Molecular Pathogens 2024, Vol.15, No.2, 93-105
http://microbescipublisher.com/index.php/mp

Feature Review **Open Access**

Integrated Approaches to Managing *Fusarium* and Other Fungal Pathogens in Maize

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Molecular Pathogens, 2024, Vol.15, No.2 doi: 10.5376/mp.2024.15.0010
Received: 18 Feb., 2024
Accepted: 31 Mar., 2024
Published: 25 Apr., 2024

Preferred citation for this article:
Tang X.Q., 2024, Integrated Approaches to managing *Fusarium* and other fungal pathogens in maize, Molecular Pathogens, 15(2): 93-105 (doi: 10.5376/mp.2024.15.0010)

Abstract As one of the world's most important food crops, the stability of corn yield and quality is crucial for ensuring global food security. However, diseases caused by *Fusarium* and other fungal pathogens pose a significant threat to corn production, leading to substantial yield losses and economic impacts. This study provides an overview of *Fusarium* and other common fungal pathogens of corn, symptom identification, life cycles, and epidemiological characteristics. It analyzes the multifaceted impacts of these fungal pathogens on corn yield, economy, health, and the environment. The study explores the importance of integrated management measures to effectively control corn fungal diseases through cultural and agronomic practices, biological control strategies, chemical control methods, and monitoring and early detection. By systematically analyzing the biological characteristics, epidemiology, and effects of *Fusarium* and other fungal pathogens on corn, the study proposes a set of scientific and effective integrated control strategies. These strategies not only help reduce disease losses in corn production, increase corn yield and quality, and ensure food security but also reduce the risk of mycotoxin contamination, protect human and animal health, and decrease the use of chemical pesticides, promoting sustainable agricultural development.

Keywords Maize; *Fusarium*; Fungal diseases; Mycotoxins; Control strategies

1 Introduction

Maize (*Zea mays* L.) is one of the most important staple crops globally, serving as a primary source of food, feed, and industrial raw material. Its cultivation spans diverse agro-ecological zones, making it a critical component of food security and economic stability in many regions. However, maize production faces significant challenges, particularly from fungal pathogens that can severely impact yield and quality.

Fungal pathogens are a major threat to maize production, with *Fusarium* species being among the most notorious. *Fusarium verticillioides*, for instance, is a common cause of ear and kernel rot in maize, leading to substantial yield losses and contamination with mycotoxins such as fumonisins (Nayaka et al., 2009; Madege et al., 2018; Naz et al., 2021). Other significant fungal pathogens include *Fusarium graminearum*, which causes Gibberella ear rot and produces harmful mycotoxins like deoxynivalenol and zearalenone (Magarini et al., 2023; Savignac et al., 2023). These pathogens not only reduce crop yield but also pose serious health risks to humans and animals consuming contaminated maize.

Effective management of *Fusarium* and other fungal pathogens is crucial for ensuring the safety and productivity of maize crops. Mycotoxin contamination, in particular, has garnered considerable attention due to its association with various animal and human diseases (Nayaka et al., 2009; Guimarães et al., 2020). Integrated management strategies, including the use of resistant cultivars, chemical and biological control methods, and cultural practices, are essential to mitigate the impact of these pathogens (Munkvold, 2003; Salgado et al., 2014; Czarnecka et al., 2022). For instance, the application of insecticides has been shown to significantly reduce *Fusarium* infection by minimizing insect damage, which often serves as an entry point for the fungi (Madege et al., 2018).

This study analyzes current research on the integrated management of *Fusarium* and other fungal pathogens in maize, evaluating the efficacy of various control methods, including chemical, biological, and cultural practices. It also assesses the role of genetic resistance in mitigating fungal infections and mycotoxin contamination, identifies gaps in current research, and suggests areas for future investigation. By summarizing existing research findings, this study provides a scientific basis for effectively controlling these diseases. Understanding and integrating different control strategies is crucial for improving maize yield and quality. This not only reduces crop losses but also ensures food security and human health.

2 Overview of *Fusarium* and Other Fungal Pathogens

Fusarium species are among the most significant fungal pathogens affecting maize, causing diseases such as ear rot, kernel rot, and stalk rot. These pathogens not only reduce crop yield and quality but also produce mycotoxins, which pose serious health risks to humans and animals (Nayaka et al., 2009; Czembor et al., 2014; Zhou et al., 2018). Other notable fungal pathogens in maize include species from the genera *Aspergillus*, *Penicillium*, and *Cladosporium*, which also contribute to crop losses and mycotoxin contamination (Munkvold, 2003; Czarnecka et al., 2022).

2.1 Common fungal pathogens in Maize

Fusarium verticillioides, *Fusarium proliferatum*, and *Fusarium graminearum* are the primary *Fusarium* species causing ear and kernel rot in maize. These species are prevalent in various regions, including China, Poland, and Spain, and are known for their ability to produce harmful mycotoxins such as fumonisins and deoxynivalenol (DON) (Varela et al., 2013; Czembor et al., 2014; Zhou et al., 2018). Additionally, *Fusarium temperatum* has been identified as a significant pathogen in both Europe and China, causing ear rot and contributing to mycotoxin contamination (Varela et al., 2013; Czembor et al., 2014; Zhang et al., 2014).

Other fungal pathogens include *Fusarium oxysporum*, *Fusarium poae*, and *Fusarium sporotrichioides*, which are frequently detected in maize fields, particularly in organic farming systems where chemical control is limited (Czarnecka et al., 2022). These pathogens, along with *Alternaria alternata*, contribute to the complex disease landscape in maize cultivation.

2.2 Symptoms and identification

Fusarium ear rot is characterized by the presence of white, pink, or salmon-colored mold on maize kernels, often accompanied by a "starburst" pattern of white streaks. Infected kernels may also exhibit discoloration and reduced size (Shang et al., 2020; 2022). Gibberella ear rot, caused by *Fusarium* graminearum, presents as red or pink mold on the ear, often starting at the tip and progressing downwards (Munkvold, 2003).

Stalk rot symptoms include the browning and softening of the stalk tissue, leading to plant lodging and reduced nutrient transport. Seedling blight, caused by *Fusarium* species such as *F. temperatum*, manifests as seedling malformations, chlorosis, and shoot reduction (Varela et al., 2013). Identification of these pathogens involves both morphological and molecular techniques. Morphological identification is based on colony characteristics, spore morphology, and growth patterns on specific media (Varela et al., 2013; Czembor et al., 2014). Molecular identification utilizes DNA sequencing of genes such as translation elongation factor 1-alpha (TEF-1α) and internal transcribed spacer (ITS) regions to accurately differentiate *Fusarium* species (Shang et al., 2020; 2022).

2.3 Life cycle and epidemiology

Fusarium species have a complex life cycle that includes both sexual and asexual reproduction. The fungi produce conidia (asexual spores) that are dispersed by wind, rain, and insects, leading to infection of maize plants. The sexual stage, producing ascospores, occurs under specific environmental conditions and contributes to the genetic diversity of the pathogen population (Munkvold, 2003).

Epidemiological studies have shown that *Fusarium* infections are influenced by various factors, including weather conditions, crop rotation practices, and the presence of insect vectors. Warm and humid conditions favor the growth and spread of *Fusarium* species, while conservation tillage and monoculture systems increase the risk of disease outbreaks (Munkvold, 2003; Czembor et al., 2014). Insects such as the European corn borer can create entry points for *Fusarium* infection, exacerbating the disease severity (Munkvold, 2003).

Understanding the life cycle and epidemiology of *Fusarium* and other fungal pathogens is crucial for developing integrated management strategies. These strategies include the use of resistant maize varieties, biological control agents such as Pseudomonas fluorescens and Glomus species, and cultural practices that reduce pathogen inoculum and spread (Nayaka et al., 2009; Olowe et al., 2020).

3 Impact of Fungal Pathogens on Maize

3.1 Yield losses and economic impact

Fusarium species are among the most studied plant-pathogenic fungi, causing diseases such as *Fusarium* head blight and ear rot in maize, which result in significant yield losses globally. These infections not only reduce the quantity of the harvest but also diminish the quality and market value of the grain, leading to substantial economic losses (Glenn, 2007; Blacutt et al., 2018). For instance, *Fusarium verticillioides*, a prominent pathogen, is notorious for its ability to produce fumonisins, which are harmful mycotoxins that further degrade the quality of maize grains (Blacutt et al., 2018).

The economic impact of *Fusarium* infections extends beyond direct yield losses. The contamination of maize with mycotoxins necessitates additional costs for testing, management, and mitigation to ensure the safety of the food and feed supply. Regulations on maximum allowable levels of mycotoxins in various countries aim to protect consumers, but compliance with these regulations can be costly for producers (Ferrigo et al., 2016; Bryła et al., 2022). Moreover, the presence of mycotoxins can lead to trade restrictions and loss of market access, further exacerbating the economic burden on maize producers.

3.2 Mycotoxin contamination and health risks

Mycotoxins produced by *Fusarium* species, such as deoxynivalenol, zearalenone, and fumonisin B1, pose significant health risks to humans and animals. These secondary metabolites are toxic and can cause a range of acute and chronic health issues, including immunosuppression, carcinogenicity, and reproductive toxicity (Figure 1) (Mielniczuk et al., 2020; Savignac et al., 2023). The contamination of maize with these mycotoxins is a major concern for food safety and public health.

Figure 1 *Fusarium* mycotoxin contamination and its mitigation strategies (Adapted from Mielniczuk et al., 2020)

Mielniczuk et al. (2020) studied crop diseases caused by *Fusarium* spp. and the resulting toxin contamination and impacts on human and animal health. *Fusarium* head blight (FHB) and ear rot in grains lead to the production of toxins such as deoxynivalenol (DON), T-2 toxin, and zearalenone (ZEA). These toxins not only contaminate grains but also affect human and animal health through the food chain. To reduce toxin contamination, the study proposed various strategies, including pre-harvest plant protection measures (agronomic, chemical, and biological methods) and post-harvest treatment methods (physical, chemical, and biological approaches). The research highlighted the importance of preventing and controlling Fusarium toxin contamination.

The health risks associated with mycotoxin contamination have led to the establishment of stringent regulations and maximum permissible levels in food and feed by various countries. Despite these measures, mycotoxin contamination remains a persistent problem due to environmental factors and agronomic practices that favor *Fusarium* infection and mycotoxin production (Ferrigo et al., 2016; Simões et al., 2023). For example, environmental conditions such as temperature and humidity significantly influence the prevalence of *Fusarium* species and the levels of mycotoxins in maize grains (Czembor et al., 2015).

3.3 Environmental impact

The environmental impact of *Fusarium* and other fungal pathogens on maize is multifaceted. These pathogens thrive under specific environmental conditions, and changes in climate can influence their prevalence and severity. For instance, increased rainfall and humidity can promote the growth of *Fusarium* species and the production of mycotoxins, leading to higher contamination levels in maize grains (Czembor et al., 2015). Conversely, extreme weather conditions such as drought can stress maize plants, making them more susceptible to fungal infections (Ferrigo et al., 2016).

In addition to the direct effects on maize production, the management practices employed to control *Fusarium* infections can also have environmental implications. The use of chemical fungicides, while effective in reducing fungal infections, can lead to environmental pollution and the development of fungicide-resistant strains of *Fusarium* (Mielniczuk et al., 2020). Therefore, integrated management strategies that include biological control methods, such as the use of endophytic fungi, and the cultivation of resistant maize varieties are essential for sustainable agriculture (Abdallah et al., 2018). These approaches not only help in managing *Fusarium* infections but also minimize the environmental footprint of maize production.

4 Cultural and Agronomic Practices

4.1 Crop rotation and tillage practices

Crop rotation and tillage practices are fundamental strategies in managing *Fusarium* and other fungal pathogens in maize. Crop rotation, particularly with non-host crops, can significantly reduce the inoculum levels of *Fusarium* spp. in the soil. For instance, rotating maize with crops like soybean and wheat has been shown to influence the population dynamics of *Fusarium* species, reducing the prevalence of *Fusarium graminearum* and *Fusarium oxysporum* (Marburger et al., 2015). Additionally, incorporating cover crops such as white mustard and Indian mustard in maize-wheat rotations under reduced tillage can decrease mycotoxin levels in subsequent wheat crops, thereby mitigating the risk of *Fusarium* head blight (Drakopoulos et al., 2021).

Tillage practices also play a crucial role in managing soilborne pathogens. No-till and reduced tillage systems can enhance the populations of beneficial soil microorganisms like actinomycetes and *Trichoderma* spp., which contribute to the natural suppression of *Fusarium* spp. (Gil et al., 2008). However, the effectiveness of tillage practices can be influenced by environmental conditions. For example, in regions with favorable weather conditions for *Fusarium* development, the impact of tillage on disease incidence may be less pronounced (Lori et al., 2009). Therefore, an integrated approach combining crop rotation and appropriate tillage practices is essential for effective *Fusarium* management.

4.2 Resistant varieties and seed treatments

The development and use of resistant maize varieties are critical components of integrated disease management strategies. Genetic resistance to *Fusarium* spp., including *Fusarium verticillioides* and *Fusarium graminearum*, has been identified and incorporated into breeding programs. However, the commercial availability of highly resistant cultivars remains limited. The use of transgenic insect-resistant maize varieties has also been explored as a means to reduce *Fusarium* infection and mycotoxin contamination, as insect damage can facilitate fungal entry into the plant (Munkvold, 2003).

Seed treatments with biological control agents offer another layer of protection against *Fusarium* spp. For example, treating maize seeds with *Bacillus amyloliquefaciens* or *Microbacterium oleovorans* has been shown to significantly reduce *Fusarium verticillioides* colonization in maize seedlings without adversely affecting the soil microbial community (Pereira et al., 2009). These treatments can enhance seedling vigor and reduce the initial inoculum load, providing a crucial early defense against fungal pathogens.

4.3 Soil health and fertility management

Maintaining soil health and fertility is vital for the sustainable management of *Fusarium* and other fungal pathogens. Healthy soils with balanced microbial communities can suppress the growth of pathogenic fungi through competitive exclusion and the production of antifungal compounds. Practices such as residue retention and the use of organic amendments can enhance soil microbial diversity and activity, promoting the proliferation of beneficial microorganisms like fluorescent *Pseudomonas* and *Actinomycetes* (Govaerts et al., 2008).

Fertilization practices also influence *Fusarium* dynamics in the soil. Intensive fertilization, particularly with nitrogen, can exacerbate *Fusarium* infections by creating favorable conditions for fungal growth (Sommermann et al., 2018). Conversely, balanced fertilization that meets crop nutrient requirements without excess can help maintain a healthy soil environment. In long-term studies, conservation tillage combined with appropriate fertilization and crop rotation has been shown to support resilient soil fungal communities, reducing the risk of *Fusarium* outbreaks (Figure 2) (Henry et al., 2022). Therefore, integrated soil health and fertility management practices are essential for mitigating the impact of *Fusarium* and other fungal pathogens in maize production systems.

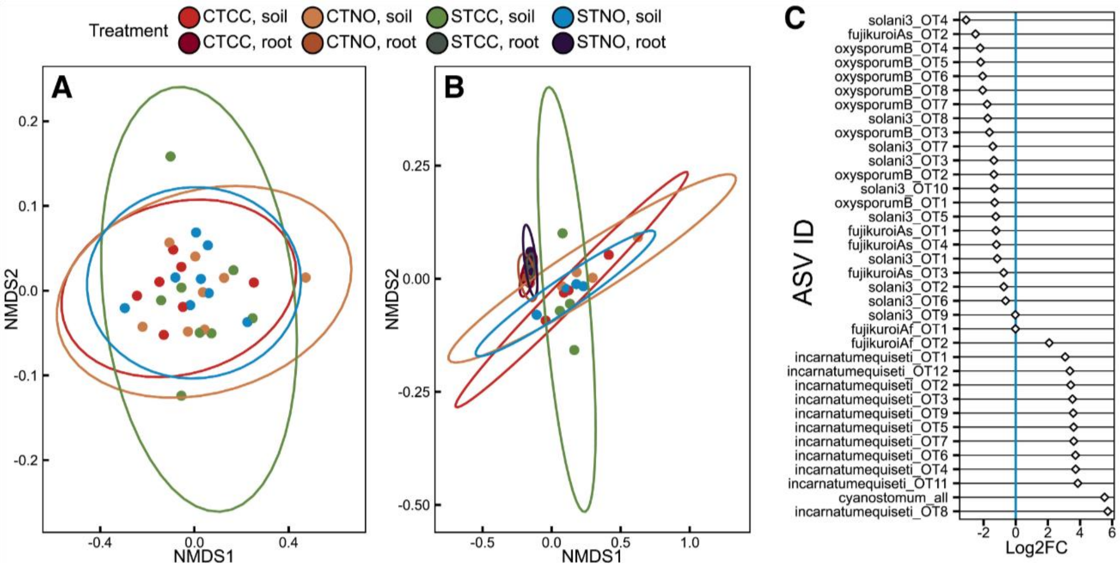

Figure 2 Long-term effects of cover crops and tillage practices on *Fusarium* community structure (Adapted from Henry et al., 2022)

Image caption: A: Non-metric multidimensional scaling (NMDS) analysis of soil *Fusarium* communities in 2017 and 2018; B: Non-metric multidimensional scaling (NMDS) analysis of root and soil *Fusarium* communities in 2017; C: Non-metric multidimensional scaling (NMDS) analysis of root and soil *Fusarium* communities in 2017 (Adapted from Henry et al., 2022)

Henry et al. (2020) studied the distribution characteristics of *Fusarium* communities in different soil and root environments after 18 years of cover crops or conservation tillage treatments. The study showed (Figure 2) that *Fusarium* communities differed significantly among the various treatments (standard tillage without cover crops (STNO), standard tillage with cover crops (STCC), conservation tillage without cover crops (CTNO), and conservation tillage with cover crops (CTCC)). This indicates that long-term tillage and cover crop practices significantly influence the structure of *Fusarium* communities in soil and roots, highlighting the importance of soil health management in optimizing agricultural management strategies.

5 Biological Control Strategies

5.1 Use of antagonistic microorganisms

Antagonistic microorganisms have shown significant potential in controlling *Fusarium* and other fungal pathogens in maize. *Bacillus subtilis*, for instance, has been identified as an effective biological control agent against *Fusarium* moniliforme. This bacterium occupies the same ecological niche within the plant as *F. moniliforme*, operating on the principle of competitive exclusion to reduce mycotoxin accumulation during the endophytic growth phase (Bacon et al., 2001). Similarly, *Clonostachys rosea* and a Gram-negative bacterium (BCA5) have demonstrated efficacy in reducing fumonisin B1 (FB1) contamination in maize cobs, with *C. rosea* achieving a reduction of over 70% at 25 °C (Samsudin et al., 2017). These findings underscore the importance of understanding the ecophysiology of both the pathogen and the antagonists to ensure effective control.

In addition to bacteria, fungal antagonists such as *Trichoderma* spp. have also been explored for their biocontrol potential. *Trichoderma gamsii*, for example, has been shown to induce systemic resistance in maize, enhancing the expression of marker genes associated with both Induced Systemic Resistance (ISR) and Systemic Acquired Resistance (SAR) pathways (Galletti et al., 2019). This dual mechanism not only reduces the endophytic development of *Fusarium verticillioides* but also promotes plant growth. The use of such antagonistic fungi offers a sustainable and environmentally friendly alternative to chemical fungicides, which are often expensive and have negative environmental impacts (Zhang et al., 2022).

5.2 Biopesticides and natural products

Biopesticides and natural products derived from microorganisms offer another promising avenue for managing *Fusarium* and other fungal pathogens in maize. *Bacillus amyloliquefaciens* and *Microbacterium oleovorans* have been tested as seed treatments and have shown significant efficacy in reducing *Fusarium verticillioides* counts in maize seedlings without altering the microbial richness and diversity in the rhizosphere (Pereira et al., 2009). These biopesticides not only control the pathogen but also maintain the ecological balance of the soil microbiome, which is crucial for plant health.

Natural products produced by antagonistic microorganisms also play a vital role in biocontrol strategies. For instance, *Pseudomonas chlororaphis* and *Pseudomonas fluorescens* have been identified for their production of antifungal metabolites that inhibit the growth of Aspergillus flavus and *Fusarium verticillioides* (Palumbo et al., 2007). These metabolites can be harnessed to develop natural biopesticides that are both effective and environmentally benign. Additionally, *Bacillus siamensis* GL-02 has shown significant inhibitory effects on *Fusarium* graminearum, both in vitro and in vivo, making it a potential candidate for biopesticide development (Zhang et al., 2022).

5.3 Enhancing plant microbiome

Enhancing the plant microbiome is a holistic approach to managing *Fusarium* and other fungal pathogens in maize. The maize-soybean relay strip intercropping system, for example, has been shown to reshape the rhizosphere bacterial community, recruiting beneficial bacteria such as *Pseudomonas*, *Bacillus*, and *Streptomyces* species that suppress *Fusarium* root rot (Figure 3) (Chang et al., 2022). This intercropping system not only increases microbial diversity but also enhances the abundance of beneficial microorganisms, thereby improving plant health and resistance to pathogens.

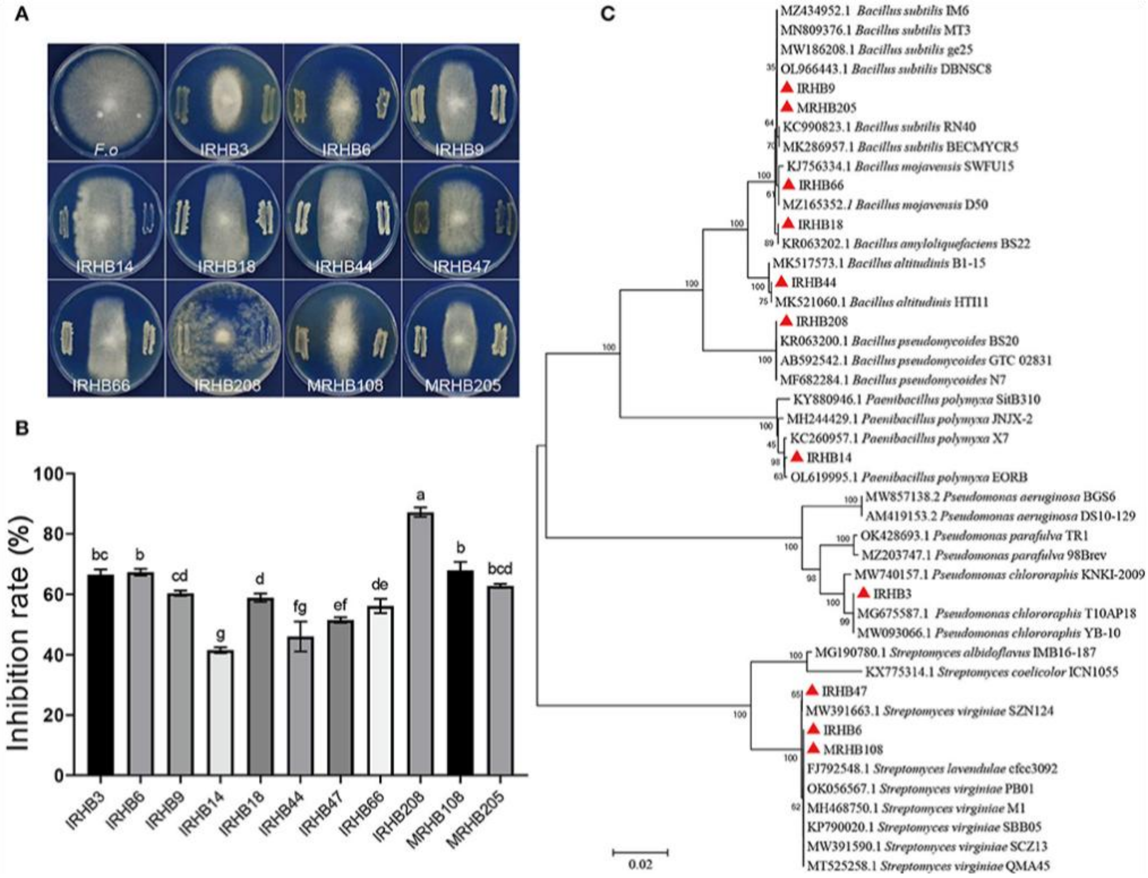

Figure 3 Screening of antagonistic bacteria against *Fusarium oxysporum* in maize-soybean relay strip intercropping (IRHB) and soybean monoculture (MRHB) systems (Adapted from Chang et al., 2022)

Image caption: A: In vitro dual culture assay showing antagonistic interactions between *Fusarium oxysporum* (F.o) and different antagonistic bacterial strains; B: Inhibition rates of different antagonistic strains on the mycelial growth of *Fusarium oxysporum*. Data are presented as mean ± standard error (SEM). Different lowercase letters indicate significant differences ($P<0.05$); C: Phylogenetic tree of 11 antagonistic bacterial strains based on 16S rDNA sequences. Red triangles indicate antagonistic strains isolated from IRHB and MRHB samples (Adapted from Chang et al., 2022)

Chang et al. (2022) compared the inhibitory effects of antagonistic bacterial strains isolated from maize-soybean relay strip intercropping (IRHB) and soybean monoculture (MRHB) systems against *Fusarium oxysporum*. The results showed significant differences in the inhibitory effects among the different strains, with some strains exhibiting particularly strong inhibition in the IRHB system. Phylogenetic analysis further identified the taxonomic positions of these antagonistic strains, providing candidate strains for developing effective biological control strategies.

Metabarcoding and co-occurrence network analysis have also been employed to profile the bacterial, fungal, and *Fusarium* communities in maize stalks. This approach has identified several genera with biocontrol activity, including Sphingomonas, Pedobacter, and Flavobacterium, which show negative correlations with *Fusarium* spp. responsible for *Fusarium* Head Blight (FHB) (Cobo-Díaz et al., 2019). By understanding these microbial interactions, it is possible to develop strategies that enhance the natural microbiome of maize plants, thereby providing a robust defense against fungal pathogens.

6 Chemical Control Methods

6.1 Fungicides and their modes of cction

Fungicides play a crucial role in managing *Fusarium* and other fungal pathogens in maize. The efficacy of fungicides such as prothioconazole, tebuconazole, and azoxystrobin has been well-documented. For instance, the combination of prothioconazole and tebuconazole has shown significant reductions in *Fusarium* head blight (FHB) and deoxynivalenol (DON) contamination in wheat, with the most effective treatment reducing FHB index by 76% and DON by 71% (Willyerd et al., 2012). Similarly, azoxystrobin, when used in combination with Trichoderma species, provided substantial protection against the maize late wilt pathogen, *Magnaporthiopsis maydis*, demonstrating the potential of integrated chemical and biological control methods (Gordani et al., 2023).

The mode of action of these fungicides involves inhibiting key enzymes in the fungal biosynthetic pathways. *Prothioconazole* and *Tebuconazole* inhibit the demethylation of lanosterol, a crucial step in ergosterol biosynthesis, which is essential for fungal cell membrane integrity. *Azoxystrobin*, on the other hand, inhibits mitochondrial respiration by blocking the electron transport chain at the cytochrome bc1 complex, leading to energy depletion and fungal cell death (Gordani et al., 2023). These modes of action not only reduce fungal growth but also limit the production of mycotoxins, thereby enhancing crop safety and yield.

6.2 Integrated pest management (IPM) approaches

Integrated Pest Management (IPM) combines multiple strategies to manage fungal pathogens effectively while minimizing the reliance on chemical fungicides. The integration of genetic resistance, fungicide application, and optimized agricultural practices has shown promising results. For example, combining moderately resistant cultivars with fungicide treatments significantly reduced FHB and DON levels in wheat, with the most effective combinations achieving up to 98.5% reduction in DON contamination (Mesterházy et al., 2017). This approach highlights the importance of using resistant cultivars to enhance the efficacy of fungicides.

Moreover, IPM strategies also involve optimizing fungicide application techniques. The use of side-spraying nozzles, for instance, has been shown to improve fungicide coverage and efficacy. A study demonstrated that a new nozzle combination reduced visual FHB scores by 50% compared to standard nozzles, emphasizing the role of application technology in IPM (Mesterházy et al., 2017). Additionally, integrating biological control agents such as *Bacillus subtilis* with chemical fungicides has been effective in reducing mycotoxin levels in maize, further supporting the benefits of a holistic IPM approach (Guimarães et al., 2020).

6.3 Resistance management

Resistance management is a critical component of sustainable fungal pathogen control. The overuse and misuse of fungicides can lead to the development of resistant fungal strains, rendering chemical treatments ineffective. Studies have shown that integrating fungicide applications with genetic resistance can mitigate the risk of resistance development. For instance, the combination of resistant cultivars and fungicide treatments not only provided effective control of FHB and DON but also reduced the likelihood of resistance development by diversifying the selection pressure on the pathogen population (Willyerd et al., 2012; Salgado et al., 2014).

Furthermore, the use of fungicides with different modes of action in rotation or combination can help manage resistance. For example, alternating between fungicides that inhibit ergosterol biosynthesis and those that disrupt mitochondrial respiration can reduce the risk of resistance development. This strategy is supported by findings that show the effectiveness of combining different fungicides to achieve better control and delay resistance (Moraes et al., 2022; Gordani et al., 2023). Additionally, the integration of biological control agents, which have different mechanisms of action compared to chemical fungicides, can further enhance resistance management and provide a sustainable approach to fungal pathogen control (Guimarães et al., 2020).

7 Monitoring and Early Detection

7.1 Field surveillance techniques

Field surveillance techniques are essential for the early detection and management of *Fusarium* and other fungal pathogens in maize. Traditional methods involve visual inspection of crops for symptoms such as discoloration, wilting, and mold growth. However, these methods can be subjective and may not detect infections until they are well-established. Recent advancements have introduced more sophisticated techniques such as the use of visible/near-infrared (Vis/NIR) spectroscopy and computer vision. These technologies allow for the on-line detection of fungal contamination in stored maize, providing a more accurate and timely assessment of infection levels. For instance, a study demonstrated that integrating Vis/NIR spectroscopy with computer vision achieved 100% accuracy in discriminating samples infected by different fungal strains, significantly improving the monitoring process (Shen et al., 2019).

Moreover, field surveillance can be enhanced by employing hyperspectral imaging combined with multivariate image analysis. This method has proven effective in differentiating between *Fusarium verticillioides* and *Fusarium* graminearum with high accuracy, sensitivity, and specificity. The non-invasive nature of hyperspectral imaging makes it a valuable tool for continuous monitoring of maize fields, allowing for early intervention and reducing the risk of widespread contamination (Conceição et al., 2020). These advanced surveillance techniques not only improve the accuracy of pathogen detection but also facilitate timely management decisions, ultimately protecting crop yield and quality.

7.2 Diagnostic tools and technologies

The development of precise diagnostic tools is crucial for the early detection and quantification of *Fusarium* spp. and other fungal pathogens in maize. One of the most promising technologies is real-time PCR (qPCR) targeting the internal transcribed spacer (ITS) region. This method allows for the specific identification and quantification of multiple *Fusarium* species, including *F. oxysporum*, *F. verticillioides*, and *F. graminearum*, as well as *Magnaporthiopsis maydis*. The high sensitivity and specificity of qPCR make it an excellent tool for early diagnosis and certification purposes, ensuring that infected plants are identified and managed promptly (Campos et al., 2019).

In addition to qPCR, near-infrared hyperspectral imaging (HSI-NIR) has emerged as a rapid and non-destructive diagnostic tool. By combining HSI-NIR with pattern recognition analysis, researchers have developed methods to accurately identify mycotoxin-producing *Fusarium* species in maize. This technology not only detects the presence of pathogens but also provides information on the level of contamination, enabling more effective management strategies (Conceição et al., 2020). The integration of these advanced diagnostic tools into routine monitoring programs can significantly enhance the early detection and control of fungal pathogens in maize.

7.3 Predictive modeling and risk assessment

Predictive modeling and risk assessment are vital components of an integrated approach to managing *Fusarium* and other fungal pathogens in maize. These models use various data inputs, including weather conditions, crop management practices, and pathogen biology, to predict the likelihood of disease outbreaks. For example, studies have shown that weather conditions, such as heavy rainfall and high humidity, significantly influence the incidence of fungal diseases in maize (Czarnecka et al., 2022). By incorporating such environmental factors into predictive models, researchers can forecast disease risk and recommend timely interventions.

Risk assessment tools also play a crucial role in identifying high-risk areas and periods for fungal contamination. For instance, a study on post-harvest practices in Vietnam highlighted the impact of traditional methods on the proliferation of *Fusarium verticillioides* and fumonisins in maize. The research identified specific practices that mitigate contamination, such as removing damaged cobs at harvest and drying maize on cement yards (Tran et al., 2020). By understanding the factors that contribute to fungal growth and mycotoxin production, predictive models can help farmers implement effective management practices, reducing the risk of contamination and ensuring the safety and quality of maize crops.

8 Concluding Remarks

The integrated management of *Fusarium* and other fungal pathogens in maize has shown promising results across various studies. The application of insecticides significantly reduces insect damage, which in turn decreases *Fusarium verticillioides* infection and fumonisin contamination. Biological control methods, such as the use of

Pseudomonas fluorescens and *Bacillus subtilis*, have also demonstrated efficacy in reducing *Fusarium* incidence and mycotoxin levels while promoting plant growth and yield. Additionally, seed treatments with natural extracts like *Jacaranda mimosifolia* have been effective in inducing defense-related enzymes and enhancing disease resistance in maize. Cultural practices and genetic approaches, including the use of resistant hybrids and Bt technology, have further contributed to reducing fungal infections and mycotoxin contamination. These findings underscore the importance of integrating multiple strategies to manage *Fusarium* and other fungal pathogens effectively.

The importance of integrated approaches in managing *Fusarium* and other fungal pathogens in maize cannot be overstated. Single-method strategies, such as the exclusive use of chemical fungicides, often fall short in providing comprehensive protection and can even exacerbate mycotoxin levels. Integrated approaches that combine chemical, biological, and cultural methods offer a more sustainable and effective solution. For instance, the combination of insecticides with biological agents like Bacillus subtilis has shown to significantly reduce fumonisin levels compared to conventionaltreatments. Similarly, the use of resistant maize genotypes in conjunction with cultural practices and biological treatments has proven to be effective in managing *Fusarium* infections and reducing mycotoxin contamination. These integrated strategies not only enhance disease control but also promote plant health and yield, making them crucial for sustainable maize production.

Future research should focus on further optimizing integrated management strategies for *Fusarium* and other fungal pathogens in maize. This includes exploring the synergistic effects of combining various biological agents with chemical treatments and cultural practices. More studies are needed to understand the molecular mechanisms underlying the efficacy of natural extracts like Jacaranda mimosifolia and their potential integration with other control methods. Additionally, the development of maize hybrids with enhanced resistance to multiple fungal pathogens should be prioritized. Research should also investigate the long-term impacts of integrated management practices on soil health and the broader agroecosystem. In practice, farmers should be encouraged to adopt integrated approaches tailored to their specific environmental conditions and pest pressures. Extension services and agricultural policies should support the dissemination of knowledge and resources necessary for implementing these integrated strategies effectively.

Acknowledgments

Thank you to each peer reviewer for the feedback on this manuscript.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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