Ecological conditions affecting mycotoxin production in cereals: a review

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ABSTRACT: Spoilage fungi are ubiquitous contaminants of cereals, pre- and post-harvest. These fungi can produce a wide range of secondary metabolites under ecological conditions which are conducive for growth. However, some of these secondary metabolites are toxic and have a significant impact if they enter the production and animal food chains. Prevention of mycotoxin contamination of feed and food raw materials is now considered more important than subsequent cure. The key ecological determinants pre- and post-harvest are water availability and temperature (climate). Accurate information is therefore needed on the impact of an association between these key factors, and it is necessary to understand which are marginal and which critical for germination and toxin production. There have only been a few studies where attempts have been made to integrate the available information on these factors in relation to different raw materials for feed and food processing, especially cereals. This review will examine the available information on the main climatic factors, i.e., water availability and temperature affecting mycotoxin production such as, aflatoxins, ochratoxins, fumonisins, zearalenone, deoxynivalenol and citrinin. This information is crucial for accurately focusing and monitoring key critical control points in the feed and food chain to optimise prevention strategies.

Keywords: climate; mycotoxins; cereals; ecology; post-harvest; fungi

Contents

1. Introduction

Mycotoxins are toxic low molecular weight compounds produced by fungi which infect food and feed. Regulations minimising human exposure to mycotoxins result in high economic loss to handlers, producers, processors, and marketers of crops. Severe health problems and death have occurred from mycotoxin exposure. Whereas there are many factors involved in mycotoxin infectivity such as biological factors, harvesting, storage and processing conditions, climate is the most important factor.

The effect of toxigenic fungi on grain products has the potential of leading to significant health hazards (Table 1). The production of these compounds, especially on grains, is highly dependent on environmental factors (e.g., temperature and moisture content), pre and/or postharvest (Table 2). Thus, when changes in the weather occur, mycotoxins will be affected. Mycotoxins are climate-dependent, plant and storage-associated problems, and are also affected by non-infectious factors, e.g., the bioavailability of micronutrients, insect damage, and other attack from other pests, that are in turn determined by climatic conditions.

Table 1. Grains that are contaminated with mycotoxins

Mycotoxin	Grain
Aflatoxins	peanuts, corn, wheat, cottonseed, nuts
Ochratoxin	wheat, barley, oats, coy, dry beans
Fumonosin	corn, wheat, sorghum, barley, oats
Zearalenone	maize, corn, wheat, barley, rye
Deoxynivalenol	corn, wheat, barley, oats
Citrinin	wheat, barley, corn, rice

Table 2. Optimum temperatures for mycotoxin production

Mycotoxin	Temperature (°C)	Water activity
Aflatoxins	33	0.99
Ochratoxin	25–30	0.98
Fumonosin	15–30	0.9–0.995
Zearalenone	25	0.96
Deoxynivalenol	26–30	0.995
Citrinin	20–30	0.75–0.85

Climate represents the key agrosystem that drives fungal colonisation and mycotoxin production (Magan et al. 2003). Thus, the scenario is complex, multifaceted and interconnected and may result in a serious impairment of the availability of food and feed in developing countries in particular (Miraglia et al. 2009). Insect and pest attack, pesticides, soil, fertilizers, and trace elements also require attention as potential triggers.

Plant, animal, and human epidemics are influenced by the climate (Wint et al. 2002; Fitt et al. 2006; Thomson et al. 2006), hence weather forecasts are already being used to guide control strategies for many important diseases worldwide (Garrett et al. 2006). The possibility now exists to relate weather-based plant disease forecasts to recent climate change models, and hence predict the effects of climate change on where, which and by how much mycotoxins will be changed. In this review the effects of climate changes on the most important mycotoxins in grains will be discussed.

2. Review

2.1. Aflatoxins

Temperature and humidity influence which fungi infect damaged crops. Aflatoxin producers are favoured by warm conditions; thus, global warming, particularly in currently temperate climates, poses a potential problem is this regard.

Developing crops are frequently very resistant to infection by *A. flavus* and subsequent aflatoxin contamination, unless environmental conditions favour fungal growth and crop susceptibility. Wounding by insects, mammals, birds, mechanical processes and/or the stress of hot dry conditions all result in significant infections during the pre-harvest period. Furthermore, climate directly influences host susceptibility. The compositions of fungal communities established during the first phase greatly influence the second phase (e.g., storage) and the influence of delayed harvest on contamination are most severe when crops are affected by rain just prior to, or during harvest (Jaime-Garcia and Cotty 2003). Some examples of the conditions resulting in increased levels of aflatoxins are discussed below.

In warm and humid subtropical and tropical conditions maize ears are ideal conditions for colonisation and dominance of *A. flavus*/*parasiticus* species, resulting in the formation of aflatoxins. The aflatoxin group is carcinogenic and thus contamination results in significant economic impact. In ground nuts drought can lead to cracking of the pods and ingress by *A. flavus* and *A. parasiticus* resulting in significant aflatoxin accumulation. Delayed harvest, late irrigation and rain and dew during warm periods are associated with increased aflatoxin levels. Aflatoxin increases were greater on crops receiving over 50 mm of rain during boll opening (Cotty and Jaime-Garcia 2007). Finally, peanuts exposed to high temperature during pod maturation and rainfalls on windrows are additional susceptibility factors.

The conditions conducive to germination, growth and aflatoxin production by *A. flavus* and *A. parasiticus* show that germination occurs over a wider range than that for growth, with the aflatoxin production range yet narrower than that for growth. Optimum conditions for aflatoxin production by these two species are at 33 °C and 0.99 a_w; while that for growth is 35 °C and 0.95 a_w. The work by Pitt and Miscamble (1995) showed that the impact of ecological factors on the growth of *A. flavus*, *A. parasiticus* and *A. oryzae* was similar with minima of 0.82 a_w at 25 °C and 0.81 a_w at 30 and 37 °C. However, this study did not include a comparison of aflatoxin production between *A. flavus* and *A. parasiticus*.

2.2. Ochratoxins

The ochratoxins (ochratoxin A and ochratoxin B) are produced by *A. ochraceus*, *P. verrucosum* and *A. carbonarius* (Frisvad and Thrane 2002). These moulds grow in conditions of relatively high moisture content, and hence the harvesting of crops under high moisture conditions and the storage of contaminated foodstuffs under damp conditions favours the production of ochratoxins (Birzele et al. 2000). The major habitat of *P. verrucosum* is cereal crops in the cool and temperate climates of northern Europe and Canada (JECFA 2001). Consequentially, ochratoxins are found in cereal products, especially flour-based foods. It is also found in commodities such as cheese and meat products from animals that eat cereals as a major dietary component.

A. ochraceus is most commonly found in dried and stored foods, such as smoked and salted dried fish, soya beans, chick peas, nuts, pepper and dried fruit. It has been reported infrequently in cereals and green coffee beans. *A. ochraceous* is the most important mould that produces ochratoxins. It can grow over the temperature range 8–37 °C with an optimum of about 30 °C on barley grains (Ramos et al. 1998). *A. ochraceus* is generally present at low levels and rarely causes spoilage. Its presence may not be a good indicator of significant ochratoxin contamination (JECFA 2001). *A. carbonarius* grows optimally at 32–35 °C and is resistant to sunlight.

In warm climates, such as those found in West and Central Africa, ochratoxin production is more commonly associated with *A. ochraceus* than it is with *P. verrucosum*, which often produces ochratoxin A in temperate climates (Sweeney and Dobson 1998). Ochratoxin A is the more toxic of the two derivatives and is nephrotoxic, immunosuppressive, carcinogenic and teratogenic in all experimental animals tested (WHO 1990). Ochratoxin A is the major metabolite found as a natural contaminant of cereal grains such as maize, barley, wheat, oats and rye. Ochratoxin A has received particular attention because of its cancer-promoting activity. It has also been described as a potent nephrotoxin and teratogen, with immunotoxic properties in rats and possibly in humans. Ochratoxin A has been extensively documented as a global contaminant of a wide variety of foods including cereal products, nuts, spices and coffee (Zimmerli and Dick 1996; Urbano et al. 2001). The highest amounts of ochratoxin A were obtained at 0.98 a_w, regardless of the temperature level, with optimum ochratoxin A production occurring between 25–30 °C, depending on the isolates. Both growth and ochratoxin A accumulation increased with increasing a_w levels until 0.96–0.98 a_w, with 0.80 a_w (at 25–30 °C) being the minimum a_w required for growth on maize-based media (Marin et al. 1998) and 0.83–0.87 a_w the minimum for ochratoxin A production (Northolt et al. 1979). The food matrix and nutritional status is very important in determining ochratoxin A production (Madhyastha et al. 1990).

Ochratoxin B has been found very occasionally in some foods (Visconti and Bottalico 1983) and is less toxic than ochratoxin A. Ochratoxin A has been shown to be produced by several species in the *A. ochraceus* group and by *A. alliaceus*, *A. albertensis*, *A. niger*, *A. carbonarius* (Abarca et al. 1994; Varga et al. 1996), and *P. verrucosum* (Northolt et al. 1979). These species contaminate different crops with different distributions depending on the climatic conditions. *Aspergillus* predominates in warm and temperate regions while *Penicillium* isolates are frequent in colder regions (Sweeney and Dobson 1998).

2.3. Fumonosins

Fumonisins have received particular attention because of their cancer promoting activity and the induction of leukoencephalomalacia in horses (Marasas et al. 1988). Tropical and subtropical climates favour fungal growth and mycotoxin contamination. Fumonisins have been reported in maize and maize-based foods (Ono et al. 1999; Rodriguez-Amaya and Sabino 2002). Maize grown in temperate regions is an appropriate substrate for *F. Liseola* colonization and production of fumonisins. *F. verticillioides* and *F. proliferatum* are the two main species from this group with the capacity to produce these mycotoxins (Chulze et al. 1996). These species have been demonstrated to be important contaminants of maize in southern European countries and in North and South America (Sydenham et al. 1993; Sanchis et al. 1995). They can colonize and produce fumonisins in the field and, if the maize grain is harvested at high moisture content, conducive to fungal growth and mycotoxin production. They can accumulate in the grain before the a_w drops low enough to control the activity of these species. Moreover, corn is a very important component in the feed and food chain

and fumonisins have been commonly found in a wide range of corn-based foods in different parts of the world (Doko and Visconti 1994; Sanchis et al. 1994; Velluti et al. 2001).

Studies on lag phases prior to growth, relative growth rates and fumonisin concentrations were carried out *in vitro* in relation to water activity (0.93–0.995 a_w) and temperature (18 and 25 °C) on a maize meal agar. Regional differences in maize consumption, Fusarium species isolation and fumonisin incidence, mainly related to climatic conditions, make it necessary to establish regulatory levels for fumonisins in food in each area. Sanchis and Magan (2004) reported temperatures of 15–30 °C and 0.9–0995 a_w as optimum conditions for toxin secretion.

2.4. Zearalenone

Zearalenone is produced mainly by *F. graminearum* and *F. culmorum* and can occur in most cereals, including maize, wheat, barley, oats and rye. Zearalenone has oestrogenic effects in various animal species that include infertility, vulvae oedema, and mammary hypertrophy in females (Peraica et al. 1999).

Stob et al. (1962) were the first to isolate an uterotrophic compound from mouldy corn, while in 1965 Christensen et al. (1965) isolated a compound (preliminarily called F-2) from corn inoculated with *Fusarium*. In 1966 Urry et al. (1966) isolated the same compound from contaminated corn and they called it zearalenone. The metabolite is considered as a natural contaminant of food of cereal origin with significant *Fusarium* infection.

Biosynthesis of the compound was observed in cereals (kernels) such as corn, rice and wheat, infected by several species of *Fusarium*, including *F. graminearum*, *F. culmorum*, *F. crookwellense*, *F. equiseti* and *F. semitectum* (Betina 1989). The concentration of accumulated zearalenone in cereals depends on many factors such as substrate, temperature, duration of *Fusarium* growth and strain of fungal species. Moreover, a humid tropical climate promotes microbial proliferation on food and feedstuffs and thus mycotoxin biosynthesis (Nuryono et al. 2005). Zearalenone and its derivatives have been observed in many important crops such as corn, wheat, sorghum, barley, oats, sesame seed, hay and corn silage (D'Mello et al. 1999). Several studies carried out in Europe and a number of transcontinental countries have reported a high incidence of zearalenone in cereals and feeds (Scudamore and Patel 2000; De-Saeger et al. 2003).

Many factor such as temperature, duration of growth, substrate and strain of fungal species influence the levels of accumulated zearalenone in crops (Jimenez and Mateo 1997). In the last few years, in the Central Europe climatic zone, studies have shown that mycotoxins produced by fungi of the *Fusarium* genus, especially zearalenone, play a dominant role in food/feed deterioration (Conkova et al. 2003). The highest amounts of zearalenone formed by *Fusarium* were observed below a temperature of 25 °C, at high amplitudes of daily temperature and at 16% humidity (Zwierzchowski et al. 2005).

Prevention of fungal development and mycotoxin biosynthesis seems to be the best way to reduce risk, e.g., by harvesting grain at maturity and low moisture content and storing it under cool and dry conditions. This is obviously problematic in countries with a warm and humid climate.

2.5. Deoxylivalenol

Deoxynivalenol is a trichothecene mycotoxin associated primarily with *F. graminearum* (Gibberella zeae) and *F. culmorum*. *F. graminearum* is the more common species and may occur in warmer climates. Temperature in particular plays an important role in *Fusarium* species, from the infection of wheat heads to the production and dispersal of inocula: small changes in temperature may subsequently influence the incidence and severity of disease. Surveys indicate an increase in *F. graminearum* at the expense of *F. culmorum* as the former species has a higher temperature optimum (Waalwijk et al. 2003; Jennings et al. 2004), and this will be a factor if climate change leads to higher temperatures as predicted.

Deoxynivalenol has toxic effects in humans and all other animal species investigated thus far. These effects lead to reduced body weight gain, particularly in growing animals. Deoxynivalenol also impairs the immune response. Deoxynivalenol has been found in grains such as wheat, barley, oats, rye and maize but it has not received significant attention in Africa. Consumption of grain contaminated with deoxynivalenol has been associated with outbreaks of acute disease involving nausea, vomiting, gastrointestinal upset, dizziness, diarrhoea and headache in Asia (WHO 2002). Only one report of deoxynivalenol in foods is available

from African regions. In the Cameroon, deoxynivalenol was present in 12/15 maize samples at levels ranging from 100–1300 ng/g (Ngoko et al. 2001). Maximum amounts of deoxynivalenol were produced at 0.995 a_w after six weeks at 30 °C (Maria et al. 2006).

2.6. Citrinin

Citrinin is a secondary toxic benzopyran metabolite produced and secreted by some *Aspergillus* and *Penicillium* species especially *P. citrinum*. Citrinin is generally formed after harvest and can be found mainly in stored grains especially barley, wheat and rice, but also in other plant products such as beans, fruits, fruit and vegetable juices, herbs and spices, and also in spoiled dairy products (Braunberg 1994).

Toxin production occurs at temperature of 20–30 °C and 0.75–0.85 a_w, depending on the species. (Frank 1992) This toxin represents a severe problem especially in countries with a hot climate as under these conditions it is a major source of food poisoning after fungal contamination (Sinha and Prasad 1996). In animals and humans the toxin accumulates in the kidneys and can cause severe renal failure (Braunberg 1994; Galtier 1998). Physiological investigations identified different adverse effects on the kidneys, liver and the gastrointestinal tract (Krejci et al. 1996).

3. Conclusions

For control measures to be effective it is essential that we have the relevant information on the ecophysiological influences of abiotic and biotic stress on mycotoxin production by key spoilage fungi in the relevant grains. There is now an important body of information on fungi and mycotoxins which have or are being legislated on. This information is critical in accurately focusing and monitoring key critical control points in grain storage and processing to optimise prevention strategies at all stages in the feed and food chain.

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