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IMPACT OF GLOBAL WARMING ON MYCOTOXINS

Ángel Medina[a], Jesús M. González-Jartín[b], María J. Sainz[c,*]

[a]Applied Mycology Group, Cranfield Soil and AgriFood Institute, Cranfield University, Cranfield, Bedford MK43 0AL, UK
[b]Departamento de Farmacología, Facultad de Veterinaria, Universidad de Santiago de Compostela, 27002 Lugo, Spain
[c]Departamento de Producción Vegetal y Proyectos de Ingeniería, Facultad de Veterinaria, Universidad de Santiago de Compostela, 27002 Lugo, Spain

*Corresponding author: MJ Sainz (mj.sainz@usc.es)

Abstract

The large impacts of global warming projected on crops worldwide will subsequently influence not only food security, by reducing yields and thus food availability, but food and feed safety, mycotoxins being considered one of the most important food safety hazards affected by climate change.

Future changes in temperature, precipitation, and atmospheric CO_2 concentration are expected to carry along an increased risk of mycotoxin contamination of cereal crops in the field and might have an impact on the geographical distribution of certain cereals, mycotoxigenic fungi and their mycotoxins.

1. Introduction

Although political tensions are arising and trying to neglect clear evidence, global warming is a widely acknowledged fact. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [1], the Earth's climate has been through a period of global warming particularly since the mid-20th century, as shown by observed increases in global mean air and ocean temperatures, changes in the global water cycle, reductions in snow and ice, and the rising of global mean sea level. Anthropogenic greenhouse gas (GHG) emissions, which are now at their highest in history, have led to large increases in the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) that are considered the dominant cause that lies behind the global warming. Continued GHG emissions will probably cause further warming and drive long-lasting changes in the climate system, though the exact changes will vary regionally. More frequent heat waves and extreme temperature and precipitation events are expected in a number of regions. Further, under the scenario of highest emissions, annual mean precipitation will likely increase at high latitudes, many mid-latitude wet regions, and the equatorial Pacific, and decrease in many mid-latitude and subtropical dry regions, which will thus likely experience an increase in the frequency of droughts.

Agriculture is highly dependent on climate variability and extremes. Changes in climate are thus expected to have a strong impact on the productivity and quality of crop and livestock production systems [2], raising uncertainties about the provision of sufficient and safe food for the increasing world population in the 21st century. Crop productivity and quality will be affected by the impact of changing climate conditions not only on plants but also on pathogens causing pests and diseases, and on host-pathogen interactions [3]. With respect to food safety, one of the most important hazards likely affected by climate change will be the contamination by mycotoxins [4], which are secondary metabolites, harmful to both humans and animals, produced by filamentous fungi. The most important mycotoxigenic species are from the genera *Fusarium*, *Aspergillus* and *Penicillium*. *Fusarium* species colonise crops in the field, some of them causing severe diseases and other living endophytically, while *Aspergillus* and *Penicillium* species usually grow on cereals and other raw materials under inadequate conditions of drying and storage. An exception is *A. flavus*, which can be a pathogen or an endophyte in the field and a storage fungus. Almost all mycotoxins present in food and feeds are produced in the field [5]. Temperature, relative humidity, and water availability, together with insect attacks, are key factors that influence the infection of plants by mycotoxigenic fungi and the production of mycotoxins [6].

Some of these fungi exhibit a tremendous physiological plasticity which has contributed to their ability to adapt, and thus colonise, to a wide range of ecological niches including many staple foods, as cereals [7,8]. In fact, cereals are the main source of mycotoxin contamination in the human food chain, either directly through the consumption of contaminated food or indirectly through the intake of milk and other animal products obtained from livestock given contaminated feeds. Mycotoxins can be also found in grapes, coffee, cocoa, groundnuts, tree nuts, some fruits and other food commodities, and in animal feeds, as spoiled stored fodder (like silage), cereal by-products used in feed processing, etc.

We present an overview of the recent evidences of the impact of global warming, and other changes in climate, on mycotoxins, related to impacts on crops and mycotoxigenic fungi.

2. Worldwide climatic changes and their effects on agriculture

Numerous studies have investigated the impact of changes in temperature, precipitation and atmospheric CO_2 concentration on crop yields trying to anticipate future food availability [2,9]. The focus has been mainly on cereals, which are grown on about 42% of global cropland, and particularly on wheat, rice and maize, as they provide directly or indirectly about half the world's food energy intake [10]. The impacts of climate on crop production at low latitudes, populated by developing countries, will be likely consistent and negative, whereas they may be positive or negative in northern latitudes. In the case of wheat, rice, and maize crops, without CO_2 fertilization, effective adaptation, and genetic improvement, increased temperatures from climate change will negatively affect production at the global scale, although varying for crops and regions [1,11].

Extreme weather events may be the principle immediate threat to global crop production and food security [1,12]. In this respect, Powell and Reinhard [13] recently reported that the number of extreme high temperature and extreme precipitation events is increasing in The Netherlands, resulting in a significantly decrease yields of winter wheat.

Global warming and changes in rainfall amount and distribution will probably bring about shifts in the onset and length of growing seasons [14] and in the geographical range of certain crops. In Europe, advancements of sowing date, flowering and maturity of cereals by 1-3 weeks have been projected in response to global warming for 2031-2050, the changes being largest in northern Europe [15. Poleward areas in Asia, Europe and North America are projected to exhibit an increase climatic suitability for maize production, while a decrease suitability in South America, Africa and Oceania [16].

Within Europe, some crops prevalent in southern regions, due to their temperature requirements, could become viable and productive further north and at higher altitude [17].

3. Global warming and expected effects on mycotoxigenic fungi and on mycotoxin contamination in food and feed

Most countries have regulations that limit the presence of the mycotoxins most frequently detected in products intended for human consumption, namely aflatoxins (AFB_1, B_2, G_1, G_2, M_1), ochratoxin A (OTA), trichothecenes (deoxynivalenol (DON), diacetoxyscirpenol, HT-2 andT-2 toxins,), zearalenone (ZEN), and fumonisins (FB_1 to B_3) [18]. Aflatoxins and OTA are produced by *Aspergillus* and *Penicillium* species, and trichothecenes, ZEN and fumonisins by *Fusarium*. The highest acute and chronic toxicity in humans and animals is produced by aflatoxins, especially the most predominant AFB_1, which is a human carcinogen.

Quantitative estimations of the effects of global warming on mycotoxin contamination has been done on DON risk on wheat in northwestern Europe [19], and on AFB_1 risk in maize and wheat cultivated in Europe [5], revealing that increased contamination of wheat grains with DON and maize kernels with AFB_1 is expected as a result of future climate.

In recent years, the so-called emerging toxins, including enniatins, beauvericin, fusaproliferin and moniliformin, all mainly produced on cereal crops by *Fusarium* species, are receiving increasing attention as some of them are present in high concentrations in food and feed and their toxic effect is starting to be known [20]. Another important issue, that is gaining high attention by the scientific community and by governments and regulators recently, is the relationship between quantifiable "free mycotoxins" (the basic mycotoxin structures formed by fungi), and the "modified mycotoxins", which are conjugated forms of *Fusarium* toxins formed in the plant or fungus, and the "matrix-associated mycotoxins", which can be covalently or non-covalently attached to certain molecules which in turn make them invisible under current routine and conventional analytical methods [21,22,23]. From our knowledge, there are no research efforts to examine how global warming, and all climatic changes related, will influence the production of these compounds. Since their discovery more and more information is available about their relative potency in comparison with the original free toxins [24]. A special case that needs mentioning would be that of α-zearalenol, α- zearalenolGlcs and α- zearalenolSulfs that, in a recent EFSA opinion, have been identified as having a relative potency factor (RPF) of 60 when compared with free ZEN (e.g. 1 mole of α- zearalenol is equivalent in oestrogenicity to 60 moles of ZEN) [25]. Research is thus needed to study whether these changes will lead to variations on the relative amount of free, modified and matrix-associated mycotoxins in food and feed raw materials. This, in turn, may lead to the need of requiring more detailed analyses to evaluate exposure in the near future.

Global warming, and associated changes in climate, will likely lead to crops being subjected to an increased number of biotic and abiotic stress combinations. The most evident abiotic stress combination under a scenario of global warming is the concurrent occurrence of drought and heat stress. Combined they exacerbate one another and can have variable effects on the interactions between crops and fungal pathogens and endophytes depending on: the severity and duration of the stress, the crop developmental stage, the plant response to stress by altering plant physiology and defense responses, or the impact of environmental stress on the survival, spread, pathogenicity and growth of the fungal species involved [17,26,27]. A very good example for these effects was observed for forage maize in northern Italy during the 2003, 2004 and subsequently in the 2012 summer seasons. Prolonged drought conditions and extreme elevated temperatures (> 35 ºC) resulted in stressed maize plants that were more prone to fungal infections. The conditions were conducive for a switch from *F. verticillioides* and contamination with fumonisins to significant contamination of maize grain with *A. flavus* and aflatoxins, with later entry of aflatoxin M_1 into milk via the animal feed chain. This had extremely pernicious economic effects on the cheese-making industry that was forced to import maize to feed the cattle [28].

The global increase in temperatures is slowly but steadily shaping the relationship between plant growth and the associated fungal diseases, and also modifying and shaping current and future pest populations. The presence of certain crop pests has been directly correlated with the higher incidence of damage and hence higher contamination with mycotoxins. Bebber et al. [29] suggested that, on a global scale, pests and diseases are moving towards the poles at the rate of 3-5 km/year. Although in this modeling approach no mycotoxigenic fungal species were included, it can be inferred that increases in pest reproduction rates would increase damage to ripening crops (during anthesis in wheat, and silking in maize) and facilitate more infection by mycotoxigenic fungi and contamination with mycotoxins [30,31]. Thus, global warming could even further indirectly contribute to the increase in mycotoxins contamination.

Mycotoxigenic fungi have their own requirements of temperature and humidity for crop infection, mycotoxin production and survival, which reflects their geographical distribution and determines a gradient of mycotoxin contamination worldwide [19]. Some species might shift their geographical distribution in response to global warming, leading to changes in the pattern of mycotoxin occurrence. Some recent results support this hypothesis. **Battilani et al.** [5] predicted that, within the next 100 years, aflatoxin B_1 will become a food safety issue in maize in Eastern Europe, Balkan Peninsula and the Mediterranean regions, especially under a +2 °C scenario. This would be related to the geographical shift of *A. flavus*, which grows well under warm and dry weather and would move from southern Europe, where those environmental conditions can now sometimes be met, to more northern and eastern regions below the 45° North latitude.

4. Recent findings with regard to global warming and GHG on mycotoxin production

To date only few studies have tried to identify the effects that global warming and GHG will have on mycotoxin accumulation and examined effects on the plant, fungal infection. Vaughan et al. [32] investigated the impact of elevated CO_2 on the interactions between maize and *F. verticillioides*, which produces fumonisins. Increments in GHG emissions like CO_2 to approx. 800 ppm CO_2 (approx. 2 x current CO_2) increased maize susceptibility to *F. verticillioides* colonisation. Interestingly, fumonisin B_1 production was unaffected by these interactions. Similarly, increased disease levels were also reported for Fusarium head blight caused by *F. graminearum* in wheat when CO_2 was doubled [33]. More recently, Bencze et al. [34] studied the effect of elevated CO_2 (750 ppm CO_2) on the resistance of wheat to *F. culmorum* and on the mycotoxin contamination of the grains. Their results indicate that changes in temperature and atmospheric CO_2 may enhance the risk of conditions favoring *Fusarium* infection and higher mycotoxin contamination under favorable conditions.

Medina et al. [35,36] studied the impact of climate change scenarios, including increases in global temperature, drought stress and CO_2 concentration, on growth and AFB_1 production by *A. flavus* (NRRL type strain) on maize-based media and subsequently on stored maize grain. While fungal growth was practically unaffected, the environmental interacting conditions had an intense stimulatory effect on AFB_1 production (70 x the control in *in vitro* studies), especially under drought stress at 37°C and 650 and 1000 ppm CO_2 exposure. With the aim to have a deep understanding on how these environmental fluctuations are regulating the synthesis of mycotoxins, Medina et al. [37] used a transcriptomic approach and examined the impact of water activity (a_w) and temperature interactions on the overall up and down regulation of genes. Important regulatory shifts were detected for some of the identified secondary metabolite gene clusters (aflatoxin, cyclopiazonic acid), universal regulators, sugar transporters, and other stress-related pathways. These are indicative of changes in relation to the three-way interaction between climate change factors. It is important to identify whether any switches in biosynthetic pathways may occur resulting in other secondary metabolites being produced rather than aflatoxins or cyclopiazonic acid by *A. flavus* under such environmental stresses. A very recent work from the same team has examined the impact that interactions between the three factors: global warming (increased temperature), drought episodes (water activity) and GHG emissions (increased CO_2; 2x and 3x current) have on mycotoxin accumulation in maize kernels (Gilbert et al., unpublished) . The results point out that increased CO_2 mediates the response to temperature and a_w allowing for an increase in the toxin accumulated under stress conditions.

5. Conclusions

Mycotoxins are unavoidable naturally occurring compounds in the field because the fungi that produce them are common components of the epiphytic and endophytic microflora in staple crops. As a result of global warming and other changes in climate, some crops, such as maize, and mycotoxigenic fungi, as *A. flavus*, might change their geographic distribution, which would determine a greater presence of the mycotoxins they produce in other latitudes. Global warming and drought conditions could also favour the infection of crops by *A. flavus* in certain regions, and increase the risk of aflatoxin formation in the field. Elevated CO_2 levels are likely to further contribute to increased mycotoxin production in crops infected by *Aspergillus* and *Fusarium* species, by enhancing fungal colonisation.

Recent quantitative estimations have shown that increased DON and aflatoxin B_1 contamination are expected in cereals in certain regions of Europe as a result of global warming. Similar research is needed for other regulated, and also not regulated, mycotoxins, and in other crops and countries, in order to have a complete view of the impact of global warming on the mycotoxin risk of food and feeds worldwide.

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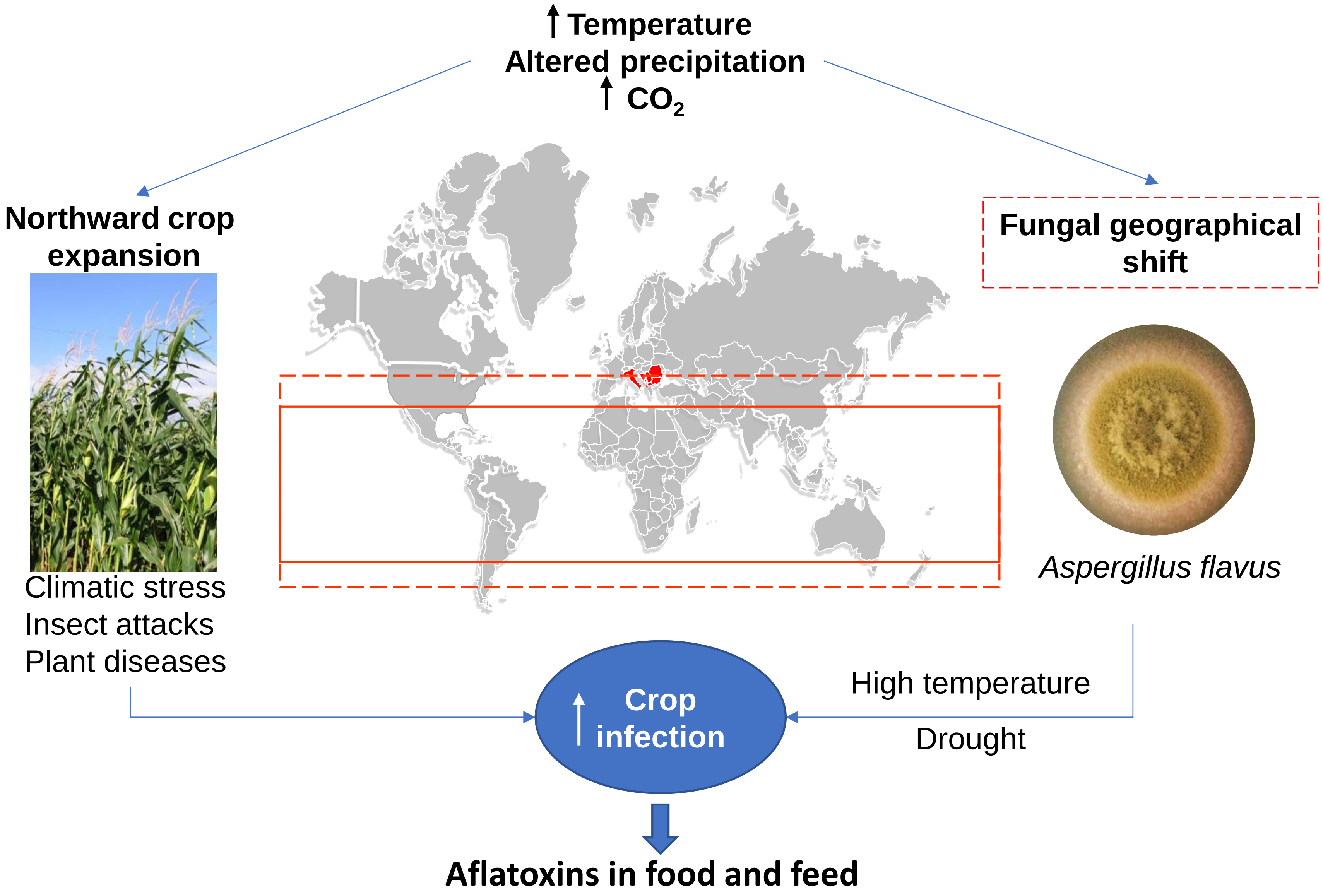
Figure legend

Impacts of global warming, altered precipitation and increase in atmospheric CO_2 concentration on geographical expansion of some crops (e.g. maize) and mycotoxigenic fungi, as *Aspergillus flavus*, as well as on plant-pathogen interactions and mycotoxin production. In red, recent outbreaks of *A. flavus* in unexpected regions: in northern Italy in 2003 and in 2008, and in Balkan regions in 2013 [19]. Red rectangle: world area with perennial contamination risk. Red dotted lines delimit expected expansion of aflatoxin contamination risk due to global warning.



↑ Temperature
Altered precipitation
↑ CO_2

Northward crop expansion

Climatic stress
Insect attacks
Plant diseases

Fungal geographical shift

Aspergillus flavus

High temperature
Drought

↑ Crop infection

Aflatoxins in food and feed

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Ángel Medina[a], Jesús M. González-Jartín[b], María J. Sainz[c,*]

[a]Applied Mycology Group, Cranfield Soil and AgriFood Institute, Cranfield University, Cranfield, Bedford MK43 0AL, UK
[b]Departamento de Farmacología, Facultad de Veterinaria, Universidad de Santiago de Compostela, 27002 Lugo, Spain
[c]Departamento de Producción Vegetal y Proyectos de Ingeniería, Facultad de Veterinaria, Universidad de Santiago de Compostela, 27002 Lugo, Spain

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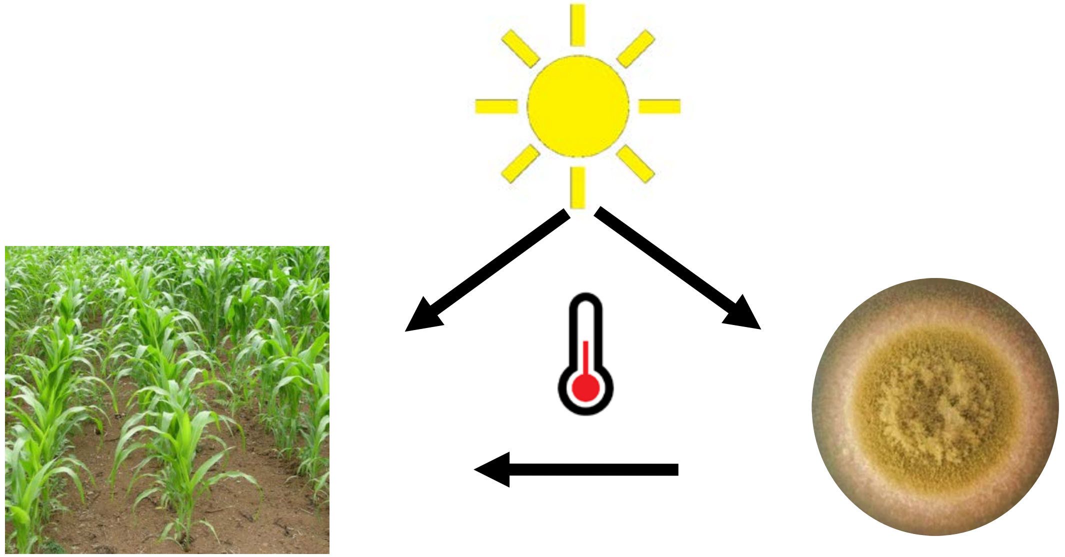
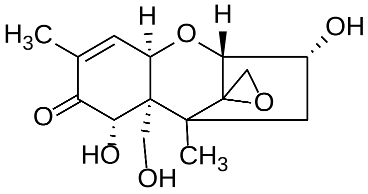
Highlights

- Global warming may affect the geographical distribution of mycotoxigenic fungi.
- Crop colonisation by mycotoxigenic fungi can be enhanced by elevated CO_2 levels.
- Higher temperature and drought will make *A. flavus* move northwards in Europe.
- Aflatoxin risk in maize will be likely higher as a result of global warming.





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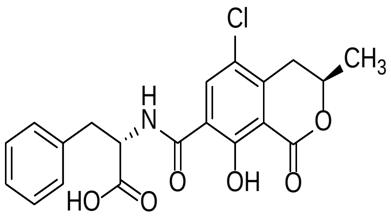

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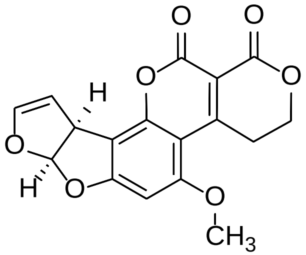

Aflatoxin B_1

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