Review article

A review: Aflatoxins: toxicity and consumer health

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Abstract

Aspergillus flavus and *Aspergillus parasiticus* are fungi that produce aflatoxins, which are harmful mycotoxins. When humidity and temperature conditions are not properly controlled, these fungi can grow on a variety of agricultural products, either before harvest or during storage. Aflatoxin contamination is a significant concern for crops such as maize, corn, grains, and dried chilies.

Cancer is one of the most serious illnesses associated with aflatoxin exposure, as aflatoxins are potent carcinogens and have been linked to liver cancer cases in many countries where exposure is common. In addition to their carcinogenic effects, aflatoxins can also weaken the immune system. Dietary exposure to aflatoxins can have both immunosuppressive and carcinogenic effects, with the severity depending on factors such as immune function, nutritional status, overall health, and the duration and amount of exposure. Aflatoxins have caused illness and death in various parts of the world.

Although regulations have reduced exposure in many countries, aflatoxins continue to accumulate and negatively impact health in regions with warm climates that favor their growth. Reducing the presence of these toxic mycotoxins-through proper drying, storage, agricultural practices, or detoxification methods that break down their chemical structure-is essential for preserving food commodities and ensuring global food security.

This study focuses on the aflatoxin contamination situation in Thailand, where the warm and humid climate creates ideal conditions for mold growth, leading to significant health risks and food safety challenges.

Keywords: Aflatoxins, health, toxicity

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Introduction

Aflatoxin is a potent carcinogenic compound, "It is mostly produced by Aspergillus flavus and Aspergillus parasiticus." (Wang, 2023; Shabeer, 2022) This is because of their stability, they are difficult to remove completely, even under extreme conditions. One of the most hazardous substances known to biology, aflatoxin primarily affects the liver tissues of humans and animals. Aflatoxin can cause cancer in the liver, pancreas, kidney, bladder, and other organs (Wang, 2023). Aflatoxins interfere with the erratic behaviour of the cells that enhance immunity, suppressing the immune systems of both people and animals. Its buildup causes liver cancer, but small, long-term dosages of the toxin have immunological or nutritional benefits. Large concentrations of the toxin cause direct mortality and damage (Cruz, 2012). Additionally, aflatoxin was the cause of many outbreaks in India and other African countries. Because there are less food regulating acts in emerging and developing countries, the outbreak's situation is worse abroad (Cruz, 2012). The ideal temperature range for aflatoxin production is between 28 and 30 degrees Celsius, although it can be formed between 12 to 40 degrees Celsius with a high moisture content.

"Aflatoxin generates significant consequences on the health of humans and animals and contaminates several crops, including cotton, peanuts, maize, and chillies." (Table 1.) (Shabeer, 2022) The primary sources of aflatoxin contamination are grain and oil crops and feed, nuts, Chinese herbal products, and other crops. Once animals have consumed aflatoxin-contaminated feed, the metabolite aflatoxin M1, which is present in the milk of those animals, can also contaminate meat, eggs, and other by-products (Wang, 2020). Aflatoxins are frequently found in peanuts, and if the right circumstances are present for mold growth, contamination can happen both during the growing season and during storage.

Aflatoxin that contaminates in food in Thailand: "For all Thai foods and food products examined, 1,248 samples (38.9%) with aflatoxin contamination are summarised. The highest contamination rate was found in peanuts (36% of all contaminated foods), followed by milk (20.7%) and poultry (17.5%)." (Table 2.) (Chupia, 2022)

Aflatoxin Producers

There are more than 20 types of aflatoxin molecules, although the most prominent are aflatoxins B1 (AFB1), B2 (AFB2), G1 (AFG1), G2 (AFG2), M1 (AFM1), and M2 (AFM2) (figure 1.) (Ismail,2018). Aflatoxin M1 is a metabolite of Aflatoxin B1 and is found in the milk of animals that have consumed contaminated feed (Shabeer, 2022). The exact structure and substituents can vary among different aflatoxins (B1, B2, G1, G2, M1, M2), and they are designated based on these structural differences. The variations in structure among aflatoxins contribute to differences in their toxicity and biochemical properties. Aflatoxin B1 (AFB1) was listed as one of the strongest carcinogens by the IARC because of its highly toxic, teratogenic, carcinogenic, and mutagenic effects Aflatoxin B1 is the most toxic and is the most commonly found aflatoxin in contaminated foods (Ismail, 2018).

Aflatoxin has been found in Thai dried chili: "Fungal contamination was detected in 86.7% (n = 52) and 96.7% (n = 58) of dried chili powder and dried chili pods, respectively. Fungal contamination levels in dried chili powder ranged from 1 × 102 to 3.68 × 102 CFU/g." Thai dried chili consists of Aspergillus section Flavi, Aspergillus section Nigri, Aspergillus section Circumdati, Aspergillus section Aspergillus, Penicillium and Rhizopus (Figure 2.) (IARC, 2019).

Moreover, aflatoxin is also found in brown and colour rice: The study assessed the aflatoxin B1 (AFB1) intake of the Thai population through consumption of contaminated brown and colour rice (Chuaysrinule, 2020). And also found in corn: "Thailand 223 samples from 2 types of corn residue - dried and wet - were collected. Mold contamination was determined by spread plate technique, and aflatoxin B1 (AFB1) quantification was performed by a commercial enzyme-linked immunosorbent assay." (Panrapee, 2016). In conclusion, aflatoxins are a group of naturally occurring toxins produced by moulds, primarily Aspergillus flavus and Aspergillus parasiticus. These toxins can contaminate dried chilli, rice, corn etc. The presence of aflatoxins in food is a global concern, particularly in regions with warm and humid climates like Thailand that favour mould growth. Chronic exposure to aflatoxins has been linked to liver cancer and other health issues. Public awareness and collaboration among researchers, farmers, and regulatory bodies are essential components of a comprehensive approach to address the challenges associated with aflatoxins in the food supply.

The regulation of aflatoxin

AflatoxinM1 has a similarity among the physicochemical properties with cholesterol so in food industry elimination of cholesterol using β-cyclodextrin and β-cyclodextrin can use without any substantial effect so in the investigate it use β-cyclodextrin to test that can be eliminate aflatoxinM1. AflatoxinM1 levels in milk samples ranged from 0.20 to 2.00 µg/kg. Cholesterol was removed using 2.0% (w/w) β-cyclodextrin, which is an effective concentration for cholesterol removal. The cholesterol decreases by 92.3%, while aflatoxinM1 decreases to 0.53 ± 0.04 µg/kg. From the above data it is easy and inexpensive to eliminate aflatoxin in milk so β-cyclodextrin can improve the food safety that is associated with aflatoxin M1 in milk and dairy products (Šimko, 2022). Aflatoxin detoxification occurs by degradation of its structure using oxidisation, hydrolase or thermal treatment. Mohammadi et al., observed aflatoxinM1 detoxification in milk using ozonation. An ozonation of aflatoxin contaminated wheat led to 95% detoxification. Rastegar et al., observed removal of aflatoxin by roasting with lemon juice. The lab showed 93.1% decrease in aflatoxinB1(Nazhand, 2020). AflatoxinM1 can be detoxified by heat-treated L. plantarum KM. Because AflatoxinM1 molecules are physically attached to bacterial cell component polysaccharides and peptidoglycans. Moreover, heat treatment can increase the attachment surface. The test took 150 LAB colonies cultivated on MRS agar and identified them based on morphology. Each bacterial strain the cells were harvested by centrifugation under aseptic conditions at room temperature, then washed 3 times with 5 ml of sterile deionized water then and divided in two groups. First group contained viable cells and the second group cells heated in a water bath at 100° C. The report shows heat-treated cells can bind AflatoxinM1. So, our most efficient AflatoxinM1 consists of refrigeration at 4°C with heat-treated L. plantarum KM then centrifugation and filtering we can see over 95 % removal of AFM1 from contaminated milk (Kuharić, 2018).

In 2014 A&M AgriLife Research launched Aflatoxin Proficiency Testing and control in Africa, is the quality systems approach to manage aflatoxin. Texas A&M AgriLife Research introduced this Aflatoxin test. This test can improve food safety for approximately 10 million Kenyans. This test was accredited by the Kenya Accreditation Service in 2014 and 2015. In 2015 the program had 15 maize mills. The test has 7 samples, which ranged from 3.1 to 28 µg/kg. resulted in average relative standard deviation of 19.2%. After analysis, implementation of the quality illustrated and improvement in measure accuracy (Herrman, 2020). Food additives are substances normally not used in food or essential ingredients of food whether such substances have food value; these are added for benefits of production. But sometimes it can be a weakness. Because of this ingredient it can have a bacteria or fungus, so it causes disease or aflatoxin.

The tolerance and max residue limits level that is allowed is set for toxic substances under the Notification of Ministry of Agriculture. According to Ministerial Notification No. 98 of B.E. 2529 and Ministerial Notification No. 273 of B.E. 2003. Food must not contain more than the following specifications.

In this table the maximum of aflatoxin in food must not contain more than 20 ppb (USDA, 2019). Countries with warmer climates that can produce aflatoxin in food resulting in frequent Aflatoxin contaminated in food. Another factor is improper storage conditions and a lack of regulation. With these factors it is so hard to control aflatoxin contamination but Pakistan has a warm climate and another factor to produce Aflatoxin can be controlled. Because Pakistan uses AflaPakTM to control Aflatoxin, it is being developed. After the test the Aflatoxin36 does not produce AFs due to a SNP stop codon in the key gene. The basic principle is dry grains to reduce moisture content and to maintain this dryness this strategy is adapted by Cotty and Bayman that use Aflatoxin occurring non-aflatoxigenic strains seedling in the soil before planting. It can help prevent AF contamination during later storage after that has been subsequently employed for the control of Aflatoxin around the world (Ajmal, 2022). Aflatoxins have remained a persistent food safety issue. Therefore countries, regions, and international agencies enacted regulations to limit the aflatoxin levels in food and feed. Aflatoxin regulations are formulated by an assessment model that developed specialised national and multilateral agencies. Different countries have risk data and approaches with these factors between countries must have different aflatoxin regulatory limits (USDA, 2019). According to Figure 3.

Toxicity of Aflatoxin

Aflatoxins are metabolites produced by toxigenic strains of moulds, mainly Aspergillus flavus and A. parasiticus. Intakes of aflatoxin have been highly associated with liver cancer but it can also have effects on other organs such as kidney, pancreas, bladder, bone, viscera, and more, which can ultimately develop cancer. Dietary exposure to aflatoxins can result in severe toxic and carcinogenic outcomes (in both humans and animals). The prognosis of aflatoxin toxicity depends on the dosage and duration of exposure, nutritional status, immunity, and health. Low doses exposure to aflatoxin may result in symptoms including nausea, vomiting, abdominal pain, convulsions, and other signs of acute liver injury such as bleeding, digestion problems, edema, malabsorption, mental changes, and coma (Dhakal, 2023; Benkerroum, 2020). Around 4.5 billion people, mostly children, in developing countries are exposed to large uncontrolled amounts of aflatoxin. These exposure to aflatoxin is associated with their growth stunting, developing delays, and liver damage which can lead to liver cancer. Studies show that adults have a higher tolerance to aflatoxin than children. 4.6% to 28.2% of all global cases of hepatocellular carcinoma (HCC) can be caused by aflatoxin and in which, 25% of all high-dose acute exposures may cause death. As of 2018, statistics show that 841,080 new cases of liver cancer caused 781,631 deaths which corresponds to an age-standardised incidence rate of 9.3 per 100,000 and mortality rate of 93% ranking as the fifth cancer type and the first cause of cancer-induced mortality. Africa and Asia are the leading continents in terms of new cases recorded each year, with 64,779 (7.7%) and 609,596 (72.0%) cases respectively, which represents about 80% of the total cases in the world. 25,200 to 155,000 cases of which are estimated to be caused from aflatoxin B1 alone.

Furthermore, the outbreak of aflatoxin in kenya in 2004 shows 317 cases with 125 deaths as well as Tanzania in 2016 shows 68 cases and a 30% fatality rate. Moreover, mortality rates in humans are estimated to be between 27% and 60% (Gilbert-Sandova, 2020). Many researches have been conducted regarding the effects of aflatoxin toxicity in rats and humans. A research conducted by Ixchel Gilbert-Sandoval, Sebastiaan Wesseling, and Ivonne M. C. M. Rietjens shows the effect after acute exposure of high dose levels of AFB1 - which can cause symptoms similar to those being exposed to AFB1 in contaminated food (Benkerroum, 2020). Primary rats and 13 individual human liver samples hepatocytes, as well as HepaRG cells were used in this experiment. Cells of each subject have been seeded, preincubated and placed into serum free medium containing different concentrations of AFB1 from 0 to 50 µm for hepatocytes, and 0 to 100 µm for HepaRG. The experiments show that AFB1 cytotoxicity in fresh hepatocytes of both rats and humans are more sensitive than cryopreserved hepatocytes from rats and humans (Figure 4,5) (Gilbert-Sandova, 2020).

Dietary Exposure to Aflatoxins

Suggestions have been made that dose of AFB1 that could result in acute aflatoxicosis and have a risk in human fatality rate were estimated to be around 20-100 µg kg-1 bw per day for 1-3 weeks (Wild, 2010). As of now, acute aflatoxin currently has no known antidote but the removal of contaminated food as well as the replacement of uncontaminated food sources may help reduce or stop additional poisoning in communities. Once HCC develops, patients have a variety of treatment options to choose from such as surgery, radiotherapy, thermal ablation, orthotopic liver transplantation, and percutaneous alcohol injection (Dhakal, 2023). Moreover, aflatoxins are one of the biochemicals of mycotoxins. Although aflatoxins are non-toxic, they can be converted into highly toxic forms depending on the activation of enzymes such as cytochrome P-450 or UV light. Covalent bonding of aflatoxins to DNA and RNA can cause acute damage as it results in inhibition of replication, transcription, and protein synthesis which can lead to inactivation of enzymes. The damage of the DNA can initiate p53-dependent apoptosis or impair the progression of the cell cycle (Stark, 2005). Some of the mechanisms for detoxification of AFB1 includes fusion of AFB1-8-9-oxide with glutathione by glutathione-S-transferase, conversion of the adduct to mercapturic acid, and excretion as urine (Stark, 2005).

Toxicity and Impact on Consumer Health

Aflatoxin can have serious consequences for human health, particularly for the liver. It can result in liver damage, which may lead to the development of cancer and hepatocellular carcinoma (Dhakal, 2023). Acute toxicity can be fatal, which is the most devastating outcome. Chronic toxicity can result in impaired growth and development, particularly in children, immune system suppression, and hepatocellular carcinoma. The liver is the primary site of aflatoxin's impact on human health, causing injury and potentially leading to cancer and hepatocellular carcinoma (Dhakal, 2023). In the case of acute toxicity, death is unfortunately the most common outcome. Chronic toxicity can result in developmental delays, immune system suppression, and the development of hepatocellular carcinoma, particularly in children (Benkerroum, 2020).

Aflatoxin is one of the problems that can make the body's immune system worse (Hassan, 2019). The study showed that humans and animals can get harmed by Aflatoxin by making the body's immune system worse. Twenty-four hours after AFB1 treatment, BL intensity/intracellular ATP content substantially decreased in leukocytes, that is, herein in human, dog, and cattle neutrophils, lymphocytes, and monocytes (Figure 6). Human, dog, and cattle neutrophils, lymphocytes, and monocytes in both AFB1-treated and control groups were tested for caspase-3/7 activity using a carboxyfluorescein FLICA apoptosis detection kit. In contrast, caspase-7/3 activity increased significantly in post-AFB1-exposed neutrophils, lymphocytes, and monocytes of all three species. For this experiment, they did not compare the values of BL intensity (either ATP or caspases) among human, dog, and cattle samples (Figure 7) (Mehrzad, 2020). Aflatoxin can make the body's immune system worse, which leads to causing any symptoms in humans and animals.

The most common symptoms that can be found in humans caused by Aflatoxin, influence a person's cognitive abilities, memory, and learning, restlessness, muscular tremors, seizures, absentmindedness, tremors, uncoordinated movement of muscles, and aberrant agitation are caused by deficiencies in the neurotransmitters (Pratap,2022) or the worst case is having hepatocellular carcinoma, which have less ways to cure (Dhakal, 2023). There were many symptoms that had effects on humans and even animals, rabbits. Rabbits are studied as the most sensitive species for aflatoxin contamination (Mehrzad, 2020). The research and experiment by Ayman A. et al, showed that animals like rabbits can have any effect from afltoxin too. The test used Eighty-four male New Zealand White rabbits divided into 4 groups to evaluate the ability of sodium bentonite and coumarin in alleviating the toxicity of aflatoxin B1. The result shows that the rabbit in group while feeding aflatoxin-contaminated diet (AFL) caused necrosis of liver tissue and reduced the weight gain, average daily gain, feed conversion ratio, nutrient digestibility coefficients, and nitrogen balance of rabbits. Most symptoms that can be shown in rabbits are quite different from humans. The rabbits can be shown symptoms like, anorexia, diarrhoea, depression, reduced weight gains, and high mortality (Figure 8) (Hassan, 2019).

Another experiment with animals to prove that aflatoxin has effects on animals, the study used rats and were caged individually with saw dust bedding. The rats were acclimatized under standard laboratory conditions. All rats were given ad libitum access to food and water throughout the study period and the AFB1 was used for sucrose preference test. The positive control group: given chronic unpredictable mild stress (CUMS) to induce persisting stress-related behavioural changes according to protocol described by He et al. The dosages of AFB1 in this study were selected based on previous experiments conducted by Wang et al. and were relevant to AFB1 exposure in humans in developing countries. Body weight and food intake of rats from all groups were recorded. Body weight (b.w.) gain and average food intake of rats throughout AFB1 and CUMS exposure period are shown in Figures 9 A, B, respectively. In week 1, all groups had an increase of b.w. However, in week 2, 3, and 4, rats exposed to high-dose AFB1 and CUMS had reduction of food intake and experienced statistically significant ($p < 0.05$) weight loss compared to the control group. It can be said that the decrease in food intake led to loss of b.w. among rats exposed to AFB1 and CUMS. This showed not only CUMS had an impact on growth, but also AFB1 which exhibited a similar pattern (Subramaniam, 2022). The researches and tests showed aflatoxin has bad effects on human and animal bodies, such as making the immune system worse, not only the disease but also has a long-term effect on the body: have bad cognitive abilities, memory,and learning.

Aflatoxin Prevention

Recent innovation that can control mycotoxin. The growing consumer awareness of food safety and the need for new ways for managing mycotoxin contaminations, toxicity, and related disorders without harmful residues on foods, with low impact on quality has directed research into some innovative strategies of cold atmospheric plasma (CAP), polyphenols and flavonoids, magnetic materials and nanoparticles and natural essential oils (NEOs) (Figure 10.) (Hamad, 2023).

Another recent innovation, Pulsed Electric Fields (PEF) have been applied to food products for the purpose of inactivating fungi and their mycotoxins, especially the removal of aflatoxin B1 and G1 produced by Aspergillus (Gavahian, 2020). In another study, PEF was classified as one of the most capable and cost-effective new food processing processes for the detoxification of aflatoxins, fumonisins, zearalenone, OTA, and trichothecenes in foods, but specific food-target assessment prior to integration in the food industry was recommended (Nunes, 2021). The decrease of Aflatoxin B1 in corn by water-assisted microwave treatment (WMT) has also been investigated. The NEOs also demonstrated advantages in terms of environmental friendliness and efficiency, but their effectiveness may be impaired by low bioavailability, high volatility, oxidative instability, and solubility. Magnetic particles and nanoparticles have enormous potential in several parts of the food, agriculture, and animal industries, and their adsorbent capability on mycotoxins is an excellent addition, but like the phytochemical inhibitors, application is still at infancy. The antifungal mechanisms of these techniques are still not completely known, and there is a lack of understanding of their potential side effects, especially for magnetic materials and nanoparticles and this may limit their full potential and applications. The approaches of detoxification and their ability to preserve nutritional and organoleptic features, as well as toxicity studies of the leftover components, need thorough investigation in order to prevent food contamination (Hamad, 2023).

Conclusion

Aflatoxins are a vigorous carcinogenic compound to humans and have high possibility to result in cancer including liver cancer which is a common form. Aflatoxins contamination in crops and grains. The toxicity depends on the dosage and duration of exposure and your immune system. Aflatoxins accumulate mainly in countries with warmer climates and according to statistical analyses, the outbreak of aflatoxins has increased mortality rates across many countries. Considerable research has been conducted regarding the effects of aflatoxin toxicity and has found that aflatoxins can be detoxified by degrading its structure using oxidation, hydrolase, or through thermal treatment. Currently, methods for controlling aflatoxins around the world include drying grains to reduce moisture content, which is one of the contributing factors of aflatoxin contamination.

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Table 1: Source and contamination of Aflatoxin in food crop (Wang, 2020)

Toxin	Fungus	Susceptible Crop(s)
aflatoxins	*Aspergillus* spp.	peanut, soybean, maize, etc. [41]
zearalenones	*Fusarium* spp.	wheat, oats, etc. [42]
ochratoxins	*Aspergillus* spp. *Penicillium* spp.	wheat, maize, rice, soybean, etc. [43]
trichothecenes	*Fusarium* spp.	wheat, oats, maize, etc. [44]
fumonisins	*Fusarium* spp.	maize [45]

Table 2: Aflatoxin contamination of food and food products in Thailand, by type of food, season and geographical area, 1967-2001. (Chupia, 2022)

Parameters	No. of samples	No. of contaminated samples	Chi-square test
Types of food			
Rice	456	13	
Peanuts	877	451	
Corn	174	77	
Soybean and other beans	402	21	p< 0.05
Milk	270	258	
Spices	258	22	
Poultry	450	219	
Dried seafood	319	187	
Season			
Summer (Mar–May)	980	97	
Rainy (Jul- Sep)	956	179	p<0.05
Winter (Nov-Jan)	693	156	
Geographical areas			
Northwest	433	47	
Central	803	80	
West	128	10	
Northeast	308	30	p>0.05
Southwest	231	18	
South	227	22	
East	49	5	

Table 3: Food shall not contain contaminants with more than the following specifications (Herrman, 2020).

1. Metal		
Tin	250	mg/kg
Zinc	100	mg/kg
Copper	20	mg/kg
Lead	1	mg/kg with the exception for foods that contain high amount of natural lead. Such foods shall seek the approval from FDA.
Inorganic Arsenic	2	mg/kg for fish and seafood
Total Arsenic	2	mg/kg for other foods
Mercury	0.5	mg/kg for seafood and not more than 0.02 mg/kg for other foods
2. Aflatoxin	20	ppb
3. Other contaminants shall be subjected to FDA approval.		

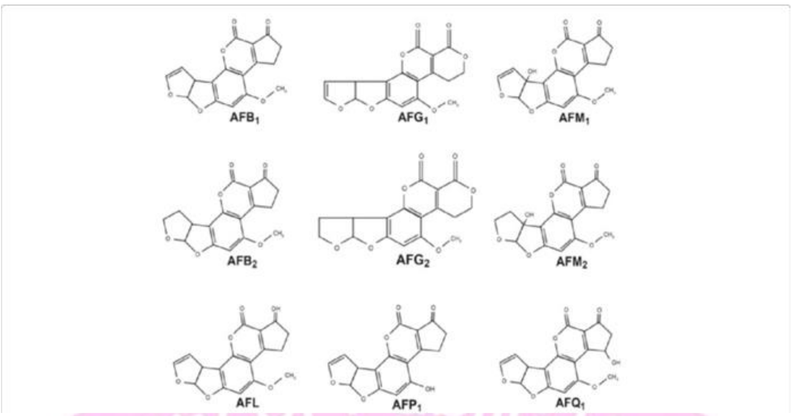

Figure 1: different structures of aflatoxin (Stephania, 2018).

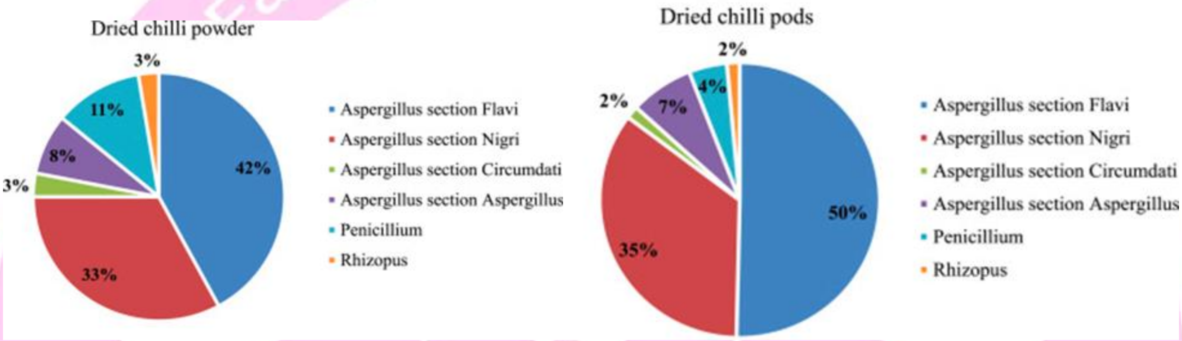

Figure 2: Incidence of contamination by Aspergillus and Penicillium spp. in dried chilli powder and dried chilli pods in Thailand. (IARC, 2019)

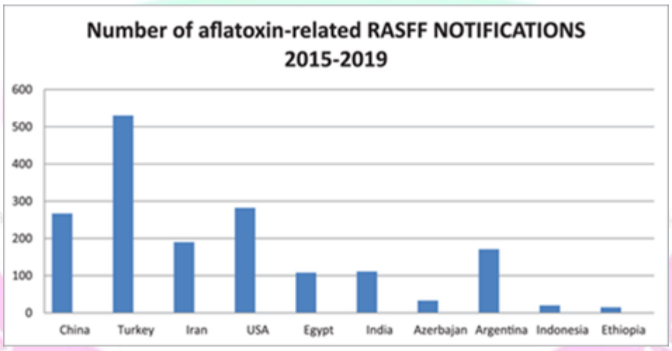

Figure 3: Number of aflatoxin-related RASS notifications of the 10 countries from 2015 to 2019 (Jallow, 2021).

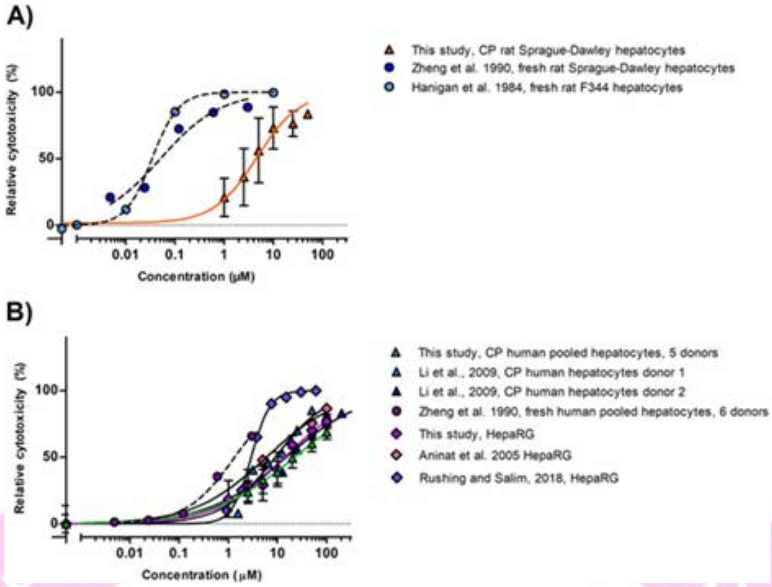

Figure 4. Concentration response curves for the cytotoxicity of AFB1 (μM) in A) rat and B) human cell models upon 24 h exposure in medium without serum (mean values + SD) (Gilbert-Sandova, 2020).

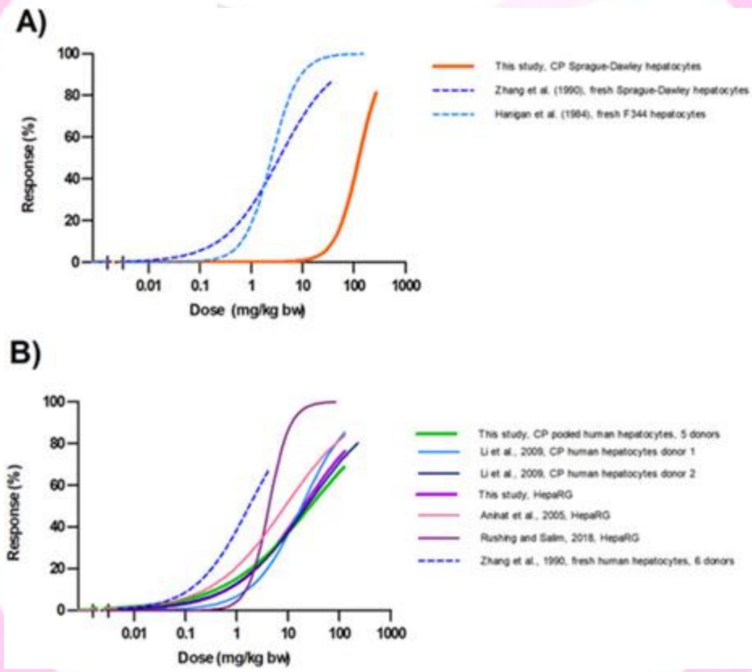

Figure 5. Predicted in vivo dose–response curves for acute liver toxicity of aflatoxin B1 in A) male rat and B) human obtained by PBK modeling facilitated reverse dosimetry of the concentration response curves presented in Figure 4 (Gilbert-Sandova, 2020).

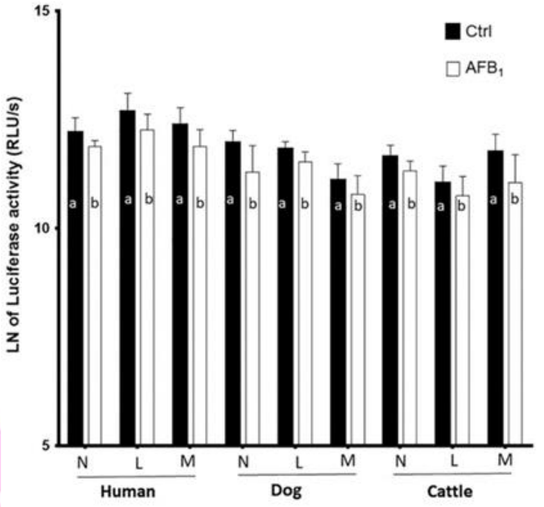

Figure 6. Changes in adenosine triphosphate (ATP) quantity of human, dogs, and cattle neutrophils (N), lymphocytes (L), and monocytes (M) caused by naturally occurring level of aflatoxin (AF) B1 exposure (Mehrzad, 2020).

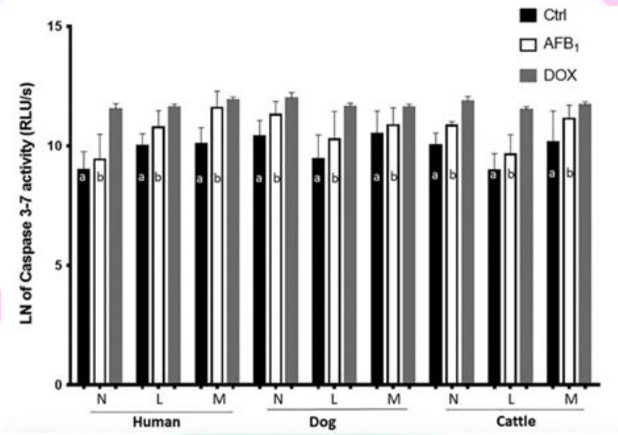

Figure 7. Changes in caspase-3/7 activity of human, dogs, and cattle neutrophils, lymphocytes, and monocytes caused by naturally occurring levels of aflatoxin (AF) B1 exposure (Mehrzad, 2020).

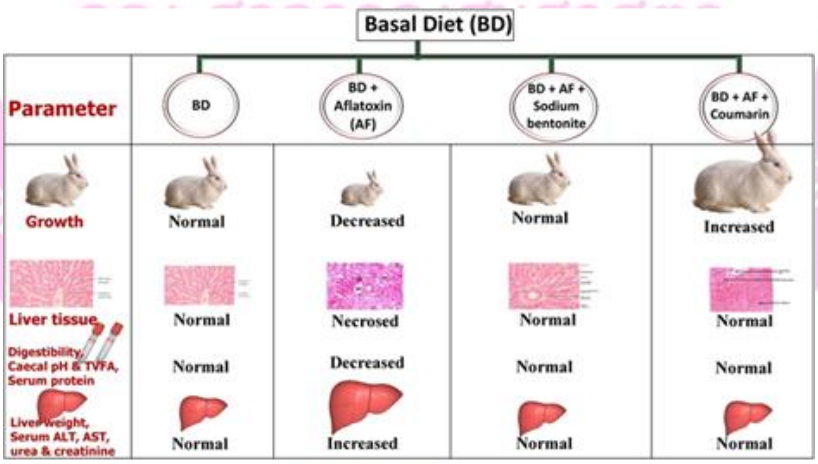

Figure 8. First groups were fed on a diet without any treatment (CON), while the remaining three diets were added with aflatoxin B1 at 0.25 ppm diet. Diet fed to the third and fourth group of rabbits were further supplemented with sodium bentonite at 5 g/kg (SOB) and coumarin at 5 g/kg (COU) of the diet, respectively (Hassan, 2019)

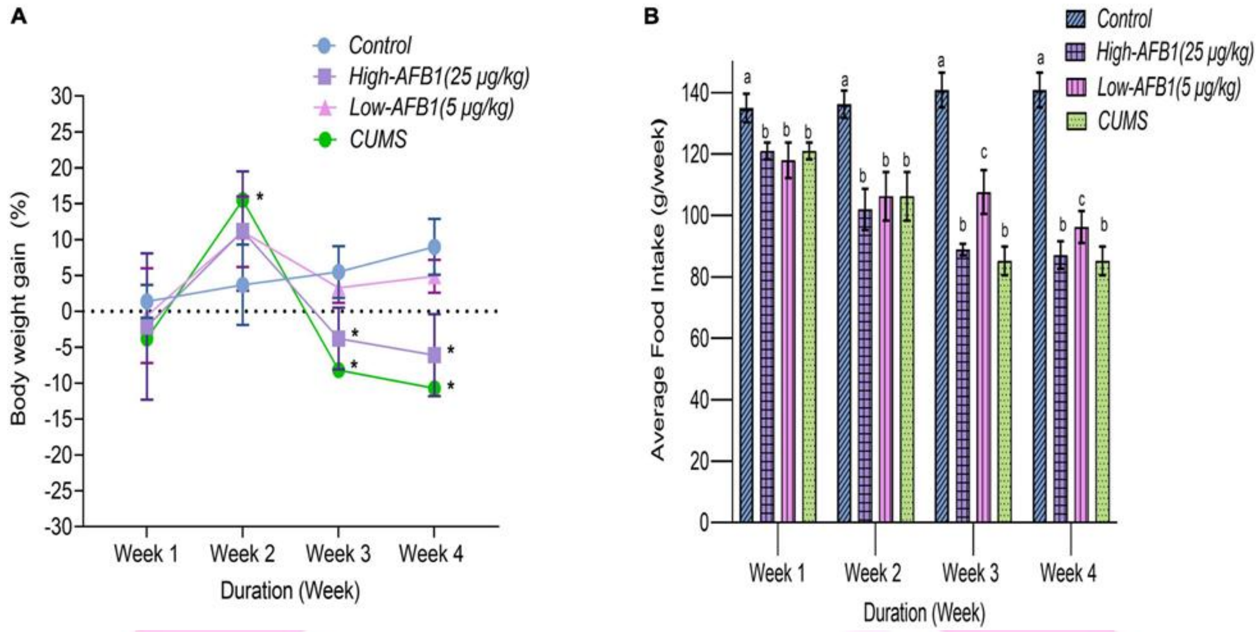

Figure 9. Percentage of body weight gain (A) and average food intake in grams per week (B) of rats from four different groups during the treatment periods; Week 1 to 4 (n = 8) (Subramaniam, 2022).

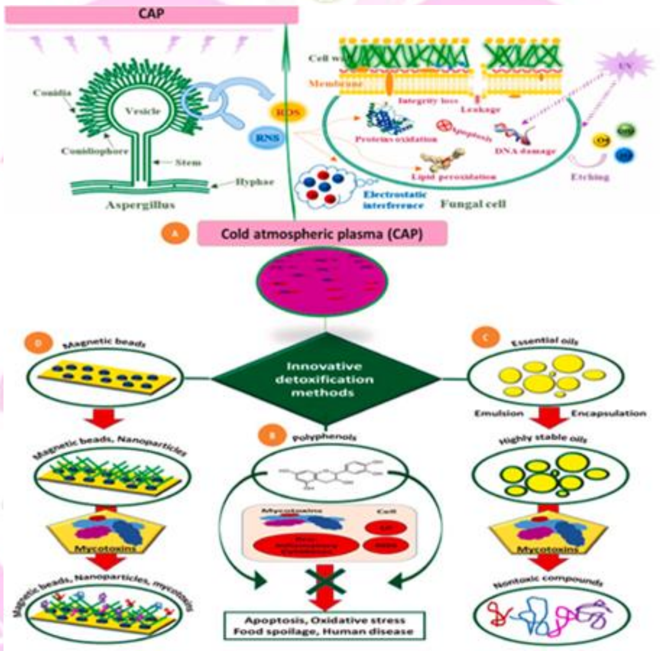

Figure 10. Innovative strategies for controlling mycotoxin contamination in the foods and their underlying mechanisms i.e., (A) cold plasma (Adapted) (Wu, 2021), (B) polyphenols, (C) natural essential oils and (D) magnetic and nanoparticles (Hamad, 2023)