Mexican Journal of Phytopathology
e-ISSN: 2007-8080

Review Article

Postharvest control of mycotoxigenic phytopathogens in maize: Conventional methods and natural alternatives

Estefanía Martínez-Batista[1], **Surelys Ramos-Bell**[1], **Edson Rayón-Díaz**[1], **Gerónimo Díaz-Cayetano**[1], **Cyndia González-Arias**[2], **Juan Antonio Herrera-González**[3], **Javier Ireta-Moreno**[4], **Porfirio Gutiérrez-Martínez**[1*], [1]Instituto Tecnológico de Tepic, Laboratorio Integral de Investigación en Alimentos, Avenida Tecnológico 2595, Col. Lagos del Country, CP 63175, Tepic, Nayarit, México. [2]Universidad Autónoma de Nayarit, Laboratorio de Contaminación y Toxicología Ambiental, Los Fresnos s/n., C.P. 63175, Tepic, Nayarit México. [3]Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo experimental Uruapan, Av. Latinoamericana 1101, Col. Revolución, CP 60150, Uruapan, Michoacán, México, [4]Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Campo experimental Centro Altos de Jalisco, CP 2470, Tepatitlán de Morelos, Jalisco, México.

***Corresponding Author:**
Porfirio Gutiérrez-Martínez
pgutierrez@itepic.edu.mx

Section:
Periodical Issue

Received:
March 17, 2025
Accepted:
November 17, 2025
Published:
November 27, 2025
Early Access 2026

Citation:
Martínez-Batista E, Ramos-Bell S, Rayón-Díaz E, Díaz-Cayetano G, González-Arias C, *et al*. 2026. Postharvest control of mycotoxigenic phytopathogens in maize: Conventional methods and natural alternatives. Mexican Journal of Phytopathology 44(1): 101. https://doi.org/10.18781/R.MEX.FIT.2503-2

ABSTRACT

Justification. Seeds are the fundamental input for agriculture and food production. Recently, an increase in the demand for maize grain production has been observed; however, annual postharvest losses range between 10 and 40%. The objective of this review is to present the main mycotoxin-producing fungi (genera/species) associated with maize grain during storage, as well as to analyze the conventional control methods and natural alternatives that have been applied to date.

Theoretical and Experimental framework. Bibliographic information was compiled on the main fungal pathogens that develop in maize grain and the most commonly employed control methods. The principal fungal genera detected in maize grain are *Aspergillus*, *Penicillium* and *Fusarium*, all of which are important mycotoxin-producing fungi. Traditional physical and chemical control methods have been used; however, their application often fails to guarantee effectiveness and biosafety. The use of natural alternatives, as well as their combination, has shown positive effects in controlling these phytopathogens and inhibiting mycotoxin production.

Conclusions and Perspectives. One of the main causes of losses and quality deterioration in maize grain is the development of mycotoxin-producing fungi and, consequently, the generation of highly toxic secondary metabolites. To prevent the deterioration of store grain, traditional practices have been employed, such as grain cleaning, aeration at low temperatures, and the use of physical and chemical treatments (synthetic fungicides). Currently, the development of eco-friendly alternatives is one of the primary goals to reduce the use of agrochemicals on seeds and grains, in order to promote more sustainable agricultural systems.

Keywords: Maize, Fungi, Mycotoxins, Storage, Alternative control

INTRODUCTION

Maize (*Zea mays*) is the world's second most widely-grown cereal, with an annual production of 1,230,241 tons. Mexico is the eight largest producer, with a total of 24,000 tons (United States Department of Agriculture-USDA, 2024). In Mexico, maize is of great relevance, since it is the main agricultural cereal and an important component in the diets of people due to its large contribution of nutrients such as essential fatty acids, carbohydrates and proteins, mainly (United Nations Food and Agriculture Organization-FAOSTAT, 2023). Additionally, it is a prominent source of income due to the marketing of livestock feed, industrial products and biofuels.

After being harvested, maize is exposed to variable environmental conditions that jeopardize grain quality, from storage to food processing and production (Abdullahi and Dandago, 2021; Fleurat-Lessard, 2017). Losses in storage can be considerable and are usually caused by different factors such as physiological deterioration, mechanical damage, inadequate management and hygiene practices postharvest, as well as the presence of pests (Moumni *et al*., 2023; Odjo *et al*., 2022).

Grains constitute a favorable environment as a source of energy and a habitat for the colonization of heterotrophic organisms including fungi, bacteria, insects and mites. The main problem with the deterioration of stored maize grains is usually insect attacks. In spite of this, the presence of phytopathogenic fungi causes greater losses postharvest (SAGARPA *et al*., 2016).

One of the main concerns behind the incidence of fungal pathogens in the grain lies in their impact on innocuousness (Carvajal-Moreno, 2022). Additionally, food security is compromised by the capacity of some strains to produce mycotoxins. These metabolites have been related to acute intoxications and chronic diseases that affect vital organs such as the kidneys, liver and lungs, as well as alterations in the immune system, nervous system, genotoxicity and carcinogenesis (Abrehame *et al*., 2023). For this reason, there are legislations and regulations worldwide that help reduce its exposure, through maximum limits permitted in foods (USDA, 2024; Regulation (EU) 2023/915; NOM 188; NOM 247).

Traditional, physical and chemical technologies have been used to preserve the quality of grain during storage. However, recent investigations have focused on the development and application of clean technologies, natural in origin, aimed at controlling fungal species in the grain and preventing the synthesis of mycotoxins (Hamad *et al*., 2023; Fleurat-Lessard, 2017). The aim of this review was to point out the main genera of phytopathogenic fungi related to maize grains during their storage in Mexico, with the potential to produce mycotoxins. Likewise, a bibliometric analysis of the conventional (chemical and physical) and alternative treatments that have been applied for fungal control, and the reduction or elimination of mycotoxins, in order to know and strengthen the identification of mycotoxigenic species, their implications on human health and the integrated management strategies that reduce the problems presented by maize in the postharvest stage in Mexico.

Main fungal genera related to the maize grain

The main filamentous fungi that grow on maize are widely distributed and are distinguished by their role in nature, related with the decomposition of organic matter in the soil due to their high saprophytic capacity (Pitt *et al*., 2012). Some of the main genera identified as maize pathogens are *Aspergillus, Penicillium* and *Fusarium* (Erasto *et al*., 2023; Qi *et al*., 2023).

These fungi have the capacity to generate losses of dry matter and inhibit germination in the seed, causing the temperature of the grain cortex to rise, as well as a reduction in their nutritional value (Fleurat-Lessard, 2017). On the other hand, some fungal species have the ability to produce highly toxic secondary metabolites known as mycotoxins, which are biosynthesized and excreted through a set of metabolic pathways that are not essential for growth or the survival of the microorganism (García-Cela *et al*., 2022; Bartholomew *et al*., 2021).

The species of *Aspergillus* present fast growth and a diversity of colors, which can vary from whitish, yellowish-green, to brownish-black in color, and present granular textures and aspects (Figure 1A-D). A relevant characteristic is its ability to develop with a low humidity content (a minimum of 13% in cereals) and a relative humidity of 78 to 80%, as well as a broad interval of temperatures, which ranges from 0 up to 55 ºC (Pérez *et al.*, 2021; Pitt *et al*., 2012).

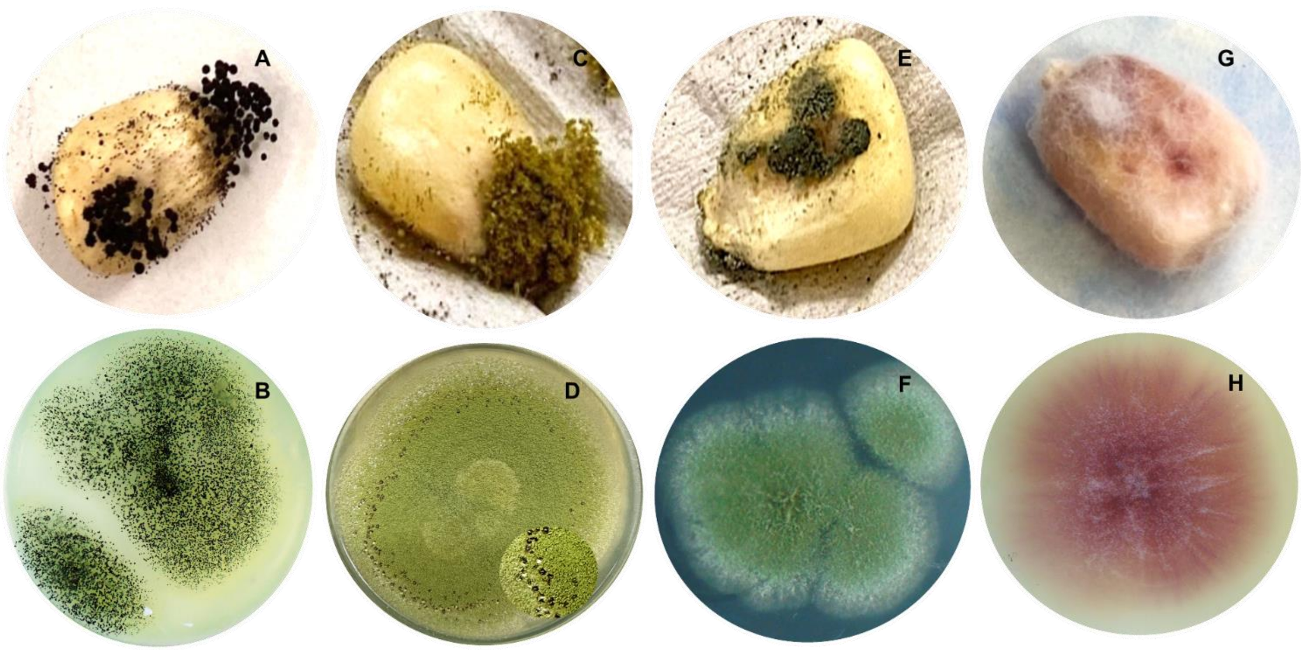

Figure 1. Mycelial characteristics in PDA medium and in maize grains of postharvest fungi; **A-D**) Genus *Aspergillus*; **E-F**) Genus *Penicillium*; **G-H**) Genus *Fusarium*.

Likewise, the species of *Penicillium* also grow quickly, developing green, bluish or gray colors and cottonlike, velvety and thread-like textures (Figure 1E-F). Its optimum growth is at temperatures between -2 to 50 ºC, with a relative humidity of 85 to 90% and a humidity content of 16% (Pérez *et al.*, 2021; Pitt *et al*., 2012). Species such as *A. flavus, A. parasiticus, P. funiculosum* and *Penicillium verrucosum* are called storage fungi, since they grow under conditions with low water activity. Unlike some *Fusarium* species, they are classified as field fungi (*F. graminearum* and *F. verticillioides*), since they invade the maize grains before harvest (Krnjaja *et al*., 2021; Adeniji and Babalola, 2018), as well as requiring more humid conditions for their development, a relative humidity of 90 to 95%, humidity contents in the grain between

20 and 22% and a temperature range from 5-35 ºC (Akbar and Alam, 2019). *Fusarium* characteristically presents mycelia with colors that can be white, beige, orange, red, purplish-pink, and others, as well as having cottonlike aerial textures (Figure 1 G-H) (Torre-Hernández *et al*., 2014; Pitt *et al*., 2012).

Mycotoxins

Mycotoxins are potentially toxic chemical metabolites than can cause adverse effects on human and animal health; the presence of one or more metabolites can lead to synergetic or additive effects (Carvajal-Moreno, 2022; International Agency for Research on Cancer [IARC], 2002). There are 5 groups of mycotoxins (1, 2A, 2B, 3, 4) that have an important economic and toxicological impact on the production of grains and cereals, as well as on health (IARC, 2002). The main mycotoxins are aflatoxins (AFL), ochratoxins (OTA), trichothecenes (deoxynivalenol and nivalenol), zearalenone (ZEA) and fumonisins (Wang *et al*., 2024; Krnjaja *et al*., 2022; IARC, 2002). Specifically, aflatoxin B1 (AFL B1) is classified as carcinogenic for humans due to its mutagenic effect and carcinogenicity in living organisms (group 1) as it binds to DNA, RNA and proteins. Unlike OTA and fumonisin B1 (FB1), they are classified as possibly carcinogenic for humans (group 2B) (Carvajal-Moreno, 2022; IARC, 2002). The presence of these metabolites has created great concern and problems, which is why diverse government regulations have been implemented to reduce and avoid the risk of contamination in the processing of cereals (USDA, 2024; Regulation (EU) 2023/915; NOM 188; NOM 247).

The main species with the ability to synthesize mycotoxins belong to the genera of *Aspergillus*, *Penicillium* and *Fusarium*, the main ones being *A. flavus*, *A. parasiticus* and *A. nomius* for the production of AFL B1; *P. verrucosum* produces OTA and *F. verticillioides*, as well as *F. proliferatum* produce FB1 (Wang *et al*., 2024; Carvajal-Moreno, 2022; IARC, 2002). However, one type of mycotoxins can be synthesized by different species and a particular strain can produce different mycotoxins (Carvajal-Moreno, 2022; García-Cela *et al*., 2022). Factors such as substrate type (maize, wheat, sorghum), dissemination of the fungal inoculum by insects and mites, the time between the harvest of humid cereals and the drying process, the initial humidity content of the grains harvested, storage time (months), accidental or environmental rehydration of the grain in storage, as well as the interactions and physiological state of the pathogens (strain variability, age, etc.) have an influence on the development of fungi and the production of mycotoxins; nevertheless, the main factor is water (García-Cela *et al*., 2022; Akbar and Alam, 2019; Fleurat-Lessard, 2017). For this reason, an adequate management of the previously mentioned factors before and during the harvest can prevent the presence of phytopathogens and the contamination by their toxic metabolites.

Control methods

For many years, synthesis fungicides have been used to control fungi, and this practice has also been very common globally. Nevertheless, it has been shown that diverse pathogens generate resistance to these compounds, as well as the significant risks they cause in food security and the environment, since they contaminate bodies of water and soils (Fleurat-Lessard, 2017; IARC, 2002). At the same time, physical methods have been frequently implemented during postharvest handling, most notably, grain cleaning and the control of moisture and temperature through low-temperature aeration. However, these strategies are not enough to mitigate the deterioration of the maize grain (Fleurat-Lessard, 2017).

Regarding an early detection of the growth of mycotoxigenic fungi, devices such as CO_2 microsensors have been used during storage as an effective alternative to detect the beginning of grain deterioration, although its high cost limits its accessibility (Vijaykumar *et al*., 2024; Fleurat-Lessard, 2017). Nowadays, the use of biocontrol agents with beneficial microorganisms and basic substances such as essential oils, plant extracts and salts are frequently used, since the elimination of fungal pathogens and the prevention of toxicological problems presented by conventional pesticides has been proven (Zhang *et al*., 2024; Hamad *et al*., 2023).

In this sense, a bibliometric analysis was performed in order to explain recent trends in treatments applied for the postharvest control of potential phytopathogens that can potentially produce mycotoxins in maize grains. Information was gathered through the ScienceDirect data base, covering the period between the years 2019-2024. The keywords used for the search were: “maize,” “chitosan,” “biological control” and “essential oils,” which gave a total of 3,132 publications. Subsequently, using the software package VOSviewer ® version 1.6.19, a bibliometric mapping was carried out based on the data obtained. As a result, a network visualization map was produced (Figure 2), which helped identify seven thematic groups or related research clusters. Every group is represented in a different color, and its size is relative to the amount of information available on it; the larger the circle, the greater the amount of information, whereas the distance between one group and another indicates how closely they are related.

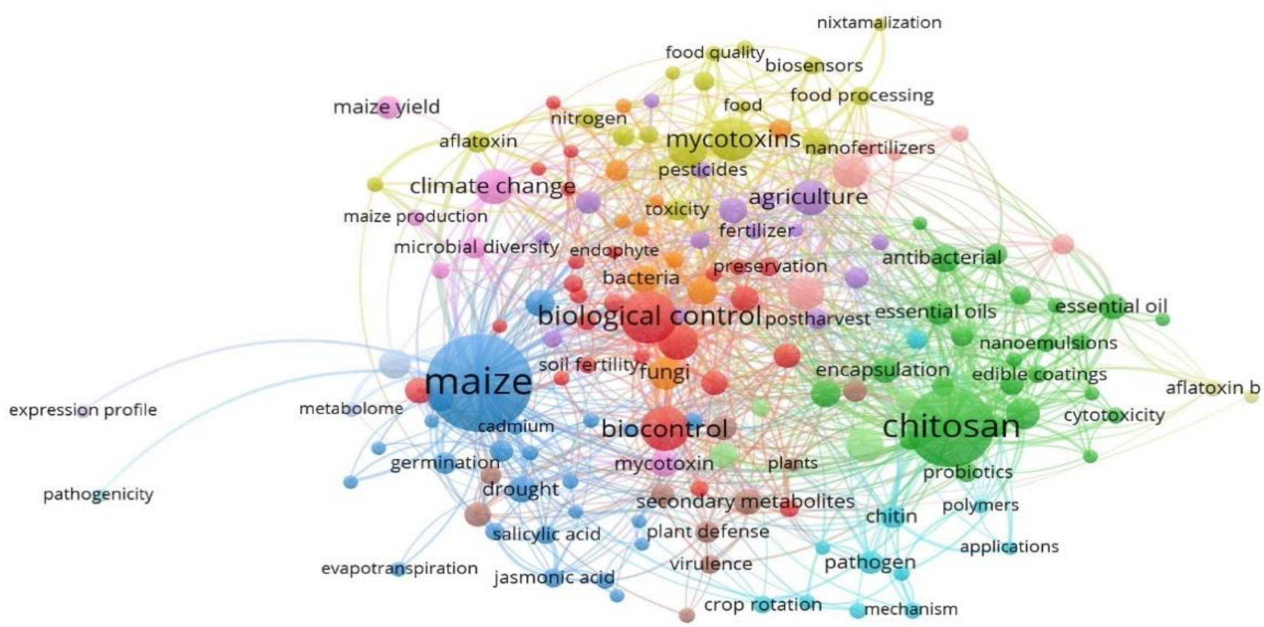

Figure 2. Visualization of the bibliometric analysis network (VOSviewer® version 1.6.19) using keywords “maize”, AND, “biological control”, OR, “chitosan”, OR, “essential oil”.

The bibliometric analysis shows that there is still a limited number of studies related to maize and the use of alternative treatments. In the case of the “chitosan” and “maize” groups, there is a large amount of information. However, these are not directly connected, since the bibliographic information reported focuses on the treatment in the field and not during storage. Similarly, the investigations related to essential oils and microorganisms do not show a direct relation within the network, which suggests more studies focused on the application of biocontrol agents in postharvest for the control of fungi and the production of mycotoxins in maize grains.

Physical methods

The application of the physical methods ranges from simple procedures such as grain cleaning by brushing, abrasion and pearling, to the use of sophisticated equipment that can help control variables such as temperature and humidity (Fleurat-Lessard, 2017). Although favorable conditions can be reached for the storage of grains, keeping grains dry, healthy and clean in time is challenging (Wang *et al*., 2024).

Some of the most noteworthy and widely used physical methods to control phytopathogens during the storage of grains include aeration at low temperatures, thermal treatments applying hot water or air and irradiation (Moumni *et al*., 2023). Particularly, irradiation treatments (gamma, ultraviolet rays) have proven to be effective in reducing and even inhibiting pathogens by inducing damages in the genetic material and their resulting cell death, significantly reducing the production of mycotoxins (Moumni *et al*., 2023; Tiwari *et al*., 2022; Khalil *et al*., 2021). However, their application has been limited due to the possible adverse effects on the quality of the grain, since its action mechanism can also affect viable maize seeds, thus compromising its nutritional and functional properties (Tiwari *et al*., 2022; Khalil *et al*., 2021).

On the other hand, physical methods can be used alongside other technologies such as modified atmospheres, with the application of gases such as carbon dioxide, nitrogen, ozone, noble gases (argon and helium), hydrogen, and others (Odjo *et al*., 2022; Riudavets *et al*., 2018). The use of ozone has been proven to reduce the growth of *Aspergillus* spp., *Fusarium* spp. and *Penicillium* spp. between 98 and 99%, respectively (Tiwari *et al*., 2022). Despite this, its use has been affected due to the alterations caused in sensorial and nutritional properties of the grain, such as changes in color, flavor and nutritional content, as well as the high cost related to implementing this type of treatments to adapt on a large scale (Moumni *et al*., 2023; Romanazzi *et al*., 2022).

Chemical methods

Applying chemical compounds, such as synthesis fungicides, continues to be one of the main practices in agriculture due to its easy access and initial effectiveness (Bartholomew *et al*., 2021). Nevertheless, its indiscriminate use at high doses has mainly caused the resistance of pathogens, contamination in grains with toxic residues and adverse effects on health and the environment. In addition, another disadvantage of these treatments is that they require the use of specialized equipment to be applied, as well as trained personnel, which can be expensive (Pereira *et al*., 2024; Costa-Becheleni *et al*., 2020).

Chemical products regularly change their commercial names, but their active ingredients are the same or some have the same fungicidal effect. Among the most widely-used compounds for the control of the development of phytopathogens in maize grain during postharvest are captan, thiram, carboxin, benomyl, quintozene and chloroneb (Dell'Olmo *et al*., 2023; Hollomon, 2015; Hernández and Carballo, 2017). In Mexico, the most widely-used fungicides are benomyl, iprodione, captan and fungicides of the carbamate group (Godínez *et al*., 2023; Ruíz *et al*., 2022).

Fungicides can be classified using different criteria, one of the most common being their form of action. In this sense, three main types can be distinguished: contact, systemic and translaminar fungicides (Hollomon, 2015; Hernández and Carballo, 2017). Systemic fungicides present greater toxicity, since they have a wider spectrum of activity. After being absorbed by the plant tissue, these compounds reach internal structures of the cells, which gives them the ability to act against a wide variety of organisms, from microorganisms to higher organisms. The main action mechanisms include the alteration of the cell membrane, the inactivation of enzymes, the alteration of breathing processes and the alteration of the genetic material or related structures. For example, benomyl is a systemic fungicide and its form of action is performed with the inhibition of cell mitosis through bonding with tubulin, thus affecting the cell and nuclear division, which finally leads to cell death (Hollomon, 2015; Hernández and Carballo, 2017).

It is worth mentioning that the toxicity stated in the fungicide containers is based on lethal dose 50 (LD50) taken orally (WHO, 2019). This measure reflects only acute toxicity, not considering the possible effects of chronic toxicity reported in the literature. Alongside this, the use of mixtures of active ingredients must be carefully considered, since these compounds can interact with each other and strengthen the long-term toxic effects (Godínez *et al*., 2023; Ruíz *et al*., 2022).

Biological methods

Control with biological methods is an important strategy to reduce the prevalence of fungal diseases in different crops. This method is based on the application of beneficial microorganisms or compounds derived from them, in order to inhibit the development of phytopathogens and prevent economic losses (Ali *et al*., 2024; Heliyon *et al*., 2024). In addition, they are a secure alternative to the use of synthetic fungicides, since these agents can act directly on the pathogens or contribute to the degradation of mycotoxins (Vijaykumar *et al*., 2024; Dell'Olmo *et al*., 2023; Orzali *et al*., 2023; Romero *et al*., 2022; Bartholomew *et al*., 2021).

Beneficial microorganisms. Biocontrol agents have been used as alternative control methods during the preharvest and postharvest stages. In Mexico, the most commonly used beneficial microorganisms are mainly fungi of the genus *Trichoderma;* and among bacteria, species such as *Bacillus subtilis, B. pumilus, B. thuringiensis,* among others (Table 1). Approximately 230 bioproducts are available, registered in COFEPRIS in the Mexican market. However, despite the significant advances in the identification and development of new biological control agents, their adoption in the field is limited due to factors such as the scarcity of information on the real efficiency of the bioproducts, or the little availability of the products, related to the limited number of active ingredients developed for each taxonomic group. These limitations contribute to the lack of awareness and the low acceptance of farmers towards the use of bioproducts

(Lahlali *et al*., 2022; Córdova-Albores *et al*., 2021). Table 1 shows the different microorganisms used recently in the control of phytopathogens transmitted by maize grains, such as microorganisms (fungi, bacteria and yeasts).

Basic substances. Numerous studies suggest the antifungal activity of substances derived from natural sources such as chitosan, salts, essential oils or plant extracts to extend the shelf life of various horticultural products (Minozzo *et al*., 2023; Terefe *et a*l., 2023; Chrapaciene *et al*., 2022; Ghule *et al*., 2021;). However, in maize grain storage, the application of these compounds is more limited and the information available is scarce (Figure 2).

Table 1. Microorganisms used to inhibit the growth of phytopathogens transmitted in maize grains.

Microorganisms	Inhibition of phytopathogens	Result	Reference
Fungi			
Trichoderma sp.	*F. oxysporum* *A. niger*	73-87% mycelial inhibition	Vijaykumar *et al*., 2024; Prasad *et al*., 2020
T. gamsi	*F. verticillioides*	72% mycelial inhibition Reduction in fumonisin content	Galletti *et al*., 2020
T. asperellum	*F. verticillioides*	88.71- 100% mycelial inhibition	Cuervo-Parra *et al*., 2022
Aspergillus flavus (atoxigenic strains)	*A. flavus*	80% Reduction in AF	Zhang *et al*., 2024; Fleurat-Lessard, 2017
Bacteria			
Bacillus sp.	*Talaromyces funiculosus*		Yang *et al*., 2020
	P. oxalicum		
	F. verticillioides	Decrease in fumonisin	Yang *et al*., 2020; Guimaraes *et al*., 2020
Yeasts			
Cyberlindnera jadinii	*A. flavus* and *A. niger*	Reduction in growth and sporulation	Alkuwari *et al.*, 2022
Debaryomyces hansenii	*Aspergillus* sp. *F. proliferatum* and *F. subglutinans*	59.8% Reduction in fumonisin	Medina-Córdova *et al*., 2016

Essential oils are extracted from aromatic plants and are composed of bioactive ingredients such as alkaloids, phenols, terpenes and organic acids, to which their antifungal activity has been attributed (Chen *et al*., 2023). The composition and concentration of these phytochemicals can vary in each essential oil; in general terms, they can have two or three major compounds and tens of minor ones. However, applying all the compounds of the essential oil has been proven to boost the inhibiting effect against the development of the pathogens, in comparison with the use of only one compound (Taheri *et al*., 2023; Romero *et al*., 2022). Likewise, essential oils have been effective to inhibit the production of mycotoxins (Chen *et al*., 2023; Minozzo *et al*., 2023; Qi *et al*., 2023; Gwiazdowska *et al*., 2022; Oliveira *et al*., 2020). Terefe *et al*. (2023) evaluated the anti-fungal effect of different plant extracts, *Artemisia glacialis*, *Cymbopogon citratus*, *Punica granatum*, *Rosmerinus officinalis*, *Ruta chalepensis* and *Thymus vulgaris,* which inhibited the mycelial growth, sporulation and germination against *F. verticillioides.* Likewise, Iwayemi *et al*. (2024) tested cinnamon (*Cinnamomum verum*), clove (*Syzygium aromaticum*), oregano (*Origanum vulgare*) and thyme (*Thymus vulgaris*) essential oils on the mycotoxigenic fungi *Aspergillus*, *Penicillium* and *Fusarium.* The results showed that the inhibition of the anti-fungal activity and reduction in the production of aflatoxins were reliant on the increase of the concentrations, until it reached an inhibiting effect of 100% in the maize grain stored at 25 ºC for 42 days.

In recent years, broad-spectrum essential oil-based botanical fungicides have been developed and registered in Mexico for agricultural use. An example of this is the fungicide Sporan (Registered: RSCO-MEZC-FUNG-0910Q-X0073-009-38.00), which contains a mixture of bioflavonoids of the essential oils of clove, rosemary (*Salvia rosmarinus*), thyme and mint (*Mentha piperita*). The registration and marketing of this botanical fungicide responds to the need to search for the development of safe and eco-friendly alternatives.

Another compound that stands out as a control agent, alternative to the use of synthetic fungicides in maize is chitosan; its efficiency has been proven un diverse crops such as avocado (*Persea americana*), mango (*Mangifera indica*), cranberry (*Vaccinium corymbosum*), cereals, and others (Rayón-Díaz *et al.*, 2025; Romanazzi *et al*., 2024; Ramos-Bell *et al*., 2023; Herrera-González *et al*., 2022; Ghule *et al*., 2021). Its application not only contributes to the control and inhibition of phytopathogenic fungi, but also improves seed quality, induces defense mechanisms, favors germination and vigor in seedlings (Martínez-Batista *et al*., 2024; Saberi *et al*., 2024; Carvalho *et al*., 2020; Gutiérrez-Martínez *et al*., 2020). Chitosan is a biopolymer composed of long N-acetyl-glucosamine and D-glucosamine chains, and is obtained from the partial deacetylation of chitin, a polysaccharide found in the exoskeleton of insects and crustaceans, as well as in the cell wall of fungi (Mukarram *et al*., 2023; Debnath *et al*., 2022). This compound is characterized for being biodegradable, biocompatible, non-toxic, with the ability to form semi-permeable films, as well as for displaying anti-microbial activity for both its direct interaction with phytopathogens and its ability to stimulate metabolic pathways and the expression of genes related to the defense mechanisms in fruits and grains. Its antimicrobial efficiency is mainly related to its physio-chemical characteristics, such as the degree of deacetylation and molecular weight, although other factors can also have an influence, such as the type of chitosan (native or modified), the host, the pH of the medium and weather conditions (Saberi *et al*., 2024; Mukarram *et al*., 2023; Debnath *et al*., 2022). The molecular structure of chitosan is versatile, allowing its chemical modification to generate certain derivatives of chitosan, thanks to the presence of active functional groups such as hydroxyls and aminos (Saberi *et al*., 2024; Mukarram *et al*., 2023). These modifications are an efficient way to optimize its physio-chemical characteristics, without compromising its unique biological properties (Jiménez-Gómez and Cecilia, 2020). The current study of chitosan has been extensive, and has led to searches for new application techniques, as well as the combination with other additives such as beneficial microorganisms, essential oils and other natural compounds, with the purpose of obtaining a more efficient control during the storage of grains (Vijaykumar *et al*., 2024; Godana *et al*., 2020; Wu *et al*., 2019).

Action mechanism of biocontrol agents

The previous application of biocontrol agents has proven to prevent the growth, sporulation and germination of the spores of pathogens such as *Fusarium, Aspergillus* and *Penicillium,* due to them being directly involved in the antifungal activity and indirectly in the activation of the grain defense system, which helps reduce the infection with a highly toxic effect (Figure 3) (Chen *et al*., 2023; Sharma *et al*., 2023).

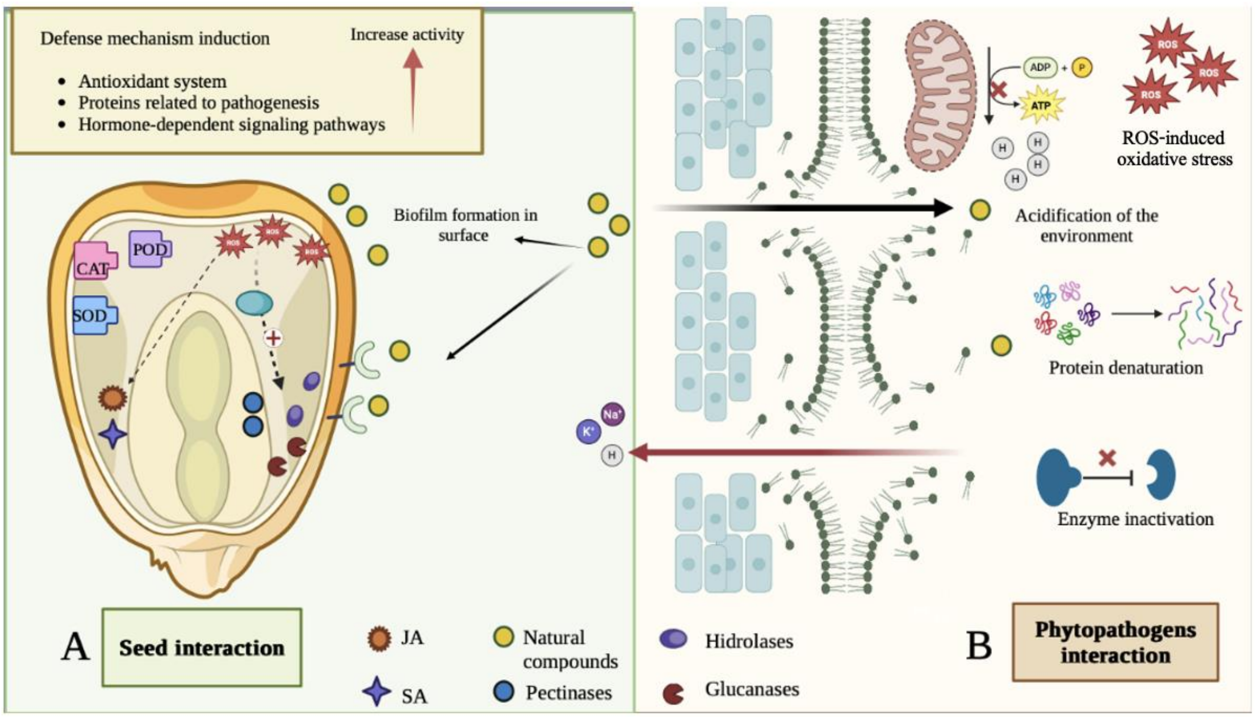

Figure 3. Action mechanisms of basic substances. **A**) Interaction with seeds: Activation of the defense mechanisms and biofilm formation. **B**) Interaction with phytopathogens: antifungal effects caused mainly by the interaction of the basic substances with the cell wall and membrane of the pathogen. RP (Related to Pathogens), JA (jasmonic acid), SA (salicylic acid), ROS (Reactive Oxygen Species), POD (Peroxidase), CAT (Catalase), SOD (Superoxide dismutase). Own creation, made using the program BioRender.

Antifungal activity takes place mainly due to the interaction between the compound and the phytopathogen. Because phytochemical compounds have liposoluble characteristics, they can join and damage the cell wall and membrane of the pathogen (Minozzo *et al*., 2023; Qi *et al*., 2023; Shabir *et al*., 2023). Similarly, due to its polycationic nature, chitosan can interact, through its amino group, with the groups of the cell wall, negatively charged (glucans, chitin) or in the cell membrane (phospholipids) of the pathogen (Vijaykumar *et al*., 2024). This interaction causes membrane permeability, affecting the transportation of ions and the absorption of nutrients (Figure 3). Damage to the shape and integrity of the fungal cells, such as severe contraction, rugged surface and partial collapse of the membrane, can trigger a cascade effect on other cell structures, such as the cytoplasmic vacuolization, enzyme deactivation, the denaturation of cellular proteins and changes in the endoplasmic reticulum and mitochondria (Vijaykumar *et al*., 2024; Terefe *et al*., 2023; Ghule *et al*., 2021; Saberi *et al*., 2014). In particular, the phytochemical compounds have been related to the mitochondria for being the target structure, with effects such as mitochondrial disfunction, which leads to a reduction of the activity of the ATPase accumulating protons within the cell and an intracellular acidification (Figure 3) (Taheri *et al*., 2023; Terefe *et al*., 2023; Gwiazdowska *et al*., 2022; Oliveira *et al*., 2020; Boukaew *et al*., 2017). After the chitosan enters the cell, it can interact with the nucleus of the pathogen and join the DNA, and thus affect its replication, and consequently, the protein and mRNA synthesis. All these effects finally lead to the cellular death of the pathogen (Saberi *et al*., 2024; Mukarram *et al*., 2023). In terms of beneficial microorganisms, the main inhibition mechanism in the growth of phytopathogens is due to the competition for space-nutrients (Figure 4A) (Oztekin *et al*., 2023; Romero *et al*., 2022).

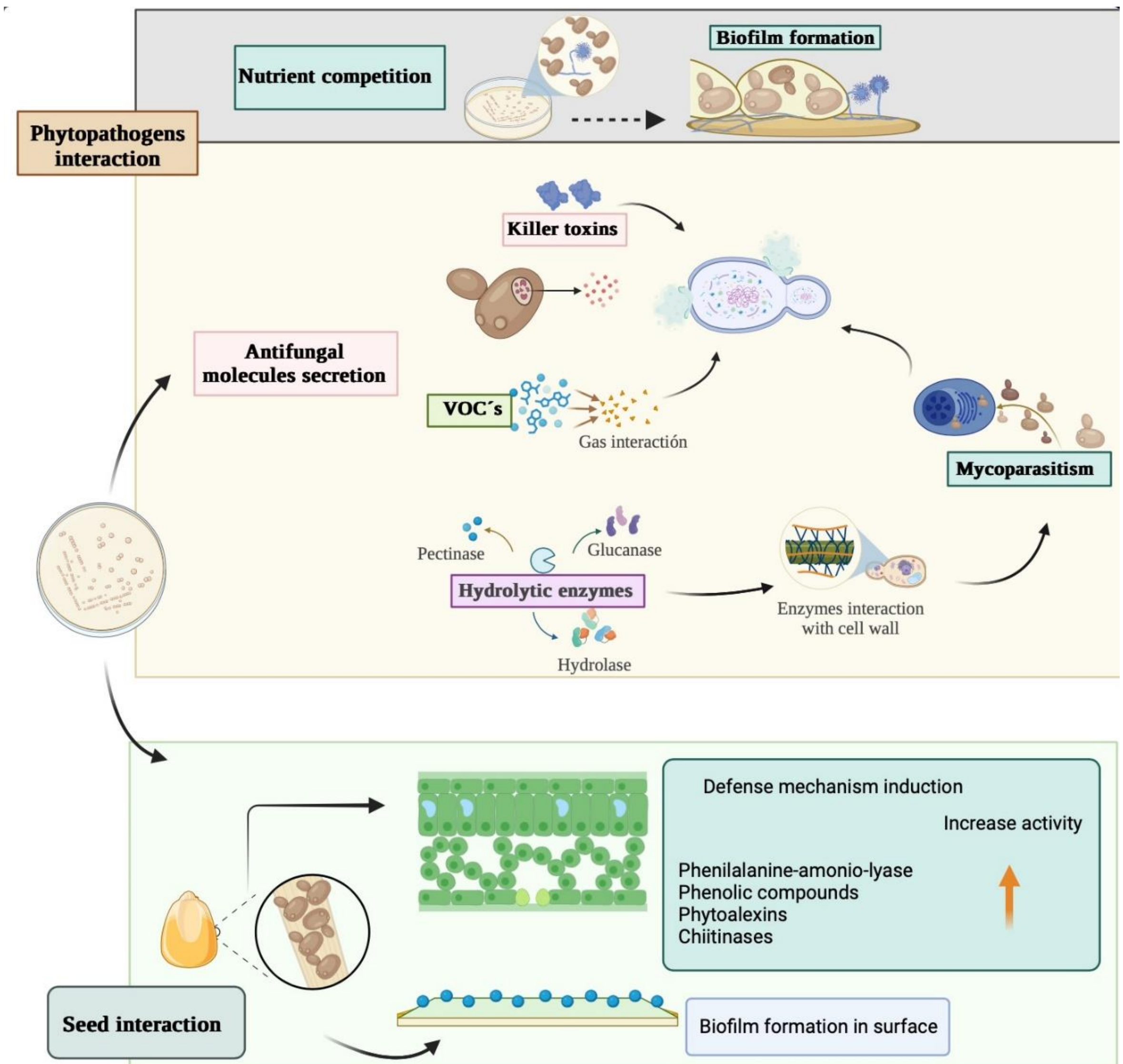

Figure 4. Action mechanisms Beneficial microorganisms. **A**) Interaction with phytopathogens. **B**) Interaction with seeds. Image created using the program BioRender.

Likewise, the secretion of antimicrobial as killer toxins, volatile organic compounds (VOCs) and hydrolytic enzymes (pectinases, glucanases and chitinases) is considered another important mechanism of beneficial microorganisms (Figure 4A) (Oztekin *et al*., 2023; Sharma *et al*., 2023). VOCs are being widely studied for their ability to inhibit the development of fungal pathogens, even at low concentrations. Their volatile nature helps them diffuse easily in different environments, without the need for direct contact with the pathogen (Vijaykumar *et al*., 2024). VOCs are produced as a competition strategy and its antimicrobial activity is related to its easy absorption or interaction in the cell membrane of the pathogen (Figure 4A). This interaction increases membrane permeability, the diffusion of ions and metabolites, resulting in the loss of homeostasis (Vijaykumar *et al*., 2024; Oztekin *et al*., 2023). Likewise, the hydrolytic enzymes secreted by beneficial microorganisms act directly on the cell wall of the pathogen, causing irreversible structural damage that results in cell lysis (Figure 4A) (Sharma *et al.,* 2023). The production of these enzymes is also associated to mycoparasitism (Figure 4A), a mechanism through which the beneficial microorganism colonizes and invades the hyphae of the pathogen, using them as a source of nutrients (Vijaykumar *et al*., 2024; Oztekin *et al*., 2023; Sharma *et al*., 2023).

On the other hand, some biocontrol agents can act as a coating or form biofilms on the surface of the grain (Figure 3A and 4B). This mechanism affects the development of the phytopathogen by limiting the availability of nutrients, as well as preventing the entry or its establishment in the grain (Debnath *et al*., 2022). An example of this is applying yeasts, which can form biofilms in a short amount of time, favoring the colonization and ability to efficiently absorb carbon sources found in the medium; thus, they limit the disposition of nutrients for the optimum development of fungal pathogens (Vijaykumar *et al*., 2024). Likewise, the coatings form a physical barrier on the grain that controls the humidity by reducing water loss, reduces respiration rate, regulating the gas exchange (low oxygen availability) and activates the defense mechanisms (Saberi *et al*., 2024; Debnath *et al*., 2022). Regarding the activation of the defense mechanisms in the maize grain, the application of biocontrol agents improves the resistance against phytopathogens (Prusky and Romanazzi, 2023). At a systematic level, the interaction of the agent with the surface of the grain unleashes multiple signaling pathways that positively regulate the expression of genes related to the induced resistance (Figure 3A y 4B) (Sharma *et al*., 2023). During this mechanism, secondary metabolites with protective functions are synthesized, including pathogenesis-related (PR) proteins such as chitinase and glucanases, phytoalexins, phytohormones (jasmonic acid [JA], ethylene [ET], salicylic acid [SA]), as well as enzymatic antioxidants (superoxide dismutase [SOD], peroxidase [POD], catalase [CAT], polyphenol oxidase [PPO] and phenylalanine ammonia-lyase [PAL]) that help alleviate oxidative stress (Chen *et al*., 2023; Shabir *et al.*, 2023; Taheri *et al*., 2023). These physiological changes give the grain the protection against a broad spectrum of pathogens and help maintain its quality during storage (Prusky and Romanazzi, 2023; Lahlali *et al*., 2022).

The effect on the production of mycotoxins has been associated with ancillary effects related to inhibiting the phytopathogen; however, research shows that fungal growth effects do not always correlate with the inhibition of mycotoxin synthesis (Haggag *et al.*, 2023; Jian *et al*., 2022). Its reduction can also be related with a low expression of genes related to biosynthesis, the activation of metabolic processes such as the generation of ROS (reactive oxygen species) or the catabolism of carbohydrates that are associated with the biosynthesis of mycotoxins (Zhang *et al*., 2024). Jian *et al*. (2022) proved that essential oils can completely inhibit the production of mycotoxins, inhibiting mycelial growth very scarcely.

Another way to decontaminate mycotoxins in the maize grain by applying biocontrol agents is with its degradation; this means that the interaction of some compounds can degrade or modify the structure of mycotoxins, generating less-toxic metabolites (Wachowska *et al*., 2023). For example, Anjum *et al*. (2020) report that some bioactive compounds, when interacting with aflatoxin, can remove the double bond of the furan ring and modify its structure, which will generate new non-toxic compounds. Particularly, with beneficial microorganisms, the inhibition of mycotoxins can also be achieved with the adhesion of the toxin to the components of the cell wall of the antagonist (Oztekin *et al*., 2023). Adsorption is a reversible physical-chemical process, but its effectiveness depends largely on structural, physical morphology and composition of the cell wall (Zhang *et al*., 2024; Oztekin *et al*., 2023; Papp *et al*., 2021).

Conclusions and Perspectives

The deterioration of the maize grain during storage, particularly due to the action of fungi and the production of mycotoxins, continues to be a challenge for food security. The main fungi related to this problem belong to the genera *Aspergillus, Penicillium* and *Fusarium*, which stand out for their ability to synthesize mycotoxins, and some of these are classified by IARC for their toxicological importance. Among these, aflatoxin B1 is especially relevant for its high toxicity and classification as a human carcinogen. Despite the efforts aimed at ensuring safe maize production and storage in Mexico—including the implementation of official standards that establish the sanitary requirements and specifications that must be met during the postharvest stage, the permissible limits for mycotoxin concentrations, and the application of Hazard Analysis and Critical Control Points (HACCP) in control systems—contamination by fungi and mycotoxins remains a recurring problem. Conventional technologies used to mitigate these effects present limitations that derive from factors such as microbial resistance, the persistence of chemical residues and environmental impact. In this context, alternative control technologies, particularly those based on biocontrol agents, have become increasingly relevant as innovative and promising approaches. Not only do these technologies offer an effective control of phytopathogens, but also contribute to the prevention of the synthesis of mycotoxins, without compromising the innocuousness and nutritional quality of the maize grain. The bibliometric analysis shows that the investigations on this area focus on the preharvest stage and very few focus on postharvest. Similarly, the research that incorporates the combination of different biocontrol agents to identify a more efficient control method is very scarce. Therefore, the systemic and integral understanding of agrobiotechnological strategies, as well as identifying the most prevalent mycotoxigenic species in Mexico must be strengthened to sustainably improve plant health and ensure food safety. Progress in this field is a priority research line, particularly towards the design of integrated management systems that combine different methods to provide a more effective control of phytopathogens, as well as reduce mycotoxin contamination in maize grain.

Acknowledgements

Our thanks go to the Consejo Nacional de Humanidades, Ciencias y Tecnologías (National Humanities, Science and Technology Council - CONAHCYT) for the support given and to the members of the Food Biotechnology Laboratory of the Instituto Tecnológico de Tepic.

REFERENCES

Abdullahi N and Dandago M. 2021. Postharvest losses in food grains – A Review. Turkish Journal of Food and Agriculture Sciences 3(2): 25–36. https://doi.org/10.53663/turjfas.958473

Abrehame S, Manoj VR, Hailu M, Chen YY, Lin YC, *et al*. 2023. Aflatoxins: Source, Detection, Clinical Features and Prevention. Processes,11, 204: 1-20. https://doi.org/10.3390/pr11010204

Adeniji A and Babalola O. 2018. Tackling maize fusariosis: in search of *Fusarium graminearum* biosuppressors. Archives of Microbiology 200(8): 1239–1255. https://doi.org/10.1007/s00203-018-1542-y

Alkuwari A, Hassan ZU, Zeidan R, Al-Thani R and Jaoua S. 2022. Occurrence of Mycotoxins and Toxigenic Fungi in Cereals and Application of Yeast Volatiles for Their Biological Control. Toxins 14(6). https://doi.org/10.3390/toxins14060404

Ali Md, Ahmed T, Ibrahim E, Rizwan M, Chong KP, *et al*. 2024. A review on mechanisms and prospects of endophytic bacteria in biocontrol of plant pathogenic fungi and their plant growth-promoting activities. Heliyon 10: 1-16. https://doi.org/10.1016/j.heliyon.2024.e31573

Anjum T, Iram W, Iqbal M, Ghaffar A and Abbas, M. 2020. Identification of degradation products of aflatoxin B1 and B2 resulting after their biodetoxification by aqueous extracts of Acacia nilotica. World Mycotoxin Journal 13(4). https://doi.org/10.3920/WMJ2018.2411

Bartholomew HP, Bradshaw M, Jurick WM and Fonseca JM. 2021. The Good, the Bad, and the Ugly: Mycotoxin Production During Postharvest Decay and Their Influence on Tritrophic Host–Pathogen–Microbe Interactions. Frontiers in Microbiology 12. https://doi.org/10.3389/fmicb.2021.611881

Boukaew S, Prasertsan P and Sattayasamitsathit S. 2017. Evaluation of antifungal activity of essential oils against aflatoxigenic *Aspergillus flavus* and their allelopathic activity from fumigation to protect maize seeds during storage. Industrial Crops and Products 97: 558-566. https://doi.org/10.1016/j.indcrop.2017.01.005

Carvajal M. 2022. Mycotoxin challenges in maize production and possible control methods in the 21st century. Journal of Cereal Science 103. https://doi.org/10.1016/j.jcs.2021.103293

Carvalho T, Costa M, Rosa LH, de Oliveira AM and de Oliveira EN. 2020. *Penicillium citrinum* and *Penicillium mallochii*: New phytopathogens of orange fruit and their control using chitosan. Carbohydrate Polymers 234: 1–31. https://doi.org/10.1016/j.carbpol.2020.115918

Chen Y, Xing M, Chen T, Tian S and Li B. 2023. Effects and mechanisms of plant bioactive compounds in preventing fungal spoilage and mycotoxin contamination in postharvest fruits: A review. Food Chemistry 415. https://doi.org/10.1016/j.foodchem.2023.135787

Chrapačienė S, Rasiukevičiūtė N, and Valiuškaitė A. 2022. Control of Seed-Borne Fungi by Selected Essential Oils. Horticulturae 8(3). https://doi.org/10.3390/horticulturae8030220

Cordova-Albores LC, Zelaya-Molina LX., Ávila-Alistac N, Valenzuela-Ruíz V, Cortés-Martínez NE, *et al*. 2021. Potencial de las ciencias ómicas en la bioprospección de agentes microbianos de control biológico: en el caso de la agro-biotecnología mexicana. Revista Mexicana de Fitopatología *39*: 147-184. https://doi.org/10.18781/r.mex.fit.2009-3

Costa FR, Del Toro CL, Wong FJ, Robles MDR, Cárdenas JL and Borboa J. 2020. Aceites esenciales para el control de *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae) y efecto sobre la calidad del grano de maíz *Zea mays* Linnaeus (Poales: Poaceae). Revista Chilena de Entomología 46: 639–652. https://doi.org/10.35249/rche.46.4.20.10

Cuervo JA, Pérez VH, Zavala EA, Peralta M, Aparicio JE and Romero T. 2022. *Trichoderma asperellum* strains as potential biological control agents against *Fusarium verticillioides* and *Ustilago maydis* in maize. Biocontrol Science and Technology 32. https://doi.org/10.1080/09583157.2022.2042196

Debnath D, Samal I, Mohapatra C, Routray S, Kesawat MS and Labanya R. 2022. Chitosan: An Autocidal Molecule of Plant Pathogenic Fungus. Life 12. https://doi.org/10.3390/life12111908

Dell'Olmo E, Tiberini A and Sigillo L. 2023. Leguminous Seedborne Pathogens: Seed Health and Sustainable Crop Management 12: 1-42. https://doi.org/10.3390/plants12102040

Erasto R, Kilasi N and Madege RR. 2023. Prevalence and Management of Phytopathogenic Seed-Borne Fungi of Maize. Seeds 2: 30–42. https://doi.org/10.3390/seeds2010003

Fleurat F. 2017. Integrated management of the risks of stored grain spoilage by seedborne fungi and contamination by storage mould mycotoxins – An update. Journal of Stored Products Research 71: 22–40. https://doi.org/10.1016/j.jspr.2016.10.002

Galletti S, Paris R and Cianchetta S. 2020. Selected isolates of *Trichoderma gamsii* induce different pathways of systemic resistance in maize upon *Fusarium verticillioides* challenge. Microbiological Research 233. https://doi.org/10.1016/j.micres.2019.126406

García E, Sulyok M, Verheecke C, Medina A, Krska R and Magan N. 2022. Interacting Environmental Stress Factors Affect Metabolomics Profiles in Stored Naturally Contaminated Maize. Microorganisms 10(5). https://doi.org/10.3390/microorganisms10050853

Ghule MR, Ramteke PK, Ramteke SD, Kodre PS, Langote A, Gaikwad AV, Holkar SK and Jambhekar H. 2021. Impact of chitosan seed treatment of fenugreek for management of root rot disease caused by *Fusarium solani* under *in vitro* and *in vivo* conditions. Biotech 11. https://doi.org/10.1007/s13205-021-02843-3

Godana EA, Yang Q, Wang K, Zhang H, Zhang X, Zhao L, Abdelhai MH and Guillaume NN. 2020. Bio-control activity of *Pichia anomala* supplemented with chitosan against *Penicillium expansum* in postharvest grapes and its possible inhibition mechanism. LWT-Food Science and Technology 124. https://doi.org/10.1016/j.lwt.2020.109188

Godínez BM, Schilmann A, Lagunas A, Escamilla C, Burguete AI, Aguilar C, Blanco J and Lacasaña M. 2023. Pesticide use patterns and their association with cytokine levels in Mexican flower workers. International Archives of Occupational and Environmental Health 97: 291-302. https//doi.org/10.1007/s00420-023-02043-x

Guimarães RA, Pherez PE, Müller H, Berg G, Medeiros FH and Cernava T. 2020. Microbiome-guided evaluation of *Bacillus subtilis* BIOUFLA2 application to reduce mycotoxins in maize kernels. Biological Control 150. https://doi.org/10.1016/j.biocontrol.2020.104370

Ramos A, González RR, Romanazzi G, Landi L and Gutierrez P. 2020. Effects of chitosan in the control of postharvest anthracnose of soursop (*Annona muricata*) Fruit. Revista Mexicana de Ingeniera Quimica 19: 99–108. https://doi.org/10.24275/rmiq/Bio527

Gwiazdowska D, Marchwińska K, Juś K, Uwineza PA, Gwiazdowski R, Waśkiewicz A and Kierzek R. 2022. The concentration-dependent effects of essential oils on the growth of *Fusarium graminearum* and mycotoxins biosynthesis in wheat and maize grain. Applied Sciences (Switzerland) 12. https://doi.org/10.3390/app12010473

Hamad GM, Mehany T, Simal-Gandara J, Abou-Alella S, Esua OJ, Abdel-Wahhab MA and Hafez EE. 2022. A review of recent strategies for controlling mycotoxins in foods. Food Control 144. https://doi.org/10.1016/j.foodcont.2022.109350

Hernández AJ and Carballo A. 2017. Almacenamiento y conservación de granos y semillas. http://somossemilla.org/wp-content/uploands/2017/06/Almacenamiento-de-semillas.pdf

Herrera JA, Hernández DA, Bueno DA, Ramos S, Velázquez RM, *et al*. 2022. Effect of commercial chitosan on *in vitro* inhibition of *Colletotrichum siamense*, fruit quality and elicitor effect on postharvest avocado fruit. Revista Mexicana de Ingeniera Quimica 21. https://doi.org/10.24275/rmiq/Bio2706

Hollomon DW. 2015. Fungicide resistance: 40 years on and still a major problem. Fungicide Resistance in Plant Pathogens: 3–11. https://doi.org/10.1007/978-4-431-55642-8_1

IARC Working Group on the Evaluation of Carcinogenic Risks to Humans., International Agency for Research on Cancer., & World Health Organization. (2002). Some traditional herbal medicines, some mycotoxins, naphthalene and styrene. International Agency for Research on Cancer.

Iwayemi EF, Yu J, Rehrah D, Davis SS and Williams LL. 2024. Inhibitory effects of essential oils on the growth of grain storage molds and the formation of aflatoxin in stored organic corn grains. JSFA Reports: 1-14. https://doi.org/10.1002/jsf2.210

Jiang N, Wang L, Jiang D, Wang M, Liu H, *et al.* 2022. Transcriptomic analysis of inhibition by eugenol of ochratoxin A biosynthesis and growth of *Aspergillus carbonarius*. Food Control 135. https://doi.org/10.1016/j.foodcont.2021.108788

Jiménez C and Cecilia JA. 2020. Chitosan: A natural biopolymer with a wide and varied range of applications. Molecules 25 (17): 2-43. https://doi.org/10.3390/molecules25173981

Khalil OA, Hammad AA and Sebaei AS. 2021. *Aspergillus flavus* and *Aspergillus ochraceus* inhibition and reduction of aflatoxins and ochratoxin A in maize by irradiation. Toxicon 198: 111–120. https://doi.org/10.1016/j.toxicon.2021.04.029

Krnjaja V, Mandić V, Bijelić Z, Stanković S, Obradović A, Petrović T, Vasić T and Radović Č. 2021. Influence of nitrogen rates and *Fusarium verticillioides* infection on *Fusarium* spp. and fumonisin contamination of maize kernels. Crop Protection 144. https://doi.org/10.1016/j.cropro.2021.105601

Krnjaja V, Mandić V, Stanković S, Obradović A, Vasić, T, *et al*. 2019. Influence of plant density on toxigenic fungal and mycotoxin contamination of maize grains. Crop Protection, 116: 126–131. https://doi.org/10.1016/j.cropro.2018.10.021

Lahlali R, Ezrari S, Radouane N, Kenfaoui J, Esmaeel Q, *et al*. 2022. Biological control of plant pathogens: A global perspective. Microorganisms 10. https://doi.org/10.3390/microorganisms10030596

Martínez E, González C, Velázquez RM, Herrera JA and Gutiérrez P. 2024. *In vitro* and *in vivo* antifungal activity of chitosan and identification of potentially toxigenic fungi in stored maize of Nayarit, Mexico. Revista Mexicana de Ingeniería Química 23: 1–15. https://doi.org/10.24275/rmiq/Bio24223

Medina N, López R, Ascencio F, Castellanos T, Campa A I, *et al*. 2016. Biocontrol activity of the marine yeast *Debaryomyces hansenii* against phytopathogenic fungi and its ability to inhibit mycotoxins production in maize grain (*Zea mays* L.). Biological Control 97: 70–79. https://doi.org/10.1016/j.biocontrol.2016.03.006

Minozzo M, de Souza MA, Bernardi JL, Puton BMS, Valduga E, *et al*. 2023. Antifungal activity and aroma persistence of free and encapsulated *Cinnamomum cassia* essential oil in maize. International Journal of Food Microbiology 394. https://doi.org/10.1016/j.ijfoodmicro.2023.110178

Moumni M, Brodal G and Romanazzi G. 2023. Recent innovative seed treatment methods in the management of seedborne pathogens. Food Security 15: 1365–1382. https://doi.org/10.1007/s12571-023-01384-2

Mukarram M, Ali J., Dadkhah H, Kurjak D, Kačík F and Ďurkovič, J. 2023. Chitosan-induced biotic stress tolerance and crosstalk with phytohormones, antioxidants, and other signalling molecules. Frontiers in Plant Science 14. https://doi.org/10.3389/fpls.2023.1217822

Odjo S, Alakonya AE, Rosales A, Molina AL, Muñoz C, *et al*. 2022. Occurrence and postharvest strategies to help mitigate aflatoxins and fumonisins in maize and their co-exposure to consumers in Mexico and Central America. Food Control 138. https://doi.org/10.1016/j.foodcont.2022.108968

Oliveira RC, Carvajal M, Mercado P, Rojo F and Correa B. 2020. Essential oils trigger an antifungal and anti-aflatoxigenic effect on *Aspergillus flavus* via the induction of apoptosis-like cell death and gene regulation. Food Control 110. https://doi.org/10.1016/j.foodcont.2019.107038

Organización de las Naciones Uniones para la Alimentación y la Agricultura. 2023. Cultivos y productos de ganaderia. https://www.fao.org/faostat/es/#data/QCL

OMS, Organización Mundial de la Salud. 2009. The WHO recommended classification of pesticides by hazard and guidelines to classification: 2009. https://iris.who.int/bitstream/handle/10665/44271/9789241547963_eng.pdf?sequence=1

Orzali L, Allagui MB, Chaves C, Molina JB, Moumni, M., *et al.* 2023. Basic Substances and Potential Basic Substances: Key Compounds for a Sustainable Management of Seedborne Pathogens. Horticulturae, 9: 1220. https://doi.org/10.3390/horticulturae9111220

Oztekin S, Dikmetas DN, Devecioglu D, Acar EG and Karbancioglu F. 2023. Recent Insights into the Use of Antagonistic Yeasts for Sustainable Biomanagement of Postharvest Pathogenic and Mycotoxigenic Fungi in Fruits with Their Prevention Strategies against Mycotoxins. Journal of Agricultural and Food Chemistry 71: 9923–9950. https://doi.org/10.1021/acs.jafc.3c00315

Papp LA, Horváth E, Peles F, Pócsi I and Miklós I. 2021. Insight into yeast–mycotoxin relations. Agriculture (Switzerland) 11. https://doi.org/10.3390/agriculture11121291

Pereira R, Braccini A, Da Silva B, Fuentes M, Volpato J, *et al*. 2024. Physiological potential of soybean seeds subjected to industrial treatment and storage time. Australian Journal of Crop Science 18: 45-49. https://doi.org/10.21475/ajcs.24.18.01.p4048

Pérez MCJ, Sánchez G, Garza JL and Espinosa J. 2021. Mohos productores de micotoxinas. https://masam.cuautitlan.unam.mx/mohos_toxigenos_unigras/generalidades.html

Pitt JI, Wild CP, Baan RA, Gelderblom WCA, Miller DJ, *et al*. 2012. Improving public health through mycotoxin control. International Agency for Research on Cancer, Lyon, France. ISBN: 978-92-832-2214-9

Prasad RD, Chandrika KSV and Godbole V. 2020. A novel chitosan biopolymer-based *Trichoderma* delivery system: Storage stability, persistence and bio efficacy against seed and soil borne diseases of oilseed crops. Microbiological Research 237. https://doi.org/10.1016/j.micres.2020.126487

Prusky D and Romanazzi, G. 2023. Induced Resistance in Fruit and Vegetables: A Host Physiological Response Limiting Postharvest Disease Development. Annual Reviews 12: 1-22. https://doi.org/10.1146/annurev-phyto-021722

Qi X, Zhong S, Schwarz P, Chen B and Rao J. 2023a. Mechanisms of antifungal and mycotoxin inhibitory properties of *Thymus vulgaris* L. essential oil and their major chemical constituents in emulsion-based delivery system. https://doi.org/10.1016/j.indcrop.2023.116575

Qi Z, Tian L, Zhang H, Lei Y and Tang F. 2023b. Fungal community analysis of hot spots in bulk maize under different storage conditions. LWT 182. https://doi.org/10.1016/j.lwt.2023.114819

Ramos S, Montiel LG, Estrada RM, Hernández CL and Gutierrez P. 2023. Chitosan and salicylic acid as alternatives for the control of postharvest fungal diseases in blueberries (*Vaccinium corymbosum*). International Food Research Journal 30: 992–1000. https://doi.org/10.47836/ifrj.30.4.16

Rayón-Díaz E, Hernández-Montiel LG, Zamora-Gasga VM, Sánchez-Burgos JA, Ramos-Bell S, *et al.* 2025. Antifungal and Toxicological Evaluation of Natural Compounds Such as Chitosan, Citral and Hexanal Against *Colletotrichum asianum*. Horticulturae, 11: 474. https://doi.org/10.3390/horticulturae11050474

Reglamento (UE) 2023/915 de la comisión, de 08 de febrero de 1993, relativo a los límites máximos de determinados contaminantes en los alimentos nº 1881/2006. Diario Oficial de la Unión Europea, L119, de 25 de abril de 2023. https://eur-lex.europa.eu/legal-content/ES/TXT/PDF/?uri=CELEX:32023R0915

Riudavets J, Pons MJ, Messeguer J and Gabarra R. 2018. Effect of CO2 modified atmosphere packaging on aflatoxin production in maize infested with *Sitophilus zeamais*. Journal of Stored Products Research 77: 89–91. https://doi.org/10.1016/j.jspr.2018.03.005

Romanazzi G, Orçonneau Y, Moumni M, Davillerd Y and Marchand PA. 2022. Basic Substances, a Sustainable Tool to Complement and Eventually Replace Synthetic Pesticides in the Management of Pre and Postharvest Diseases: Reviewed Instructions for Users. Molecules 27. https://doi.org/10.3390/molecules27113484

Romanazzi G, Piancatelli S, Potentini R, D'Ignazi G and Moumni M. 2024. Applications of chitosan alone, alternated or combined with copper for grapevine downy mildew management in large scale trials. Journal of Cleaner Production, 451. https://doi.org/10.1016/j.jclepro.2024.142131

Romero J, Albertos I, Díez A and Poveda J. 2022. Control of postharvest diseases in berries through edible coatings and bacterial probiotics. Scientia Horticulturae 304. https://doi.org/10.1016/j.scienta.2022.111326

Ruíz MA, Medina IM, Bernal YY, Agraz JM, González CA, *et al*. 2022. Hematological indices as indicators of inflammation induces by exposure to pesticides. Environmental Science and Pollution Research 30: 19466-19476. https://doi.org/10.1007/s11356-022-23509-4

Saberi R, Vatankhah M, Hassanisaadi M, Shafiei Z and Kennedy JF. 2024. Advancements in coating technologies: Unveiling the potential of chitosan for the preservation of fruits and vegetables. International Journal of Biological Macromolecules 254. https://doi.org/10.1016/j.ijbiomac.2023.127677

SAGARPA, Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. 2016. Claridades agropecuarias: almacenamiento en México 271: 1-50. https://www.gob.mx/cms/uploads/attachment/file/185452/revista_271.pdf

Shabir S, Aftab H, Tehmina A, Waheed A, Saddam H, *et al.* 2023. Biological evaluation, GC–MS profiling, and molecular docking studies of some essential oils against postharvest pathogens of maize. Arabian Journal of Chemistry 16. https://doi.org/10.1016/j.arabjc.2023.105339

Sharma I, Raina A, Choudhary M, Kaul S and Dhar M. 2023. Fungal endophyte bioinoculants as a green alternative towards sustainable agriculture. *Heliyon, 9*: 1-17. https://doi.org/10.1016/j.heliyon.2024.e31573

SSA, Secretaria de Salud. 2002. NOM-188-SSA1-2002: Norma Oficial Mexicana, productos y servicios. Control de aflatoxinas en cereales para consumo humano y animal. Especificaciones sanitarias.https://www.dof.gob.mx/nota_detalle.php?codigo=719385&fecha=15/10/2002#gsc.tab=0

SSA, Secretaria de Salud. 2008. NOM-247-SSA1-2008: Productos y servicios. Cereales y sus productos. Cereales, harinas de cereales, sémolas o semolinas. Alimentos a base de: cereales, semillas comestibles, de harinas, sémolas o semolinas o sus mezclas. Productos de panificación. Disposiciones y especificaciones sanitarias y nutrimentales. Métodos de prueba. https://dof.gob.mx/nota_detalle.php?codigo=5100356&fecha=27/07/2009#gsc.tab=0

Taheri P, Soweizy M and Tarighi S. 2023. Application of essential oils to control some important fungi and bacteria pathogenic on cereals. Journal of Natural Pesticide Research 6. https://doi.org/10.1016/j.napere.2023.100052

Terefe H, Yitayih G and Mengesha GG. 2023. Phytochemicals reduced growth, sporulation and conidial dimensions of *Fusarium verticillioides*, cause of fumonisin contamination in maize grains. Biotechnology Reports 40. https://doi.org/10.1016/j.btre.2023.e00819

Tiwari S, Singh BK, Kishore V and Dubey NK. 2022. Boosting modern technologies with emphasis on biological approaches to potentiate prevention and control of aflatoxins: recent advances. Toxin Reviews 41: 1007–1017). https://doi.org/10.1080/15569543.2021.1933534

Torre ME, De Sánchez D, Galeana E y Plasencia J. 2014. Fumonisinas –Síntesis y función en la interacción *Fusarium verticilloides* -maíz. Revista Especializada En Ciencias Químico-Biológicas 17: 77–91. https://www.scielo.org.mx/pdf/tip/v17n1/v17n1a6.pdf

USDA, United States Department of Agriculture. 2024. National Agricultural Statistics Service. https://quickstats.nass.usda.gov (Consulta, junio 2024).

Vecchi B, Orella G and Miotto E. 2022. Micotoxinas: Prevalencia en Latinoamérica, monitoreo de materias primas y alimentos balanceados. 1-23. https://www.vetanco.com/mx/wp-content/uploads/sites/9/2023/03/e-Book-Micotoxinas-Vetanco-prevalencia-2022.pdf

Vijaykumar S, Rajeswari B, Kavya M, Chandrika KS, Prasad RD, *et al*. 2024. Programmable chitosan-based double layer seed coating for biotic and abiotic-stress tolerance in groundnut. International Journal of Biological Macromolecules 275. https://doi.org/10.1016/j.ijbiomac.2024.133586

Wu D, Lu J, Zhong S, Schwarz P, Chen B and Rao J. 2019. Effect of chitosan coatings on physical stability, antifungal and mycotoxin inhibitory activities of lecithin stabilized cinnamon oil-in-water emulsions. Lwt, 106: 98–104. https://doi.org/10.1016/j.lwt.2019.02.029

Wang J, Sufar EK, Bernhoft A, Seal C, Rempelos L, *et al*. 2024. Mycotoxin contamination in organic and conventional cereal grain and products: A systematic literature review and meta-analysis. Comprehensive Reviews in Food Science and Food Safety, 23: 1-43. https://doi.org/10.1111/1541-4337.13363

Yang F, Zhang R, Wu X, Xu T, Ahmad S, *et al.* 2020. An endophytic strain of the genus *Bacillus* isolated from the seeds of maize (*Zea mays* L.) has antagonistic activity against maize pathogenic strains. Microbial Pathogenesis 142. https://doi.org/10.1016/j.micpath.2020.104074

Zhang C, Qu Z, Hou J and Yao Y. 2024. Contamination and Control of Mycotoxins in Grain and Oil Crops. Microorganisms 12. https://doi.org/10.3390/microorganisms 12030567