DOI: 10.34101/ACTAAGRAR/2/15262

Pathogenic fungal pathogens and diseases: a mini review of effects on maize production

Magdoline Mustafa Ahmed Osman[1,2*] – Ronald Kuunya[1] – Andras Tamas[1] – Ratonyi Tamas[1]

[1]Institute of Land Use, Engineering and Precision Farming Technology, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 138 Böszörményi street, 4032, Debrecen, Hungary

[2]Environment, Natural Resources and Desertification Research Institute, National Center for Research, Khartoum, Sudan

[*]Correspondence: magdoline.osman@agr.unideb.com

SUMMARY

Maize, the most important cereal globally in terms of nutrition and income, is highly susceptible to biotic stresses caused by various pathogens, including fungi, bacteria, viruses, nematodes, and parasitic plants. This review gives an account of the epidemiology, diversity, and effect of fungal diseases on maize, with a focus on common pathogens, namely Ustilago sp. and Fusarium sp. Additionally, the review explores the major contributors to the pathogen and disease development, namely: soil quality, temperature, and humidity. Clarity is made herein about the damages and effects on maize growth, including development, yield, and grain quality, with marked economic losses recorded annually. The increasing threat of climate change escalates the dangers, pointing out the urgency for sustainable control strategies of the diseases. Conventional methods of using chemicals have been rendered inadequate for maize fungal disease control, underscoring the need for applying biopesticides and natural products obtained from microorganisms as innovative, remediation strategies. Together with these innovations are biocontrol agents that provide better solutions for reducing the reliance on chemical formulations as well as strengthening a healthier agricultural environment. Finally, a comprehensive understanding of the interaction between maize pathogens and environmental determinants is vital for the development of more effective integrated pest management strategies to enhance maize productivity and subsequent food safety.

Keywords: *maize; fungal disease; grain quality; crop yield*

INTRODUCTION

Maize (*Zea mays* L.), produced heavily in 2019 and 2020 on a global scale, according to the International Grains Council (2019), makes it the most important cereal crop. As noted by Zhan et al. (2022), the maize has been grown for hundreds of years, primarily by smallholder farmers. The crop is known to be susceptible to biotic stresses that are associated with pathogenic organisms, namely; bacteria, fungi, nematodes, viruses, and parasitic plants. Kramer et al. (2020) describes the economic losses caused by those pathogens through damage of the crop, many of which are related to growth, development, yield, and the quality of grain. Approximately 112 different diseases commonly affect a maize crop, and nearly 70 of these are spread through maize seed (Xu et al., 2021).

One category, maize fungal diseases, use their various forms to damage maize on a wide scale since they are able to spread and proliferate under specific conditions of environment in various places around the world. Some diseases thrive in warm, humid climates, while others prefer cooler, humid environments. Among the most damaging seed-borne fungal diseases impacting maize are Gibberella stalk rot, Fusarium stalk rot, false head smut, head smut, late wilt, and black bundle disease (Rehman et al., 2021). Other significant fungal infections include charcoal stalk rot, Anthracnose stalk rot, Fusarium and Gibberella ear rots, Aspergillus ear rot, charcoal ear rot, Penicillium ear rot, gray ear rot, Nigrospora ear rot, common smut, downy mildew, black kernel rot, Horse's tooth disease, Alternaria leaf blight, and *Acremonium zeae* stalk rot (Cimmyt, 2004).

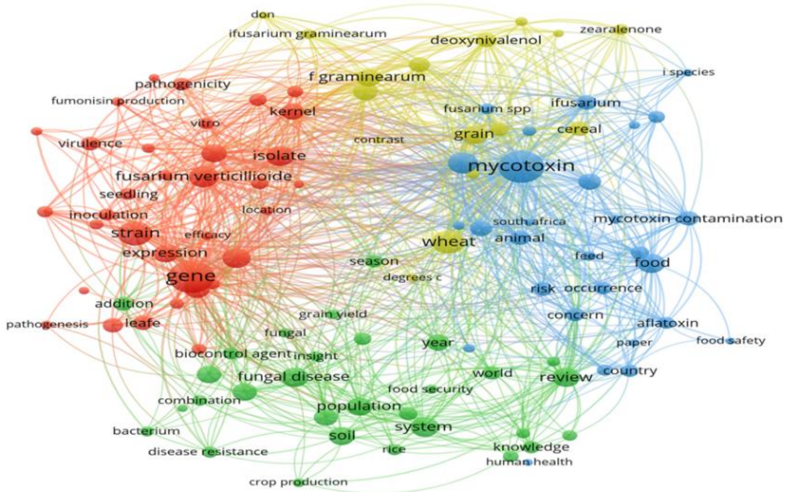
Among these, some of the most noteworthy and prevalent seed-borne and seed-transmitted fungal diseases include black bundle, Anthracnose rots, black kernel rot, crazy top downy mildew, brown stripe downy mildew, ear and root rot, Java downy mildew, Horse's tooth disease, Nigrospora ear rot, Philippine downy mildew disease, and Penicillium ear rot (Rehman et al., 2021). These diseases pose significant threats to maize crops by reducing yield, quality, and overall plant health, and are often difficult to control once established in the field. Farmers lose between 10 and 23% of their crops to fungal infection each year, despite widespread use of antifungals (Stukenbrock and Gurr, 2023). These fungi cause losses sufficient to feed 600 million people with 2000 calories per day for an entire year (Stukenbrock and Gurr, 2023), and with climate change, the number of people left without food will increase (Stukenbrock and Gurr, 2023) if no measures are adopted against maize fungal pathogens, as shown in the bibliometric network of *Figure 1*.

Consequently, the physiological, nutritional, and biochemical processes of plant disease require thorough research that informs development of justifiable methodologies for control. Matos et al. (2024) explain the importance of comprehensive exploration of those processes as a guide to disease management and proper adjustment of environmental conditions that contribute to crop plant health. Additionally, Khan et al. (2017) suggest many approaches for controlling phytopathogens, and Rahman (2018) adds more alternatives to biological control. *Biopesticides and natural products obtained from microorganisms could effectively control fusarium and several other maize fungal pathogens.* These substances are incorporated into maize growing to provide an agricultural system in an objective, flourishing environment that is characterised by freedom from harmful chemicals (Pereira et al., 2009).

DOI: 10.34101/ACTAAGRAR/2/15262

In light of the above, this mini review aims to highlight the types, infection processes, and effects of the common fungal diseases on the productivity and quality of maize crop and grain respectively.

Figure 1. **Bibliometric network of maize fungal pathogens**



MATERIALS AND METHODS

A comprehensive literature review was conducted using Scopus, Web of Science, and Google Scholar databases, covering publications from 1990 to 2024. Search terms included combinations of "maize" or "corn" with "fungal pathogens," "yield loss," "mycotoxins," "aflatoxins," "fumonisins," and "management strategies."

Inclusion Criteria:

Only peer-reviewed articles, authoritative reports, and reviews focusing specifically on maize fungal diseases were included. Studies addressing symptomatology, epidemiology, mycotoxin risks, yield impacts, and integrated disease management approaches were considered relevant.

Exclusion Criteria:

Excluded from the review were non-peer-reviewed or anecdotal reports, as well as research unrelated to maize or lacking sufficient data.

Data were organized into thematic categories: major fungal pathogens, symptomatology, yield and economic impact, mycotoxin production, and management methods. Cross validation was done across multiple sources for accuracy and consistency.

REVIEW RESULTS

Overview of Major Fungal Pathogens and Diseases in Maize

Maize is susceptible to a wide range of fungal pathogens that affect various parts of the plant during all growth stages. Foliar diseases such as Gray Leaf Spot (*Cercospora zeae-maydis*), Northern Corn Leaf Blight (*Exserohilum turcicum*), and Southern Corn Leaf Blight (*Bipolaris maydis*) cause defoliation, reduce photosynthetic capacity, and can lead to premature plant death (Savary et al., 2019; Nisbo et al., 2024). Ear rots, caused by fungi such as Fusarium species (*Fusarium verticillioides*, *F. graminearum*), Aspergillus (*Aspergillus flavus*) (Robertson-Hoyt et al., 2007), and Diplodia (*Stenocarpella maydis*), smut corn (*Ustilago maydis*), Maize rust (*Puccinia sorghi*), Anthracnose stalk rot (*Gromerella graminicola*), Charcoal corn rot (*Macrophomina phaseolina*), Late wilt (*Magnaporthiopsis maydis*), not only reduce grain quality but are frequently associated with the production of harmful mycotoxins such as fumonisins, aflatoxins (Robertson-Hoyt et al., 2007), and deoxynivalenol (DON) (Thompson and Raizada, 2018).

Common fungal diseases

Ear rot

Ear (and/or kernel) rot in maize is commonly caused by fungal species such as *Fusarium verticillioides*, *Fusarium graminearum*, and *Fusarium subglutinans*. The fungal species can infect a maize crop, particularly under warm, humid environment at all stages pre and post-harvest, according to Miller (1994). Together with Logrieco et al. (2002), Miller (1994) notes several species associated with Fusarium disease although, in Europe, *Fusarium culmorum* is more particular. More researchers (Bottalico, 1998; Koehler, 1959; Logrieco et al., 1993; Smith and White, 1988) identify the predominance of Gibberella ear rot in places that are cooler and with higher precipitation during the growing season of the maize crop. The same pathogens are also able to flourish in environments pronounced by heavy rainfall and high temperatures that comprise warmth and substantial humidity. These conditions facilitate the production of aflatoxins and fumonisins that are

DOI: 10.34101/ACTAAGRAR/2/15262

harmful enough to contaminate maize produce, rendering it unfit for consumption (Falade et al., 2022). The substances not only endanger life but they also negatively affect the economic status of farmers and countries. According to Mukanga et al. (2010), international markets tend to reject contaminated maize and its related products and, most times, the produce is sold at lower prices due to its poor quality. Mukanga et al. (2010) additionally cite Zambia and Tanzania as countries having scaring levels of mycotoxins, as per the tested maize samples, which is a threat to the health of the population. Concerning spread, these pathogens originate from inoculum sources such as insects, airborne spores, soil, and crop residues, and easily move to vast distances (Mehl and Cotty, 2010). Specifically, about 10 to 40% losses are recorded in maize yield as a result of contamination by fumonisins, particularly in Sub-Saharan Africa (Chilaka et al., 2022). Symptoms of maize ear rot diseases vary significantly depending on the causal fungal agent, the maize genotype, and the severity of the disease, which can differ from region to region. Symptoms of Fusarium ear rot is white to pink or salmon colored mold at the tip of the ear (Wang et al., 2014) as shown in *Figure 2*. As fungal pathogens continue causing significant losses to maize crop, the need for the effective management of Fusarium and related pathogens is crucial for the attainment of crop safety and productivity. According to Nayaka et al. (2009) and Guimarães et al. (2020), such management can lower the rate of mycotoxin contamination on maize kernels.

The practices for managing Fusarium infections may pose environmental challenges. For instance, according to Mielniczuk et al. (2020), chemical fungicides can lead to environmental pollution and increased growth of strains that are resistant to fungicides. This makes crop rotation and tillage approaches more suitable for the management of Fusarium and related fungal pathogens in maize (Marburger et al., 2015). Relatedly, the use of multiple strategies, especially Integrated Pest Management (IPM), has proved effective against fungal pathogens through reduced reliance on chemicals (Mesterházy et al., 2017).

Figure 2. **Symptoms of ear rot in maize cobs (CIMMYT, 2004)**

Maize smut

This disease, sometimes referred to as common smut corn is caused by *Ustilago maydis*. As stated by Merkevičiūte-Venslovė et al. (2023), the disease affects maize crop by reducing the yield and its quality of forage. High temperature and low moisture conditions are favorable for its development. *U. maydis* is a parasitic, biotrophic fungus and a plant pathogen, mainly infecting gramineous plants (Zou et al., 2022). The fungus infects primarily gramineous (grass-like) plants, including maize, and results in the formation of tumor-like galls. These galls can vary significantly in size, from less than 1 cm to over 30 cm in diameter. The fungus can infect all meristematic tissues of the plant, including ears, tassels, stalks, shoots, (Pataky and Snetselaar, 2006). Corn smut is considered a delicacy in some parts of the world, it can lead to significant economic losses, particularly in maize production. Aydogdu and Boyraz (2011) found that maize infected with corn smut experienced a 33% yield loss, which could have serious implications for food supply, as maize serves as a key food source for both humans and animals. Among the different varieties of maize, sweet maize is the most vulnerable to the disease. In addition to reduced yield, the unsightly appearance of maize smut makes the affected crops difficult to market, further exacerbating the economic impact. Maize smut caused by *Ustilago maydis* cannot be effectively controlled by common fungicides; however, several management strategies can help mitigate its impact (Mohan, 2013). These include using resistant maize varieties, practicing crop rotation, preventing mechanical damage to plants, and managing soil nitrogen levels. Djawu (2017) suggests a long-term strategy of using crop rotation and clearing debris from

DOI: 10.34101/ACTAAGRAR/2/15262

planting areas as an effective long-term strategy against maize smut. Such strategy can help farmers to control the disease in a better manner while reducing adverse effects on overall production of the crop.

Maize rust

Also known as *Puccinia sorghi* Schw., common maize rust is prevalent in regions having an elevation of 1500 to 2000 metres above sea level. The disease significantly affects the foliar parts of the crops, affecting the production of maize at a global scale. Generally, the disease has been recorded in areas that produce maize on a wide scale such as Ethiopia, East Africa, Latin America, United States, Asia, Mexico, Australia, and Canada (Schieber, 1965).

The causal agent of *Puccinia sorghi* Schw. is *Puccinia sorghi*, which is a rust fungus damaging maize plants by creating leaf lesions. Zúñiga-Silvestre et al. (2020) note that the disease reduces photosynthetic efficiency, which may advance to significant yield loss of the crop. According to Programa de Maíz (2004), the disease thrives in warm and humid weather, and notably causes great economic losses in maize cultivation. However, the critical levels of the disease vary from one year to the other, posing little impact in cases. Due to such wide distribution and variation in severity, farmers need to monitor the occurrence of maize rust and formulate integrated control strategies that facilitate improved crop yield. These include, but not limited to, good agricultural practices, resistant maize varieties, and application of appropriate fungicide.

Anthracnose stalk rot

This is a fungal disease caused by *Glomerella graminicola*, and affects the whole maize plant. At any time, this disease can show its symptoms during the growing season. Usually, this disease can be easily observed in the form of stalk rot or leaf blight (Tesso et al., 2012). Symptoms may appear several weeks after tassels formation on maize during mid-season. The outstanding symptom is the top dieback, which occurs after spread of the disease to several points of the crop plant. The whole plant will become necrotic and die in this dieback, starting from the tassel and then spreading through the whole stalk and the lowest leaves. The production grain loss due to this disease is estimated to vary from 0 to 40% depending on the climate, disease timing, hybrid, and other stress factors (Fazal et al., 2021). Crop rotation on maize, especially for a minimum of one year, is effective for the management of a similar fungal infection, *Colletotrichum graminicola*, on maize. The study supports the reduction of the pathogen on soil surfaces, which interrupts the life cycle of the organism. More strategies can help mitigate the disease and the saprophytic stage of the pathogen, and these include pest management, burying of maize residues through deep ploughing, and growing of resistant hybrid cultivars. Biological control could facilitate the inhibition of conidial spore infection using yeasts; however, this strategy requires thorough study especially if applications are to be performed on a large scale (Jirak-Peterson and Esker, 2011). A combination of these strategies, thus, can specifically provide a clear approach to the control of leaf blight maize anthracnose.

Charcoal corn rot disease

This is an infection associated with *Macrophomina phaseolina* (Tassi), a soil borne pathogen. The disease affects the production of maize globally and leads to marked economic losses in major maize growing regions, as shown in the global distributions of charcoal rot of maize in *Figure 3*. Prevalence of the disease is in warm, dry regions, where it affects crop yield and quality severely (Harlapur et al., 2023). The fungus thrives under soil conditions that promote repeated germination of microsclerotia during the crop's growing season. However, a low C: N soil ratio, high bulk density, and high quantity of soil moisture can deter adverse survival of the organism. The fibrovascular structure of the host's roots and basal internodes is compromised by *M. phaseolina*, which disrupts the transport of water and nutrients to the upper parts of the plant (Rehman et al., 2021). Consequently, infection by *M. phaseolina* leads to premature plant death, progressive wilting, decreased yield, and diminished vigor. Pathogen is also responsible for a range of diseases, including damping off, charcoal rot, seedling blight, basal stem rot, root rot, and stem rot (Babu et al., 2007). Similar strategies such as organic amendments, seed treatment, genetic host resistance, and cultural practices can be used to control charcoal corn rot disease (Gupta et al., 2012).

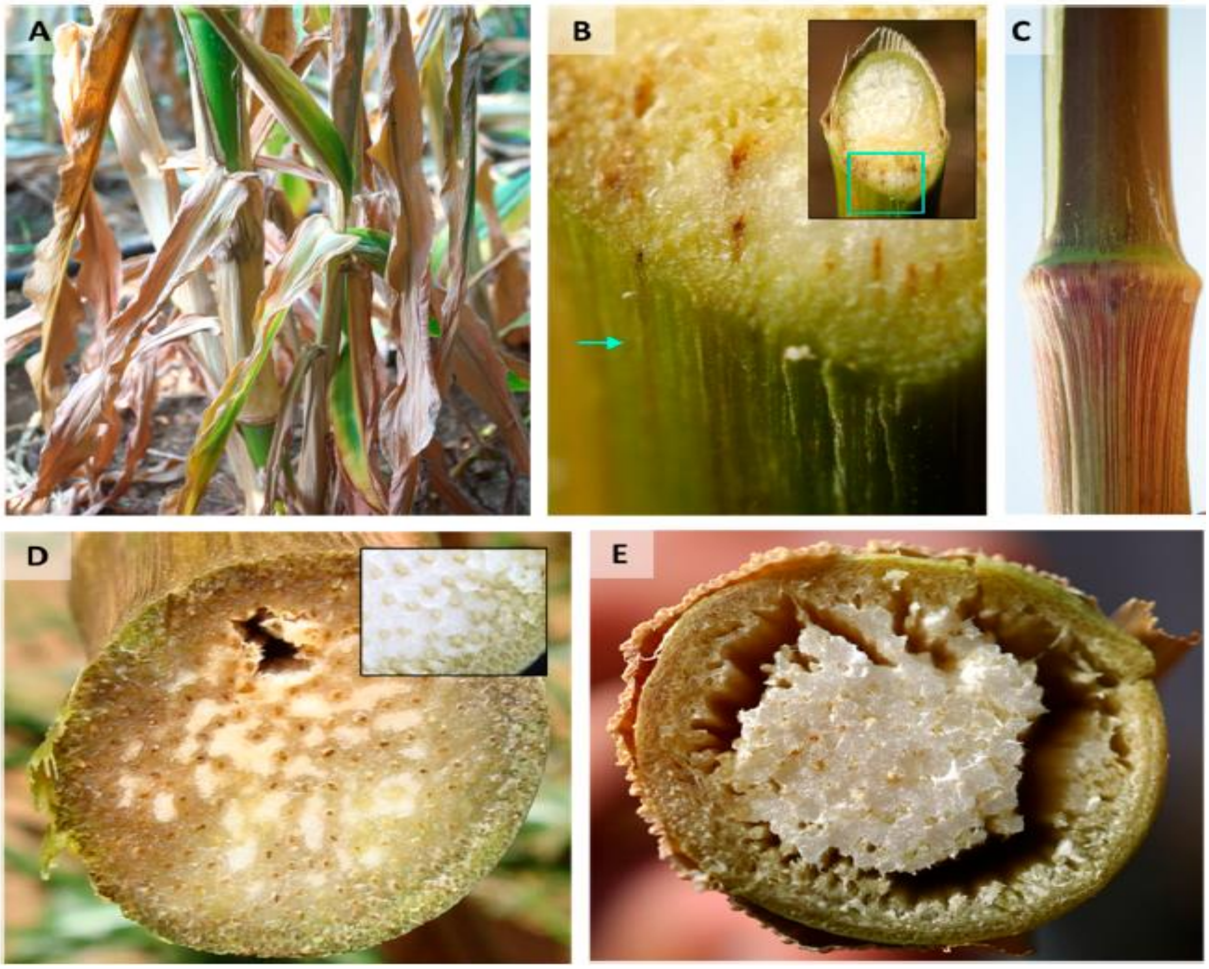
Figure 3. **Global distributions of charcoal rot of maize (CIMMYT 2004)**

DOI: 10.34101/ACTAAGRAR/2/15262

Late wilt disease

Late wilt is a vascular disease caused by the pathogen *Magnaporthiopsis maydis* (Degani, 2021). Late wilt was reported in Egypt (1961), India (1970), Hungary (1998), Spain and Portugal (2011), Israel (2018) and possibly in Nepal (2015) (Pecsi and Nemeth, 1998; Molinero et al., 2011; Drori et al., 2013; Subedi, 2015). The infection occurs within the first three weeks of growth (Degani, 2021). The fungi easily infect young maize sprouts through the roots (Degani, 2021). The fungus penetrates the maize roots and moves into the vascular system 21 days after sowing (DAS) (Degani, 2021), as shown in the symptoms of late wilt disease (LWD) of maize in *Figure 4*. The disease is characterized by a fast wilting of maize plants from the tasselling stage until just before maturity (Degani and Gordani, 2022). The management of late wilt disease in maize involves a combination of cultural, biological, and chemical practices. Integrating resistant varieties, crop rotation, proper soil management, and early detection can significantly reduce the impact of the disease. *Magnaporthipsis* infections can be managed through a multidimensional strategy, the result of which will be health maize crops and high crop yield. However, with limited impact on severe disease outbreaks, biological control agents like *Trichoderma spp.* can be a reliable solution against wilt infections. In many instances, biological and chemical control methods can be integrated to provide the farmer with synergy amidst minimal limitations (Gordani et al., 2023).

Figure 4. **Symptoms of late wilt disease (LWD) of maize. (A) Wilt symptoms appear on lower leaves and stems in the field. (B) Cross-section magnification shows vascular bundles turn red-brown. Insert: cross section with green frame marking magnification area, green arrow points to surface color change. (C) Red strips from vascular bundles visible on lower stem surface. (D) Cross section of wilt diseased plants shows yellow-brown tissue and occluded vascular bundles (Degani, 2022)**



Effects of diseases on maize production

Fungal diseases represent a significant constraint on global maize production, causing considerable losses in both yield quantity and quality (Mitrović et al., 2025). The extent of damage depends on factors such as the specific pathogen involved, environmental conditions, maize genotype, and the timing of infection. Foliar, stalk, and ear rot fungi impair photosynthesis, disrupt nutrient transport, and hinder grain development, while some pathogens also induce the accumulation of harmful secondary metabolites like aflatoxins and fumonisins (Ferrigo et al., 2016). Yield reductions due

DOI: 10.34101/ACTAAGRAR/2/15262

to fungal diseases can vary widely, ranging from 5% to over 60% depending on disease pressure. For example, Gray Leaf Spot (GLS) and Northern Corn Leaf Blight (NCLB) can cause yield losses of 10–25% and 30–60%, respectively, under favorable conditions (Sibiya et al., 2012; Rehman et al., 2021). Ear rot diseases such as Fusarium and Aspergillus not only reduce yield by up to 50% but also degrade grain quality and seed viability (Chen et al., 2023). Historically, Southern Corn Leaf Blight caused catastrophic crop failures in the United States during the 1970 epidemic, highlighting the potential for rapid economic devastation from foliar pathogens (Bruns, 2017). A critical concern is the contamination of maize with mycotoxins produced by pathogens such as *Fusarium* spp. (fumonisins) and *Aspergillus flavus* (aflatoxins), which pose serious health risks due to their carcinogenic, immune suppression and liver damage (Khan et al., 2024). The economic impact of fungal diseases is twofold: direct yield losses in the field and indirect costs related to quality degradation, mycotoxin testing, trade rejections, and health expenses. In maize dependent countries, these losses threaten food security, income stability, and rural livelihoods (Almeida et al., 2019). Smallholder farmers in developing regions are especially vulnerable due to limited access to resistant varieties, fungicides, and improved storage technologies. Given maize's role as a staple crop, disease outbreaks can precipitate acute food shortages, elevate market prices, and reduce household nutrition (Biswal et al., 2022). The fungal pathogens of maize and their effects on yield and quality are shown in *Table 1*.

Table 1. **Fungal pathogens of maize and their effects on yield and quality**

Disease	Pathogen	Symptoms	Yield Loss (%)	Mycotoxins Production	Reference
Ear rot	*Fusarium verticillioides*, *Fusarium graminearum*, and *Fusarium subglutinans*	White to pink or salmon colored mold at the ear tip	5–15	Yes	(Chilaka et al., 2022; Ako et al., 2003)
Maize smut	*Ustilago maydis*	Galls formation like mushroom	33	No	(Merkevičiūte-Venslovė et al., 2023)
Maize rust	*Puccinia sorghi*	Leaf lesions	18–49	No	(Kohkhar et al., 2014)
Anthracnose stalk rot	*Glomerella graminicola*	Top dieback	0–40	No	(Kleczewski, 2014, Tesso et al., 2012)
Charcoal ear rot	*Macrophomina phaseolina*	Damping off, stalk and root rot	20–30	No	(Mueller et al., 2016; Babu et al., 2007)
Late wilt disease	*Macnaporthiopsis maydis*	Wilt near flowering; stalk reddish-brown	40–100	No	(Degani, 2021)
Aspergillus Ear and kernel Rot	*Aspergillus flavus*	Yellow-green spores; reddish-gold leaf underside	10–30	Yes	(Mukanga et al., 2010)
Southern corn leaf blight	*Bipolaris maydis*	Ear killed prematurely, cob rot	30–50	No	(Bruns, 2017)
Corn gray leaf spot	*Cercospora zeae-maydis*	Leaf grey lesions	10–25	No	(Sibiya et al., 2012)
Northern Corn Leaf Blight	*Exserohilum turcicum*	Purple/dark brown leaf discoloration	30–60	No	(Rehman et al., 2021)

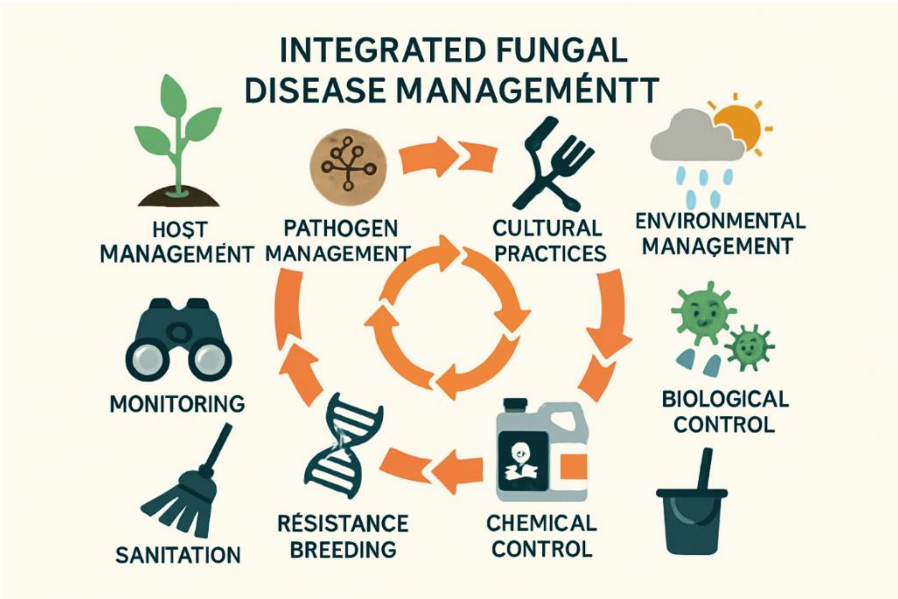
Integrated disease management (IDM)

Integrated fungal disease management (IDM) in maize is a comprehensive approach that combines multiple control strategies to effectively minimize the impact of fungal pathogens such as *Fusarium verticillioides*, *Puccinia sorghi*, and *Exserohilum turcicum*, which cause diseases like ear rot, common rust, and northern corn leaf blight (Gurjar et al., 2018). This strategy involves the integration of cultural practices such as crop rotation, selection of resistant or tolerant varieties, deep ploughing, and sanitation by removing crop debris to reduce inoculum sources (Khoury and Makkouk, 2010). Tillage practices decrease the inoculum potential of the fungus because the fungus survives best on residue left on or above the soil surface (Gurjar et al., 2018). Biological control agents have been reported to play a crucial role in effectively managing fungal plant pathogens (Zhang et al., 2013). Biological control agents, for example *Trichoderma viride*, *Trichderma harzianum* are employed as seed treatments and soil amendments to suppress fungal pathogens naturally (Yassin et al., 2021). Chemical fungicides, applied judiciously in foliar sprays (e.g., Azoxystrobin + Difenoconazole, Tebuconazole), complement these methods to enhance control efficiency and reduce disease severity. Field studies have demonstrated that such IDM modules significantly lower disease incidence and severity, promote healthier plant growth indicated by increased plant height and cob number, and ultimately result in

DOI: 10.34101/ACTAAGRAR/2/15262

higher grain and fodder yields compared to untreated controls. This combination of biological, cultural, and chemical interventions under IDM not only ensures sustainable disease control but also improves the economic returns and environmental safety of maize production systems (Ons et al., 2020) as shown in *Figure 5*.

Figure 5. **Integrated fungal Disease Management in Maize Production**



Source: Authors

CONCLUSIONS

Pathogenic fungal pathogens are a global threat to the growing of maize, in terms of losses in yield. This state informs the need for combining multiple approaches, namely: cultural, biological, and chemical, with a focus on integrated disease management. These approaches are effectively applied to specific environments and pathogen dynamics to control Fusarium and other fungal related maize pathogens. Basing on all the several strategies, a holistic approach aims to provide agricultural sustainability and food safety, while improving maize crop health and reducing the contamination of maize produce by mycotoxin.

ACKNOWLEDGEMENTS

Thanks go to the TKP2021-NKTA funding scheme which supported this study, under implementation by the Ministry of Culture and Innovation of Hungary, as part of the National Research, Development and Innovation Fund, Project number TKP2021-NKTA-32.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Ako, M.; Schulthess, F.; Gumedzoe, M.Y.D.; Cardwell, K.F. (2003): The effect of Fusarium verticillioides on oviposition behaviour and bionomics of lepidopteran and coleopteran pests attacking the stem and cobs of maize in West Africa. Entomol. *Exp. Appl. 106*:201–210.

Almeida, F.; Rodrigues; M.L.; Coelho, C. (2019): The Still Underestimated Problem of Fungal Diseases Worldwide. *Front. Microbiol. 10*:214. https://doi.org/10.3389/fmicb.2019.00214

Aydogdu, M.; Boyraz, N. (2011): Effects of nitrogen and organic fertilization on corn smut (*Ustilago maydis* (DC) Corda.). *African Journal of Agricultural Research*, *6*(19), 4539–4543. https://doi.org/10.5897/AJAR10.1166

Babu, B.K.; Saxena, A.K.; Srivastava, A.K.; Arora, D.K. (2007): Identification and detection of *Macrophomina phaseolina* by using species-specific oligonucleotide primers and probe. *Mycologia*, *99*(6), 797–803. https://doi.org/10.1080/15572536.2007.11832511

Biswal, A.K.; Alakonya, A.E.; Mottaleb, K.A.; Hearne, S.J.; Sonder, K.; Molnar, T.L.; Jones, A.M.; Pixley K.V.; Prasanna, B.M. (2022): Maize Lethal Necrosis disease: review of molecular and genetic resistance mechanisms, socio-economic impacts, and mitigation strategies in sub-Saharan Africa. *BMC Plant Biology 22*:542. https://doi.org/10.1186/s12870-022-03932-y

Bottalico, A. (1998): Fusarium diseases of cereals: Species complex and related mycotoxin profiles in Europe. *Journal of Plant Pathology*, *80*: 85–103.

DOI: 10.34101/ACTAAGRAR/2/15262

Bruns, H.A. (2017): Southern corn leaf blight: a story worth retelling. *Agronomy Journal, 109*(4), 1218–1224. https://doi.org/10.2134/agronj2017.01.0006

Chen, J.; Zhou, L.; Din, I. U.; Arafat, Y., Li, Q.; Wang, J. et al. (2021): Antagonistic activity of *Trichoderma* spp. against *Fusarium oxysporum* in rhizosphere of *Radix pseudostellariae* triggers the expression of host defense genes and improves its growth under long-term monoculture system. *Front. Microbiol. 12*:579920. https://doi.org/10.3389/FMICB.2021.579920

Chen, X.; Abdallah, M.F.; Landschoot, S.; Audenaert, K.; De Saeger, S.; Chen, X.; Rajkovic, A. (2023): *Aspergillus flavus* and *Fusarium verticillioides* and Their Main Mycotoxins: Global Distribution and Scenarios of Interactions in Maize. *Toxins, 15*, 577. https://doi.org/10.3390/toxins15090577

Chilaka, C.A.; Obidiegwu, J.E.; Chilaka, A.C.; Atanda, O.O.; Mally, A. (2022): Mycotoxin Regulatory Status in Africa: A Decade of Weak Institutional Efforts. *Toxins*, *14*, 442. https://doi.org/10.3390/ toxins14070442

Cimmyt (2004): The Cimmyt Maize Program 2004. *Maize diseases: A guide for field identification.* 4th edition. Mexico, D.F., International Maize and Wheat Improvement Centre (CIMMYT).

Degani, O. (2021): A review: late wilt of maize—the pathogen, the disease, current status, and future perspective. *J. Fungi. 7*(11), 989; https://doi.org/10.3390/jof7110989

Degani, O. (2022): Control Strategies to Cope with Late Wilt of Maize. *Pathogens, 11*, 13. https://doi.org/10.3390/pathogens11010013

Degani, O.; Gordani, A. (2022): New Antifungal Compound, 6-Pentyl-α-Pyrone, against the Maize Late Wilt Pathogen, *Magnaporthiopsis maydis*. *Agronomy*, *12*, 2339. https://doi.org/10.3390/agronomy12102339

Djawu, B.P. (2017): Compost and nitrogen fertilizer on maize (*Zea mays* L.) growth and yield and residual effects on cowpea (*Vigna unguiculata* (L) Walp) in a rotation. Thesis. University of Ghana.

Drori, R.; Sharon, A.; Goldberg, D.; Rabinovitz, O.; Levy, M.; Degani, O. (2013): Molecular diagnosis for *Harpophora maydis*, the cause of maize late wilt in Israel. *Phytopathol. Mediterr*. *52*, 16–29.

El-Shenawy, A.A.; Hassan, M.A.A.; El-Haress, S.M.A.; Abd-Elaziz, M.A.A. (2022): Assessment of Combining Ability in Some Newly Maize Inbred Lines for Grain Yield and Late Wilt Resistance. *J. Plant Prod.* , *13*, 45–48.

Falade, T.D.O.; Neya, A.; Bonkoungou, S.; Dagno, K.; Basso, A.; Senghor, A.L.; Atehnkeng, J.; Ortega-Beltran, A.; Bandyopadhyay, R. (2022): Aflatoxin Contamination of Maize, Groundnut, and Sorghum Grown in Burkina Faso, Mali, and Niger and Aflatoxin Exposure Assessment. *Toxins, 14*, 700. https://doi.org/10.3390/toxins1410070

Fazal, ur R.; Muhammad, A.; Maria, K.; Nageen, N.; Muhammad, G.H.; Haroon, I.; Muhammad, A.I.; Gulfam, Y.; Rohoma, T.; Usama, A. (2021): Seed-borne fungal diseases of maize (*Zea mays* L.): a review. *Agrinula: Jurnal Agroteknologi dan Perkebunan* vol. *4* (1): 43–60. https://doi.org/10.36490/agri.v4i1.123

Ferrigo, D.; Raiola, A.; Causin, R. (2016): Fusarium Toxins in Cereals: Occurrence, Legislation, Factors Promoting the Appearance and Their Management. *Molecules, 21*, 627; https://doi.org/10.3390/molecules21050627

Gordani, A.; Hijazi, B.; Dimant, E.; Degani, O. (2023): Integrated Biological and Chemical Control against the Maize Late Wilt Agent *Magnaporthiopsis maydis*. *Soil Syst. 7*, 1. https://doi.org/10.3390/soilsystems7010001

Gupta, G.K.; Sharma, S.K.; Ramteke, R. (2012): Biology, Epidemiology and Management of the Pathogenic Fungus *Macrophomina phaseolina* (Tassi) Goid with Special Reference to Charcoal Rot of Soybean (*Glycine max* (L.) Merrill). *J. Phytopathol., 160*, 167–180, https://doi.org/10.1111/j.1439-0434.2012.01884.x

Gurjar, M.S.; Saharan, M.S.; Aggarwal Rashmi (2018): Integrated Disease Management Practices for Sustainable Agriculture under ICM Approach. *Integrated crop management practices* (ed:Anil K. Choudhary R.S. Bana Vijay Pooniya). ICAR–Indian Agricultural Research Institute, New Delhi.113–120.

Harlapur, S.I.; Khokhar, M.K.; Hooda, K.S. (2023): Epidemiology and management of charcoal rot of maize caused by *Macrophomina phaseolina* (Tassi.) Goid. *Ecobiology, Pathology and Management*, 83–89.

International Grains Council. International Grains Council Grain Market Report Five-Year Baseline Projections of Supply and Demand for Wheat, Maize (Corn), Rice and Soyabeans to 2023/24 March 2019; *International Grains Council: London*, UK, pp. 1–4. Available online: http://www.igc.int/en/downloads/gmrsummary/gmrsumme.pdf (accessed on 15 January 2020).

Jirak-Peterson, J.C.; Esker, P.D. (2011): Tillage, crop rotation, and hybrid effects on residue and corn anthracnose occurrence in Wisconsin. *Plant Disease*, *95*(5), 601–610. https://doi.org/10.1094/PDIS-11-10-0837

Khan, N.; Maymon, M.; Hirsch, A.M. (1959): Combating *Fusarium* Infection Using *Bacillus*-Koehler B Corn ear rots in Illinois. University of Illinois Agriculture Experiment Station Bulletin 639.

Khan, R.; Anwar, F.; Ghazali, F.M. (2024): A comprehensive review of mycotoxins: Toxicology, detection, and effective mitigation approaches. *Heliyon, 10*(8) https://doi.org/10.1016/j.heliyon.2024.e28361

Khokhar, M.; Hooda, K.; Sharma, S.; Singh, V. (2014): Post Flowering Stalk Rot Complex of Maize - Present Status and Future Prospects. *Maydica electronic publication. 59*: 226–242.

Khoury, W.; Makkouk (2010): Integrated plant disease management in developing countries. *Journal of Plant Pathology 92*(4)

Kleczewski, N. (2014): *Anthracnose Leaf Blight and Stalk Rot of Corn*. University of Delaware Cooperative Extension, Fact Sheet S107.

Kramer, J.; Ozkaya, O.; Kummerli, R. (2020): Bacterial siderophores in community and host interactions. *Nat. Rev. Microbiol. 18*, 152–163. https://doi.org/10.1038/s41579-019-0284-4

Logrieco, A.; Moretti, A.; Altomare, C.; Bottalico A and Carbonell Torres, E. (1993): Occurrence and toxicity of *Fusarium subglutinans* from Peruvian maize. *Mycopathologia, 122*: 185–190.

Logrieco, A.; Mule, G.; Moretti, A.; Bottalico, A. (2002): Toxigenic Fusarium species and mycotoxins associated with maize ear rot in Europe. *European Journal of Plant Pathology, 108:* 597–609

Marburger, D.; Venkateshwaran, M.; Conley S.; Esker, P.; Lauer, J.; and Ané, J. (2015): Crop rotation and management effect on *Fusarium* spp. Populations, *Crop Science, 55*: 365–376. https://doi.org/10.2135/CROPSCI2014.03.0199

Matos, D.; Cardoso, P.; Almeida, S.; Figueira, E. (2024): Challenges in maize production: A review on late wilt disease control strategies. *Fungal Biology Reviews*. *50*. 10.1016/j.fbr.2024.100396

DOI: 10.34101/ACTAAGRAR/2/15262

Mehl, H.L.; Cotty, P.J. (2010): Variation in Competitive Ability Among Isolates of *Aspergillus flavus* from Different Vegetative Compatibility Groups During Maize Infection. *Phytopathology*, Vol. *100*, No. 2.

Merkevičiūte-Venslovė, L.; Venslovas, E.; Mankevičienė, A.; Šlepetienė, A.; Cesevičienė, J. (2023): Effect of *Ustilago maydis* on the Nutritive Value and Aerobic Deterioration of Maize Silage. *Agronomy*, *13*, 111. https://doi.org/10.3390/agronomy13010111

Mesterházy, Á.; Varga, M.; Tóth, B.; Kótai, C.; Bartók, T.; Véha, A.; Acs, K.; Vágvölgyi, C.; Lehoczki-Krsjak, S. (2017): Reduction of deoxynivalenol (DON) contamination by improved fungicide use in wheat, Part 2. farm scale tests with different nozzle types and updating the integrated approach, *European Journal of Plant Pathology*, *151*: 1–20. https://doi.org/10.1007/s10658-017-1347-x

Mielniczuk, E.,; Skwaryło-Bednarz, B. (2020): *Fusarium* head blight, mycotoxins and strategies for their reduction, *Agronomy*, *10*(4): 509. https://doi.org/10.3390/agronomy10040509

Miller, J.D. (1994): Epidemiology of Fusarium diseases of cereals. In: Miller JD and Trenholm HL (eds) *Mycotoxins in Grain*: Compounds other than Aflatoxin (pp 19–36) Eagan Press, St. Paul, MN, USA.

Mitrović, I.; Čanak, P.; Tančić Živanov, S.; Farkaš, H.; Vasiljević, M.; Ćujić, S.; Zorić, M.; Mitrović, B. (2025): *Trichoderma harzianum* in Biocontrol of Maize Fungal Diseases and Relevant Mycotoxins: From the Laboratory to the Field. *J. Fungi, 11*, 416. https://doi.org/ 10.3390/jof11060416

Mohan, S.K.; Hamm, P.B.; Clough, G.H.; du Toit, L.J. (2013): "Corn smuts" Oregon State University, A Pacific Northwest Extension. https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/pnw647.pdf

Molinero-Ruiz, M.L.; Melero-Vara, J.M.; Mateos, A. (2011): *Cephalosporium maydis*, the cause of late wilt in maize, a pathogen new to Portugal and Spain. *Plant Dis*., *94*, 379.

Mueller, D.S.; Wise, K.A.; Sisson, A.J.; Allen, T.W.; Bergstrom, G.C.; Bosley, D.B.; Bradley, C.A.; Broders, K.D.; Byamukama, E.; Chilvers, M.I.; Collins, A.; Faske, T.R.; Friskop, A.J.; Heiniger, R.W.; Hollier, C.A.; Hooker, D.C.; Isakeit, T.; Jackson-Ziems, T.A.; Jardine, D.J.; Kelly, H.M.; Kinzer, K; Koenning, S.R.; Malvick, D.K.; McMullen, M.; Meyer, R.F.; Paul, P.A.; Robertson, A.E.; Roth, G.W.; Smith, D.L.; Tande, C.A.; Tenuta, A.U.; Vincelli, P.; Warner, F. (2016): Corn yield loss estimates due to diseases in the United States and Ontario, Canada from 2012 to 2015. *Plant Health Progress, 17*(3), 211–222. https://doi.org/10.1094/PHP-RS-16-0030

Mukanga, M.; Derera, J.; Tongoona, P.; Laing, M.D. (2010): A survey of pre-harvest ear rot diseases of maize and associated mycotoxins in south and central Zambia. *International Journal of Food Microbiology, 141*(3), 213–221. https://doi.org/10.1016/j.ijfoodmicro.2010.05.011

Nsibo, D.L.; Barnes, I.; Berger, D.K. (2024): Recent advances in the population biology and management of maize foliar fungal pathogens *Exserohilum turcicum, Cercospora zeina* and *Bipolaris maydis* in Africa. *Front. Plant Sci. 15:*1404483. https://doi.org/10.3389/fpls.2024.1404483

Ons, L.; Dany, B.; Thevissen, K.; Cammue, B.P.A. (2020): Combining Biocontrol Agents with Chemical Fungicides for Integrated Plant Fungal Disease Control. *Microorganisms, 8*: 1930. https://doi.org/10.3390/microorganisms8121930

Pataky, J.; Snetselaar, K. (2006): Common smut of corn (Syn. boil smut, blister smut). Plant Disease Profiles, *The Plant Health Instructor. Volume 6*. https://doi.org/10.1094/PHI-I-2006-0927-01

Pecsi, S.; Nemeth, L. (1998): Appearance of *Cephalosporium maydis* Samra Sabet and Hingorani in Hungary. Meded. Fac. Landbouwkd. En Toegep. Biol. Wet. Univ. Gent., 63, 873–877.

Pereira, P.; Nesci A.; Etcheverry, M. (2009): Efficacy of bacterial seed treatments for the control of *Fusarium verticillioides* in maize, *Bio. Control*, *54*:103–111. https://doi.org/10.1007/s10526-007-9148-3

Programa de Maíz, Centro Internacional de Mejoramiento del Maíz y Trigo (CIMMYT). (2004): Enfermedades del Maíz: Una Guía Para su Identificación en el Campo. 4th ed. Centro Internacional de Mejoramiento del Maíz y Trigo (CIMMYT), México, D.F, p. 118.

Rahman, S.F.S. AB.; Singh, E.; Pieterse, C.M.J.; Schenk, P.M. (2018): Emerging microbial biocontrol strategies for Plant Pathogens. *Plant Science*, v. *267*,. 102–111. DOI https://doi.org/10.1016/j.plantsci.2017.11.012

Rehman, F.; Adnan, M.; Kalsoom, M.; Naz, N.;, Husnain, M.G.; Ilahi, H.; Ilyas, M.A.; Yousaf, G.; Tahir, R.; Ahmad, U. (2021): Seed-Borne Fungal Diseases of Maize (*Zea mays* L.): A Review. *Agrinula: Jurnal Agroteknologi Dan Perkebunan*, *4*(1), 43–60. https://doi.org/10.36490/agri.v4i1.123

Robertson-Hoyt, L.A.; Betrán J.; Payne, G.A.; White, D.G.; Maragos T.I.M.; Molnár, T.L.; Holland, J.B. (2007): Relationships Among Resistances to Fusarium and Aspergillus Ear Rotsand Contamination by Fumonisin and Aflatoxin in Maize. *Phytopathology*, *97*:311–317. https://doi.org/10.1094/PHYTO-97-3-0311

Savary, S.; Willocquet, L.; Pethybridge, S.J.; Esker, P.; McRoberts, N.; Nelson, A. (2019): The global burden of pathogens and pests on major food crops. *Nat. Ecol. Evol. 3* (3), 430–439. https://doi.org/10.1038/s41559-018-0793-y

Schieber, E. (1965): Distribution of *Puccinia sorghi* and *P. polysora* in Africa and pathogenecity of these species on corn lines with Latin American germplasm. *Phytopathology*, *55*: 1074 (Abstract).

Smith, D.R.; White, D.G. (1988): Diseases of corn. In: Sprague GF and Dudley JW (eds) *Corn and Corn Improvement*, 3rd edn (pp 687–766) Agronomy Series No. 18. Am. Soc. Agronomy, Madison, WI, USA

Stukenbrock, E.; Gurr, S. (2023): Address the growing urgency of fungal disease in crops. *Nature 617*, 31–34. https://doi.org/10.1038/d41586-023-01465-4

Subedi, S.A. (2015): Review on important maize diseases and their management in Nepal. *J. Maize Res. Dev*., *1*, 28–52.

Tesso, T.T.; Perumal, R.; Little, C.R.; Adeyanju, A.; Radwan, G.L.; Prom, L.K.; Magill, C.W. (2012): Sorghum pathology and biotechnology-a fungal disease perspective: Part II. Anthracnose, stalk rot, and downy mildew. *European Journal of Plant Science and Biotechnology*, *6*(Special Issue 1), 31–44.

Thompson, M.E.H.; Raizada, M.N. (2018): Fungal Pathogens of Maize Gaining Free Passage Along the Silk Road. *Pathogens, 7*:81. https://doi.org/10.3390/pathogens7040081

Wang, J.H; Li, H.P.; Zhang, J.B.; Wang, B.T.; Liao, Y.C. (2014): First report of Fusarium maize ear rot caused by *Fusarium kyushuense* in China. *Plant Dis*, *98*:279. Disease notes, http://dx.doi.org/10.1094/PDIS-05-13-0558-PDN

Xu, Y.; Zhao, B.; Zhai, Y.; Chen, Q.; Zhou, Y. (2021): Maize diseases identification method based on multi-scale convolutional global pooling neural network. *IEEE Access 9*, 27959–27970.

DOI: 10.34101/ACTAAGRAR/2/15262

Yassin, M.T.; Mostafa, A.A.; Al-Askar, A.A.; Sayed, S. R.M.; Rady, A.M. (2021): Antagonistic activity of *Trichoderma harzianum* and *Trichoderma viride* strains against some fusarial pathogens causing stalk rot disease of maize, *in vitro*. *Journal of King Saud University – Science 33*:101363. https://doi.org/10.1016/j.jksus.2021.101363.

Zhan, B.-h.; Yang, X.-l.; Lommel, S.A.; Zhou, X.-p. (2022): Recent progress in maize lethal necrosis disease: From pathogens to integrated pest management. *Journal of Integrative Agriculture*, *21*(12): 3445–3455.

Zhang, F., Yuan, J., Yang, X., Cui, Y., Chen, L., Ran, W., Shen, Q., (2013): Putative *Trichoderma harzianum* mutant promotes cucumber growth by enhanced production of indole acetic acid and plant colonization. *Plant Soil, 368* (1-2), 433–444.

Zou, K.K.; Li Y.; Zhang W.J.; Jia Y.F.; Wang, Y.; Ma, Y.T.; Lv, X.L.; Xuan Y.H.; Du W.L. (2022): Early infection response of fungal biotroph Ustilago maydis in maize. *Front. Plant Sci.*; *13*:970897. https://doi.org/10.3389/fpls.2022.970897

Zúñiga-Silvestre, C.A., De-León-García-de-Alba, C.; Ayala-Escobar, V.; González-Hernández, V.A. (2020): Induced Resistance to Common Rust (*Puccinia sorghi*), in Maize (*Zea Mays*). *Emirates Journal of Food and Agriculture*, *vol. 32*, no. 1, 11–18., doi:10.9755/ejfa.2020.v32.i1.2053