indoors and in polypropylene grain bags. Issues to do with insect infestation, ventilation and improper storage facilities often characterize grain storage conditions in Zimbabwe. Such conditions are generally experienced in settings within Sub-Saharan Africa were traditional storage methods are in use (Tefera et al. 2011; Bankole and Adebanjo 2003). Traditionally in Zimbabwe, crops are stored in a granary, constructed from mud, home-made bricks and/or poles and thatched with grass. Sometimes the traditional granary may be raised, and the base constructed of wooden logs (Figure 2). Most times, the granary is not raised and the base is constructed from cement mortar.

A modified version of the traditional granary, which is a brick structure raised off the ground with a concrete ceiling, is being proposed. The modified granary provides an appropriate microclimate for grain storage, allowing proper ventilation throughout the storage period. It is expected that fungal growth and subsequent mycotoxin contamination is curtailed when crops are stored in this facility. The transition to the modified granary technology entails financial investments which may be problematic in rural or subsistence farming set-ups where resources are limited. In the absence of external funding, through private-public partnerships (PPPs), this intervention strategy may be difficult to implement. A cheaper lower-cost option would be the use of hermetic storage technologies. Hermetic grain storage is a technology in which grain is stored in an airtight container/bag which creates an elevated carbon dioxide (CO_2) modified atmosphere over time (Kumar and Kalita 2017; Samapundo et al. 2007). Increased CO_2 has been found to inhibit fungal growth and deprive insects of oxygen leading to a decrease in populations (Magan and Aldred 2007; Kumar and Kalita 2017; Tefera et al. 2011). Hermetic storage may be in the form of metal silos, silo bags, SuperGrain® bags or Purdue Improved Crop Storage (PICS) bags (Kumar and Kalita 2017; Chulze 2010). Metal silos may be made from galvanised iron, steel sheets or painted aluminium (Tefera et al. 2011; Kumar and Kalita 2017). Metal silos are costly and this has affected the rate of adoption of this technology by farmers in Africa (Tefera et al. 2011). For example, in Malawi, the cost of a metal silo was found to range between US$320 and US$480 in 2010, depending on size (between 1 000 and 3 000 kg) (Tefera et al. 2011). Hermetic bags are a cheaper option in low-resource settings.

Table 1. Global overview of maximum limits (μg/kg) of mycotoxins in food.

Country/Region	Mycotoxin	Maize subject to processing	Maize intended for human consumption	Reference
Australia	Total AF	n.s.	5	(F Wu 2006)
Brazil	Total AF	n.s.	20	(Martins et al. 2017)
China	Total AF	n.s.	20	(F Wu 2006)
Egypt	AFB1 (Total AF)	5 (10)	2 (4)	(Felicia Wu, Stacy, and Kensler 2013)
European Union	AFB1 (Total AF)	5 (10)	2 (4)	(F Wu 2006; Felicia Wu, Stacy, and Kensler 2013; European Commission (EC) 2006)
	Total FB	4000	800	(European Commission (EC) 2006)
	Total FB*	n.a.	200	(European Commission (EC) 2006)
	DON	1750	1250	(European Commission (EC) 2006)
Kenya	All**	n.s.	20	(F Wu 2006; Felicia Wu, Stacy, and Kensler 2013)
South Africa	AFB1 (Total AF)	n.s.	5 (10)	(Felicia Wu, Stacy, and Kensler 2013)
Tanzania	Total AF	n.s.	10	(Felicia Wu, Stacy, and Kensler 2013)
United States of America	Total AF	n.s.	20	(P. Singh and Cotty 2017; Bhatnagar et al. 2004)
	Total FB	4000	2000	(Bhatnagar et al. 2004)
	DON	n.s.	1000	(Bhatnagar et al. 2004)
Zambia	Total AF	n.s.	10	(ZABS 2008)
Zimbabwe	Total AF	n.s.	10	(Felicia Wu, Stacy, and Kensler 2013)

*Maximum limit in baby food.
**Advisory limit.
n.a. – not applicable
n.s. – not specified
AF = aflatoxins, AFB1 = aflatoxin B1, FB = fumonisins B, DON = deoxynivalenol.

Hermetic bags are made of high density polypropylene material (> 75 μm thickness), which may be used as a single-layer lining a woven polypropylene bag (SuperGrain® bags) or a double-layer contained within a woven nylon bag (PICS bags) (Kumar and Kalita 2017). Hermetic storage options are available in Zimbabwe, with the bags being preferred to the metal silos. However, the costs of hermetic storage are prohibitive to the uptake of this technology by subsistence farmers who fall under the low or no-income category. A normal polypropylene grain bag costs at least 10 times less than hermetic storage bags in Zimbabwe. Moreover, subsistence farmers do not fully appreciate the advantages of hermetic storage vs non-hermetic storage yet, and therefore cannot buy in to the technology. Farmer education is thus necessary as a post-harvest intervention strategy, and this can be through existing communication structures vis-à-vis agricultural extension services in Zimbabwe. Another strategy would be to provide the hermetic bags at a subsidized price to the subsistence farmers, and to encourage recycling and re-use of these bags over time.

Other post-harvest mycotoxin management strategies that have been proposed include enzymatic detoxification, chemical decontamination using fungicidal applications such as ozone, sulphur dioxide or antioxidants (butylated-hydroxyanisole (BHA), butylated-hydroxy-toluene (BHT) or propyl paraben) during storage (Torres et al. 2014; Magan and Aldred 2007) and nixtamalization prior to milling (Pitt, Taniwaki, and Cole 2013). While chemical methods have a degree of efficacy, they fall short when it comes to adoptability particularly in set-ups where conservatism is the dominant culture. People tend to shy away from the idea of chemicals being introduced into the food supply. Risk assessments on the safety of such interventions need to be carried out especially for high-intake populations such as contained in Zimbabwe and Sub-Saharan Africa with respect to maize. Density segregation *i.e.* immersing maize into water so that low-weight grains are removed by floatation is another method currently applied in Malawi, for example (Matumba et al. 2015). The logic of this method in reducing mycotoxin exposure rests in the fact that shrivelled or damaged grain (which is mostly contaminated with mycotoxins) is more buoyant than the sound grain and thus removed by floatation. However, the applicability of this method depends on the end use of the grain, that is, if the grain is to be immediately consumed, or if it will undergo further processes and storage afterwards. Due to the addition of moisture during floatation, a drying step is necessary if the grain is to be stored for later use either as sound grains or in the milled form. However, the stability of the maize under storage needs to be investigated, because there is a possibility that the introduction of moisture during floatation would create a micro-environment for the growth of toxigenic fungi and/or the production of mycotoxins, whether it is stored as grain or in the milled forms.

The role of legislation, human and institutional capacity in mycotoxin mitigation

Pre- and post-harvest mycotoxin mitigation must be complemented and validated by mycotoxin monitoring in food commodities if human exposure is to be minimized. Monitoring mycotoxin contamination post-harvest is ideal, and, as alluded to before, can be achieved with ease in developed countries, which are capacitated in terms of financial, infrastructural and human capital. In addition to high capitalization, food safety is a high priority in first-world countries, which is demonstrated by high compliance to prescribed food safety legislation, subscription to various standardization and food quality assurance programmes and the existence of functional food safety 'watch-dogs' which serve the purpose of alerting stakeholders of the existence of mycotoxin-related hazards and potential incidences. The European Food Safety Authority (EFSA)'s Rapid Alert System for Food and Feed (RASSF), set up at the European level, is one such 'watch-dog'. The precautionary principle, which is a pivotal pillar in the food safety law in Europe is another measure aimed at ensuring safe food, from farm to fork. The adoption of strict legislation by EU member states and conformance to CODEX Alimentarius standards are pivotal actions that have resulted in decreased mycotoxin exposure particularly in developed countries. In addition, there are various committees at European level that are engaged in assessing risks related to food safety by scientific means of knowledge gathering (e.g. EFSA and The Joint FAO/WHO Expert Committee on Food Additives (JECFA)). As such, a robust toolbox has been evidently set up to address the issue of mycotoxin exposure. Pitt et al. (2013) present the ideal scenario, that is, monitoring and rejecting non-compliant food lots in the food chain, which is somewhat unachievable in most developing countries, and is currently not being implemented in Zimbabwe. Furthermore, mycotoxin exposure in Zimbabwe is not typically attributed to high contamination of food commodities, but rather chronic exposure due to high dietary intake of low-level contaminated food (Hove et al. 2016). Therefore, an all-encompassing approach which emphasizes human-centred interventions as the critical methodology is required if mycotoxin management is to be successful. To this end, both agronomic and socio-cultural factors need to be incorporated. Of importance is the feasibility and applicability of mycotoxin legislation and management plans particularly in a developing country context such as Zimbabwe.

Mycotoxin regulations differ globally, and are generally more specified and stringent in developed countries (Unnevehr 2015). Generally, high producers also have more specified mycotoxin regulations. Member states in the European Union (EU) are guided by Regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs, the strictest compared to other global legislation on mycotoxins. Considering aflatoxins (AF), fumonisins (FB) and deoxynivalenol (DON), the maximum limits in maize intended for human consumption and maize subject to further processing are summarized in Table 1. In developing countries, legislation exists largely for aflatoxins, in contrast to *Fusarium* mycotoxins such as FB1 and DON. Varying regulatory limits can become problematic if, for example trade disputes arise regarding contaminated commodities. They give rise to the placement of technical barriers to trade and even the malicious practice of 'dumping' non-compliant commodities in countries with less strict regulations as in Zimbabwe. This is a cause for concern as far as public health is to be guaranteed. Coupled with the fact that most developing countries like Zimbabwe have limited capacity to precisely and timeously analyse commodities for mycotoxin contamination, the risk of receiving and allowing non-compliant imported commodities cannot be ruled out and is a cause for concern. Locally-produced commodities have been shown to be contaminated by mycotoxins (Murashiki et al. 2017; Gamanya and Sibanda 2001; Hove et al. 2016; Doko et al. 1996). These commodities easily enter the local food basket, and consequently result in dietary exposure to mycotoxins among consumers. Even though Zimbabwe has been a net importer of food over the past decade, the risk of exporting contaminated produce still exists, and this is undesirable for trade. In view of this, more needs to be done on the legislative front to ensure minimized mycotoxin contamination in the food basket and in cereals specifically.

A closer examination of the food legislative framework in Zimbabwe reveals loop holes which may pose challenges in effective mycotoxin management. In principle, food safety regulations exist, as contained in the Public Health Act (Chapter 15:09) and the Food and Food Standards Act (Chapter 15:04) of Zimbabwe. In practice, these laws are not enforceable to the necessary extent where an ALOP is attained and guaranteed. Furthermore, enforcement rests in a complex maze of shared responsibility among various entities in the government. The current status of food regulation has been summarized to be a compendium of various government departments, including local authorities, acting independently of each other but with overlapping functions (Pswarayi et al. 2014). This fact alone creates exploitable gaps which may compromise food safety especially mycotoxin management. In Zimbabwe, maximum mycotoxin limits are not explicitly prescribed in legislation but are rather contained in voluntary standards which have no legal power except when referred to in legal instruments. However, the Public Health Act (Chapter 15:09) does prescribe prosecution of food manufacturers and food business operators if their food products are deemed to be unsafe. In this case, the regulator is the local authority under whose jurisdiction the manufacturer/food business operator is. These provisions in the Public Health Act require effective and timeous monitoring and surveillance activities to ensure compliance. Unfortunately, this is not the case in Zimbabwe. The content of food law in Zimbabwe requires urgent revision, to match the ever-changing global food safety environment which is now more technology-driven, stringent and consumer-focused. The law must be specific and itemised to cater for specific food hazards or classes of food hazards, detailing maximum allowable limits. With respect to mycotoxin management, a leaf can be taken from the example of developed nations and their trading blocs, who have identified toxicologically relevant mycotoxins and determined maximum limits which are aimed at ensuring uncompromised public health. Because these limits are set in legislation, instruments can be developed to ensure compliance to legislation. Therefore, as a starting point, there needs to be direct legislation for specific mycotoxins for which maximum limits exist in other countries and trading blocs. There needs to be policy and guidance documents on what various stakeholders (primary producers, retailers, manufacturers and aid/donor agencies) need to do to comply with the slated legislation. Furthermore, a harmonised approach must be adopted to ensure one regulator and enforcer of mycotoxin legislation in Zimbabwe. This is the base upon which mycotoxin management in Zimbabwe should be built upon, being a starting point and solid foundation to effective management of mycotoxin related human health risk. Following appropriate legislation, a mandate to identify high risk commodities and to perform periodic surveillance and risk assessment is necessary in Zimbabwe. It is also necessary to extrapolate the same to other developing countries, providing room for adaptation using a needs-based approach.

The prevailing economic climate in Zimbabwe has resulted in a ballooning of informal small-to-medium scale enterprises (SMEs), with no food safety management structures (Macheka et al. 2013), making it difficult to monitor and manage the quality and safety of their food products. Other Sub-Saharan countries with large informal sector activities include Nigeria, Kenya, Uganda and Tanzania, where food is sold in open markets. Many of these SMEs have penetrated the retail market, with most supermarkets stocking at least one SMEs produced commodity on their shelves. Due to financial and production constraints, as well as ignorance on the presence of hazards such as mycotoxins, most SMEs do not perform raw material testing for compliance to regulatory or food safety standards. Visual perception is mainly the determinant of quality of the raw material. To add to this, consumers in Zimbabwe themselves are not aware of the potential hazards contained in these and many other food products. This is not only typical in Zimbabwe but also in many other developing country nations where food safety information does not filter to the consumer as efficiently as is necessary (Unnevehr 2015). A primary solution to mycotoxin management in such a setting as Zimbabwe is to monitor and control raw materials for compliance. By eliminating contaminated raw materials from the supply chain, a substantive reduction in contaminated processed products is achievable, provided contamination is avoided throughout all stages of production (e.g. during processing and storage). In this way, and because it is difficult to follow up and rein in SMEs with respect to food safety precautions, the focus of risk management is directed towards an intervention with the greatest impact from a commodity-centred perspective. Ideally, monitoring of mycotoxin contamination should be applied throughout the entire supply chain. However, in developing country settings where resource limitations exist, it is impractical to do this and a more targeted results-oriented approach is better. If we consider the example of locally produced maize, mycotoxin contamination can be said to be moderate, on average, based on recent data (Hove et al. 2016; Murashiki et al. 2017). On the contrary, mycotoxin exposure is high as is evident in both direct and indirect exposure estimates (Hove et al. 2016; Murashiki et al. 2017). Evidently, mycotoxin contamination is not localised to Zimbabwean produce alone (nor is it limited to maize, however, maize is the staple diet and is consumed on an almost daily basis in Zimbabwe). Thus, a robust and overarching mycotoxin surveillance strategy needs to be put in place, involving but not limited to pre-shipment and border inspections of imported food commodities. Surveillance priority must include other high-intake foods such as groundnuts, beans as well as food aid and donations. In neighbouring South Africa, for example, there are active food control measures and legislation is enforced regarding the safety of imported food commodities. It is not uncommon to see inspection of consignments at various ports of entry. In the United States of America (USA) and EU, high risk food commodities are routinely monitored for the presence of mycotoxins.

It is important to note that mycotoxin monitoring of food commodities necessitates accurate and efficient analytical capacity so that any management actions can be evidence-based per the requirements of risk assessment. Mycotoxin analytical capacity in developing countries is compromised owing to inadequate infrastructure and capitalisation (Matumba et al. 2017), and Zimbabwe is no exception. Even though rapid test kits are becoming popular, highly specialised equipment and methodologies involving high performance liquid chromatography (HPLC) coupled to, for example, tandem mass spectrometry, are required to perform confirmatory quantitative analysis. The detection and accuracy capabilities of the latter cannot be overlooked when considering fitness-for-purpose. While specialized and high-throughput equipment are requisite, the pre-requisite is highly-trained human resources who can utilise the equipment and facilities. As such, it is worthwhile to invest in human and infrastructure capacity building, as a second step towards mycotoxin management. GAP, improved and up-to-date mycotoxin regulations, and human and institutional capacity building are well applicable to achieve an appropriate level of protection for citizens as well as to guarantee compliant products (import/export and local markets). With respect to subsistence farmers, who consume what they produce, human-centred interventions will be more effective in reducing mycotoxin exposure. In settings such as Zimbabwe, where high mycotoxin exposure has been associated with high consumption of low-level contaminated produce (Hove et al. 2016), a pragmatic human-centred approach is required to augment GAP, legislation and surveillance efforts in mycotoxin management.

Human-centred interventions

Dietary diversity as a means of reducing mycotoxin exposure

High dietary intake of particular foodstuffs, even though mycotoxin contamination may be within maximum allowable limits, is one of the causal factors in human dietary exposure to mycotoxins (Hove et al. 2016; Matumba et al. 2017). In this case, though regulation will ensure compliant commodities, it does not ensure public health protection especially in populations with high consumption patterns (Matumba et al. 2017; Williams et al. 2004; Wu et al. 2014) and limited dietary diversity. There are theories to support links between mycotoxin exposure as a confounding factor in malnutrition in developing countries (Etzel 2014; Laura E. Smith et al. 2015; L. E. Smith, Stoltzfus, and Prendergast 2012). Therefore, reducing dietary exposure is key in tackling human health risk from mycotoxins. Limited dietary diversity in Zimbabwe among subsistence farming populations (ZimVAC 2014) and overreliance on maize as the staple diet is the greatest challenge in reducing mycotoxin exposure in Zimbabwe. Nowadays, several starch and cereal options are available locally, such as rice, potatoes, small-grain cereal products and pasta products. The monotonic diet of subsistence farming populations is not necessarily an issue of affordability, but rather an issue of convenience. Pasta products and rice are sometimes beyond the reach of many low-income subsistence farmers as they are purchased rather than cultivated by subsistence farmers themselves. Small grains (millet and sorghum varieties) on the other hand are cultivatable. If introduced into the diet of subsistence farming communities, these small grains would significantly improve dietary diversity. Apart from improving dietary diversity small grains also contribute significantly to improved nutrition and health (Vanegas et al. 2017; Karl et al. 2017; Klerman, Collins, and Olsho 2017; Singh 2016; Jevcsák and Sipos 2016; Proietti, Frazzoli, and Mantovani 2015).

The importance of advocating for dietary diversity among populations from developing countries has been underscored as a critical intervention in the management of mycotoxin exposure (Wu et al. 2014; Alberts et al. 2017). In the recent years, several nutrition programmes promoting the importance of dietary diversity have been implemented in Zimbabwe under the Ministry of Health and Child Care (MoHCC) (Marume et al., n.d.; Sadza and Nherera 2015; World Health Organisation 2017). Advocacy and education at grassroots level, making use of village structures and village health centres, has proven to be an efficient method of nutrition information dissemination in Zimbabwe. The government of Zimbabwe, bearing in mind the human health risk associated with mycotoxin exposure and considering the current data on this exposure in Zimbabwe, should consider incorporating mycotoxin awareness and nutrition education. It will be beneficial to devise a policy aimed at ensuring dietary diversity particularly among vulnerable population groups, as a means of reducing mycotoxin exposure while achieving food and nutrition security. For example, based on the findings of Hove et al. (2016), reducing maize intake to 4 instead of 7 days a week would reduce the average FB1 exposure from a range of 2.3 to 5.2 μg/kg bw/day to 1.3–3.0 μg/kg bw/day, respectively. In this way, a considerable part of the population will be within the ALOP, though children under 5 years of age will remain a vulnerable sub-population. Wu et al. (2014) suggest that policy makers and programme implementers should emphasize on the added benefit of agricultural and dietary diversity, and devising incentive schemes to generate public interest and involvement. However, given that there is limited data on which to draw conclusions on mycotoxin exposure from food commodities other than maize, it is important to employ a holistic approach to advocating dietary diversity, beginning with an analysis of mycotoxin exposure from the proposed food sources.

Socio-cultural approaches for modified crop agronomy

It is easy to devise policies on paper, but it is more difficult to implement these policies where socio-cultural factors and traditions are a back-bone of societal behaviour. This is a challenge faced in many settings, when interventions go against the grain of set cultural norms and practices (Wu et al. 2014; IARC 2015; Alonso 2015). For example, exploring alternative staple crops to maize is a good idea but will be met with a series of setbacks. If millet/sorghum are proposed to be cultivated as an alternative to maize, some of the challenges subsistence farmers will experience are: (1) the crops are labour intensive from cultivation to processing; (2) farmers often lose substantive portions of their crops to birds in the field; (3) there are no established markets for the produce; the demand is very low as compared to other crops like maize. As such, very few farmers will buy into that idea. It is important to note that these crops were initially a substantial part of the traditional Zimbabwean diet (Chivenge et al. 2015; Mawere and Mubaya 2015; Mawere 2017). However, the advent of maize and its economic superiority over sorghum and millet resulted in a cultural shift towards preferring maize production and consumption (Chivenge et al. 2015). An advantage of small grains over maize is that the former are naturally drought and insect-tolerant (Chivenge et al. 2015; Hadebe, Modi, and Mabhaudhi 2017; Rurinda et al. 2014; Jukanti et al. 2016; Proietti, Frazzoli, and Mantovani 2015). This is a natural advantage against mycotoxin contamination which is known to be predisposed by plant stress and insect infestation (Bankole and Adebanjo 2003; Battilani et al. 2008; Massimo Blandino, Reyneri, and Vanara 2008b; Munkvold 2003). This is not to say that small grains are immune from fungal infection and mycotoxin contamination as mycotoxin occurrence has also been reported in sorghum and millet grains (Lahouar et al. 2015; Taye et al. 2016; Chala et al. 2014; Ratnavathi et al. 2016). A way of circumventing resistance to modified agronomic practices is to encourage and/or set-up community gardens or farms, whereby small groups can share a piece of land and practice collective farming. An ideal scenario would be for government to provide inputs (seed, fertilizer, agrochemicals) and the necessary support and extension services for the cultivation of alternative crops to maize. The communities will collectively grow crops and share the harvest. The government can also create or identify markets for these communities to trade their surplus produce. This approach has worked in various settings in Zimbabwe to tackle malnutrition in vulnerable populations, whereby communities had collective nutrition gardens, growing fruits and vegetables for communal consumption (Katunga and Lombard 2016; Puett et al. 2014). If properly coordinated, long-term health and nutrition benefits will be realised.

Conclusion

This paper sought to elaborate on a practical and achievable science-based mycotoxin management strategy for use in developing country contexts. The strategy, proposed in Figure 1, should have a revolving element of monitoring and surveillance to protect consumers and ensure that safe products are traded between Zimbabwe and her partners. Periodic risk assessments should be undertaken to assess the magnitude and severity of risks associated with dietary exposure to mycotoxins in Zimbabwe. This will provide a scientific backbone on which risk management measures will be taken, and this is a pre-requisite of the risk analysis paradigm. With respect to mycotoxin exposure, the proposed strategy will ensure an appropriate level of protection, is attained thus managing the associated human health risk, in Zimbabwe.

Acknowledgments

The authors would like to acknowledge the Ghent University special research fund (Ghent BOF) for students from developing countries, grant no. 01W02813.

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