Navigating the Complexities of Fusarium Head Blight in Wheat: Insight from Ethiopian Agriculture

Abstract

Wheat, a vital staple crop feeding 35% of the global population, faces significant threats from plant diseases and climate change, with Fusarium Head Blight (FHB) being one of the most severe challenges. FHB, primarily caused by Fusarium graminearum, leads to substantial yield losses and mycotoxin contamination, particularly deoxynivalenol (DON) and zearalenone (ZEA), which pose serious health risks and complicate international trade. Chronic exposure to mycotoxins, especially aflatoxins, poses serious health risks. Aflatoxins are carcinogenic, particularly associated with an increased risk of liver cancer. In Ethiopia, the risk is exacerbated by the prevalence of hepatitis B, which can synergize with aflatoxins, heightening liver cancer cases. Mycotoxins are also linked to stunted growth and malnutrition in children, a critical public health concern in a country with high rates of undernutrition. Additionally, mycotoxin-contaminated animal feed affects livestock health, leading to reduced productivity, milk, and meat contamination, which further threatens food security. *In Ethiopia, FHB prevalence can reach up to 90% in regions with high humidity and warm temperatures during wheat anthesis, severely affecting grain quality. Over 20 Fusarium species have been identified in the country, further raising concerns about mycotoxin contamination. Current management strategies include cultural practices such as crop rotation and tillage, fungicide applications, and breeding for resistance. However, these methods are not fully reliable, and integrated approaches are essential to sustainably manage FHB and mitigate resistance development. This review synthesizes existing research on FHB, focusing on its impact in Ethiopian agriculture and exploring effective management strategies to improve wheat productivity and food security.*

Key words*: wheat, fusarium head blight, Fusarium species*

Introduction

Wheat is a vital staple crop, feeding approximately 35% of the global population, with annual production surpassing 700 million tons. By 2050, global wheat production must significantly increase to meet the demands of an estimated population of 9 billion. Wheat is the most vital staple food, giving roughly 55% of the starches and over 20% of the food calories (FAO, 2020; Gupta *et al*. 2021). However, wheat production is increasingly threatened by plant diseases and climate change, with Fusarium Head Blight (FHB) standing out as one of the most severe challenges. Wheat is an important staple and cash crop in Ethiopia, helping to increase income, food security, employment and national GDP growth (Anteneh and Asrat 2020). Fusarium Head Blight, primarily caused by *Fusarium graminearum*, is a destructive disease that affects wheat and other cereals globally, leading to substantial yield losses and mycotoxin contamination. These mycotoxins, particularly deoxynivalenol (DON) and zearalenone (ZEA), pose serious health risks to humans and animals and affect grain quality, complicating international cereal trade due to stringent regulatory limits (Pestka, 2010; Muluken Getahun *et al*., 2023). The FHB species complex includes over 19 *Fusarium* species, which thrive under favorable environmental conditions during wheat anthesis, causing extensive blight symptoms and significant yield reductions (Goswami & Kistler, 2004).

In Ethiopia, FHB prevalence can reach up to 90% in regions with high humidity and warm temperatures during wheat anthesis (Minyahil kebede *et al*., 2021). The disease, primarily caused by *Fusarium graminearum* and *Fusarium culmorum*, leads to premature bleaching of spikelets, shriveled kernels, and reduced grain quality. The management of FHB is challenging due to the pathogen's ability to spread over long distances by air and the coinciding favorable conditions during wheat flowering.

Current management strategies are limited, with no single reliable method available. Integrated approaches combining host resistance, cultural practices, and chemical control have shown some effectiveness, but comprehensive research, particularly in Ethiopia, remains scarce (McMullen *et al*., 2012). Despite advances in molecular techniques and hyperspectral imaging, which offer promising tools for early detection and management of FHB, the need for further research on FHB in Ethiopia is critical (Abate *et al*., 2015).

This review aims to synthesize existing research on Fusarium Head Blight, with a particular focus on Ethiopian agriculture. By examining the impact of FHB and exploring effective management strategies, this review seeks to contribute to improving wheat productivity and ensuring food security in Ethiopia and other regions affected by this devastating disease.

Epidemiology of Fusarium Head Blight

FHB development is heavily influenced by environmental conditions, particularly during and after anthesis. Fusarium graminearum produces ascospores and macroconidia in perithecia and sporodochia, respectively, with ascospores serving as the primary inoculum source for epidemics (Osborne & Stein, 2007). Warm temperatures and high humidity favor complete head blighting within 2 to 4 days post-infection (Fernando *et al*., 1997). The optimal temperature for ascospore formation ranges from 25°C to 28°C, while infection occurs between 20°C and 30°C (McMullen *et al*., 2012).

Perithecia and sporodochia, the fungus's fruiting structures, overwinter in crop debris. The relationship between crop debris and FHB epidemics is well-documented (Dill-Macky & Jones, 2000; Sturz & Johnston, 1985). Minimum soil temperatures for perithecia production are between 6°C and 10°C, with an optimum range of 15°C to 20°C (Gilbert *et al*., 2008; Pereira *et al*., 2004). High relative humidity and soil moisture favor perithecia formation, making humid weather in August and September conducive to FHB epidemics in the following growing season.

In spring, ascospores and macroconidia are released from the fruiting bodies, with optimal production conditions being a wet substrate and high temperatures. The optimum temperatures for ascospore production are 29°C for F. graminearum and 32°C for F. culmorum. Spore production is inhibited when temperatures exceed 36°C (Osborne & Stein, 2007). Ascospore discharge is triggered by temperatures between 20°C and 30°C and high relative humidity (80–92%). Rainfall events preceding and during anthesis ensure the presence of inoculum for FHB epidemics.

Ascospores and macroconidia land on wheat heads during the flowering stage, initiating infection. Wet and rainy conditions facilitate propagule dispersion via water splash or wind, leading to infection of internal flower parts, glumes, lemma, and palea. Rain splash is a major pathogen dispersal mechanism (Schmale & Bergstrom, 2003). Infection is favored by relative humidity above 80%, wind, and rain, with optimal conditions being temperatures between 10°C and 30°C and relative humidity above 90% for 4 to 6 hours during flowering.

Penetration by the fungus is enhanced by low temperature and high relative humidity, with optimal infection occurring around 20°C and relative humidity near 100% (Beyer *et al*., 2006; Osborne & Stein, 2007). Following infection, complete head blighting can occur under wet conditions with temperatures around 25°C to 30°C, explaining the sudden appearance of symptoms in wheat fields. The main field symptom is the sudden presence of bleached spikelets, with pink to orange spore masses evident on wheat spikes during FHB epidemics.

An important factor in the wheat-F. graminearum interaction is the production of choline and betaine by wheat during anthesis, which are growth stimulants for Fusarium graminearum (Strange *et al*., 1972). Hyphal orientation is crucial for successful infection (Brand & Gow, 2012), with penetration directed towards anthers, pollen, and ovaries of wheat (Buerstmayr & Buerstmayr, 2015). F. graminearum hyphal growth shows affinity for these floral organs or wheat germ (Strange *et al*., 1974). Experimentally, F. graminearum conidia growth after germination is directed to the ovary of the floret (Blumke *et al*., 2014). Choline and betaine significantly attract the fungus, with these compounds serving as carbon sources for F. graminearum (Strange & Smith, 1971, 1978; Markham *et al*., 1993). Choline increases hyphal extension rate and inhibits branching frequency (Robson et al., 1995; Wiebe *et al*., 1992). The accumulation of choline and betaine in wheat anthers is considered a susceptibility factor for F. graminearum (Strange *et al*., 1972). While hyphal chemotropism towards nutrients is widely accepted, the underlying mechanisms remain largely unknown (Turrà *et al*., 2015).

In the spikelet, Fusarium-damaged kernels (FDK) result from the infection and colonization of the head tissue by Fusarium graminearum. These kernels are characterized by their white, chalky appearance and are often referred to as shriveled kernels, scabby seeds, or tombstones. FDK are typically associated with severe Fusarium head blight (FHB) and have elevated levels of mycotoxins, particularly deoxynivalenol (DON), which can be harmful to both humans and animals.

Fusarium graminearum isolates are classified based on their chemotype. There are three main chemotypes:

- 3-ADON: Produces DON and 3-acetyl-DON.
- 15-ADON: Produces DON and 15-acetyl-DON.
- Nivalenol (NIV): Produces NIV and 4-acetyl-NIV.

In the NIV chemotype, the genes responsible for producing the enzyme calonectrin 4-oxygenase (Tri13) and trichothecene 4-O-acetyltransferase (Tri7) are functional. These enzymes facilitate the conversion of trichodiene, a product of trichodiene synthase (Tri5), into NIV. Thus, in the NIV chemotype, the final product of the biosynthetic pathway is NIV rather than DON. Despite all three chemotypes belonging to the same species, their genetic variations and geographical distributions lead to the formation of distinct genetic populations (Ward *et al*., 2002).

Historical and Recent Outbreaks of FHB

North America: Major epidemics occurred in the 1980s and 1990s across the United States and Canada, causing extensive damage to wheat and barley crops. These outbreaks were linked to changes in agricultural practices, such as increased corn-wheat rotation and minimum tillage, which favored the persistence of *Fusarium* spores (McMullen *et al*., 1997). Significant FHB outbreaks continued in the 2010s, particularly in the Midwest and Northern Plains, attributed to favorable weather conditions and the widespread cultivation of susceptible wheat varieties (Nganje *et al*., 2004; Figueroa *et al*., 2018).

Europe: European countries have faced severe FHB outbreaks, with significant epidemics reported in the UK during the 1970s and 1980s. These outbreaks coincided with wet weather conditions during the flowering period of wheat (Parry *et al*., 1995). In recent years, fluctuating levels of FHB severity have been observed across Europe, with countries like Germany and Poland reporting increased incidences due to wetter growing seasons and changes in farming practices (Chunzhao *et al*., 2011; Miedaner *et al*., 2023).

Asia: China has experienced recurring FHB epidemics since the 1950s, with major outbreaks in the 1990s affecting vast wheat-growing regions. These epidemics were often associated with heavy rainfall and humid conditions during the growing season (Bai & Shaner, 1994). FHB remains a recurrent issue in China, with recent studies highlighting the impact of climate change on the frequency and severity of epidemics. Warmer temperatures and increased precipitation are expected to exacerbate FHB outbreaks in the coming decades (Tang *et al*., 2022).

Ethiopia: FHB is becoming a growing concern in Ethiopia, where wheat is a staple crop. Despite being historically considered a minor problem, FHB has emerged as one of the most destructive diseases in recent times, particularly during wet, warm, and high-rainfall periods from anthesis to the soft dough stage of wheat growth. Epidemics are primarily initiated by initial inoculum from infected crop residue (Kebede *et al*., 2021; Getachew *et al*., 2022).

Reports indicate that FHB prevalence in Ethiopia is linked to changes in weather patterns and agricultural practices. Preliminary data suggest that FHB could pose a significant threat to wheat production in the region (Temesgen *et al*., 2018). Recent surveys have detected the presence of FHB in major wheat-growing regions, associated with the adoption of improved wheat varieties and changes in crop management practices. The country's reliance on wheat imports also raises concerns about the potential introduction of new *Fusarium* strains through international trade (Abate *et al*., 2020).

Identification of Fusarium Species in Ethiopia

Bekele (1990) was the first to identify FHB species in Ethiopia, identifying several species from stored wheat grains and blighted wheat heads, including *F. avenaceum*, *F. graminearum, F. poae, F. lateritium, F. sambucinum, F. semitectum, F. sporotrichioides, F. udum,* and *F. heterosporum*.

In a study conducted during the 2017 main season, Minhayil *et al*. (2020) identified twelve *Fusarium* species in southwestern Ethiopia based on their cultural and microscopical characteristics: *F. graminearum, F. culmorum, F. poae, F. avenaceum, F. ussurianum, F. semitectum, F. lateritium, F. sambucinum, F. pseudograminearum, F. heterosporum,* and *F. udum*. Similarly, Getachew *et al*. (2022) reported nine *Fusarium* species, including *F. graminearum, F. culmorum, F. avenaceum, F. poae, F. ussurianum, F. semitectum, F. lateritium, F. sambucinum,* and *F. heterosporum*, from the Southern Nations, Nationalities, and Peoples' Region (SNNP) during the 2019 main season.

In the 2022 main cropping season, FHB-infected wheat spikes were collected from East Shoa, North Shoa, and Arsi, Ethiopia. Pure cultured isolates were analyzed at the Debrezeit Agricultural Research Center Pathology Laboratory and sent to the University of Minnesota for identification. Eleven *Fusarium* species were identified: *F. graminearum, F. avenaceum, F. boothii, F. equiseti, F. guttiforme, F. sp. strain, F. verticillioides, F. arcuatisporum, F. hainanense, F. iranicum,* and *F. pseudocircinatum*. Among these, *F. graminearum* and *F. equiseti* were the most dominant, followed by *F. boothii*. Notably, six of these species (54.5%) had not previously been reported in Ethiopia, while the remaining 45.5% had been described by other researchers (Gizachew, 2022).

Despite limited research on the identification and distribution of Fusarium species in Ethiopia, 20 distinct species have been identified to date. This indicates a significant prevalence of these pathogens, suggesting a substantial potential for mycotoxin production. The diversity and distribution of Fusarium species highlight the need for further investigation and management efforts to mitigate the risks associated with mycotoxin contamination in Ethiopian wheat production.

Impact of FHB in Ethiopia

FHB produce mycotoxins, secondary metabolites that contaminate food and feed during pre- or post-harvest stages (Frisvad *et al.*, 2006; Marta & Kebede, 2016; Hocking & Pitt, 2011). Key mycotoxins include aflatoxins (AFs), fumonisins (FUMs), deoxynivalenol (DON), ochratoxin A (OTA), and zearalenone (ZEN), which pose significant health risks such as cancer, immune suppression, and developmental issues in children (Milićević *et al.*, 2010; IARC, 2015; Zain, 2011; Watson *et al.*, 2018). Contaminated animal feed can also cause severe health problems (Zain, 2011; Bhat *et al.*, 2010). The FAO estimates that mycotoxins affect about 25% of global crops, leading to substantial economic losses (Bhat et al., 2010; CAST, 2003).

In sub-Saharan Africa, where agriculture is vital, mycotoxin contamination is a major concern due to reliance on rain-fed agriculture and poor farming practices (OECD/FAO, 2016). Studies show high contamination in crops with health impacts including a notable incidence of liver cancer linked to AFs (Udomkun *et al.*, 2017). Economic losses from mycotoxins in Africa exceed USD 750 million annually (Bhat et al., 2010). Contributing factors include climate change, inadequate infrastructure, and weak regulations (OECD/FAO, 2016; Neme & Mohammed, 2017). Ethiopia, with over 100 million people and a heavily agriculture-dependent economy, faces significant mycotoxin issues due to smallholder farming and outdated storage methods (OECD/FAO, 2016; Udomkun *et al.*, 2017; Neme & Mohammed, 2017).

A mycotoxin analysis conducted on stored wheat samples from the Amhara, Oromia, and Southern regions of Ethiopia revealed that polypropylene bags were the predominant storage material, accounting for 92.2% of the total samples (n=179). The study detected FUM (fumonisin) and DON (deoxynivalenol) toxins in 16.2% and 9.5% of the samples, respectively. The maximum levels of FUM and DON detected were 0.71 mg/kg and 1.14 mg/kg, respectively. Notably, 3.4% of the wheat samples exceeded the maximum limit for DON set by the European Union, which is 0.75 mg/kg. Additionally, the co-occurrence of AFT (aflatoxin) and FUM mycotoxins was observed in 7.3% of the samples. (Worku *et al*., 2019).

Research in Ethiopia has highlighted significant mycotoxin contamination in major cereals, with Aspergillus and Fusarium species being the primary culprits. In a study of 90 maize samples from the West Showa and East Wallega zones, Aspergillus spp. was the most prevalent, found in 50.7% of samples, followed by Fusarium spp. (26.4%), Penicillium spp. (22.3%), and Trichoderma spp. (1.07%) (Neme & Mohammed, 2017). Aflatoxin B1 (AFB1) levels in these samples ranged from 3.9 to 381.6 µg/kg, with 7.7% surpassing the EU limit of 5 µg/kg for foodstuffs (Frisvad *et al*., 2006). Additionally, 88% of maize samples contained aflatoxins, while Fumonisins (B1+B2) were found in 2%, Deoxynivalenol (DON) in 29.4%, and Nivalenol (NIV) in 17.7%. Total aflatoxins exceeded the EU limit of 10 µg/kg in 5.8% of the samples (Frisvad *et al*., 2006).

Similarly, a survey of 90 sorghum samples from eastern Ethiopia identified Aspergillus spp. and Fusarium spp. as the main sources of contamination. Aspergillus spp. counts ranged from 1 to 2.5 log cfu/g, and Fusarium spp. from 0.5 to 1.3 log cfu/g (Marta & Kebede, 2016). AFB1 was detected in 94% of the sorghum samples with concentrations from 0 to 33.1 µg/kg, while Fumonisins were present in 71.1% of samples, ranging from 907 to 2041 µg/kg. Notably, 2.22% of Fumonisins-positive samples exceeded the EU limit of 1000 µg/kg for cereals intended for direct human consumption (Frisvad *et al*., 2006).

Of the chemotyped samples, 71.4% were identified as species outside the *Fusarium graminearum* species complex, while 28.6% were classified as part of the *Fusarium graminearum* species complex (FGSC). Notably, *Fusarium boothii*, a newly identified species, was found to produce 15-ADON mycotoxin in both durum and bread wheat. This species, which was recently reported in the USA but has not previously been documented in Africa, represents a first finding and report for both Ethiopia and the African continent. On the other hand, *Fusarium graminearum* was observed to produce 15-ADON, 3-ADON, and NIV in both bread and durum wheat. As the most dominant and significant species, *Fusarium graminearum* is notable for its production of all three mycotoxins associated with this complex.

FHB management strategies

Cultural management methods of FHB

Tillage can significantly reduce the amount of *F. graminearum* inoculum, which helps delay disease progression and lower DON production (Beyer *et al*., 2006). Research by Blandino *et al*. (2012) found that direct sowing with a susceptible cultivar without fungicide treatment led to a 97% higher incidence of DON compared to plowing and using a moderately resistant cultivar with a triazole fungicide application at heading. Crop rotation is essential for managing FHB, as the primary source of inoculum is ascospores from fruiting bodies overwintering in crop debris, particularly from corn and wheat stubble. Continuous wheat or planting wheat after corn is not recommended due to the risk of inoculum accumulation (Lawrence et al., 2007; McMullen *et al.*, 1997b). *F. graminearum* primarily survives in crop stubble rather than in the soil (Leslie *et al*., 1990). Incorporating a legume crop after wheat or corn can improve the carbon-to-nitrogen ratio, which accelerates stubble decomposition and may reduce the survival and initial population of *F. graminearum.*

Managing Fusarium Head Blight (FHB), and Deoxynivalenol (DON) Contamination in Wheat through Fungicides

Fungicides play a critical role in managing foliar fungal diseases and Fusarium head blight (FHB) in wheat, as well as preventing contamination of wheat grains with deoxynivalenol (DON). However, only a limited number of fungicides have demonstrated efficacy against FHB, highlighting the need for targeted strategies in disease management (McMullen *et al*., 1997b; Mesterházy *et al*., 2011).

Triazoles: The Most Effective Fungicides for FHB Control

Currently, triazoles are recognized as the most effective class of fungicides for controlling FHB (Wegulo *et al*., 2015c). These fungicides belong to the demethylation inhibitors (DMIs) category, which inhibit the C14 demethylase enzyme within the ergosterol biosynthetic pathway, crucial for maintaining fungal cell membrane integrity (Myung and Klittich, 2015). Ergosterol, a vital component of the fungal cell membrane, is essential for membrane function and also acts as a growth stimulant in fungi (Kathiravan *et al*., 2012). By targeting this pathway, triazoles effectively inhibit hyphal growth, thereby controlling the spread of the fungus (Ha and White, 1999).

Mechanism of Action of Tebuconazole Against FHB Pathogens

Tebuconazole, a widely used triazole fungicide, has been extensively studied for its efficacy against *Fusarium culmorum*, a major FHB pathogen in Europe. Research by Zange et al. (2005) using Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) revealed significant morphological changes in the fungus following treatment. These changes included excessive branching, bulb-like structures at the tips of germ tubes, severe inhibition of hyphal growth, and a disrupted mycelial network. TEM analysis further demonstrated thickened fungal cell walls, increased vacuole accumulation, and abnormal inclusion body formation, all indicative of the fungicide's potent inhibitory effects on the pathogen.

Strobilurins: Benefits and Challenges

Strobilurin fungicides, introduced in 1996 and derived from the natural compound Strobilurus tenacellus, have been employed to target fungal respiration by binding to cytochrome b within the cytochrome bc1 complex (Kathiravan *et al*., 2012). In addition to their broad-spectrum activity against fungal diseases, strobilurins are known to enhance plant physiological responses, including improved water use efficiency, delayed senescence, and increased nitrate reductase activity (Barlett *et al*., 2002; Tedford, 2009). For instance, azoxystrobin, a strobilurin fungicide, has been shown to extend the green period of wheat leaves by 8.2 to 11.2 days, contributing to higher yields (Reddy, 2012).

However, while strobilurins can reduce FHB severity, they have been linked to increased DON levels in treated wheat plots compared to untreated controls (Amarasinghe *et al*., 2013). This paradox presents a significant challenge, as the goal of reducing FHB severity must be balanced against the risk of DON contamination. To facilitate understanding of two important classes of fungicides, I have organized the information into Table 1.

Table 1: Detailed Descriptions of Strobilurin and Triazole Fungicides

Fungicide Class	Common Name	Trade Names	Mode of Action
Triazole Fungicides	Tebuconazole	Folicur, Orius, Raxil	Inhibits the biosynthesis of ergosterol, essential for fungal cell membranes.
	Propiconazole	. Tilt, Banner, Orbit	Inhibits ergosterol biosynthesis, disrupting fungal cell membrane integrity
	Difenoconazole	Score, Divident, Rally	Inhibits ergosterol biosynthesis, vital for maintaining fungal cell membrane structure.
	Flutriafol	. Topguard, Impact	Inhibits ergosterol biosynthesis, critical for fungal cell membrane formation
	Metconazole	Caramba, Quash	Inhibits ergosterol biosynthesis, necessary for fungal cell membrane stability.
Strobilurin Fungicides	Azoxystrobin	Quadris, Abound, Amistar	Inhibits mitochondrial respiration, preventing energy production in fungi.
	Pyraclostrobin	. Headline, Cabrio, Insignia	Inhibits mitochondrial respiration, blocking ATP synthesis in fungal cells
	Trifloxystrobin	. Flint, Compass, Gem	Inhibits mitochondrial respiration, leading to fungal cell death
	Kresoxim-methyl	. Sovran, Discus	Inhibits mitochondrial respiration, causing disruption of energy metabolism in fungi
	Fluoxastrobin	Evito, Disarm	Inhibits mitochondrial respiration, impairing fungal growth and survival.

Resistance Concerns and Alternative Strategies

Despite their effectiveness, triazoles are associated with a medium risk of resistance development, as classified by the Fungicide Resistance Action Committee (FRAC). The widespread and prolonged use of these fungicides has led to growing concerns about resistance, particularly in Fusarium graminearum, the primary FHB pathogen. The first reports of tebuconazole-resistant F. graminearum strains in the Americas emerged in 2014, underscoring the urgency for developing new fungicide chemistries and strategies (Spolti *et al.*, 2014).

The Need for Integrated Fungicide Management

Given the limitations and resistance issues associated with triazoles and strobilurins, there is a growing need for integrated fungicide management strategies. Dual applications targeting both foliar and head diseases are often not cost-effective, and the variability in fungicide efficacy across different wheat cultivars further complicates control efforts (Wegulo *et al*., 2012; Blandino *et al*., 2006, 2012; Mesterházy, 2003, 2014; Paul *et al*., 2008; Pirgozliev *et al*., 2002).

One promising approach is the use of aminoglycoside fungicides (metabolites) such as K20, produced by bacterial actinomycetes. These compounds have shown synergistic effects when combined with triazoles, offering a potential solution for overcoming resistance and enhancing disease control (Takemoto *et al*., 2018). By combining fungicides with different modes of action, the risk of resistance development can be mitigated, leading to more sustainable and effective disease management in wheat production.

Aminoglycoside fungicides like K20 are synthesized through the complex metabolic pathways of actinomycetes. These pathways involve the use of various enzymes to assemble the aminoglycoside molecule, which typically consists of amino sugars linked by glycosidic bonds to a central aminocyclitol nucleus. The antifungal activity of aminoglycosides is believed to result from their ability to bind to ribosomal RNA in the fungal cells, interfering with protein synthesis and leading to cell death (Umezawa *et al*., 1982).

K20, like other aminoglycosides, may exhibit its fungicidal action by binding to the 30S subunit of the ribosome in fungal cells, disrupting the process of translation. This binding interferes with the initiation complex of protein synthesis, misreading of mRNA, and ultimately results in the inhibition of essential protein production, which is vital for fungal growth and survival (Doi & Arakawa, 2007).

The use of aminoglycoside fungicides such as K20 in agriculture is particularly attractive due to their dual role as both antifungal agents and plant growth promoters. This dual functionality can be attributed to their broad-spectrum activity against various fungal pathogens, which helps in controlling diseases that affect crop yield and quality. Additionally, their production by naturally occurring soil bacteria, such as Streptomyces species, aligns well with the principles of sustainable agriculture, reducing the reliance on synthetic chemical fungicides (Tanaka & Omura, 1993).

Cultivar Resistance and Techniques for Evaluating Breeding Lines in Fusarium Head Blight Management

Genetic resistance is a cornerstone of Fusarium head blight (FHB) management in wheat, offering ecological and economic advantages over chemical controls (Wegulo *et al*., 2015c). As a result, enhancing resistance to FHB has become a primary objective in wheat breeding programs worldwide (Bai and Shaner, 2004). However, breeding for FHB resistance presents significant challenges due to the quantitative nature of the trait, the complexity of the wheat genome, and difficulties in accurately screening for resistance in controlled environments (Tucker *et al*., 2017).

Types of FHB Resistance and Associated QTLs

FHB resistance in wheat can be oligogenic or polygenic, with quantitative trait loci (QTLs) linked to resistance identified on all wheat chromosomes (Eckard, 2015). The effort to breed for FHB resistance in the United States dates to 1929 when Christensen conducted large-scale screenings of wheat varieties. Despite his extensive work, all tested lines displayed some degree of infection, underscoring the difficulty of achieving complete resistance.

In 1963, Schroeder and Christensen classified FHB resistance into two primary types:

1. **Type I Resistance**: This form of resistance involves defense mechanisms that prevent the initial infection, such as enzyme activation to degrade the fungal cell wall. It is assessed by spraying spore suspensions over flowering spikes and counting the number of diseased spikelets. QTLs Fhb4 and Fhb5 have been linked to Type I resistance (Kosaka *et al*., 2015).
2. **Type II Resistance**: This resistance type limits the spread of FHB symptoms within the wheat spike. It is measured by inoculating a single floret and counting the number of blighted spikelets. Key QTLs associated with Type II resistance include Fhb1, Fhb2, and Fhb3 (Kosaka *et al*., 2015).

Mesterházy (1995) expanded this classification by identifying additional resistance types:

- **Type III Resistance**: Involves the ability of the wheat kernels to retain their size and quality despite infection.
- **Type IV Resistance**: Refers to yield tolerance, where the plant maintains yield despite infection.
- **Type V Resistance**: Focuses on reducing or detoxifying DON (deoxynivalenol) accumulation, a harmful mycotoxin produced by FHB pathogens.

The focus of many breeding programs has been to incorporate resistance genes from cultivars with inherent FHB resistance. A notable example is the Chinese cultivar Sumai 3, which possesses unique resistance genes, including the Fhb1 QTL, known for converting DON into a less toxic form, D3G, thereby enhancing resistance (Clark *et al*., 2016; Kolb *et al*., 2001; Li *et al.*, 2015).

Notable FHB-Resistant Cultivars

A significant milestone in the development of FHB-resistant wheat cultivars was the release of Overland (NE01643) by Husker Genetics in 2006. Overland is a semi-dwarf hard red winter wheat cultivar that exhibits moderate resistance to FHB. It carries resistance alleles on chromosomes 1A, 1B, 3A, 4A, and 6A, including QTLs such as Fhb1 and Fhb5 (Baenziger *et al*., 2008; Eckard *et al.*, 2015). However, even cultivars like Overland, with moderate resistance, can sometimes exhibit high DON levels, whereas some susceptible cultivars may have lower DON concentrations, indicating a complex relationship between visual symptoms and DON accumulation (Hernandez-Nopsa *et al.*, 2014).

Challenges in Evaluating FHB Resistance

Field evaluation of FHB-resistant cultivars is particularly challenging due to the sporadic nature of FHB epidemics and the need for precise inoculation methods to consistently replicate results. Current screening techniques are often plagued by high experimental error and inconsistent genotype rankings, complicating the selection process (Kumar *et al*., 2015). Although visual symptoms of FHB are generally correlated with DON levels during epidemic years, this relationship can be unclear, further complicating evaluations.

Advances in Breeding Techniques: Marker-Assisted Selection and Genomic Selection

To overcome these challenges, molecular techniques such as Marker-Assisted Selection (MAS) and Genomic Selection have become valuable tools in breeding programs. MAS utilizes molecular markers linked to specific alleles or QTLs of interest, allowing for more precise selection and reducing reliance on phenotypic screening (Collard *et al*., 2008). QTLs, which are regions of the genome that influence a trait, can be monitored during the introgression process to ensure the desired resistance traits are successfully incorporated (Acquaah, 2009).

Genomic selection takes this approach further by using comprehensive genomic data to predict the performance of genotypes with greater accuracy than classical MAS (Hayes and Goddard, 2001; Hefner, 2010; Lorenz *et al*., 2012). This technique has facilitated significant advancements, such as the map-based cloning of the Fhb1 QTL from Sumai 3, which represents a major step forward in developing durable FHB resistance strategies (Rawat *et al*., 2016).

In conclusion, while breeding for FHB resistance in wheat is challenging, advances in understanding the genetic basis of resistance, combined with modern molecular breeding techniques, offer promising avenues for developing cultivars with improved resistance to FHB and reduced DON contamination.

Integrated Management of Fusarium Head Blight (FHB)

Integrated management is widely acknowledged as the most effective strategy for controlling Fusarium Head Blight (FHB) and minimizing deoxynivalenol (DON) contamination in wheat (Wegulo *et al*., 2015c; Muluken *et al*., 2023). The unpredictable nature of FHB outbreaks presents considerable challenges, necessitating a comprehensive approach. Key components of an integrated FHB management strategy include the use of forecasting systems, selection of tolerant or moderately resistant cultivars, cultural practices such as residue management and tillage, and the precise application of fungicides at optimal timings (Wegulo *et al*., 2015c). Among these strategies, employing resistant cultivars is often the most cost-effective approach.

Recent studies have highlighted the efficacy of integrated management strategies in reducing both FHB and DON contamination in wheat. Muluken *et al*. (2023) demonstrated that combining fungicide application at the anthesis growth stage with the use of moderately resistant wheat varieties yields superior results compared to using either method in isolation. Specifically, the application of tebuconazole at anthesis and the use of the wheat variety 'King Bird' significantly reduced FHB severity and DON contamination, leading to increased wheat production and enhanced food security in key wheat-growing regions of Ethiopia.

Similarly, Getachew *et al.* (2023) showed that integrating moderately resistant wheat cultivars with fungicide application, when applied at appropriate frequencies starting at disease onset, effectively reduced disease pressure and improved grain yield. Particularly, the combination of the 'Shorima' variety with three applications of tebuconazole proved effective in controlling FHB epidemics.

These findings collectively underscore the advantages of an integrated approach, combining resistant cultivars with targeted fungicide applications to manage FHB and DON contamination effectively.

Conclusions and Recommendations

Fusarium Head Blight (FHB) is a significant fungal disease that severely impacts wheat production, with its prevalence heavily influenced by environmental factors such as temperature, humidity, and rainfall. The disease is primarily caused by *Fusarium graminearum*, a pathogen known for producing harmful mycotoxins like deoxynivalenol (DON), which contaminate crops and pose serious health risks to both humans and animals.

In Ethiopia, FHB has recently become an increasing concern due to changing weather patterns and evolving agricultural practices. Multiple Fusarium species, including new and dominant strains, have been identified, exacerbating the problem. The rising prevalence of these pathogens and their associated mycotoxins underscores the urgent need for further research and the development of management strategies to safeguard wheat production in the region and mitigate the risks associated with mycotoxin contamination.

Effective management of FHB requires an integrated approach that combines cultural practices, the use of resistant cultivars, and fungicide applications. Key strategies include the following:

- **Adoption of Integrated Management Practices:** Farmers should implement a combination of cultural practices, resistant cultivars, and fungicide applications, particularly triazoles, to manage FHB effectively.
- **Utilization of Resistant Cultivars:** Breeding programs should prioritize the development and promotion of wheat cultivars with proven resistance to FHB, focusing on key quantitative trait loci (QTLs) such as *Fhb1*.
- **Optimization of Fungicide Application:** Fungicides should be applied at critical growth stages, such as anthesis, to maximize their effectiveness in controlling FHB and minimizing DON contamination.
- **Advancement of Breeding Techniques:** Continued investment in molecular breeding techniques, including Marker-Assisted Selection (MAS) and Genomic Selection, is essential to accelerate the development of FHB-resistant wheat varieties.
- **Monitoring for Fungicide Resistance:** It is crucial to monitor pathogen populations for signs of resistance development. Considering alternative fungicides or combining fungicides can help maintain effective disease control.

These integrated management strategies have proven effective in reducing both FHB severity and DON contamination, making them essential for ensuring wheat yield and quality. Implementing these recommendations will be crucial for protecting wheat production in Ethiopia and other regions affected by FHB.

Disclaimer (Artificial intelligence)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

References

Abate, T., Shiferaw, B., Menkir, A., Wegary, D., Kebede, Y., Tesfaye, K., ... Keno, T. (2015). Factors that transformed maize productivity in Ethiopia. Food Security, 7(5), 965-981. https://doi.org/10.1007/s12571-015-0488-z

Acquaah, G. (2009). Principles of plant genetics and breeding. John Wiley & Sons.

Amarasinghe, C. C., Tamburic-Ilincic, L., Gilbert, J., Babel, A. L., & Fernando, W. G. D. (2013). Evaluation of different fungicides for control of Fusarium head blight in wheat inoculated with 3ADON and 15ADON chemotypes of Fusarium graminearum in Canada. Canadian Journal of Plant Pathology, 35(2), 200-208.

Anteneh, A., Asrat, D., & Moral, M. T. (2020). Wheat production and marketing in Ethiopia: Review study. Cogent Food & Agriculture, 6(1). https://doi.org/10.1080/23311932.2020.1778893

Baenziger, P. S., Beecher, B., Graybosch, R. A., Ibrahim, A., Baltensperger, D. D., Nelson, L. A., Jin, Y., Wegulo, S. N., Watkins, J. E., & Hatchett, J. H. (2008). Registration of 'NE01643' wheat. Journal of Plant Registrations, 2(1), 36-42.

Bai, G., & Shaner, G. (2004). Management and resistance in wheat and barley to Fusarium head blight. Annual Review of Phytopathology, 42, 135-161.

Bai, G., Su, Z., & Cai, J. (2018). Wheat resistance to Fusarium head blight. Canadian Journal of Plant Pathology, 40(3), 336–346. https://doi.org/10.1080/07060661.2018.1476411

Bartlett, D. W., Clough, J. M., Godwin, J. R., Hall, A. A., Hamer, M., & Parr-Dobrzanski, B. (2002). The strobilurin fungicides. Pest Management Science, 58(7), 649-662.

Bekele, E. (1990). Identification of Fusarium spp. and mycotoxins associated with head blight of wheat in Ethiopia [Doctoral dissertation, Addis Ababa University].

Beyer, M., Klix, M. B., Klink, H., & Verreet, J. (2006). Quantifying the effects of previous crop, tillage, cultivar, and triazole fungicides on the deoxynivalenol content of wheat grain—a review. Journal of Plant Diseases and Protection, 113(6), 241-246.

Bhat, R., Rai, R. V., & Karim, A. A. (2010). Mycotoxins in food and feed: Present status and future concerns. Comprehensive Reviews in Food Science and Food Safety, 9(1), 57-81.

Blandino, M., Haidukowski, M., Pascale, M., Plizzari, L., Scudellari, D., & Reyneri, A. (2012). Integrated strategies for the control of Fusarium head blight and deoxynivalenol contamination in winter wheat. *Field Crops Research, 133, 139-149*.

Blandino, M., Minelli, L., & Reyneri, A. (2006). Strategies for the chemical control of Fusarium head blight: Effect on yield, alveographic parameters and deoxynivalenol contamination in winter wheat grain. European Journal of Agronomy, 25(3), 193-201.

Blumke, A., Falter, C., Herrfurth, C., Sode, B., Bode, R., Schäfer, W., Feussner, I., & Voigt, C. A. (2014). Secreted fungal effector lipase releases free fatty acids to inhibit innate immunity-related callose formation during wheat head infection. Plant Physiology, 114, 236737.

Brand, A., & Gow, N. A. (2012). Tropic orientation responses of pathogenic fungi. In Morphogenesis and pathogenicity in fungi (pp. 21-41). Springer.

Buerstmayr, M., & Buerstmayr, H. (2015). Comparative mapping of quantitative trait loci for Fusarium head blight resistance and anther retention in the winter wheat population Capo × Arina. Theoretical and Applied Genetics, 128(8), 1519-1530.

Clark, A. J., Sarti-Dvorjak, D., Brown-Guedira, G., Dong, Y., Baik, B., & Van Sanford, D. A. (2016). Identifying rare FHB-resistant segregants in intransigent backcross and F2 winter wheat populations. Frontiers in Microbiology, 7, 277.

Collard, B. C., & Mackill, D. J. (2008). Marker-assisted selection: An approach for precision plant breeding in the twenty-first century. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1491), 557-572.

Council for Agricultural Science and Technology (CAST). (2003). Mycotoxins: Risks in plant, animal, and human systems (D. Bhatnagar, W. Bryden, W. de Koe, J. Gilbert, & A. E. Pohland, Eds.). CAST Press. Available online: www.cast-science.org (accessed on 15 June 2016).

Dill-Macky, R., & Jones, R. K. (2000). The effect of previous crop residues and tillage on Fusarium head blight of wheat. Plant Disease, 84(1), 71–76.

Eckard, J. T., Gonzalez-Hernandez, J. L., Caffe, M., Berzonsky, W., Bockus, W. W., Marais, G. F., & Baenziger, P. S. (2015). Native Fusarium head blight resistance from winter wheat cultivars ‘Lyman,’ ‘Overland,’ ‘Ernie,’ and ‘Freedom’ mapped and pyramided onto ‘Wesley’-Fhb1 backgrounds. Molecular Breeding, 35(1), 6.

Fernando, W. G. D., Paulitz, T. C., Seaman, W. L., Dutilleul, P., & Miller, J. D. (1997). Head blight gradients caused by Gibberella zeae from area sources of inoculum in wheat field plots. Phytopathology, 87(4), 414–421.

Figueroa, M., Hammond-Kosack, K. E., & Solomon, P. S. (2018). A review of wheat diseases—a field perspective. Molecular Plant Pathology, 19(6), 1523–1536. https://doi.org/10.1111/mpp.12618

Frisvad, J. C., Thrane, U., Samson, R. A., & Pitt, J. I. (2006). Important mycotoxins and the fungi which produce them. In A. D. Hocking, J. I. Pitt, R. A. Samson, & U. Thrane (Eds.), Advances in Experimental Medicine and Biology (pp. 3–31). Springer. https://doi.org/10.1007/978-0-387-28385-2_1

Getachew Gudero Mengesha, Shiferaw Mekonnen Abebe, Asaminew Amare Mekonnen, Abate G/Mikael Esho, Zerhun Tomas Lera, Misgana Mitku Shertore, Kedir Bamud Fedilu, Yosef Berihun Tadesse, Yisahak Tsegaye Tsakamo, Bilal Temmam Issa, Dizgo Chencha Cheleko, & Agdew Bekele W/Silassie. (2022). Effects of cultivar resistance and chemical seed treatments on Fusarium head blight and bread wheat yield-related parameters under field conditions in southern Ethiopia. Heliyon, 8(1), e08659. https://doi.org/10.1016/j.heliyon.2021.e08659

Getahun, M., Fininsa, C., Mohammed, A., & Bekeko, Z. (2024). Resistance of bread wheat (Triticum aestivum L.) varieties to Fusarium head blight (Fusarium graminearum) in Ethiopia. Agrosystems, Geosciences & Environment, 7, e20531. https://doi.org/10.1002/agg2.20531

Gilbert, J., Woods, S. M., & Kromer, U. (2008). Germination of ascospores of Gibberella zeae after exposure to various levels of relative humidity and temperature. Phytopathology, 98(5), 504–508.

Gizachew Hirpa. (2022). Harnessing and sounding the alarm on Fusarium head blight of wheat: Current status, biology, detection and diagnosis methods, mycotoxins, and integrated management options. Greener Journal of Agricultural Science.

Goswami, R. S., & Kistler, H. C. (2004). Heading for disaster: Fusarium graminearum on cereal crops. Molecular Plant Pathology, 5(6), 515–525. https://doi.org/10.1111/j.1364-3703.2004.00252.x

Gupta, R., Meghwal, M., & Prabhakar, P. K. (2021). Bioactive compounds of pigmented wheat (Triticum aestivum): Potential benefits in human health. Trends in Food Science & Technology, 110, 240-252.

Ha, K. C., & White, T. C. (1999). Effects of azole antifungal drugs on the transition from yeast cells to hyphae in susceptible and resistant isolates of the pathogenic yeast Candida albicans. Antimicrobial Agents and Chemotherapy, 43(4), 763–768.

Hayes, B. J., & Goddard, M. E. (2001). Prediction of total genetic value using genome-wide dense marker maps. Genetics, 157(4), 1819–1829.

Heffner, E. L., Lorenz, A. J., Jannink, J. L., & Sorrells, M. E. (2010). Plant breeding with genomic selection: Gain per unit time and cost. Crop Science, 50(5), 1681–1690.

Hernandez-Nopsa, H., John, F., Wegulo, S. N., Panthi, A., Hallen-Adams, H. E., Harris, S. D., & Baenziger, P. S. (2014). Characterization of Nebraska isolates of Fusarium graminearum causing head blight of wheat. Crop Science, 54(1), 310–317.

Hocking, A. D., & Pitt, J. I. (2011). Food, fungi and mycotoxins: An update. Mycology, 32(1), 5–8.

International Agency for Research on Cancer (IARC). (2015). Mycotoxin control in low- and middle-income countries (C. P. Wild, J. D. Miller, & J. D. Groopman, Eds.). IARC Press.

Kathiravan, M. K., Salake, A. B., Chothe, A. S., Dudhe, P. B., Watode, R. P., Mukta, M. S., & Gadhwe, S. (2012). The biology and chemistry of antifungal agents: A review. Bioorganic & Medicinal Chemistry, 20(19), 5678–5698.

Kolb, F. L., Bai, G. H., Muehlbauer, G. J., Anderson, J. A., Smith, K. P., & Fedak, G. (2001). Host plant resistance genes for Fusarium head blight. Crop Science, 41(3), 611–619.

Kosaka, A., Manickavelu, A., Kajihara, D., Nakagawa, H., & Ban, T. (2015). Altered gene expression profiles of wheat genotypes against Fusarium head blight. Toxins, 7(2), 604–620.

Kumar, A., Karre, S., Dhokane, D., Kage, U., Hukkeri, S., & Kushalappa, A. C. (2015). Real-time quantitative PCR-based method for the quantification of fungal biomass to discriminate quantitative resistance in barley and wheat genotypes to Fusarium head blight. Journal of Cereal Science, 64, 16–22.

Lawrence, E. O., & Stein, J. M. (2007). Epidemiology of Fusarium head blight on small-grain cereals. International Journal of Food Microbiology, 119(1–2), 103–108. https://doi.org/10.1016/j.ijfoodmicro.2007.07.032

Leslie, J. F., Pearson, C. A., Nelson, P. E., & Toussoun, T. A. (1990). Fusarium spp. from corn, sorghum, and soybean fields in the central and eastern United States. Ecological Studies, 44(1), 63–66.

Li, X., Shin, S., Heinen, S., Dill-Macky, R., Berthiller, F., Nersesian, N., Clemente, T., McCormick, S., & Muehlbauer, G. J. (2015). Transgenic wheat expressing a barley UDP-glucosyltransferase detoxifies deoxynivalenol and provides high levels of resistance to Fusarium graminearum. Molecular Plant-Microbe Interactions, 28(11), 1237–1246.

Lorenz, A. J., Smith, K. P., & Jannink, J. (2012). Potential and optimization of genomic selection for Fusarium head blight resistance in six-row barley. Crop Science, 52(4), 1609–1621.

Markham, P., Robson, G. D., Bainbridge, B. W., & Trinci, A. P. (1993). Choline: Its role in the growth of filamentous fungi and the regulation of mycelial morphology. FEMS Microbiology Reviews, 10(3-4), 287-300.

Marta, T., & Kebede, B. (2016). Occurrence, importance, and control of mycotoxins: A review. Cogent Food & Agriculture, 2(1), 1-26.

McMullen, M., Bergstrom, G., De Wolf, E., Dill-Macky, R., Hershman, D., Shaner, G., & Van Sanford, D. (2012). A unified effort to fight an enemy of wheat and barley: Fusarium head blight. Plant Disease, 96(12), 1712-1728.

McMullen, M., Jones, R., & Gallenberg, D. (1997). Scab of wheat and barley: A reemerging disease of devastating impact. Plant Disease, 81(12), 1340-1348.

Mesterházy, Á. (1995). Types and components of resistance to Fusarium head blight of wheat. Plant Breeding, 114(5), 377-386.

Mesterházy, Á., Bartók, T., & Lamper, C. (2003). Influence of wheat cultivar, species of Fusarium, and isolate aggressiveness on the efficacy of fungicides for control of Fusarium head blight. Plant Disease, 87(9), 1107-1115.

Mesterházy, Á., Tóth, B., Varga, M., Bartók, T., Szabó-Hever, Á., Farady, L., & Lehoczki-Krsjak, S. (2011). Role of fungicides, application of nozzle types, and the resistance level of wheat varieties in the control of Fusarium head blight and deoxynivalenol. Toxins, 3(11), 1453-1483.

Miedaner, T., Korzun, V., & Wilde, P. (2023). Correction: Miedaner et al. Effective pollen-fertility restoration is the basis of hybrid rye production and ergot mitigation. Plants, 12(12), 2261. https://doi.org/10.3390/plants12122261

Milićević, D. R., Škrinjar, M., & Baltić, T. (2010). Real and perceived risks for mycotoxin contamination in foods and feeds: Challenges for food safety control. Toxins, 2(4), 572-592.

Minyahil, K., Adugna, G., & Hundie, B. (2020). Identification of Fusarium species responsible for causing wheat head blight in southwestern Ethiopia. Research Journal of Plant Pathology, 3(1), 3.

Myung, K., & Klittich, C. J. (2015). Can agricultural fungicides accelerate the discovery of human antifungal drugs? Drug Discovery Today, 20(1), 7-10.

Neme, K., & Mohammed, A. (2017). Mycotoxin occurrence in grains and the role of postharvest management as a mitigation strategy: A review. Food Control, 78, 412-425.

OECD/FAO. (2016). Agriculture in sub-Saharan Africa: Prospects and challenges for the next decades. In OECD-FAO Agricultural Outlook 2016–2025 (pp. 59–95). OECD Publishing.

Osborne, L. E., & Stein, J. M. (2007). Epidemiology of Fusarium head blight on small-grain cereals. International Journal of Food Microbiology, 119(1-2), 103-108.

Parry, D. W., Jenkinson, P., & McLeod, L. (1995). Fusarium ear blight (scab) in small grain cereals a review. Plant Pathology, 44(2), 207-238. https://doi.org/10.1111/j.1365-3059.1995.tb02773.x

Paul, P. A., Lipps, P. E., Hershman, D. E., McMullen, M. P., Draper, M. A., & Madden, L. V. (2008). Efficacy of triazole-based fungicides for Fusarium head blight and deoxynivalenol control in wheat: A multivariate meta-analysis. Phytopathology, 98(9), 999-1011.

Pereira, S. A., Dill-Macky, R., & Sims, A. L. (2004). Survival and inoculum production of Gibberella zeae in wheat residue. Plant Disease, 88(7), 724-730.

Pestka, J. J. (2010). Deoxynivalenol: Mechanisms of action, human exposure, and toxicological relevance. Archives of Toxicology, 84(9), 663-679. https://doi.org/10.1007/s00204-010-0579-8

Pirgozliev, S. R., Edwards, S. G., Hare, M. C., & Jenkinson, P. (2002). Effect of dose rate of azoxystrobin and metconazole on the development of Fusarium head blight and the accumulation of deoxynivalenol (DON) in wheat grain. European Journal of Plant Pathology, 108(5), 469-478.

Rawat, N., Pumphrey, M. O., Liu, S., Zhang, X., Tiwari, V. K., Ando, K., ... & Anderson, J. A. (2016). Wheat Fhb1 encodes a chimeric lectin with agglutinin domains and a pore-forming toxin-like domain conferring resistance to Fusarium head blight. Nature Genetics, 48(12), 1576-1580.

Reddy, P. P. (2012). Recent advances in crop protection. Springer Science & Business Media.

Robson, G. D., Wiebe, M. G., & Trinci, A. P. (1991). Exogenous cAMP and cGMP modulate branching in Fusarium graminearum. Microbiology, 137(4), 963-969.

Schmale III, D. G., & Bergstrom, G. C. (2003). Fusarium head blight in wheat. The Plant Health Instructor. https://doi.org/10.1094/PHI-I-2003-0612-01

Schroeder, H. W., & Christensen, J. J. (1963). Factors affecting resistance of wheat to scab caused by Gibberella zeae. Phytopathology, 53(7), 831-838.

Spolti, P., Del Ponte, E. M., Dong, Y., Cummings, J. A., & Bergstrom, G. C. (2014). Triazole sensitivity in a contemporary population of Fusarium graminearum from New York wheat and competitiveness of a tebuconazole-resistant isolate. Plant Disease, 98(5), 607-613.

Strange, R. N., & Smith, H. (1971). A fungal growth stimulant in anthers which predisposes wheat to attack by Fusarium graminearum. Physiological Plant Pathology, 1(2), 141-150.

Strange, R. N., & Smith, H. (1978). Specificity of choline and betaine as stimulants of Fusarium graminearum. Transactions of the British Mycological Society, 70(2), 187-192.

Strange, R. N., Majer, J. R., & Smith, H. (1974). The isolation and identification of choline and betaine as the two major components in anthers and wheat germ that stimulate Fusarium graminearum in vitro. Physiological Plant Pathology, 4(2), 277-290.

Strange, R. N., Smith, H., & Majer, J. R. (1972). Choline, one of two fungal growth stimulants in anthers responsible for the susceptibility of wheat to Fusarium graminearum. Nature, 238(5359), 103.

Sturz, A. V., & Johnston, H. W. (1985). Characterization of Fusarium colonization of spring barley and wheat produced on stubble or fallow soil. Canadian Journal of Plant Pathology, 7(3), 270-276.

Takemoto, J. Y., Wegulo, S. N., Yuen, G. Y., Stevens, J. A., Jochum, C. C., & Campbell, K. B. (2016). Disease Management Strategies for Fusarium Head Blight and Associated Mycotoxins. Retrieved from https://digitalcommons.unl.edu/plantpathpapers/529

Tanaka, T., Hasegawa, A., Yamamoto, S., Lee, U. S., Sugiura, Y., & Ueno, Y. (1988). Worldwide contamination of cereals by the Fusarium mycotoxins nivalenol, deoxynivalenol, and zearalenone. IARC Scientific Publications, 115, 83-98.

Trail, F. (2009). For blighted waves of grain: Fusarium graminearum in the postgenomics era. Plant Physiology, 149(1), 103-110.

Trail, F., & Common, R. H. (2000). Perithecial development by Gibberella zeae: A light and electron microscopic study. Mycologia, 92(1), 110-117.

van der Lee, T., Zhang, H., van Diepeningen, A., & Waalwijk, C. (2015). Biogeography of Fusarium graminearum species complex and chemotypes: A review. Food Additives & Contaminants: Part A, 32(4), 453-460.

Van Sanford, D. A., Anderson, J. A., Campbell, K., Costa, J. M., David, M., Griffey, C., ... & Shaner, G. (2001). Registration of 'Ernie' wheat. Crop Science, 41(3), 937-938.

Waalwijk, C., van der Lee, T., de Vries, I., Hesselink, T., Arts, J., & Kema, G. H. (2004). Synteny in toxigenic Fusarium species: The comparative mapping of the Tri1 and Tri8 genes in Fusarium graminearum and Fusarium sporotrichioides. Fungal Genetics and Biology, 41(3), 190-201.

Wegulo, S. N., Baenziger, P. S., Hernandez Nopsa, J., Bockus, W. W., & Hallen-Adams, H. (2015). Management of Fusarium head blight of wheat and barley. Crop Protection, 73, 100-107.

Whitlow, L. W., & Hagler, W. M. (2005). Mycotoxins in feeds. Veterinary Clinics of North America: Food Animal Practice, 21(2), 507-528.

Windels, C. E. (2000). Economic and social impacts of Fusarium head blight: Changing farms and rural communities in the northern Great Plains. Phytopathology, 90(1), 17-21.

Yoshida, M., Kawada, N., & Tohnooka, T. (2007). Effect of zero tillage and fungicide application on Fusarium head blight and mycotoxin contamination in wheat. Plant Disease, 91(2), 210-214.

Zhao, C., Waalwij, C., de Wit, P. J. G. M., van der Lee, T., & Tang, D. (2011). EBR1, a novel Zn2Cys6 transcription factor, affects virulence and apical dominance of the hyphal tip in Fusarium graminearum. International Society for Molecular Plant-Microbe Interactions.