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An insight into mycotoxins decontamination from corn and corn-based products: an updated review of methods, challenges, and perspectives

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REVIEW ARTICLE

Abstract

Corn is a vital cereal consumed globally because of its rich nutritional value. However, corn grains are prone to contamination with numerous mycotoxin-producing fungi from farm to fork. Mycotoxins are secondary metabolites that severely threaten the human health and lead to economic loss of the grain industry. Various techniques are applied at different stages after harvesting corn to remove or degrade mycotoxins. The decontamination techniques are categorized into physical (cold plasma, irradiation, and microwave), chemical (ozone, chlorine dioxide, and ammonia), and biological methods (non-toxigenic strains, lactic acid bacteria, and enzymes). These techniques have varied efficiencies for the degradation of mycotoxins from corn or corn-based products. The decontamination technologies are selected based on the maximum reduction of mycotoxins and minimum effect on corn's nutritional and bioactive properties. This review addressed the role of corn-based products in human health, mycotoxin contamination, and decontamination techniques, challenges, and possible approaches. Researchers are in the process of developing and optimizing new decontamination techniques that might reduce toxigenic fungi or mycotoxins from corn without adversely affecting corn-based products.

Keywords: aflatoxin; fumonisin; contamination; human health; cold plasma; metabolites

Introduction

Corn, also known as maize, is a cereal crop cultivated globally with agricultural and economic importance and represents a primary food crop for human nutrition (An *et al.*, 2023; Siyuan *et al.*, 2018). Corn is a staple food of some Asia, African, and Latin American countries (Guzzon *et al.*, 2021). It is commonly consumed as corn kernel and corn on the cob, and various products are prepared alone or combined with other ingredients globally (Palacios-Rojas *et al.*, 2020). The color of corn kernels varies depending on the cultivar type, such as yellow, red, white, and purple (Salvador-Reyes *et al.*, 2021). Corn is cultivated in different geographical regions depending on cultivar and environmental conditions (Baum *et al.*, 2020). The size and color of corn determine its quality and marketability for its use in different foods (Mutlu *et al.*, 2018). Owing to its versatility, it is used in various forms for human consumption and as an important ingredient for dairy and poultry feed industries (Deng *et al.*, 2023; Tanumihardjo *et al.*, 2020).

Corn grain is prone to microbial contamination at the field and during harvesting and storage (Mahuku *et al.*, 2019). The corn grain is affected by many fungi that produce metabolites under suitable environmental conditions (Dövényi-Nagy *et al.*, 2020; Matumba *et al.*, 2021). Contamination of corn grain by the accumulation of mycotoxins is a severe threat to human health (Kortei *et al.*, 2021). Corn is susceptible to contamination by numerous mycotoxigenic fungi, such as *Aspergillus, Fusarium*, and *Penicillium* (Mihalcea and Amariei 2022). These fungi produce different mycotoxins, including aflatoxins, fumonisins, trichothecenes, and zearalenone, in corn or corn-based products, which are harmful to human health (Tarazona *et al.*, 2020). Furthermore, mycotoxin contamination also leads to a significant loss in corn production as well as economical loss to crop growers (Chukwudi *et al.*, 2021). Legal consumer regulations for mycotoxins are established in many countries to protect consumers from the harmful effects of these compounds. Setting limits for mycotoxins involves many factors, such as toxicological data, occurrence data, knowledge about the sampling and analysis, and socioeconomic issues. In 2003, 100 countries had settled specific regulations for limit of mycotoxins in foods (Van Egmond *et al.*, 2007).

A significant risk associated with consuming corn and corn-based products is the presence of mycotoxins because they contain toxigenic fungi (Geary *et al.*, 2016). Therefore, decontamination of mycotoxins in corn is necessary because of several adverse effects on human health (Mir *et al.*, 2021). Several physical, chemical, and biological methods have been explored to decontaminate mycotoxins from corn and corn-based products (Table 1). Decontamination methods show different intensities for reducing mycotoxins from corn and corn products depending on concentration and processing conditions (Moosavi *et al.*, 2021; Schmidt *et al.*, 2019). Different methods are applied for decontamination, but only a few techniques have shown practical application in the corn industry. New technologies have significantly degraded mycotoxins in the last few decades and have shown promising results. This paper provides data to the scientific community regarding existing research, gaps, and future research needed on mycotoxin methods to be used for bulk grains at commercial scale. The paper highlights the decontamination methods effective for the degradation of mycotoxins and addresses the limitations and challenges related with the decontamination of corn. Therefore, this study provides an overview about corn's mycotoxins and different methods used for decontaminating corn and corn-based products.

Mycotoxins: a threat from corn farm to fork

Corn is cultivated and harvested throughout the year under diverse climatic conditions. The cultivation and harvesting procedures vary from one geographic region to another (Baum *et al.*, 2020). Climatic conditions, harvesting, transport, and storage conditions affect corn quality, which ultimately leads to the production of mycotoxin-producing fungi. Mycotoxins are known for high safety risks in food (Farhadi *et al.*, 2021). Mycotoxins are toxic secondary metabolites produced by some species of fungi in cereals during preharvest and postharvest stages (Gurikar *et al.*, 2023). These metabolites threaten food and feed safety and quality, leading to considerable agro-economic deprivations (Matumba *et al.*, 2021). The toxic substances produced are due to the adaptation of fungi to environmental and climatic conditions (Krnjaja *et al.*, 2019). Different factors, such as temperature, water activity, nutrient content, and relative humidity, play a role in the growth of fungal species and mycotoxin production (Leite *et al.*, 2021). Corn is one of the widely consumed cereals frequently contaminated by mycotoxins, resulting in economic diminutions to growers as well as adverse effects on human health (Magnoli *et al.*, 2019).

The mycotoxigenic fungi usually develop as crops start growing in the field. Corn is prone to fungal contamination during harvesting and storage (Tarazona *et al.*, 2020). Several factors, such as crop density, harvest time, crop rotation, and environmental conditions, are responsible for the contamination of corn with mycotoxin-producing fungi (Krnjaja *et al.*, 2019). Contamination intensity by mycotoxin also varies with corn cultivar because of the resistance of some varieties to certain fungal species. The fungi transmission to grains starts at the preharvest stage and colonize and produce mycotoxins during the postharvest stage (García-Díaz *et al.*, 2020).

Table 1. Advantages and disadvantages of decontamination techniques on corn.

Method	Treatment	Advantages	Disadvantages	Advancement requirements	References
Physical	Cleaning, dehulling, and milling	Effective for early reduction of mycotoxins. Important unit operation for converting inedible grain to edible.	Only early reduction of mycotoxins	Automated and AI machine learning-based cleaning and milling techniques should be explored which increase the efficiency for removal of microbial contamination from corn	Karlovsky *et al.*, 2016; Siwela *et al.*, 2005
	Heat treatment	Reduces considerable percentage of mycotoxins at higher temperature. Helps for the preparation of different products.	Negatively affect nutritional properties. Changes sensory properties of food material. Not effective at low temperature.	The precision temperature control of heat treatment methods for degradation of mycotoxins should be optimized and should not affect the nutritional properties at significant level.	Schaarschmidt and Fauhl-Hassek, 2021
	Cold plasma	High efficiency for degradation of mycotoxins. Nonsignificant effect on nutritional properties. No chemical residue	Expensive. Effects color properties.	Cold plasma techniques should be designed to target degradation of mycotoxins in corn and should be available at commercial scale for large volumes of grains.	Gavahian *et al.*, 2020; Wielogorska *et al.*, 2019
	Irradiation	Efficient for reduction of mycotoxins. Nonthermal.	High capital cost. Negatively affect the quality of whole grains.	Irradiation technique should be optimized for commercial scale for decontamination of corn.	Aziz *et al.*, 2007; Khalil *et al.*, 2021
	Microwave	Easy to operate. Low energy consumption.	Commonly used for heating purpose. Efficiency for reducing mycotoxins depends on the composition of food.	Microwave method should be optimized with other decontamination techniques, which will increase their efficiency.	Zhang *et al.*, 2020
Chemical	Ozone	Easy to operate. Eco-friendly nature. Does not have any residue.	Oxidation of bioactive compounds.	Optimized protocol and concentrations of grain should be explored. This technique should be used with other methods for increasing the effectiveness and control of mycotoxins.	An *et al.*, 2024; Krstović *et al.*, 2021
	Ammonization, organic acids, gases	Most inexpensive method. Simple technique.	Leaves chemical residue. Negative effects on human health. Alters the properties of food material.	The use of safe and eco-friendly chemicals for decontamination purposes should be explored. The chemicals should not leave any residues or harmful by-products in the grain. There is also a need to use sensors that will control the use of chemicals above optimized level in the grain.	Yu *et al.*, 2020
Biological	Fungi, yeast	High efficiency. Environment-friendly.	Difficult to remove mycotoxin binder. Difficult to select nontoxigenic biocompetitive microorganisms. Long period is required for detoxification.	There is a need to use selective biological agents having high efficiency for mycotoxin degradation. Furthermore, conditions for biological agents should be optimized for efficient degradation of mycotoxins from corn, and it is possible to apply at industrial scale.	Dorner, 2009; Oluwafemi *et al.*, 2010
	Enzymes	Selective technique for degrading mycotoxins. Specificity and predictability of end point	Expensive technique. Effect only on specific mycotoxins.	Enzymes should be explored at commercial scale and should have targeted mycotoxin degradation. The enzyme technique should have cost-benefits.	de Oliveira *et al.*, 2020

There are some critical stages, such as preharvest, harvest, drying, packaging, and storage, in the production chain that favor the production of mycotoxins (Fleurat-Lessard, 2017). Environmental conditions during these critical stages significantly influence the level of mycotoxins (García-Díaz *et al.*, 2020). Some species of fungi grown in the field during the preharvest stage are called field fungi. These fungi grow continuously and produce mycotoxins if conditions are favorable (Sserumaga *et al.*, 2020). The concentration of mycotoxins is accelerated if corn is not dried correctly to a suitable moisture content. Furthermore, climate changes also accelerate mycotoxin production in corn (Chhaya *et al.*, 2022).

Corn crops in fields are infected by *Fusarium* species, producing fumonisin. Fumonisin is primarily produced by the same species of fungi, such *as Fusarium verticillioides* and *Fusarium proliferatum* (Ekwomadu *et al.*, 2020). Among these mycotoxins, Fumonisin B_1 and Fumonisin B_2 are important and commonly found in corn-based products (Khodaei *et al.*, 2021). Corn cobs are also infected in the field by *Aspergillus* spp., producing aflatoxin (Munkvold *et al.*, 2019; Sserumaga *et al.*, 2020). Aflatoxins are popular mycotoxins widely known for their toxicity and carcinogenic properties. *Aspergillus* and *Penicillium* species are storage fungi that infect corn at the time of harvest or postharvest stage (Nada *et al.*, 2022), usually because of the physical damage to the kernel (Kumar, *et al.*, 2021). Zearalenone is another globally discovered mycotoxin formed during the preharvest stage of corn (Munkvold *et al.*, 2019). Improper storage and humid conditions favor zearalenone production during drying. Zearalenone is formed by fungi such as *Fusarium graminearum*, *Fusarium culmorum*, *Fusarium cerealis*, and *Fusarium exquisite* (Tan *et al.*, 2021). Climate represents a key factor for fungal contamination and mycotoxin production. Impact of climatic changes are expected to increase the occurrence of mycotoxins in food commodities. As climate becomes warmer, temperature reaches to 33°C, which is close to the optimal, temperature required for mycotoxin production. Frequent and prolonged periods of drought stimulate mycotoxin production in preharvest and postharvest stages. Climatic changes considerably affect fungal and mycotoxin patterns and lead to a high risk of mycotoxin contamination in corn (Chhaya *et al.*, 2022). Climatic changes, such as increased temperature and extended drought periods, considerably affect the growth of *Aspergillus* and *Fusarium* species (Loi *et al.*, 2023).

Role of corn and corn-based products in human life

Corn is an important cereal crop after rice and wheat that is cultivated and extensively consumed globally (Siyuan *et al.*, 2018). Corn is generally used for human nutrition and is an essential source of calories, valuable bioactive compounds, and has a delicate flavour (Mir *et al.*, 2017; Rochín *et al.*, 2021). It is a good source of carbohydrates, minerals, vitamins, and phenolic compounds (Radosavljevic, 2020). Corn also has high potassium, sodium, and sulfur elements. The nutritive value of corn depends on many factors, such as genetic constitution, climatic conditions, irrigation facility, fertilizer dose, and processing conditions (Prasanthi *et al.*, 2017). The protein content of corn is approximately 10% and is mostly concentrated in the endosperm and germ. Fat is also present in good amount after starch and protein. The average fat content of corn kernels is about 4.5%. The oil concentration is observed in corn's germ layer (Siyuan *et al.*, 2018).

Corn is also a good source of many vitamins important for human health. Vitamins A and E are the predominant vitamins found in corn grain. Corn also contains water-soluble vitamins, such as niacin, pantothenic acid, thiamine, riboflavin, and folic acid (Singh *et al.*, 2019). Yellow and white are the common corn varieties used for human consumption. However, pigmented varieties, such as black, red, and blue, have gained popularity because of anthocyanins (Siyuan *et al.*, 2018, Košutić *et al.*, 2023). Corn contains phytochemicals, such as phenolics, carotenoids, and phytosterols, which are essential for human health. The consumption of corn is associated with reducing certain diseases, such as diabetes, colon cancer, and cardiovascular diseases (Ai and Jane 2016).

Corn is a staple food in many countries. It is also a main ingredient in many cuisines. The preparation of corn grains for human consumption includes a great diversity in food products such as popcorn, breakfast cereals, snack foods, bakery products, tortillas, porridges, pasta, and cornmeal (Serna-Saldivar 2021). In addition to carbohydrates and protein, corn also provides other nutritional compounds, including vitamins and minerals, with potential health benefits.

Corn is a staple diet of Mexican population and accounts for about 75% of its consumption in tortillas (Wall-Martínez *et al.*, 2019). Besides this, some indigenous corn products, such as *arepa* (South America), *muufo* (Somalia), *tamales* (Latin America), and corn dumplings (Africa), are also popular globally (Rochín *et al.*, 2019). Corn is combined with other cereals and legumes to prepare different products (Gao *et al.*, 2018). Corn is also consumed after nixtamalization, a traditional maize preparation process, and increases the bioaccessibility of other nutritional components. Nixtamalized products, such as tortillas, tamales, and snacks, have gained global popularity (Escalante-Aburto *et al.*, 2020; Košutić *et al.*, 2023).

Different types of corn-based products and associated mycotoxins

Corn, a popular cereal worldwide, is known for its flavor and nutritional properties (Siyuan *et al.*, 2018). Different products, such as cornflakes, cornbread, tortillas, breakfast cereal, and popcorn, are developed from corn globally. However, corn products are contaminated with different toxigenic fungi, producing mycotoxins and contaminating corn-based products (Carvajal-Moreno, 2022). The severity of mycotoxin contamination is also increased in corn-based products because it provides suitable nutrients for the growth of toxigenic fungi (Khodaei *et al.*, 2021).

Aflatoxins and fumonisins are commonly found in different types of contaminated corn products (Chavez *et al.*, 2020). These mycotoxins are highly toxic, mutagenic, and carcinogenic, leading to dangerous consequences to human health (Park *et al.*, 2018). Research studies have reported that different processing operations are used to prepare cereal products to reduce mycotoxins (Schaarschmidt and Fauhl-Hassek, 2021). However, a certain amount of mycotoxins remain in cereal-based products, and the concentration depends on the applied processing conditions. Mycotoxin analyses have been conducted in different types of corn-based products. Different concentrations of fumonisins are observed in corn, and corn-based product samples are analyzed in different countries. The distribution of fumonisins and total aflatoxins are observed in various types of processed corn products (Castells *et al.*, 2008; Mihalcea and Amariei 2022). The level of fumonisins in cornflakes is found to be lower than the maximum tolerable limit of 400 μg/kg set by the European Union (EU). Corn tortillas are found to be a leading dietary risk in Veracruz, Mexico because of aflatoxin (85%) and fumonisin (90%) contamination (Wall-Martínez *et al.*, 2019). The total aflatoxin concentration was 22.17 μg/kg and that of fumonisin 526.6 μg/kg, leading to health risks to larger population. Geary *et al.* (2016) evaluated corn-based porridge samples from different areas of Tanzania, and found that 82% of the corn samples were contaminated with mycotoxins. The results indicated the presence of different types of mycotoxins in various corn-based products, resulting in significant adverse effects to human health (Sarmast *et al.*, 2021).

Consuming corn and corn-based products leads to multiple health risks for Nigerian population because of mycotoxin contamination (Liverpool-Tasie *et al.*, 2019). In case of aflatoxins, 52% of the studied maize product samples were found above the regulatory level. Mycotoxin contamination was analyzed in cornmeal and corn flour in the Sao Paulo region of Brazil (Bittencourt *et al.*, 2005). However, no contamination with aflatoxin was observed in corn flour and cornmeal, but fumonisin B1 contamination was detected in the studied samples. In cornmeal, the level of fumonisin B_1 was detected in the range of 1.1–15.3 mg/kg whereas in corn flour, the range was 0.5–7.2 mg/kg. Milanez *et al.* (et al.2006) studied trichothecene mycotoxins in corn products. The study reported a low concentration of trichothecene in corn products commercialized in Sao Paulo, Brazil. A high presence of fumonisins was observed in corn-based products in the Federal District of Brazil (Caldas and Silva, 2007). Among the total samples analyzed forfumonisin incidence, 81% were observed for fumonisin B_1 and 72 % for fumonisin B_2. The total concentration of fumonisins was observed as 0.127 mg/kg in cornflakes and 2.04 mg/kg in cornmeals.

Corn-based products were found to be contaminated with multiple mycotoxins in the Shandong region of China (Jiang *et al.*, 2019). The mean concentration of total mycotoxins in corn-based products was 197.2 μg/kg. The most common mycotoxin contamination was deoxynivalenol (96.7%) and fumonisin B_1 (94.4%). Among the studied samples, the highest concentration was observed in pancake (886.7 μg/kg), followed by wood product (143.7 μg/kg) and corn cake (135.4 μg/kg). The Nigerian corn and corn-based products were analyzed for aflatoxins and ochratoxin A (Adebajo *et al.*, 1994). Ochratoxin A was detected in 15% of the studied samples. A total aflatoxin concentration of 200, 233, and 55 μg/kg was observed in corn, corn cake, and corn roll, respectively. Corn and corn-based product samples from different districts of Egypt were analyzed for fusarium mycotoxin (El-Sayed *et al.*, 2003). Fumonisin B_1 was detected in 80% yellow corn, 54% cornmeal, 33% white corn, and 29% popcorn samples. Deoxynivalenol concentration of 28.8 μg/kg was found in white corn whereas 10.1 μg/kg was detected in popcorn.

Decontamination of mycotoxins in corn and corn-based products

The safety of any cereal crops, including corn, is a significant factor, and contamination of products with mycotoxins is an important problem. As already mentioned, several factors during harvesting, transport, and storage influence the production of mycotoxins, which are usually unrestrained by humans. Therefore, many techniques, categorized into physical, chemical, and biological methods, have been used to decontaminate corn (Kalagatur *et al.*, 2018; Wielogorska *et al.*, 2019). Depending on the technique and processing conditions, these methods help to degrade mycotoxins from corn and corn-based products, ultimately leading to safety and stable shelf-life.

Physical treatments

Different physical methods are used to reduce mycotoxin levels in both corn and corn products (Schaarschmidt and Fauhl-Hassek, 2021). Grains are damaged during postharvest processing and are prone to mycotoxin contamination. The initial sorting and sieving process helps to remove damaged kernels, effectively lowering the total mycotoxin contamination (Karlovsky *et al.*, 2016). Processing operations, such as dehulling and milling, are used in the grain industry to convert raw corn into an edible end product. A high concentration of mycotoxins is found in the grain's outer layers (Odukoya *et al.*, 2024). Milling reduces a significant amount of mycotoxins from corn because of the removal of bran and germ layers. The dehulling process of corn decreases >90% of aflatoxin concentration (Siwela *et al.*, 2005).

Thermal treatments are used during the preparation of different types of corn-based products. Heat treatments result in the reduction of various types of mycotoxins in corn. The frying and baking operations are reported to reduce fumonisins in corn-based products (Schaarschmidt and Fauhl-Hassek, 2021). The cited authors also reported a significant reduction of fumonisin B_1 at higher temperatures. Fumonisin contamination was reduced during the production of fried tortilla chips (Voss, *et al.*, 2001). Fumonisin levels in fried chips were significantly reduced to 80%. Processing of cornflake also reduces aflatoxin and fumonisin (Castells *et al.*, 2008).

Extrusion process is used to prepare different types of food products from cereals. This technique also has a considerable effect in reducing different mycotoxins in corn. In another study, Scudamore *et al.* (2008) reported that deoxynivalenol and zearalenone were more stable than fumonisins in corn flour and grits during extrusion.

The moisture content of flour feed is a more critical parameter than the reduction of fumonisins. Extrusion cooking reduces fumonisin toxicity in whole-kernel corn and corn grits (Voss *et al.*, 2017). However, the reduction efficiency of fumonisins depends on corn matrix, processing conditions, and addition of other ingredients. Addition of other ingredients, such as glucose, enhances the reduction capacity of extruded product.

Reducing mycotoxins from food material is not the main aim of the above-mentioned methods. Techniques that reduce the concentration of mycotoxins and consequently the human exposure are required. Various emerging physical methods have been used to degrade mycotoxins from corn and corn-based products. Physical techniques, such as irradiation, pulsed light, cold plasma, and microwaves, are explored on a large scale to degrade mycotoxins. Each physical method used for decontamination has its advantages and disadvantages. Depending on the conditions applied, decontamination techniques have different efficiencies for the degrading of mycotoxins (Gavahian *et al.*, 2020).

Cold plasma

Cold plasma has proven to be the most successful decontamination tool for removing mycotoxins from grains (Mir *et al.*, 2016). Plasma's mycotoxin degradation capacity depends on many parameters, such as mycotoxin type, plasma source, and process conditions. Cold plasma generates reactive species, such as free radicals, electrons, and ions, and degrade mycotoxins. Its primary specialty is reducing mycotoxin contamination without affecting grain's nutritional and qualitative aspects (Misra *et al.*, 2019).

The decontamination efficiency of cold atmospheric pressure plasma was assessed to reduce mycotoxins in corn (Wielogorska *et al.*, 2019). Cold plasma significantly reduced mycotoxins, such as aflatoxin B_1 and fumonisin B_1, commonly used in corn contamination. Cold plasma treatment for 10 min reduced about 65% of contamination, thereby reducing aflatoxin B_1 (65%) and fumonisin 1 (64%). Aflatoxins are also removed from corn by cold plasma treatment (Shi *et al.*, 2017). A high-voltage atmospheric cold plasma treatment for 10 min reduced 85% of aflatoxin. Generating reactive species, such as charged particles, free radicals, and gas molecules, leads to the degradation of mycotoxins.

Furthermore, gas and relative humidity determine the generation of reactive species. The cold atmospheric pressure plasma generated with the air surface barrier discharge system removed aflatoxin B_1 from contaminated corn surfaces (Hojnik *et al.*, 2021). The highest reduction of aflatoxin B_1 was achieved at an exposure time of 240 s with 100% decontamination efficiency.

Irradiation

Irradiation is one of the nonthermal techniques used to decontaminate food material. This technique shows a promising approach for the degradation of mycotoxins from different types of cereals (Akhila *et al.*, 2021). Irradiation is a non-chemical energy-efficient method that exposes food to ionizing and non-ionizing radiations. Irradiation treatment partially reduces aflatoxin B_1 and aflatoxin B_2 after a reduction dose of 2–5 kiloGray (kGy) (Khalil *et al.*, 2021). Complete degradation of aflatoxins was observed at 10 kGy. Humidity considerably affects the degradation efficiency of aflatoxins by irradiation. The radiolysis of water produces reactive free radicals, which attack aflatoxins and produce products of lower biological activity. The electron beam irradiation significantly degrades zearalenone and ochratoxin A. At 10-kGy irradiation, zearalenone was reduced to 65% and ochratoxin to 75% (Luo *et al.*, 2017). Moisture content also considerably affects the degradation efficiency of mycotoxins (Gibellato *et al.*, 2021). Higher moisture content leads to a higher percentage of degradation of zearalenone and ochratoxin. Furthermore, the authors also reported that zearalenone and ochratoxin were easily degraded in corn grain, compared to corn flour.

Gamma irradiation also has shown the potential for reducing aflatoxins and ochratoxin A from corn (Khalil *et al.*, 2021). The maximum reduction was observed at 20 kGy. A maximum reduction of 61% was observed for ochratoxin A, followed by aflatoxin B_1 (40%) and aflatoxin B2 (33%). Aziz *et al.* (2007) demonstrated the effect of gamma irradiation on the degradation of fumonisin B_1 in various cereal grains, including corn. The authors reported that the irradiation dose of 5 kGy reduced 87% of fumonisin B_1 in corn. Furthermore, the authors observed that a 7-kGy irradiation dose was sufficient for the complete degradation of fumonisin B_1.

Microwave

Microwaves are commonly used in the food industry because of their heating efficiency. Microwaves are electromagnetic waves ranging from 300 MHz to 300 GHz (Guzik *et al.*, 2022). The literature demonstrates that microwave heating reduces mycotoxins from corn as well as aflatoxin B_1 and ochratoxin A from corn flour (Alkadi and Altal, 2019). The degree of degradation of aflatoxin B_1 and ochratoxin A depends on the heat exposure time and the initial concentration of mycotoxins. Microwave processing for a longer period increases microwave's penetration and temperature, ultimately removing mycotoxins from corn flour. The water-assisted microwave treatment significantly reduces aflatoxin B_1 contamination from corn (Zhang *et al.*, 2020). Increase in microwave power and treatment time enhances the reduction of aflatoxin with the maximum reduction of aflatoxin B_1 (58.6%). Water has shown a considerable effect on reducing aflatoxin from corn.

Chemical decontamination

Various chemicals, in different concentrations, are used to decontaminate corn grains of mycotoxins (Yu *et al.*, 2020). Chemical techniques are inexpensive and simple for decontaminating different types of grains and can be applied at a large scale (Pankaj *et al.*, 2018). However, chemical treatments adversely affect human health and alter food material properties.

Sodium bicarbonate and electrolyzed water were used to reduce the contamination of aflatoxin B_1, B_2, G_1, and G_2 from corn (Castro-Ríos *et al.*, 2021). The highest reduction of aflatoxins was observed by using sodium bicarbonate solutions, with the maximum reduction for aflatoxin B_1 at 74%, aflatoxin B_2 at 70%, aflatoxin G_1 at 87%, and 75% for aflatoxin G_2. Bicarbonate salts are also used to decontaminate stored grains. The application of ammonium and sodium bicarbonate salts was practical in controlling the growth of fumonisin B1 and aflatoxin B_1 in corn (Samapundo *et al.*, 2007). The authors also reported that sodium bicarbonate is more effective against fumonisin production development than ammonium carbonate. Chlorine dioxide is a potent oxidizing agent used for various applications in the grain industry. It detoxifies aflatoxin B1 from corn grains (Yu *et al.*, 2020). Chlorine dioxide gas reduces >70% of aflatoxin B1 from corn grain. The mentioned study confirmed that the biological activity of aflatoxin is reduced due to the change in furan and lactone rings and the modification in cyclopentanone and methoxy structure.

Ammonization is an approved and effective method for reducing mycotoxins from agricultural products, including maize (Doğan and Hayırlı, 2022). Ammonization of grains leads to the reduction of mycotoxins by up to 75%. Ammonia has nitrogen as a central atom and has strong hydrogen bonding between molecules. Ammonia reacts with mycotoxins through Van der Waals force, leading to breakdown into nontoxic compounds (Leslie *et al.*, 2021).

Ozone

Ozone is one of the methods used to decontaminate different types of cereal grains. The potential application of ozone in the food industry is due to its eco-friendly nature, which does not leave any residue. Efficiency of the ozone process depends on several factors, such as gas flow, exposure time, sample moisture, and physical properties of the grain (Conte *et al.*, 2020). Krstović *et al.* (2021) studied the influence of ozone technique on the reduction of deoxynivalenol, ochratoxin A, and zearalenone in ground corn. Ozone treatment reduced 43% of deoxynivalenol, 70% of ochratoxin A, and 68% of zearalenone. Ozone levels of 40 mg/L resulted in the highest reduction of ochratoxin A and zearalenone. In contrast, the highest reduction of deoxynivalenol was observed at 85 mg/L of ozone exposure (Krstović *et al.* 2021).

Ozone effectively reduces aflatoxins from corn grits (An *et al.*, 2024; Porto *et al.*, 2019). Ozone treatment results in 57% reduction of aflatoxin B_1, 54.6% reduction of aflatoxin G_1, 36% reduction of aflatoxin G_2, and 30% diminution of aflatoxin B_2. The increased degradation capacity of aflatoxin B_1 and aflatoxin G_1 is due to double bonds in their molecules. The ozone treatment leads to the breakdown of mycotoxin into lower molecular weight compounds, such as aldehydes, ketones, and organic acids. Ozonation effectively degrades aflatoxin B_1 in corn (Luo *et al.*, 2014). The degradation rate of aflatoxin B_1 varied with moisture content and increased with concentration and treatment time. Ozone treatment for 40 min with 90 mg/L concentration at a moisture content of 13.47% decreased aflatoxin B_1 from 83 μg/kG to 9.9 μg/kg.

Ozone treatment effectively degrades zearalenone and ochratoxin A in corn (Daou *et al.*, 2024; Qi *et al.*, 2016). The degradation percentage of zearalenone and ochratoxin A increased with treatment time and ozone concentration. Water plays a vital role in the degradation of mycotoxins during ozone treatment. Results demonstrated that increased moisture was more sensitive to ozone treatment. High moisture content during ozone treatment favors ozone adsorption by grain's surface and increases its reactivity. The ozone treatment of 100 mg/L for 180 min at a moisture content of 19.6 reduced 91% of zearalenone and 71% of ochratoxin A. Ozone process considerably reduced zearalenone content in whole corn flour (Alexandre *et al.*, 2019). The maximum reduction of zearalenone (62.3%) was observed at a processing time of 60 min. The authors also observed that increased moisture content enhanced the efficiency of the degradation of zearalenone.

Nixtamalization

Nixtamalization is a traditional food processing procedure developed by Mesoamerican cultures (Mir *et al.*, 2019). In this method, grain is soaked and cooked in an alkaline solution, washed and then hulled. The nixtamalization process leads to many physical and sensory changes in corn (Escalante-Aburto *et al.*, 2020). Several studies have reported that nixtamalization has a great potential for lowering mycotoxin concentrations (Odukoya *et al.*, 2021).

Nixtamalization and tortilla production leads to the complete reduction of aflatoxin B1 contamination. After nixtamalization, the alkaline pH of corn dough and resting it for 30-40 min at room temperature resulted in a 100% reduction of aflatoxin B1 (Moreno-Pedraza *et al.*, 2015).

Méndez-Albores *et al.* (2004) reported that nixtamalization reduces 90% of aflatoxins in corn tortillas. Nixtamalization significantly reduced fumonisin content in masa, a corn dough commonly used in Mexican cuisine, and converted it into partially hydrolyzed fumonisins (De Girolamo *et al.*, 2016). The reduction of mycotoxin levels in tortillas depends on the type of mycotoxin and concentration of lime. The increased *calcium hydroxide* [$Ca(OH)_2$] concentration during cooking and steeping leads to the more pronounced effect of reducing aflatoxins in tortillas. Furthermore, the reduction percentage depends on the initial concentration of aflatoxin and its structural complexity and stability. Odukoya *et al.* (2021) studied the influence of cooking ingredients during nixtamalization on fumonisin concentration in corn. All ingredients, such as sodium hydroxide, calcium hydroxide, wood ash, potassium hydroxide, and calcium chloride, were considerably effective in reducing fumonisins from contaminated corn (Odukoya *et al.*, 2021).

Biological decontamination

Biological agents are mostly used for mycotoxin decontamination of food commodities (Muhialdin *et al.*, 2020). The fungal strains that do not produce mycotoxins are used for biological control of toxin-producing fungi in the grain. Biological methods control mycotoxin contamination by competitive interaction of toxigenic and non-toxigenic strains of fungi (Piotrowska, 2021). Biological agents are applied at preharvest or postharvest stage to reduce mycotoxins. Brown *et al.* (1991) reported that aflatoxin production in corn is decreased with inoculation of non-toxigenic *Aspergillus flavus* strains. Abbas *et al.* (2006) used non-aflatoxigenic Aspergillus isolates CT3 and K49 to reduce aflatoxin contamination in corn. The results demonstrated that non-aflatoxigenic isolate reduced aflatoxin contamination by more than 60% (Abbas *et al.*, 2006).

Aflatoxin contamination in Serbian corn is controlled by a biological technique using a non-toxigenic strain of *Aspergillus* (Savić *et al.*, 2020). The native non-toxigenic strain (MyToolBox Af01) was used to produce biocontrol agent and applied in the cornfield. Biocontrol agents significantly reduced the total aflatoxin contamination by 73%. In another study, biological agents controlled aflatoxin contamination of corn in West Africa. Atehnkeng *et al.* (2008) reported that non-toxigenic isolates of *Aspergillus flavus*, native to Nigeria, were used to control the aflatoxin contamination of corn. Toxigenic isolates reduced the concentration of aflatoxin B_1 by 71% and aflatoxin B_2 by 99.99%.

The microbial strains showed different efficiency for the reduction of mycotoxins. Mycotoxin contamination was controlled in corn by applying the non-aflatoxigenic strain of *Aspergillus flavus* or *Aspergillus parasiticus* (Dorner, 2009). The non-aflatoxigenic isolates of *Aspergillus flavus* or *Aspergillus parasiticus* were cultured from wild-type samples. The results demonstrated that *Aspergillus* strain controlled aflatoxin contamination by a competitive mechanism. Furthermore, the author also reported that

Aspergillus flavus considerably reduced aflatoxin contamination, compared to *Aspergillus parasiticus.*

Different strains of Lactobacillus species, including *Bifidobacterium*, *Lactococcus*, *Leuconostoc*, *Pediococcus*, and *Streptococcus*, are used to eliminate mycotoxins from grains (Liu *et al.*, 2020). Lactic acid bacteria are generally considered as safe compounds and are one of the most effective methodologies because of their potential release of antifungal metabolites against various fungal species. The detoxifying capacity of lactic acid bacteria is due to metabolites, including organic acids, such as lactic, acetic, citric, fumaric, and malic acid as well as diacetyl, ethanol, acetaldehyde, hydrogen peroxide, rutherin, acetonin, and bacteriocins., which inactive, remove, and detoxify mycotoxins (Shetty and Jespersen 2006). Furthermore, the lactic acid bacteria cell wall contains many components, such as peptidoglycan, teichoic acid, protein, and exopolysaccharides, which are considered to be the main factors for the adsorption of toxic compounds. Lactic acid bacteria are biotoxifying agents for aflatoxin-contaminated corn (Oluwafemi *et al.*, 2010). Lactic acid bacteria significantly reduce aflatoxin contamination and are explored as a biocontrol agent. Different lactobacillus strains are used to reduce aflatoxins in corn. *Lactobacillus acidophilus* and *Lactobacillus casei* reduced more than 50% of aflatoxin B_1. Lactic acid bacteria bind to the surface of aflatoxin, which is also strain-specific.

Enzyme decontamination is a selective technique used to degrade mycotoxins from grains. The enzyme method has several advantages compared to other decontamination methods, such as specificity and predictability of endpoint composition. Enzymes detoxify fumonisins by genetically modifying the varieties. Furthermore, enzyme decontamination is not widely explored due to the difficulties and expenses for applying it on a larger scale and the need for safety testing of end products. Several enzymes attack a wide range of mycotoxins, including deoxynivalenol, ochratoxin A, deoxynivalenol, ochratoxin A, and zearalenone (Yao and Long, 2020). Enzymes such as lipases and peptidases reduce the toxicity of ochratoxin A. The primary target of enzymes is the amide bond that breaks down into phenylalanine and ochratoxin α, which is less toxic than ochratoxin A. Similarly, zearalenon is degraded by the enzyme lactonohydrolase, which breaks the lactone ring and reduces toxicity (Wang *et al.*, 2019).

Challenges and possible approaches

The contamination of corn by mycotoxins is a significant challenge for the food industry. Mycotoxin contamination leads to severe toxicological effects on consumers. Favorable environmental conditions at any stage, from farm to table, produce mycotoxins. Climatic changes also result in mycotoxin production in the passage of time. It is a significant challenge for countries to control the production of mycotoxins, especially in corn, which is a staple food. Many possible approaches are applied, especially from harvest to table, to minimize the risk of mycotoxin contamination. Infrared drying technique to save moisture content does not favor mycotoxigenic fungal contamination.

Furthermore, suitable techniques must be explored at farms or in industries to reduce mycotoxin contamination. Different decontamination technologies require research investigation to identify the toxicity of degradation compounds from mycotoxins. Furthermore, the interaction of degraded mycotoxin products with food compounds is also needed. Developing cost-effective technologies for decontaminating mycotoxins from corn is also recommended.

Conclusion

The contamination of toxigenic fungi can occur at different stages of production and processing under favorable conditions of temperature and humidity. The common toxigenic fungi involved in the contamination of corn are *Aspergillus flavus*, *Aspergillus parasiticus*, and *Fusarium verticillioide*. There is a need to develop practices and procedures to control mycotoxin contamination from farm level. Considerable reduction of mycotoxins was observed in corn and corn-based products using different decontamination strategies. Protocols are optimized for the maximum reduction of mycotoxins from corn and corn-based products. New technologies have shown maximum decrease in mycotoxins without considerably affecting quality properties. Combination of decontamination methods (gamma irradiation and essential oil) are considered to increase the efficiency of reducing mycotoxins from cereal grains. Researchers are developing and optimizing new decontamination techniques that might reduce toxigenic fungi or mycotoxins from corn without any adverse effects on corn-based products. Future research is needed to evaluate the occurrence and potential toxicity degradation products formed by various decontamination methods.

Authors Contribution

Shabir Ahmad Mir and Saqib Farooq: investigation, supervision, data curation, resources, conceptualization, methodology, writing of original draft. Jasmeet Kour and Manzoor Ahmad Shah: literature searching, writing and editing. Kappat Valiyapeediyekkal Sunooj and Amin

Mousavi Khaneghah: supervision, conceptualization, review, and editing.

Conflict of Interest

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