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Narrative Review

Review on non-thermal plasma technology: FROM aflatoxins degradation to effect on medicinal plants

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Abstract

Background and aims: Aflatoxins, toxic secondary metabolites produced by certain fungi, pose significant risks to human and animal health due to their presence in food and agricultural products. Traditional methods of aflatoxin degradation often compromise product quality. This study aimed to evaluate the effectiveness of cold plasma technology in degrading aflatoxins while preserving the quality of the treated products.

Methods: A comprehensive review of the current literature focused on studies that applied cold plasma technology for aflatoxin degradation. The analysis included parameters such as plasma generation methods, exposure times, and the impact on the nutritional and sensory quality of the treated products.

Results: Cold plasma technology significantly degraded aflatoxins across different food matrices. Its low-temperature operation ensures minimal impact on the quality of agricultural and food products, making it especially suitable for temperature-sensitive items. The technology works by generating reactive species that target and neutralize the toxic properties of aflatoxins.

Conclusion: Compared to traditional methods, cold plasma offers a safer and more efficient alternative for aflatoxin degradation. Cold plasma technology presents a promising solution for aflatoxin degradation with significant advantages over conventional methods. Its ability to maintain product quality while effectively neutralizing aflatoxins underscores its potential for broader application in food safety management. Further research is warranted to optimize its use and fully understand its implications for human and animal health.

Keywords: Non-thermal plasma, Mycotoxins, Aflatoxins, Medicinal plants, *Aspergillus* fungi, Degradation of aflatoxins

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Introduction

According to the FAO (Food and Agriculture Organization of the United Nations) report, 25% of the world's crops are contaminated with mycotoxins during growth or storage. Mycotoxins are harmful secondary metabolites produced by certain types of fungi. Mycotoxins affect human and animal health, cause serious diseases, and even cause death (1,2). The most common producers of mycotoxins are *Aspergillus, Fusarium*, and *Penicillium*. Among them, toxins secreted by *Aspergillus flavus* and Aspergillus parasiticus are the most dangerous for animal and human health (3). The main concern about *Aspergillus* fungi, especially in agriculture, is that this fungus produces a harmful toxin called aflatoxin, and this toxin is mainly found in oilseeds, corn, peanuts, and nuts. This toxin can enter the human body in two ways: through contaminated food or indirectly through consuming products related to animals whose bodies were contaminated with this toxin (3).

Exposure to aflatoxins is called aflatoxicosis and is manifested as acute poisoning caused by short-term exposure to large amounts of aflatoxins. It leads to severe liver damage, and aflatoxin poison leads to suppression of the immune system, nutritional disorders, and cancer (4). Therefore, it is essential to use methods to reduce, destroy, and eliminate this poison. Aflatoxin reduction operations can include pre-harvest and post-harvest operations. Good Agricultural Practices, i.e., appropriate fertilizers, pest control, timely harvesting of agricultural products, and maintaining low humidity and temperature during storage, can prevent the growth of Aspergillus and the production of aflatoxins. However, this is not enough to eliminate or reduce aflatoxins, and it is better to carry out an operation after harvesting these products to eliminate aflatoxin contamination (5).

Recently, many strategies have been used to destroy, reduce, and eliminate aflatoxins. These strategies include physical, chemical, and biological methods. Among the physical approaches that can be mentioned are radiation and the application of cold plasma, which provides the possibility of rapid destruction of aflatoxins. Chemical approaches to eliminate or reduce aflatoxins include ozone, electrolyzed oxidizing water, organic acids, and natural plant extracts, widely accepted as food additives in many countries. Biological methods are also called

microbial and enzymatic transformation of aflatoxins into non-toxic or toxic metabolites with a lower dose (6-8). However, it should also be considered that these strategies are usually time-consuming, reduce the product's nutrients, cause environmental pollution, and, most importantly, affect the quality of the product (9,10). Of course, research has shown that aflatoxins are highly resistant to heat, and thermal processes can destroy this toxin and harm agricultural products, plants, and food (9). Therefore, today, new methods such as non-thermal plasma (cold plasma) have been developed, which are an emerging technology and have brought promising results in eliminating aflatoxins.

Cold plasma is a non-thermal method that is very popular today in most industries, including the food industry. Plasma is the fourth state of matter, which is formed from the ionization of gas and has high-energy substances consisting of charged particles, free radicals, and radiation. Compared to other states of matter, plasma has a higher energy level. To form a plasma, it is necessary to give enough energy to a gas to overcome the power of the connection of electrons in the outermost circuit of the particles that make up that gas; finally, the electrons are separated from the gas, and ionized gas is created. It is called plasma (11). Plasma-producing systems include corona discharge, dielectric barrier discharge, and atmospheric pressure plasma jet (11). The primary mechanism of the plasma effect on aflatoxin includes hydrogenation, hydration, and oxidation of the furan ring. Cold plasma has shown its potential to be used as a suitable process for the degradation and removal of aflatoxins. This article provides a review of the research conducted in the field of reduction, destruction, or elimination of aflatoxins so that by examining them, helpful information can be obtained, especially in the discussion of food industries and medicinal plants.

Materials and Methods

Aflatoxins

Aflatoxins are poisons produced by *A. flavus* and Aspergillus parasiticus, and they are found in agricultural products, medicinal plants, and food. So far, about 18 types of aflatoxins have been introduced, among which six types, B1, B2, G1, G2, M1, and M2, are more common and known according to the fluorescence color under ultraviolet light. Two groups, G, green, and B, are divided, which include AFB1 AFB2 AFG1 AFG2. *A. flavus* and *Aspergillus parasiticus* can produce AFB1 and AFB2, but only *Aspergillus parasiticus* produces AFG1 and AFG2 (12, 13). When animal feed is contaminated with aflatoxin type B1 and B2, this toxin is hydroxylated inside the animal's body and turns into aflatoxin M1 and M2, which is excreted through milk or urine, and is very harmful to human health. It is hazardous for children (14). The International Agency for Research on Cancer has classified AFB1 as a group 1 carcinogen (15). Their classification in terms of degree and strength of toxicity is AFB1, AFM1, AFG1, AFB2, AFM2, and AFG2, respectively. All aflatoxins have a furan and coumarin ring, where the furan ring indicates the toxic structure of aflatoxins, and the coumarin ring indicates the carcinogenicity of this toxin. Liver cancer is one of the most common and dangerous side effects of being infected with aflatoxins (16). Various factors influence aflatoxin production in agricultural products, food, and medicinal plants. For example, humidity, temperature, and relative humidity, as well as factors such as oxygen supply, the presence of insects and inappropriate product storage conditions, and hot and humid weather conditions, especially in tropical and subtropical countries, are favorable for the production of aflatoxins and intensify its production (17).

The structure of aflatoxins is shown in Figure 1. According to this figure, the ranges (1) and (2) define the furan ring and lactone (coumarin) of aflatoxins, respectively. The structure of aflatoxins is shown in Figure 1. According to this figure, the specified parts (1) and (2), respectively, specify the furan ring and the lactone (coumarin) of aflatoxins.

Using different methods to eliminate aflatoxins by affecting these rings, the structure of this toxin changes into a structure with a lower degree of toxicity or a non-toxic structure (18).

Aflatoxins in medicinal plants

Medicinal plants are used as home remedies and raw materials in pharmaceutical industries. Herbal medicines have been used to prevent, treat, and cure disorders and diseases since ancient times. According to the opinion of the World Health Organization (WHO), plants have medicinal properties that contain substances in one or more of their organs that can be used to treat diseases or be used to manufacture chemical drugs (19). The WHO has announced that at least 50% of the European population has used herbal medicines more than once. Recently, the use of medicinal plants for treating and preventing many diseases has received attention in many countries. However, it should be noted that the quality and safety requirements may need to be met in using medicinal plants, and the possibility that the plant may be infected with various fungi and mycotoxins during harvesting, storage, transportation, and distribution. It

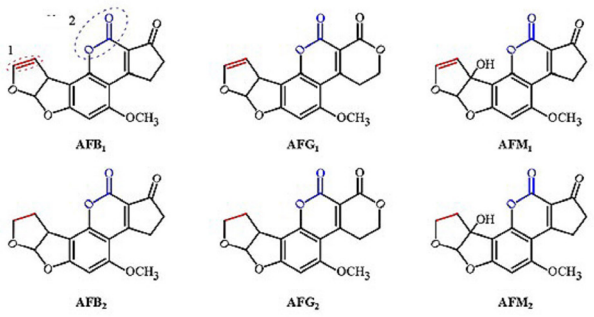

Figure 1. Structure of aflatoxins

is a lot; finally, the use of medicinal plants contaminated with mycotoxins will create irreparable risks to human health (17,20).

Cold plasma

Cold plasma is an emerging technology that is very popular in most industries, including food. Plasma is the fourth state of matter and contains energetic materials of charged particles, free radicals, and radiation. Compared to other states of matter, plasma has a higher energy level. Plasma is formed when a gas is ionized; due to the creation of an electric field, a gas is given enough energy to overcome the power of the electrons in the outermost orbit of the particles that make up that gas. Finally, electrons are separated from this gas, forming plasma (21). Since cold plasma occurs at low temperatures (usually between 30 °C and 60 °C), it does not have a thermal effect on the quality of food and agricultural products. Different methods of producing cold plasma are corona discharge, dielectric barrier discharge, and atmospheric pressure plasma jet.

The effect of plasma on the elimination of aflatoxins

Destructive mechanisms of aflatoxins by applying cold plasma are related to the structure of aflatoxins. The toxicity of aflatoxins is associated with the double bond C8 = C9 on the furan ring, which is precisely the place of toxicity of this toxin. The product obtained after the destruction of this bond is much less toxic than the original. This mechanism is mainly carried out in two ways; in the first method, which includes a series of addition reactions, H2O, H, or CHO was added to the C8-C9 double bond in aflatoxin B1 under the partial influence of ozone. The second method resulted from epoxidation by HO2 and oxidation by the combined operation of OH, H2O2, and O3 on the difuran ring of aflatoxin B1 (13). The results of Wang and colleagues' research (22) showed that the use of radio frequency plasma is a very efficient method to destroy aflatoxin B1, which destroys aflatoxins by destroying the terminal lactone ring of this toxin by hydrolysis. Figures 2a and 2b, respectively, show the process of aflatoxin degradation due to the application of radio frequency plasma and the application of high voltage cold plasma (10). As this figure shows, all C8 = C9 double bonds are destroyed so that aflatoxins lose their toxic nature.

One of the most influential parameters in plasma performance is voltage. The experiments' results showed that increasing the voltage had the greatest effect on reducing *A. flavus*. Similar results have been reported by Esmaeili et al (23). This research used atmospheric pressure cold plasma to reduce aflatoxins in pistachio samples. The results showed that plasma had no effect on the pistachio product's quality properties and successfully removed aflatoxins.

Plasma-activated water has also shown excellent performance in eliminating aflatoxins from food and agricultural products. In a similar study conducted by Arabi et al (24), plasma-activated water was used to remove aflatoxin B1 from almond samples.

Also, plasma has performed well in eliminating microorganisms in fluids. In research conducted by Hosseini et al, cold plasma technology was used to eliminate microorganisms in sour cherry juice. Using plasma to destroy microorganisms such as *E. coli* from liquids such as fruit juices is an effective method that does not impact the product's quality properties while performing a non-thermal pasteurization process (25).

In addition, previous research has shown that exposing agricultural products, medicinal plants, and food to plasma in a short period (about a few minutes) can destroy aflatoxins and Aspergillus fungus. Dasan et al (26) destroyed *A. flavus* and *A. parasiticus* fungi by applying plasma to hazelnut samples for 5 minutes.

Recent studies have shown that plasma is a promising pest and insect control technology. Research conducted by Abd El-Aziz et al (27) showed that the number of pest and insect deaths increased significantly with the increase of cold plasma pulses and the decrease in the distance between the nozzles. Therefore, according to the research, cold plasma technology is widely used to eliminate mycotoxins, especially aflatoxins.

Table 1 compares aflatoxin removal methods. This table clearly and concisely compares the cold plasma method with other conventional methods, detailing their advantages, disadvantages, and limitations.

The effect of plasma on medicinal plants

Various studies have investigated the effect of cold plasma on medicinal plants, and they show promising results in increasing seed germination, plant growth, and biochemical properties. Applying cold plasma produces active species that affect plants' physical and chemical properties and even increase the germination and growth rate.

The use of cold plasma technology or non-thermal plasma in medicinal plants has attracted considerable attention due to its potential to increase various properties and benefits. In fact, applying cold plasma and forming ions, electrons, free radicals, and reactive species generally establish a good interaction with biological materials.

The effect of cold plasma on plant seed germination

Atmospheric pressure cold plasma or low-pressure plasma activates seed germination, plant growth, and plant stability. Data from previous studies show that active species produced by atmospheric pressure cold plasma may play a role in changing and activating physical and chemical properties, physiology, and biochemical and molecular processes in plants, which increases germination, growth, and stability. The results of Adhikari and colleagues' research (30) also show that the atmospheric pressure cold plasma method has been very efficient in increasing the germination and growth of plants.

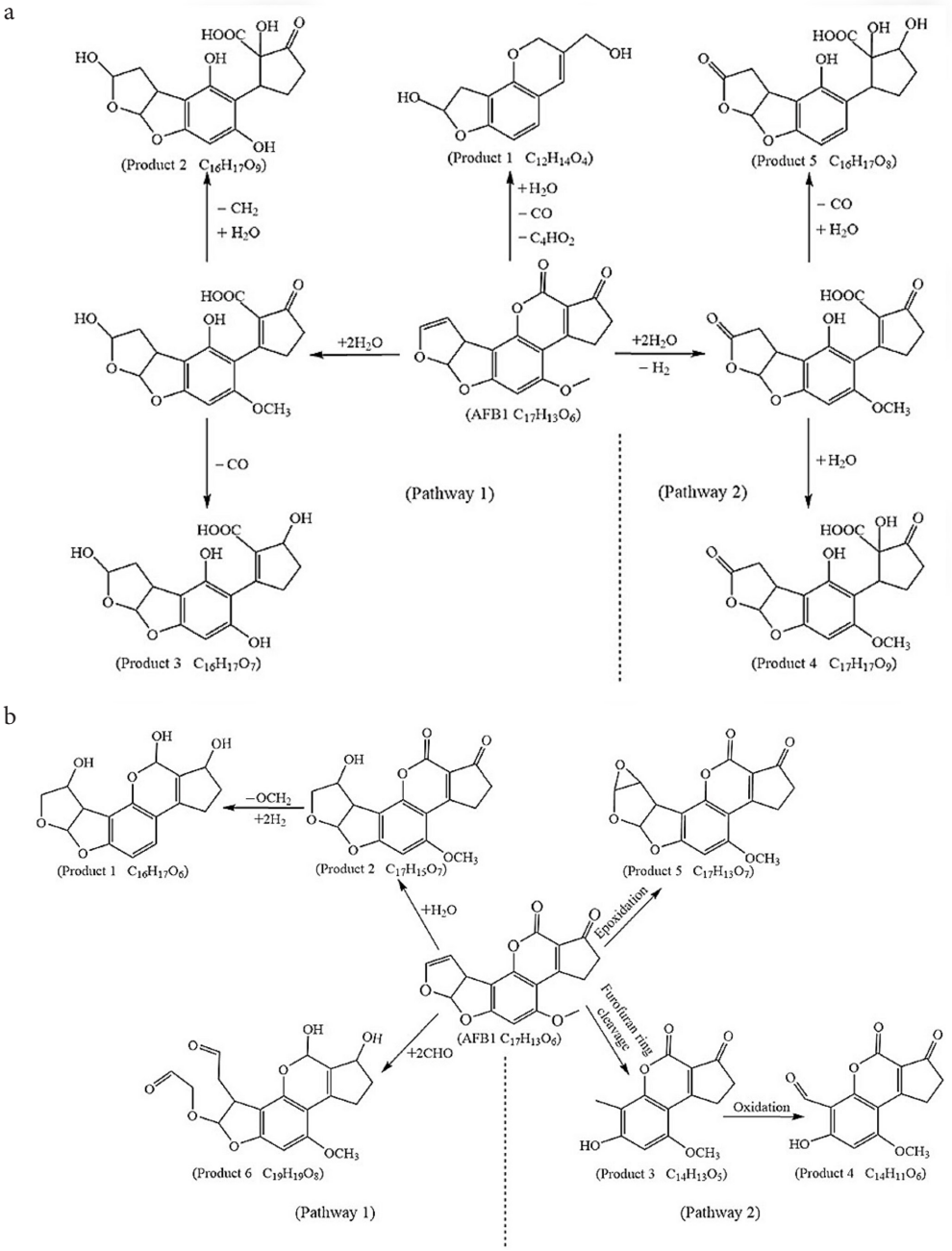

Figure 2. The process of aflatoxins degradation: a) due to the application of radio frequency plasma, and b) due to the application of high voltage cold plasma

Efficiency in seed germination depends on the source of plasma formation, plant species type, and plant moisture level. The mechanism of the effect of plasma on seed germination is that by creating physicochemical changes caused by the application of plasma in the characteristics of the seed coating or surface (for example, high hydrophilicity and water permeability), water absorption increases, and this increase in Seed germination is effective. Similar results have been reported in the review article by Attri et al, and it has been determined that the application of plasma plays a significant role in the growth and germination of plants (31). Wang and colleagues' research results have shown that even 1-minute atmospheric pressure cold plasma treatment significantly promoted the growth of *Arabidopsis thaliana*. It depends on seed metabolism and external environmental factors. Plasma treatment accelerates the accumulation of plant abscisic acid (ABA) in the early stages of growth (32). ABA also regulates the concentration of calcium (Ca^{2+}) and RONS (such as OH, H2O2, NO2, and NO3). Active species are easily transported through the cell membrane. RONS also act as nutrients and signaling molecules in growth (31).

The effect of cold plasma on the production of phytochemicals

One of the primary effects of cold plasma on medicinal plants is the production of phytochemicals. Phytochemicals, such as alkaloids, flavonoids, and

Table 1. Summary of recent studies on the degradation of aflatoxins with different methods

Treatment Method	Results	Advantages	Disadvantages	Limitations	References
Heating at 150-180 ˚C for 1 h with conventional heating operations	70% degradation of AFB1	Effective in reducing aflatoxin levels in some foods	Nutrient loss, potential formation of toxic by-products	Limited to certain food types may not eliminate all aflatoxins	(28)
Microwave heating at 92 ˚C for 6 min	50%-60% degradation of AFB1 and AFB2	Effective in reducing and degrading aflatoxins in some foods	Requires high power level	The rate of microwave heating has little effect on aflatoxin degradation; degradation of aflatoxin obtained at a higher power level for a shorter treatment time or at a lower power level for a longer treatment time	(29)
Ozone	81%-95% reduction in aflatoxin	Fast reaction time, environmentally friendly	It may nutritionally degrade the product, and it may not be cost-effective	The application of ozone for aflatoxin degradation is limited in food products	
Cold plasma	80%-90% degradation of aflatoxins	Non-thermal maintains food quality, eco-friendly, effective on various food matrices	Equipment cost process parameters need optimization	It has some limitations for large-scale applications	(22)

phenolic compounds, are bioactive molecules responsible for medicinal plants' therapeutic properties.

In fact, the application of cold plasma creates stress reactions in plants and medicinal plants, which positively regulates secondary metabolite pathways and increases the synthesis of these valuable and important compounds. For example, previous studies have shown that cold plasma can increase the production of phenolic compounds and flavonoids, known for their antioxidant and anti-inflammatory properties.

Research has shown that the plasma effect mechanism, in this case, is due to the destruction of the cell membrane by active plasma species such as UV photons and charged particles, making extracting phenolic compounds from the plant easier. Also, applying cold plasma provides enough energy to break phenolic covalent bonds in polysaccharides. In addition, the hydration of ground plants can facilitate the extraction process due to the equal penetration of radicals in the entire surface of the sample (33,34). In a research, Pogorzelska-Nowicka et al (35) also stated that by applying atmospheric pressure to cold plasma, the decomposition of larger polyphenols into minor and smaller compounds can increase the total phenol content of the extract. Anthocyanin and flavonoid content also increase (35).

Other researchers have also determined that combining the ultrasonic method with cold plasma has worked very well as a pretreatment in the extraction of phenolic compounds compared to the ultrasonic method alone (36).

The effect of plasma on the control of pathogens and diseases

Cold plasma technology also offers a very efficient method of controlling pathogens and pests of medicinal plants so that reactive oxygen and nitrogen species produced by cold plasma can disrupt the cell structure of bacteria, fungi, and viruses. Slow down and cause them to be deactivated. This helps maintain medicinal plants' health and integrity without pesticides and harmful chemicals. This work results in acquiring clean, healthy, and safe plant materials for use in the pharmaceutical industry.

Reactive oxygen species (ROS) include superoxide ($O_2^{\bullet-}$), hydrogen peroxide (H2O2), hydroxyl radical (•OH), singlet oxygen (1O2), ozone (O3), alkoxyl (RO•) and peroxyl (RO2•). as well as nitrogen-based species (RNS), for example, nitric oxide (•NO), nitrogen dioxide (•NO2) and proximities (ONOO-). These active species (ROS, RNS = RONS) play an essential role in the inactivation of pathogens; in this way, they can disrupt the environment of cells and affect them (37,38).

Cold plasma treatment can reduce the microbial load and eliminate antibiotics. In fact, by disrupting the integrity of the membrane of these bacteria, cold plasma reduces the microbial load and deactivates bacteria and diseases.

Application and benefits of using plasma in eliminating aflatoxins in medicinal plants

Since plasma application is formed at a low temperature (usually close to the ambient temperature), it is suitable for medicinal plants sensitive to heat. Plasma, because it is a clean technology and does not introduce any chemical agents to medicinal plants or food and agricultural products, is a valuable method for detoxification. Also, plasma is a fast method that can be quickly applied to the desired product and perform the disinfection operation quickly. Most importantly, this method preserves the phytochemical content and the overall quality of medicinal plants, agricultural products, and food.

Aflatoxins detection methods

Since aflatoxins are poisons found in food, agricultural products, and medicinal plants, their detection is very important for safety and health. Several common methods for detecting this poison exist, including chromatography-based methods, immunoassay methods, spectroscopic methods, and biosensors.

Chromatographic technique

Chromatographic techniques are one of the

most common analytical methods for detecting aflatoxins. Chromatography techniques include gas chromatography (GC), liquid chromatography (LC), high-performance liquid chromatography (HPLC), thin layer chromatography (TLC) and high-performance thin layer chromatography (HP-TLC). Among these, LC, TLC and HPLC methods are more common. These techniques have excellent sensitivity in detecting aflatoxins but require skilled operators and expensive equipment.

Chromatographic techniques are based on the physical interaction between a movable phase (liquid or gas components) and a stationary phase (liquid or solid). Chromatography involves the separation of molecules in a mixture applied to a surface or a solid with the help of a movable phase. Because of the difference in molecular weight, certain parts of the mixture remain in the stationary phase and move slowly through the chromatographic system. In contrast, others enter the movable phase quickly and leave the system more quickly. Research conducted by Al-Gamal et al used the same technique to detect Aspergillus fungus in meat samples (22).

Due to the dangers caused by the presence of aflatoxins in unrefined olive oil in the Zanjan province of Iran, the HPLC method was used to detect aflatoxin B2 in oil samples (22). Also, due to the harmfulness of aflatoxin B1 for humans, especially children, and teenagers, and also due to the possibility of liver cancer, chromatography, and LC methods were used to detect aflatoxins in rice and nuts samples (18).

Immunoassay methods

Immunoassay methods, including ELISA, radioimmunoassay (RIA), and immunodipsticks, use specific binding of antigens and antibodies. Among these methods, the ELISA method is one of the most famous immunoassay methods and has excellent sensitivity. This method is a way to determine the amount of an antigen or antibody molecule. This method uses the solid phase to create a suitable substrate for antigen or antibody binding. Then, the enzyme attached to the antigen-antibody complex converts the suitable substrate into a colored product. The amount of conversion of the colorless substrate into a colored product by the enzyme, which indicates the presence of an antigen or an antibody and its concentration, is determined by measuring the optical density with a spectrophotometer.

The basis of ELISA work is that an antibody or antigen attached to an enzyme produces a colored product after reacting with its substrate, and a spectrophotometer measures its color change. Finally, according to the intensity of the color and the amount of absorption, the desired substance is estimated (reserved).

Since the presence of a very small amount of aflatoxins can cause serious risks and problems for human health, and also due to the high consumption of rice by the people of Iran, research conducted by Eslami et al used the ELISA method to determine the amount of aflatoxins in rice samples. This research showed that the amount of aflatoxin B1 detected by this method was higher than the permissible limit in 25 samples out of 40 (39).

Due to the increasing consumption of milk and dairy products by people and the presence of aflatoxin m1 in these livestock products, the need to detect the amount of aflatoxin in milk and dairy samples is felt more than ever. In research conducted by Al Amiri (20), the ELISA method was used to estimate the amount of AFM1 in milk, dairy products, and infant formula.

Spectroscopy methods

Various spectroscopic techniques include fluorescence spectroscopy, infrared spectroscopy (IR), terahertz spectroscopy (THz), and enhanced Raman spectroscopy (SERS). Zhongzhi et al (40) used a spectroscopic method to detect aflatoxins rapidly. The results of this research showed that spectrometry is a valuable tool in aflatoxins detection, and by using this method, aflatoxins can be determined in the range of 5 ppb to 5000 ppb in less than 5 minutes.

Infrared spectrometry is also a quick method to identify the desired samples. The wavelength of these waves is from 780 to 2500 nm and is known as a safety control and diagnosis method. When IR radiation penetrates the sample, the radiation is reflected, absorbed, or transmitted by molecular bonds, resulting in a change in light energy that can reflect some characteristic chemical bonds, thus reflecting the properties of the tested product. However, with the introduction of THz in this field, a great revolution took place, and it has a very high potential for detecting the desired samples.

THz has become a powerful technical tool in the food industry due to its strong detection capability. Researchers have developed a rapid non-destructive detection model for AFB1 in food by combining this method with chemistry. Although the accuracy is slightly lower than other conventional analysis methods, it enables THz in food safety diagnosis.

One advantage of the Raman technique is that it is fast, sensitive, and simple to detect and evaluate food. In recent years, researchers have reported a variety of SERS schemes to detect AFB1 in edible oil, such as SERS label detection using antibodies and aptamers, SERS-based sandwich immunoassay, etc. Growing research results show that SERS technology is becoming a powerful tool to ensure the development of food industry safety and aflatoxin detection.

Biosensors

A biosensor detects an analyte that combines a biological component with a physicochemical detector component. These sensors consist of 3 parts:

1. Sensitive biological elements or materials include tissue, microorganisms, organelles, cell receptors, enzymes, antibodies, and nucleic acids.

2. A transducer or detector element works physicochemically; its types are optical, piezoelectric, and electrochemical. It converts the signal resulting from the interaction of the analyte with the biological element into another signal that can be made easier.
3. The third part is the associated electronic or signal processors, which are mainly responsible for displaying the results in a user-friendly way.

Biosensors have been used to detect aflatoxin M1 in milk samples, and the results of this test have shown that biosensors perform well in evaluating and detecting aflatoxin M1 and have good reproducibility (41).

The advantages of using a biosensor (piezoelectric) in detecting aflatoxin b1 are its unique sensitivity, independence from markers and radiation, low cost, recyclability, reproducibility, and ease of on-site detection. This same sensor has been used to detect aflatoxins in grains, and it has been proven in all these cases. Also, according to this research, the disadvantages of using these biosensors were that they had little stability at high temperatures and were only used for dynamic evaluation (42).

Conclusion

Considering that the poison produced by *A. flavus* and Parasiticus, which is called aflatoxin, is harmful to human health, from children to adults, and even to the health of animals because this poison is found in agricultural products, plants, medicinal plants, and food, and it deals directly with food, it is felt that more studies and researches are needed in this field. Many methods have been used to destroy this poison, including chemical, biological, and physical. Cold plasma, a non-thermal method, has worked well among the techniques.

Unlike traditional thermal methods, this method preserves the nutritional and sensory qualities of food products, which can result in the loss of these qualities. Conventional heating methods, such as standard heat, can reduce aflatoxins by up to 70%, but often at the cost of nutritional degradation. Similarly, microwave heating shows a reduction of 50%-60%, which is less effective compared to cold plasma. Furthermore, while ozone treatment demonstrates a high reduction rate of 81%-95%, it can also lead to the degradation of food quality. It may not be cost-effective for widespread use.

The key advantage of cold plasma is its non-thermal nature, which prevents the degradation of food quality often associated with traditional heat treatments. Furthermore, it is a versatile and environmentally friendly option, effective across various substrates, including sensitive agricultural products and medicinal plants, without leaving harmful chemical residues. However, cold plasma is not without its disadvantages.

The equipment's high initial costs and the process's complexity, requiring precise control and specialized knowledge, present barriers to widespread adoption. Additionally, the scalability of cold plasma remains a significant challenge. While it has shown great promise in laboratory settings, scaling up for industrial applications is difficult, particularly ensuring uniform treatment across large volumes of products. The need for specific equipment and infrastructure may further limit its use, especially in resource-poor settings or industries with limited capital investment.

Looking forward, future studies should focus on optimizing the scalability of cold plasma technology to enhance its accessibility for industrial applications. Research into developing more cost-effective and portable equipment could make this technology feasible for broader use, particularly in developing countries. Additionally, long-term studies on the impact of cold plasma on various food matrices and its potential interactions with different food components could further clarify its effectiveness and safety. Exploring the combination of cold plasma with other decontamination methods could also provide synergistic effects, potentially enhancing overall efficacy and offering new solutions in the ongoing effort to ensure food safety.

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Competing Interests

The authors declare that there is no conflict of interest.

Ethical Approval

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