Mycotoxin incidents associated with cereals: lessons learnt and risk reduction strategies

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Abstract

This paper explores the occurrence and impact of mycotoxins linked to cereals and their indirect impact on human food safety. Epidemiological cases are used to evaluate the impact of mycotoxins on food and feed supply chains. It is shown that mycotoxins pose significant problems and, the implementation and enforcement of legislation, and the development of efficient supply chain strategies including private standards to reduce the risks of contamination and subsequent health issues are considered. Further, the paper identifies the different challenges faced by developing and developed nations in relation to managing the risks associated with mycotoxins relative to local, regional and global trading systems.

Keywords: case study, food safety, risk analysis, risk reduction strategies

Background

Mycotoxins are toxic secondary metabolites produced by various fungi that contaminate the feed and food chain. Fungal species involved in contamination of feed and food chains belong to genera such as *Aspergillus*, *Penicillium*, *Fusarium*, *Alternatia* and *Claviceps* (Bennett and Klich, 2003; Patriarca and Pinto, 2017). Mycotoxins of major public concern include aflatoxins (AF), ochratoxin A (OTA), fumonisins, (FUM), deoxynivalenol (DON) and zearalenone (ZEA) (Marroquin-Cardona et al., 2014). Mycotoxins are argued to contaminate the diet of a large proportion of the world's population, especially in developing countries (CAST 2003, Wild and Gong 2010). Developing regions are often associated with high humidity and temperature and lack of appropriate storage conditions which contribute to fungal growth and mycotoxin production (Cotty and Jaime-Garcia, 2007). In contrast, strict food safety regulations and modern agronomic practices have reduced mycotoxin contamination in food supply chains of developed regions (Shephard, 2007). The main focus in developed regions continues to be the establishment of legal limits linked to import regulations for food and feed in order to protect humans and livestock. Mycotoxins have been implicated in a number of human diseases (Table 1); however, demonstration of direct connections between the mycotoxins and resulting human illnesses is relatively rare due to the many confounding factors that can influence the pathway of toxins from the fungus to an affected person (Bryden, 2007). As a result, many cases would be most likely classed as

probable. Table 1 summarises the human diseases, major fungal species that can give rise to mycotoxins in foods,, typical food sources and symptoms.

Insert Table 1 here

The aim of the paper is to explore the occurrence and impact of mycotoxins linked to cereals and their indirect impact on human food safety. Epidemiological cases, both historic and contemporary, are used to evaluate the impact of mycotoxins on food and feed supply chains. Human exposure to mycotoxins can be the result of consuming plant derived foods that have been contaminated (CAST 2003) or from animal derived products where the animal has consumed contaminated plant materials (Boudra *et al*. 2007; Coffey *et al,* 2009); exposure may also come from the surrounding environment if air and dust is contaminated with toxins (Jarvis 2002) where it is sometimes referred to as 'sick building syndrome'. The Food and Agriculture Organization (FAO) estimated that 25% of the world's cereal production is likely to be contaminated with mycotoxins leading to an estimated 1 billion metric tonnes of annual losses in food and feed (Maestroni and Cannavan, 2011). Meanwhile, Binder *et al.* (2007) reported on a two year survey of animal feeds and feed raw materials, of those mycotoxins known to have an impact on animals (e.g. *Fusarium* mycotoxins deoxynivalenol [DON], T-2 Toxin, Zearalerone, Fumonisins B_1, B_2 and B_3); in addition, samples were screened for ochratoxin A and aflatoxin B1 as there is evidence of interactions between these toxins. The results of some 3,000 samples showed that more than half of European samples were contaminated with one or more mycotoxins and one third of Asian and Pacific samples also had measurable concentrations. Global occurrence data on the incidences of mycotoxins in raw cereal grains were reported as 55% for AF, 29% for OTA, 61% for FUM, 58% for DON and 46% for ZEA (Lee and Ryu, 2017).

Under ideal conditions the determination of mycotoxicoses in human and animal subjects should depend on the presence of the toxin in suspected food or feed and the patient(s) along with the presence of the fungus and the absence of other disease agents that can cause similar effects (Richard and Thurston 1986). In other words, it is not sufficient to isolate and identify the suspected fungus as it is the concentration of the toxin that is important both in the food source and in the individuals affected. However, such analytical approaches are confounded by a number of factors including:

- the large number of mycotoxins identified to date and their varied bio-chemical structures;
- the non-uniform distribution of toxins in bulk foods and feed during storage, making sampling a significant challenge;
- expensive laboratory assay procedures, though more recent bio-assay kits are able to qualitatively identify specific toxins;
- low level exposure over time can result in chronic conditions that can be mistaken for other diseases, especially in developing countries where public health resources are limited and mycotoxins are prevalent in food systems, and
- the often sporadic nature of cases making it difficult for health professionals to isolate suspect foods when cases present.

It is interesting to note that most evidence in developing countries today reflect incidents that occurred in developed economies in previous centuries. However, contemporary staple diets are shown to contain mycotoxins and the incidence of human disorders associated with these toxins are prevalent in developing countries, but often the symptoms in the consuming population are not treated as public health cases (Wild and Gong 2010). The diverse nature of mycotoxin contamination is reflected in the wide array of evidence associated with human incidents of mycotoxin related disease collated in Table 2.

Table 2 here

This summary of incidents illustrates a number of points peculiar to mycotoxin poisoning and associated human diseases. It is clear that the majority of human cases identified in the literature, some of which are reported here, have occurred in the developing world. There are a number of factors contributing to this. In tropical conditions of high temperatures and high moisture, including monsoons and flash floods, fungal growth proliferates as does the production of mycotoxins. At the same time, crops are often grown for home consumption under subsistence farming systems with crops often stored in sub-optimal conditions. Furthermore, surplus crops may be sold locally in informal markets with little or no inspection or regulation from public authorities. Such short supply chains make it difficult for government agencies to monitor the health impacts of mycotoxins unless acute cases occur and post disease case studies are carried out. The incidents in Table 2 also demonstrate the relative toxicity of mycotoxins in causing human fatalities; in particular, the high mortality

rates reported for aflatoxin contaminations and the ergot poisoning incident in Ethiopia lead to vascular restrictions and subsequently gangrene. It is also interesting to note the associations between aflatoxins, Reyes disease and Kwashiorkor. In studies where case and control groups were evaluated, both showed these diseases and the control groups demonstrated the presence of a range of aflatoxins in a number of individuals screened. To further illustrate the challenges in determining whether mycotoxins are indeed the cause of a number of human conditions and diseases; one historic and two contemporary case studies linked to human disease are presented. One contemporary study is from the developing world and the other from the developed world.

Case 1: Salem 1692

The challenge of mycotoxins to human health has been known since time immemorial with issues such as 'Witchcraft or mycotoxin?', as noted by Woolf (2000), the Dead Sea Scrolls referring to the destruction of 'houses of mildew' and that one of the ten plagues on Egypt was attributed to humans and animals succumbing to contaminated stored grain (Marr and Malloy 1996).. However, perhaps the most infamous incident in the early history of mycotoxins was the Witch Trials in 1692 in Salem, Massachusetts. How does this historic incident stand up to epidemiological case review? In Europe and the United States (US) in the Middle Ages bread, often made with rye, was an important staple especially during the winter months. In early 1692 a number of girls in Salem suffered violent fits, convulsions and complained of itchy skin before lapsing into incoherent rants and hallucinations. Finding no physical cause for these symptoms, the local doctor considered the incidents to be witchcraft. By September of that year, 140 suspected witches had been arrested and 19 executed. We can derive from this, other cases and related evidence point to a causal agent. On the one hand the incidents stopped in the summer months of 1692 which was an unusually dry period. Secondly, the preceding summer was recorded as a warm and damp season which was ideal for fungal growth. Finally, most of the cases were from the west of the village, which was a marshy area and thus more prone to fungal growth (Caporael 1976). To add to this case, historians are aware of several incidents of mass insanity in medieval Europe (often termed St. Anthony's Fire) (Lee, 2009). However, it was not until nearly three hundred years later that a plausible link was postulated for the Salem case by Caporael (1976). More recently, toxicologists have identified that a number of grasses and cereals including rye can be infected by species from the genera *Claviceps* whose complex life cycle results in developing plant ovaries becoming masses of fungal tissue which harden into sclerotia, similar to hard

tubers (Eadie, 2003; Schiff, 2006). Sclerotia can be harvested along with the grain and if not removed e.g. by beating, sieving or other separation process, can then contaminate the food chain (Dellafiora et al., 2015; Eadie, 2003). Sclerotia contain ergot alkaloids that can cause gangrenous ergotism with symptoms such as circulation disorders and convulsive ergotism causing nervous disorders, spasms, and hallucinations (see Hulvova et al., 2013; Mulac and Humpf, 2011). The witchcraft trials of 1692 in Salem and in Finnmark, Norway in the 17th century have been studied retrospectively and revealed that ergot alkaloids from *Claviceps purpurea* were responsible for the ergotism disease in humans (Alm, 2003; Dellafiora et al., 2015; Dellafiora and Dall'Asta, 2017). In seeking to retrospectively determine the cause of food poisoning incidents, evidence presented can lead researchers to consider progressing from suspected causal agent, through probable causal agent to finally confirm the agent responsible. How does the evidence from the Salem case stand up to this scrutiny? The case definitions of Belson *et al.* (2005) have been adapted to the mycotoxin outbreak in Salem:

- *Suspected ~ a case in which a potentially exposed person is being evaluated by health-care workers or public health officials for poisoning by a particular chemical agent* (Belson *et al.* 2005). In the Salem case the exposed people were evaluated by a doctor; however, no agent was suspected or determined and an alternative narrative was postulated and believed by the community.
- *Probable ~ a clinically compatible case in which a high index of suspicion exists for chemical agent exposure or an epidemiologic link exists between this case and a laboratory-confirmed case* (Belson *et al.* 2005). By piecing the evidence together retrospectively then it can be argued that there was a high probability of ergot infestation of rye in Salem, especially in the western marshy fields due to the warm and wet summer of 1691 In addition, the symptoms recorded in the trials and times of ingestion are consistent with ergot poisoning from stored grain. Finally, the use of new grain in the dry summer of 1692 was less likely to have been infected.
- *Confirmed ~ a clinically compatible case in which laboratory tests of environmental samples have confirmed exposure* (Belson *et al.* 2005). This is not possible in the Salem case as no samples of rye or bread for cross referencing were taken or stored and no food diaries were logged.

Case 2: Aflatoxin Poisoning in the Eastern and Central Provinces of Kenya, January – July 2004

This aflatoxin outbreak in Kenya was one of the most severe cases globally with 317 case patients in seven districts and 125 deaths (CDC 2004). The outbreak was caused by the S strain of *Aspergillus flavus* (Probst et al., 2007). In this case, maize harvested in the off-season, with early rains was implicated. During preliminary examinations of food collected, aflatoxins were found at high levels especially in locally grown maize. A joint Kenyan and Centre for Disease Control and Prevention (CDC) team then conducted patient interviews and reviewed medical records in health facilities dating back to January of the same year. Any case presenting acute jaundice after January in the affected provinces were listed as potential aflatoxin poisoning. In addition, any patient diagnosed with jaundice at Kenyatta National Hospital that had not got a history of chronic liver disease or other causes of jaundice were also listed as suspected cases (CDC 2004). Reported cases increased during April and continued through to mid-July. Age data was collected on just over 300 patients and showed that 22% were under 5 and 29% were 5-14 years; in other words, almost half of those affected were children and juveniles.

The study also carried out a case control study on 80 controls (healthy) and 40 cases in the same districts. This highlighted that those individuals showing symptoms of jaundice were associated with a number of environmental factors linked to increased aflatoxin growth in maize.. These included reported home storage of discoloured home grown maize, consumption of cooked maize kernels as well as home and damp storage of maize. Food samples were also collected from households in May of the same year which included maize flour, dry maize cobs and grains, de-hulled maize, millet, sorghum and beans. Of these, half of the samples had aflatoxin B_1 significantly above regulatory levels. Further market samples in the districts also showed that over 53% of samples exceeded regulatory levels for aflatoxins. The case control study revealed that aflatoxin concentration found in homegrown maize kernels from case households were 8 times higher compared to control households. Case patients were also more likely to store wet maize in their homes and reported higher rate of pet deaths (Azziz-Baumgartner et al., 2005).

In response to this outbreak, the Kenyan Government provided replacement food to affected districts and advised residents not to eat maize and other foods suspected of being mouldy. Food inspections were carried out and any suspected foods were removed, destroyed and

replaced. Following on from this, surveillance for aflatoxin poisoning had been extended to other parts of Kenya by the Ministry of Health and screening of maize in store for aflatoxins has been increased (CDC 2004). As an aside to the public response, some concerns were raised over the safety of alternative maize provided by the government as samples taken at the time showed that 55% of publicly stored grain had aflatoxin levels above 20 µg/kg (Lewis et al., 2005; Muture and Ogana, 2005) and 35% had levels above 100 µg/kg. However, these were significantly lower than those of local markets in the affected districts that were in some cases in excess of 8000 µg/kg (Lewis et al., 2005).

What lessons can be learned from this case? Maize is the major staple food in Kenya and accounted for 40% of the population's daily food intake. This means that Kenyans are potentially exposed to regular doses of aflatoxins through their staple diet (Probst et al., 2010). High levels of aflatoxin was found in maize samples (some in excess of 8,000 µg/kg when the regulatory level is 20 µg/kg). The outbreak was caused by the S strain of *A. flavus* – a strain that was not previously found in Africa. The S strain consistently produced larger amount of aflatoxin (Probst et al., 2007). Both the high amount of aflatoxin and regular doses of maize summatively led to patients consuming higher concentrations of aflatoxin. Evidence of clinical illness was grounded in the use of a sound rule base to separate out other factors that may have caused jaundice; clusters of cases were identified within households who would have consumed the same samples of maize; case patients and controls were interviewed and samples of blood and foods were taken for analysis; and there were also reports of animal deaths where they had consumed the same maize as affected householders. The government implemented a corrective action strategy to remove contaminated food and replace this with safer foods and from a preventative point of view, the government of Kenya implemented screening for aflatoxins symptoms through public health facilities and also increased screening of stored maize. Maize from affected regions are destroyed and replaced (with grains from less affected regions). Public health authorities should be aware of potential contaminated maize entering the distribution system leading to continuous exposure to aflatoxin (Lewis et al., 2005).

In epidemiological terms, this case would be classed as being a confirmed case. A final benefit that accrued as a result of this case was the willingness of national and international bodies to co-operate in building capacity and the outbreak provided valuable field training for Kenyan public health workers under the mentorship of the CDC. The incident and subsequent

investigations also provided case workers with an opportunity to trial novel approaches to epidemiological studies.

Case 3. Gastrointestinal Illness in US School Children Linked to Eating Burritos

Between October 1997 and March 1998, three outbreaks of gastrointestinal illness in schools were traced back to one company and were linked to burritos containing either: chicken and bean, pork sausage and egg or beef. A further 13 outbreaks in schools from between May and October 1998 were traced back to a second company producing beef and pinto bean burritos (CDC 1999). Both companies used wheat flour to make the tortillas; furthermore, all burritos were distributed to six of the seven affected States as frozen pre-packed product apart from Florida where the fillings were prepared locally. The outbreaks affected 1908 persons from 125 schools (Steinberg et al., 2006) Symptoms include nausea, vomiting, headache and abdominal cramps and occurred within an hour of consuming a burrito. Although no one was hospitalised and no one died, this group of incidents showed how epidemiological patient studies can be used to determine the likely cause of such illnesses. Even when links to a given source are not statistically proven, it is important that government and industries work together to reduce food safety risks. As part of the epidemiological investigation case control studies were set up. The first school showed that 57% of case and 13% of control cases ate burritos. In a second school, 85% of case and 33% of control cases ate burritos. In both schools, the fillings were made locally and only the tortillas were common to one of the companies under suspicion. The case study also had to identify possible causes of the symptoms presented as a number of agents could be responsible and had to be eliminated. For example, *Staphylococcus aureus* and *Bacillus cereus* both produce toxins linked to food poisoning; however, headaches are not normally associated with these and the incubation periods were longer compared to the observed outbreak.. Evidently, food samples from 5 outbreaks were also negative for the pathogens.. Heavy metal contamination could have also caused some of the symptoms; however, none of these were at high levels in the burritos sampled. Previous outbreaks due to ingestion of cereal grains contaminated with DON occurred in China between 1961 – 1985. Patients suffered from similar clinical manifestations such as nausea, vomiting, headache, dizziness and abdominal cramps (Luo, 1988a). Another outbreak in India were caused by consumption of bread made with wheat contaminated with trichothecene mycotoxins. Patients also suffered from abdominal cramps within 15 minutes to an hour after consumption of the bread (Bhat et al., 1989). This led the US investigators to suspect natural toxins, in particular DON as other studies had shown such

links. Sampled burritos showed DON levels to be within the FDA advisory limit of 1 ppm for finished wheat products; however, children are more vulnerable to such toxins since they consume more of the suspect food than adults when expressed as amount of food consumerd per kg body weight. This result in higher exposures to potential mycotoxins from eating an equivalent amount (Raiola et al., 2015). The companies implicated in supplying contaminated tortillas, both use different raw material suppliers and no common first line supplier was identified. Therefore, it was not determined whether any ingredients were of common origin or shared in any way. Although the link was not proven, the US Department of Agriculture (USDA) requested that both companies initiate national recalls and as a result some two million lbs of burritos were either withheld from distribution or recalled (CDC 1999).

What lessons can be learned from this case? Again the approach was based on the patient epidemiological case studies. The incidents of food poisoning in the schools initiated patient-case studies to be carried out; samples of product were collected and analysed though they were found to be within FDA limits for adult consumption. The symptoms displayed were assessed against a range of causal agents and then each was assessed for probability. Traceback studies were carried out to identify companies' that may have supplied contaminated product. Based on lessons learnt from similar outbreaks in other countries i.e. China and India, mycotoxin food poisoning from DON was considered the most likely cause in these cases. From an epidemiological perspective these cases would be classified as 'most' probable. Furthermore, although mycotoxin poisoning was not proven in these cases, it is important to note that the government requested a product recall (a precautionary approach) and the companies in question complied, as not to do so may have harmed their reputations and hence future business.

In order to carry out such a recall, industry must have effective product trace and recall systems in place that can be embedded into food safety management systems. In this incident, traceability systems and associated records were crucial. Limited shipping records for affected burritos may have hampered further investigation as some lots were not listed (Steinberg et al., 2006). Within the US food industry this may be enforced for high risk foods by legislation mandating the need for hazard analysis critical control point (HACCP) plans or may be a condition of supply under a number of global and national private food standards (Baines 2009). Although HACCP systems are considered to be problematic at the primary production level, particularly the identification of robust critical control points

(CCP) for the prevention or reduction of hazards and associated record keeping for measures taken, it is still important to have traceability and recall systems in place. Good Agricultural Practice (GAP) is an integral part of food safety at the primary production level, but continuous food safety issues and contaminations may warrant further investigation. Hence this triggers the question: "Is this issue of mycotoxins a call for HACCP based on-farm food safety management systems?" If yes, this will then lead to the critical question: "Is a true HACCP plan possible?". Whilst a true HACCP plan may be possible for addressing chemical hazards (MacDonald 2005, Soon *et al.* 2012), HACCP is not only about elimination of hazards, but also emphasises risk reduction of biological, chemical and physical hazards. This will be very much relevant to the risk reduction strategies to be applied at the primary production level for mycotoxin reduction. Given the understanding of the range of mycotoxins and the impacts they can cause on human and animal health shown in this paper, allied to the value of patient case studies to determine actual causes of illness or disease; the next section of this paper considers how the risks associated with mycotoxins can be mitigated.

Risk Reduction Strategies

The first step in reducing the risks associated with mycotoxins is to develop standards for the maximum limits of these natural toxins. These standards need to be linked to the best scientific evidence on what concentrations of toxin are acceptable or not acceptable. This is not a simple task as a number of factors have to be taken into account to determine risk levels such as: age and health of individuals; whether ingestion or exposure is at a low level over long periods i.e. accumulative or higher doses in a short time span; the impact of environmental conditions on the presence and growth of fungi; and the availability of technology to separate, reduce or denature toxins before food or feed is consumed. It is also important to remember that exposure may come from environmental exposure to spores and toxins as well as through ingestion.

Prior to developing and enforcing maximum limits, risk assessment of mycotoxins is the primary scientific basis to determine food safety limits (van Egmond et al., 2007) such as risk assessment of OTA in the US (Mitchell et al., 2017), DON in Norway (Sundheim et al., 2017) and various mycotoxins in Spain (Quiles et al., 2016; Saladino et al., 2017). Similarly a number of studies reported risk assessments of mycotoxins in maize in Zimbabwe (Hove et al., 2016), groundnuts in Nigeria (Oluwawapelumi et al., 2017) and spices in Sri Lanka

(Jacxsens et al., 2016). Risk assessments are carried out for one mycotoxin, but most fungi are able to produce several mycotoxins at the same time. Similarly, food commodities can be contaminated by several fungi or animal feed made from different grains or sources (Streit et al., 2012), further complicating the mechanisms for risk assessment. Humans and animals can be exposed to a combination of low level mycotoxins. These considerations collectively highlight the challenges of risk assessing multiple mycotoxins in food (Assuncao et al., 2016; Grenier and Oswald, 2011). In addition to studying the interactions of multiple mycotoxins, research on modified forms of mycotoxins (also known as masked mycotoxins) has increased (De Saeger and van Egmond, 2012). Masked mycotoxins are metabolites of the parent mycotoxin formed in the fungus or plant e.g. by conjugation with a polar compound (CONTAM, 2014). It occurs when the mycotoxin conjugate was not detected in routine food or feed testing, but contributed to the total mycotoxin content (Gareis et al., 1990). Recent studies by Dellafiora et al. (2017), Gratz et al. (2017) and De Boevre et al. (2013) contribute to toxicological data and setting up of future regulations (Dellafiora and Dall'Asta, 2016).

As many food and feed raw materials are traded globally, it is important to set minimum rules for mycotoxin levels in line with international trade. This is the responsibility of the Codex Alimentarius Commission (CAC). Established in the early 1960's under the Food and Agriculture and World Health Organisations, Codex's role is to elaborate minimum international food safety regulations and then seek approval for these from member countries (Berg 2003). Risk management associated with chemical contaminants including mycotoxins are dealt with by the Codex Committee for Food Additives and Contaminants (CCFAC), a sub-committee under the CAC. However, the body responsible for the risk assessment component is the Joint Expert Committee on Food Additives (JECFA) who provides scientifically based evidence of the toxicity of chemicals and is charged with establishing safe levels for human consumption. From this information General Standards are developed through a stepwise procedure involving expert committees and national bodies. For mycotoxins the standard is 'The General Standard for Contaminants and Toxins in Food' (CAC, no date) which is updated annually. This standard was accepted by the CAC in 1997 (FAO 2000) with annexes to cover:

- Criteria for the Establishment of Maximum Limits in Food
- Procedure for Risk Management Decisions
- Format of the Standard

- Annotated list of Contaminants and Toxins, and,
- The Food Categorisation System to be used.

Such standards set maximum limits for toxins using the ALARA acronym - 'As Low As Reasonably Achievable'. International action is based on meeting certain criteria that including that the substance in question is shown to be: in the food or feed at certain levels as determined by reliable analysis; is of toxicological concern at this level; the food or feed is sufficiently important in the potential consumption of the substance; and, the food/feed is traded internationally (Gawalko *et al.* 2009).

Codex standards are designed to define the minimum legal standards for international trade and are often then used as the basis for national legislation. Furthermore, should member countries be in dispute over whether respective legislation is acting as a trade barrier, Codex standards are often referenced in arbitration, though this process is managed under the World Trade Organisation (WTO). As stated above, national legislation in many countries is based on Codex principles but may be set at more stringent levels depending on the expert evidence put forward by national expert committees or at the Trading block level. As an example, significant legislation has been developed in the European Union and is beyond the scope to reference in full here. However, the European Commission, the Joint Research Centre and the Institute for Reference Materials and Measurements jointly publish summary technical notes for government and industry (Lerda 2011).

Where food and feeds are produced and used within a particular jurisdiction, then the level of mycotoxin contamination deemed to be acceptable or unacceptable will be clearly defined in legislation and material will be sampled and analysed by public inspection agencies. In some regions this may be supplemented by private standards that are often equivalent or more stringent than those set by legislation. However, when food and feed is traded internationally, then different levels of 'acceptable contamination limits' may be enforced. As a rule of thumb, any producer of grains and pulses intended for the international market and any agri-business trading in raw and finished products should be aware of the limits set in the final destination country or trading block. To exemplify this point, the acceptable levels of aflatoxins are compared for the US, the largest exporter of agri-food products, and the EU, the largest importer of agri-food products (Table 3).

Insert Table 3 here

This indicative data on mycotoxin limits in cereals, pulses, nuts, milk and animal feed shows that the levels imposed in the EU are more comprehensive and restrictive. In terms of aflatoxins, the US restricts levels of aflatoxin B_1 while the EU refers to both aflatoxin B_1 plus total aflatoxins (B_1, B_2, G_1, G_2). Moreover, the limits set in the EU are 10 fold more restrictive. In terms of aflatoxin M_1 in milk, the EU limits are also 10 fold lower. These lower acceptable levels are also reflected in maximum limits in domestic animal feed with EU levels 2-5 fold lower than the US. In the late 1960s, US FDA set an action level for aflatoxins at 20 µg/kg for all foods including animal feeds. However, animal feeding studies demonstrated that levels of aflatoxins above 20 could be fed to certain food-producing animals without harming the health of these animals and consumers of food derived from the exposed animals. Thus, on the basis of these scientific studies, FDA revised its actions level for animal feed products. There exist stark differences between US and EU standards and this may lead to potential trade implications.

The notification and enforcement of food and feed legislation in the EU is through the Rapid Alert System for Food and Feed system (RASFF). This provides EU food and feed control authorities with shared information about measures taken in responding to serious risks detected in food or feed. Member States are therefore able to act more rapidly and in a coordinated manner in response to a health threat caused by food or feed. RASFF is made up of clearly identified contact points in the Commission, European Food Safety Authority, and European Environment Agency, and at national level in member countries including port and airport authorities (RASFF 2015). The output of the system is RASFF notifications that report on risks identified in food, feed or food contact materials that are placed on the market in the notifying country or detained at an EU point of entry at the border with an EU neighbouring country. The notifying country reports on the risks it has identified, the product and its traceability and the measures it has taken. After verification by the Commission, notifications are transmitted to all contact points under one of the following types of notifications (RASFF 2015):

- **Alert notifications:** when a food, feed or food contact material presenting a serious risk is on the market and when rapid action is or might be required such as withdrawal or recall. The

notification aims at giving all the members of the network the information to verify whether the concerned product is on their market, so that they can take the necessary measures.

- **Information notifications:** concerns a food, feed or food contact material for which a risk has been identified that does not require rapid action either because the risk is not considered serious or the product is not on the market at the time of notification. The EU defines two types of information notification: information notifications for followup if a product is or may be placed on the market in another member country: and information notifications for attention if a product is present only in the notifying member country; or has not been placed on the market; or is no longer on the market
- **Border rejection notifications:** concerns consignments of food, feed or food contact material that was refused entry into the Community for reason of a risk to human or animal health or to the environment if it concerns feed.

The RASFF system also allows for follow up notifications which refer to previously notified consignments in order to add information to the original notification such as information on hazards, product traceability or measures taken. Due to the global scale of cereal and pulse trade and the dominance of northern hemisphere agribusinesses, the levels of mycotoxins set for global trading are effectively those of the US or the EU depending on final destination of shipments. Indeed, shipments destined for the EU that might exceed the more restrictive limits may be diverted to the US or 'dumped' in third countries with less restrictive limits or poorly developed enforcement. This leads us to a questioning of what the size and scale of the problem is in internationally traded cereals and derived products. Imposing stricter regulations would result in economic losses in certain countries. For example, Wu (2004) demonstrated that by implementing an international fumonisin standard < 0.5 ppm would result in US$300 million export losses by the US, Argentina and China (top corn exporting countries). Stricter limits may also mean that countries may export the best quality crops whilst poor quality crops are kept for domestic consumption hence increasing internal country health risks (Wu, 2004).

In addition to EFSA and RASFF, the establishment of the European Union Reference Laboratory (EU-RL) and European Standardization Committee (CEN) with validated methods helped to facilitate the implementation of EU legislation in monitoring mycotoxins in food and feed (EU Science Hub, 2016; FAO, 2004). Projects such as BioCop resulted in

development of novel methods for early detection of mycotoxins (EC, 2011) whilst MoniQA provided a platform for experts to harmonise worldwide food safety and quality monitoring and control strategies (MoniQA Association, 2017). These pan-European projects are important to ensure the safety and quality of the food and feed supply chain.

Risk Reduction Strategies at Supply Chain Level

Given the number of notifications in the EU for example that relate to cereals and mycotoxins, a key challenge is for public administrations and food supply chains to carry out appropriate risk characterisation strategies in order to inform food and feed safety policies and reduce risks and liability in food trade. Characterising food safety risks in order to inform both policy options and supply chain process controls should follow the same steps but with different operational outcomes. These steps include:

- **Risk assessments:** Systematic evaluation of all relevant information to quantify the magnitude, exposure and probability of a potential food hazard to individuals or populations. This includes hazard identification (mycotoxins), characterisation (effect on humans and animals), exposure assessment (consumption of mycotoxins and dose effects) and risk characterisation (the impact on target consuming population including vulnerable individuals) (Kuiper-Goodman, 2004).
- **Risk management**: The process of weighing policy or private standard alternatives against the risk assessment in order to set appropriate regulatory measures and control options (Kuiper-Goodman, 1999). In developing options, it is also critical for public administrations to also weigh up public health, economic, social and political consequences; equally, the private sector through various standards will primarily evaluate food safety risks and liability whilst also considering economic and corporate issues. In both cases this contributes to risk characterisation.
- **Risk communication**: The exchange of relevant information, including uncertainties and precautionary approaches, on risk management decisions taken and the implications for key stakeholders (van Dijk et al., 2008). In the case of public administrations this may include public health officials, industry and consumers; in contrast, the private sector will largely operate through inspection and certification mechanisms to inform business to business communications as opposed to business to consumer communication.

In order to reduce the economic and health consequences of mycotoxin contamination in cereals and other crops across supply chains, a number of intervention strategies can be employed along with assessment of key risk factors from crop production to final consumer purchase. The aim of such strategies is to ensure that the food or feed product has the lowest practical mycotoxin concentrations. While it is beyond the scope of this review to develop specific mycotoxin strategies, it is important to note that the toxins in question are produced by fungal species that are in turn influenced by local environmental factors, especially in terms of temperature and water availability (a_w) which affect their scope for growth. A number of factors are important in reducing or eliminating such toxins from food and feed at key stages along supply chains (Table 4).

Insert Table 4 here

In considering the whole supply chain, it can be seen that there are several key stages where risk assessments and risk reduction strategies should be prioritised where fungal infections can lead to a build up of mycotoxins in raw materials, feed and food. These stages are critical as once grains, food or feed are contaminated then it is difficult if not impossible to economically remove these mycotoxins whether in the developed or developing world. The key risk reduction stages are:

- **Pre-crop site assessment**: as part of crop rotations, it is critical to evaluate sites in terms of the climatic conditions that may predispose the area to a higher risk of fungal growth. The risk rating would be further increased if previous crops and weeds were susceptible to fungal attack or have been previously infected and where surface trash is not buried through ploughing.
- **Ear emergence to grain filling**: this is a critical time to try and keep grains and seed heads clean for harvest; therefore, regular crop inspection especially in relation to weather conditions (warm and humid) are important with tactical use of fungicides where thresholds of infection are exceeded.
- **Harvesting, processing and storage**: harvesting early allied to rapid drying below 18% moisture content and cooling to <15°C reduces the initial risks of fungal growth in stores. Further drying and cooling is advocated for longer term storage along with monitoring and pest controls.

- **Sampling and assessment**: whether for food or feed, it is essential to sample and determine levels of mycotoxins in relation to legal limits and intended use. This is a major challenge as mycotoxins will not be evenly distributed through grains, feed and food. In the EU for example, guidance is given under Regulation 401/2006. Under this guidance food lots of 500kg – 1 tonne require an aggregate sample of 10 incremental samples totalling 1 kg while lots of >10 tonnes to 20 tonnes requires 60 samples aggregated and weighing 6 kg (Food Standards Agency 2014).
- **Processing**: Thermal processing can denature some mycotoxins to more acceptable levels (see Table 4).

Other approaches to reducing the mycotoxin burden have been evaluated including mixing, decontamination through adsorbents, and chemical and biological treatments (Binder 2007, Wagacha and Muthomi 2008). The simplest approach, unless prohibited by legislation, would be to mix contaminated grains or feed with uncontaminated parts to reduce the average contamination level. However mycotoxin concentration in grains is not homogenous and so this is not recommended as it is ineffective. Blending batches containing ,myctoxin in excess of a limitation established by regulations is not permissible (NebGuide 2003). The most commonly used method, however, is to include various binding agents or adsorbents which reduces mycotoxin uptake and distribution in animals; examples include aluminium silicates, clays and zeolitic minerals (Huwig *et al.* 2001). Other compounds may act as binding agents such as hydrated aluminosilicate which is particularly effective at binding with aflatoxins (Jouany 2007). However, no compounds were found to have binding capacity for a broad range of mycotoxins. For example, cholestyramine appears to be an effective binder for fumonisins and zearalenone *in vitro* while activated carbon was the only compound to bind with DON and nivalenol (Avanttaggiato et al. 2006). An alternative strategy is to manipulate existing gut microbes to further denature mycotoxins. For example, some rumen protozoa are known to degrade some mycotoxins (Schatzmayr *et al*. 2006), however they disappear if livestock are fed diets high in fermentable carbohydrates (Jouany 2007, Kiessling *et al*. 1984). Finally, potential bio-control agents have been considered where antitoxigenic strains of *A. flavus* and *A. parasiticus* have been introduced to soils to out-compete the toxin producing natural strains for these fungi (Ehrlich 2014). Overall corrective action of this nature is not to recommended.

Conclusion

Mycotoxins are a growing public concern and can affect human and animal health. Many are harmful to animals and can lead to poor performance and productivity or even fatalities; human exposure can also lead to illness and death. In order to reduce the impact of mycotoxins, it is necessary to try and prevent their occurrence in the first place and to have robust risk reduction strategies at the key stages in supply chains per. se. Every mycotoxin incident that occurs provides health authorities, regulators, food and farming industry with key lessons. It is essential that these lessons are learnt and considered to prevent and/or control future incidents. Comprehensive food safety programmes are needed that target both farmers and market supply chains. Given this insight into the relationships between food commodities, the environment and supply chains, it is important to consider how such knowledge could be applied to food safety programmes and the challenges facing developing and developed nations.

With regard to developing countries, mycotoxins are contaminating a large proportion of the world's food including maize, other cereals, groundnuts and other seeds. Many of these commodities are the staple diets of the population in developing countries in Africa, Asia and Latin America (Wild and Gong 2010). This is especially important for small-scale and subsistence farmers and their families where the bulk of their staple food is home grown, stored, prepared and consumed often in sub-optimal conditions. This means that there is little opportunity for public inspection and control as was the case in Kenya in 2004. Furthermore, many developing countries have poorly developed legislation and enforcement along with health services that are often stretched due to the ravages of poverty and malnutrition related illnesses. Indeed, mycotoxins are often not prioritised as a public health issue. At the same time agriculture is seen as an engine for development and governments are looking to export agricultural commodities as part of their development strategies, which is of limited value if products contain significant levels of mycotoxins. This leaves many developing countries with a dilemma of how to improve the health of local people whilst also increasing the export of agricultural commodities. To address this, the following strategies could be considered. Firstly engendering political will to address mycotoxin contamination and the capability to carry out tests for food and feed contamination. This is fundamental to protecting the country's population from mycotoxin exposure in the food and feed supply chain (Milicevic et al., 2015). Secondly building resilience in primary production with appropriate mycotoxin reduction strategies (Table 4) as part of agricultural extension by government agencies. This should include focus on the high risk stages of site selection and home saved seed and crop

monitoring, especially at seed emergence, effective drying and storage. Thirdly, grain storage needs to be more robust. Significant contamination occurs in locally stored grains and pulses, especially if stored at home and in makeshift stores. The investment in locally available and well-designed public storage could contribute not only to safer staples but also to the provision of strategic local food reserves for communities. Public health programmes aimed at informing households about the risks of sourcing and storing grains and flours could be combined with food security and health messages. In stating this, there is an opportunity for joint promotion of safer food by health officers working with agricultural extension officers. There are also potential capacity building benefits from developed and developing public health officials working together as was shown in Kenya. In local, national and international value markets small-scale farmers are often seen as a source of new land and labour for formal marketing channels. Under these types of in-grower or out-grower schemes, the technical support and food safety systems are delivered to farmers through private sector agents and through the adoption of farm standards necessary for access to international markets. By including public extension in the model, wider benefits could accrue. Alternatively, both public health regulation and private sector standards are well developed in most first world countries. As such, much of the concern over mycotoxins in developed countries is linked to global sourcing of raw materials for animal feeds and food processing. Although this is no reason for reducing the preventative programmes implemented in the UK to minimise mycotoxin contamination.

The combination of targeted legislation and efficient enforcement means that mycotoxin incidents in humans are relatively rare. This is further backed up by the risk reduction strategies built into farm assurance schemes and robust food industry standards underpinned by HACCP plans. However, as demand grows for raw materials for feed and food, then more is being sourced from developing countries. Thus, there is a need to ensure both risk reduction strategies and HACCP plans are extended to primary production and processing in extended global supply chains. Research institutions and agricultural departments of developed countries are continuously seeking to develop resistant cultivars. Development and careful selection of cultivars resistant to a broad range of mycotoxins and the sharing of resistant cultivars with producers from developing countries along with further mycotoxin mitigation strategies will help to ensure continued safe and sustainable production of cereal and pulses globally.

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943 Table 1 Human diseases associated with cereals and pulses contaminated with mycotoxins
944 and indicative health effects in humans and animals (Adapted from Binder 2007, Bryden
945 2007, CAST 2003, Etzel 2006, Riley 1998, Sherif *et al*. 2009)

Classic Disease Association	**Typical Food Sources**	**Fungal Group or species**	**Associated Mycotoxins**	**Health Effects Associated with Mycotoxins**
Akakabio-byo	wheat, barley, oats, rice	*Fusarium* spp.	*Fusarium* toxins	Vomiting, central nervous system damage, haemorrhaging cell necrosis associated with inhibition of protein synthesis and elevated CA^{2+} initiating endonuclease activation – cell apoptosis
Alimentary toxic aleukia (ATA or septic angina)	cereal grains (toxic bread)	*Fusarium* spp.	T-2 Toxin	
Kashin Beck disease, Urov disease	cereal grains	*Fusarium* spp.	T-2 Toxin but not proven	
Onyalai	millet	*Phoma sorghina*	Aetiology unknown possibly *Fusarium* toxins	
Balkan nephropathy	cereal grains	*Penicillium* spp., *Aspergillus* spp.	Ochratoxin A – not proven	Renal cancer. Reduced immune system. Reduced glyconeogenesis – cell death. Inhibition of protein synthesis – cell apoptosis. Disruption of Ca transport – cell deregulation and apoptosis.
Cardiac beriberi	rice	*Aspergillus* spp., *Penicillium* spp.	Not specified	
Dendrodochiotoxicosis	fodder (skin contact, inhaled fodder particles)	*Dendrodochium toxicum*	Possibly Verrucarin A	Oral lesions, diarrhea, hemorrhagic gastroenterocolitis, oedema. Inhibits protein synthesis in cells – cell apoptosis
Ergotism	rye, cereal grains	*Claviceps purpurea*	Ergotamines – alkaloids produced by plants in response to infection	Nervous disorders (itching skin and nervous convulsions) and gangrene due to vascular restrictions.
Oesophageal tumors	corn	*Fusarium verticillioides*	Fumonisins	Vomiting, neural tube defects, pulmonary oedema and oesophageal cancer. Disrupted lipid metabolism – cell deregulation – cell apoptosis
Hepatocarcinoma (acute aflatoxicosis)	cereal grains, peanuts	*Aspergillus flavus, A. parasiticus*	Aflatoxins B_1, B_2, G_1, G_2	Vomiting, hepatitis, liver disease and cancer (DNA modification – cell deregulation – cell death/transformation)
Reye's syndrome	Cereal grains	*Aspergillus* spp.	Aflatoxins may play a part in some cases	
Kwashiorkor	cereal grains	*Aspergillus flavus, A. parasiticus*	Aflatoxins but not a proven link	
Stachybotryotoxicosis	hay, cereal grains, fodder	*Stachybotrys chartarum*	Trichothecene -satratoxins	Rashes, especially in areas subject to perspiration, dermatitis, pain and

	(skin contact, inhaled hay dust)		(L, D, F, G and H)	inflammation of the mucous membranes, a burning sensation of the eyes and nasal passages, tightness of the chest, cough, bloody rhinitis, fever, headache, and fatigue.

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949 Table 2 Examples of mycotoxicoses in terms of people affected (and deaths), food sources
950 and toxins identified (Adapted from Peraica *et al.* 1999, Wild and Gong 2010)

Location	Affected (Fatalities)	Source	Toxin	References
India	397 (106)	Maize	Aflatoxin unspecified	Krishnamachari *et al.* (1975) Bhat and Krishnamachari (1977)
	994 (97)	Maize	Aflatoxin B_1	Tandon *et al.* (1977)
	397 (106)	Maize	Aflatoxins not specified	Krishnamachari *et al.* (1975)
	78 (not available)	Pearl millet	Clavine alkaloids	Krishnamachari and Bhat (1976)
	97 (0)	Wheat	Nivalenol, DON, T-2 Toxin	Bhat *et al.* (1989) Ramakrishna *et al.* (1989)
Kenya	20 (12)	Maize	Aflatoxin B_1 and B_2	Ngindu *et al.* (1982)
	12 (5)	Kwashiorkor	Aflatoxin B_1, few B_2, M_1 & M_2	de Vries *et al.* (1990)
	317 (125)	Maize	Aflatoxins not specified	Azziz-Baumgartner *et al.* (2005)
USA	1 (0)	Purified Aflatoxin	Aflatoxin B_1	Willis *et al.* (1980)
	22 (22) 10 (10)	Reye Syndrome Control	Aflatoxin B_1 Aflatoxin B_1	Hogan *et al.* (1978) Ryan *et al.* (1979) Ryan *et al.* (1979)
Czechoslovakia	27 (27) 25 (25)	Reye Syndrome Non Reye Syndrome	Aflatoxin B_1 and M_1 Aflatoxin B1 and M_1	Dvorackova *et al.* (1977) Dvorackova *et al.* (1979)
New Zealand	2 (2)	Rye Syndrome	Aflatoxin B_1	Becroft and Webster (1972)
Uganda	1 (1)	Cassava	Aflatoxin unspecified	Serck-Hanssen (1970)
Thailand	23 (23) 15 (15)	Reye Syndrome Control	Aflatoxin B_1, B_2 and M_1 Aflatoxin B_1 and B_2	Shank *et al.* (1971)
Nigeria	38 (38) 39 (39)	Kwashiorkor Controls	B_1, B_2, G_1, G_2, M_1, M_2 in both groups	Oyelami *et al.* (1995) Oyelami *et al.* (1997)
Ethiopia	140 (48)	Grain	Ergotamine-ergocristine alkaloid	King (1979)
China 1984-85	463 (0)	Maize, Wheat	DON, Zearalenone	Luo (1988b)

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954 Table 3 A comparison of regulations in the US and the EU for aflatoxins (Adapted from EC
955 No 1881/2006, Richard 2007, US FDA 2000)

US		**EU**	
Commodity and intended use	**Maximum levels µg/kg (aflatoxin type)**	**Commodity and intended use**	**Maximum levels µg/kg (aflatoxin type)**
All products except milk for human consumption	20	Groundnuts (peanuts), dried fruit and processed products thereof for direct human consumption	2.0 (B1) 4.0 (Sum of B_1, B_2, G_1 and G_2)
		Almonds, pistachios and apricot kernels intended for direct human consumption	8.0 (B1) 10.0 (Sum of B_1, B_2, G_1 and G_2)
		Hazelnuts and Brazil nuts intended for direct human consumption	5.0 (B1) 10.0 (Sum of B_1, B_2, G_1 and G_2)
		Tree nuts, other than the tree nuts listed above and processed products thereof intended for direct human consumption	2.0 (B1) 4.0 (Sum of B_1, B_2, G_1 and G_2)
		Cereals including maize and processed products thereof	2.0 (B1) 4.0 (Sum of B_1, B_2, G_1 and G_2)
		Processed cereal based-foods and baby foods for infants and young children	0.10 (B1)
Milk	0.5 (M1)	Milk for the manufacture of milk-based products	0.05 (M1)
Feed			
Cottonseed meal as feed ingredient	300	All feed materials except	20 (B1)
Corn and peanut products for finishing beef cattle	300	Complete feedingstuffs for cattle, sheep and goats	20 (B1)
Corn, peanut products, cottonseed meal and other animals feeds for dairy animals	20	Complete feedingstuffs for dairy feed	5 (B1)
Corn and peanut products and other animals feeds (excluding cottonseed meal) for immature animals	20	Complete feedingstuffs for calves and lambs	10 (B1)
Corn or peanut products for finishing swine	200	Complete feedingstuffs for pigs and poultry	20 (B1)

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959 Table 4 Mycotoxin risk reduction actions along cereal supply chain

Supply Chain Stage	Actions	Impact	Notes
Primary production			
Site selection	Evaluate production site in terms of seasonal temperature and precipitation	High	Regions with higher temperatures and high precipitation often have higher fungal growth but this is specific to species e.g. *A. flavus* is prevalent in hot humid climes while *P. parasiticus* prefers cooler conditions but both produce aflatoxins
Previous crop and rotations	Avoid sites that have previously grown maize or other susceptible cereal crops, especially if fungal infestations detected in previous season.	High	Intensive cereal rotations or monocultures can lead to carry over of diseases, pests and fungal spores that can lead to infection of subsequent crops.
Crop residue management	If previous crop was susceptible and may hold fungal spores, bury residues by soil inversion	High	Burying previous crop results in a clean seed bed and less risk of fungal infection. See also weeds
Variety choice	Select varieties with higher levels of fungal resistance if available. Also crops with drought, and temperature stress resistance may be more resistant to fungal infection.	Medium	Increased genetic resistance to fungal attack. Earlier ripening varieties can allow harvesting in better weather conditions. See also Harvesting time
Fertiliser inputs	Match inputs to crop requirements and weather conditions	Low	Excessive fertiliser inputs, especially nitrogen, can result in crops lodging. This creates a more humid micro-climate conducive to fungal growth. See also growth regulators.
Growth regulators	Dose and timing should be at correct growth stage to ensure stem elongation is reduced	Medium	Growth regulators result in shorter crops that can take up more nitrogen without lodging
Fungicide applications	Detection of outbreaks of ear blight can be controlled by fungicides	Medium	
Weed & Insect Controls	Certain weeds may harbour fungi and insect pests. Insects can cause physical damage allowing a potential route for fungal infection	Low	Weeds can be a source of fungi in a similar way to crop residues while physical damage to the crop by insects can provide a route for fungi to enter crops
Harvesting and drying	Test grain moisture content before harvesting and dry to below safe moisture content before longer term storage. Minimise holding times before drying is completed	Medium	Maize harvested at 25% m.c. with delayed drying to <14% m.c. can have significant growth in fumonisins and zearalernone. Other cereals should be dried to 14-15% m.c.
Harvesting time	Early maturing varieties allow for an earlier start to harvesting in better weather conditions and spread the throughput of crop through drying facilities	Medium	Earlier harvests can reduce risk of fungal infections is weather conditions deteriorate.
Storage			
Store design	Stores should be well designed and maintained with good ventilation and airflow through stored grains	High	Airflow and temperature are critical to maintaining grains under safe storage conditions. Any areas with poor ventilation can become hot-spots for fungal infection.

Harvest and store Hygiene	Cleaning of harvesting, drying and storage equipment can reduce spore carry over between seasons and between crops within a season	High	Poor hygiene can lead to inoculation of clean crops with fungal spores.
Adequate capacity for rapid grain drying	High capacity reduces the risk of a backlog of higher moisture content grain in temporary storage. The aim is to dry below 18% m.c. as quickly as possible.	High	If grain is stored above 18% m.c. then the risk of ochratoxin A is increased during storage.
Rapid cooling	Fungal growth can be inhibited if grains are cooled and maintained cool	High	Rapid cooling to below 15ºC reduces fungal activity
Continued drying and cooling	Dry grains to recommended safe storage moisture content. Long term cooling to 5ºC	Medium	Other fungi are restricted at lower m.c. and temperature See also Harvesting and drying.
Grain store monitoring	Continued monitoring of temperature, moisture content and insect/mite activity	Low	Monitoring enables any problems to be detected and acted on immediately.
Processing			
Milling	Milling can redistribute mycotoxins into different fractions of the process	Medium	Dry milling results in more fumonisins , zearfalernone, DON, aflatoxins and ochrtixin A in the bran used for animal feed as opposed to fractions used for food. Wet milling results in more fumonisins, zearalernone and aflatoxin in the steep water as opposed to milled products.
Brewing	Mycotoxins may transfer from contaminated grain to the beer during the brewing process	High	Aflatoxins, ochratoxin A, zearalernone, DON and fumonisins can withstand the brewing process including the boiling of the wort (100ºC). Reductions in mycotoxins from brewing range from 2-28%.
Thermal processing	Cooking of products can denature some mycotoxins. Processes may include boiling (as with brewing), roasting, bakoing and frying.	High	Aflatoixins may be reduced by cooking (30%), pressure cooking (80%) and frying (35%). Roasting at 150ºC for 120 mins reduced aflatoxins by 63%. Ochartoxin A denatured at temps > 250ºC Fumonisins denature at tems > 150ºC
Extrusion	Extrusion is a process often used for cereals and snack foods which includes thermal processes. This can denature some mycotoxins	High	Extrusion temperatures can reach 160oC or higher for a short period. This can result in denaturing of those mycotoxins that are susceptible to these temperatures. The reduced heating tome may however, reduce the efficacy of this heat process

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