Progress in the management of Fusarium head blight of wheat: An overview

Fusarium head blight (FHB), also known as head scab, is a devastating fungal disease that affects small grain cereal crops such as wheat (Triticum aestivum L.). It is regarded as a major limiting factor in wheat and barley (Hordeum vulgare L.) production across the world.\(^1,2\) The disease is caused by the FHB species complex which consists of more than 17 Fusarium species.\(^3,4\) However, in South Africa, FHB is predominantly caused by Fusarium graminearum Schwabe (teleomorph: Gibberella zeae (Schwein.) Petch).\(^7\) The FHB pathogen is capable of causing head blight or scab on wheat, barley, rice (Oryza sativa L.) and oats (Avena sativa L.), and Gibberella stalk and ear rot disease on maize (Zea mays L.). The pathogen may infect other host genera without causing disease symptoms. These genera include Agrasta, Bromus, Calamagrostis, Cortaderia, Cucumis, Echinochloa, Glycine, Lolium, Lycopersicon, Medicago, Phleum, Poa, Secale, Setaria, Sorghum, Spartina and Tifolium. Apart from F. graminearum, the Fusarium species that occur in South Africa are: F. acaciae-mearnsii O’Donnell, T. Aoki, Kistler & Geiser, F. boothii O’Donnell, T. Aoki, Kistler & Geiser, F. brasiliicum T. Aoki, Kistler, Geiser & O’Donnell, F. cortaderiae O’Donnell, T. Aoki, Kistler & Geiser and F. meridionale T. Aoki, Kistler, Geiser & O’Donnell.\(^9\)

F. graminearum is distributed worldwide, and is especially prominent in temperate regions where its hosts are mostly cultivated.\(^4\) The pathogen infects spikelets at anthesis and thereafter colonises the entire head systemically, thus producing extensive blight symptoms.\(^10,11\) This happens when the presence of favourable environmental conditions coincide with high disease pressure and susceptible host tissue.\(^6,11\) Disease progress is accompanied by the production of trichotheccene mycotoxins (primarily deoxynivalenol (DON), nivalenol (NIV) and zearalenone (ZEA)), which not only pose a threat to the health of humans and other animals, but also reduce grain quality.\(^12,13\)

Challenges involved in the management of FHB are because the favourable conditions for disease development often coincide with the conditions that trigger anthesis. Moreover, the fast progress and epidemic development of FHB limits the effectiveness of certain control methods.\(^14\) Nevertheless, some management strategies have been reported to provide certain levels of FHB and DON reduction on infected hosts.\(^15-21\) There are no registered fungicides\(^2\) and no completely resistant wheat cultivars\(^1,22\) in South Africa or elsewhere, whilst only limited control is achieved by cultural control methods.\(^1\) Therefore, the development of more effective FHB management strategies is essential.

Wheat production

Wheat is a cereal grain that is native to the Levant region of the Near East and Ethiopian highlands.\(^23\) It is cultivated worldwide and is one of the three most produced cereal crops in the world.\(^23,24\) Wheat is a good source of carbohydrates (78.10%), proteins (14.70%), minerals (2.10%), fat (2.10%), B-group vitamins and dietary fibre.\(^24\) It can be consumed as an ingredient in foods such as bread, pasta, crackers, cakes, noodles and couscous.\(^23,25\)
Epidemiology of *F. graminearum*

Wheat plants are mostly susceptible during anthesis, because during this stage the wheat anthers split to discharge pollen (a process known as anther extrusion), which serves as an opening and provides entry for the pathogen.\textsuperscript{26,27} The favourable conditions for infection are prolonged periods (48–72 hours) of high moisture or relative humidity (<90%), moderately warm temperature (15–30 °C), frequent rainfall and the occurrence of air currents.\textsuperscript{2,28,29} These conditions usually occur in spring. Trail et al.\textsuperscript{30} reported that an increase in relative humidity results in a build-up of turgor pressure within the ascus and consequently the forcible discharge of ascospores. Rainfall has been reported to cause the rupturing of the ascus wall which consequently encourages the dispersal of ascospores.\textsuperscript{14,30}

The occurrence of these conditions and the abundance of inoculum before, during and after anthesis of susceptible cultivars, therefore results in yield and quality losses as well as the development of severe epidemics.\textsuperscript{2,26,31} The host remains susceptible throughout the flowering stage; however, late infections have been associated with reduced disease severity and high DON accumulation.\textsuperscript{32} Due to differences in climatic requirements, and genetic and environmental adaptations within the FHB species complex, these species are capable of causing disease in a variety of conditions, resulting in the worldwide distribution of FHB (Figure 1).\textsuperscript{2,8} For example, *F. culmorum* (Fc) (W.G. Smith) and *F. avenaceum* (Fr.) Sacc are more predominant in cooler regions (such as Western Europe) whereas *F. graminearum* predominates in warmer and more humid regions of the world (such as North America and Australia).\textsuperscript{33}

Disease cycle and symptom development

During overwintering or over-summering, the pathogen survives as a precursor to perithecia from which ascospores (primary inoculum) are forcibly discharged under favourable environmental conditions (warm, wet and moist) (Figure 2).\textsuperscript{11,30} The ascospores are dispersed by wind or rain splashes, land on susceptible plant tissue and colonise the plant surfaces (Figure 2).\textsuperscript{1,11,33} After entry, *Fusarium* runner hyphae grow intercellularly and asymptomatically in the inner tissue of the spikelets (palea, lemma and glumes).\textsuperscript{11,33}

*Source: Reproduced from Trail\textsuperscript{11} with permission.*

**Figure 1:** The global distribution of *Fusarium graminearum* (orange dots) as per documented outbreaks.

**Figure 2:** The life cycle of *Fusarium graminearum*, the causal pathogen of Fusarium head blight disease of wheat.
Thereafter, the hyphae grow intracellularly, which leads to plant cell death. This is accompanied by the production of mycotoxins such as DON which has virulent properties that lead to tissue necrosis. Mycotoxins are capable of disabling the plant defence mechanisms and defending the fungus from other microorganisms, thus promoting infection. A study by Boenisch and Schäfer revealed that F. graminearum forms lobate appressoria and infection cushions during FHB pathogen infection in wheat tissue and trichothecene biosynthesis occurs in these structures. The authors further reported that trichothecene biosynthesis is not necessary for the formation of these structures nor the initial infection of wheat tissue.

Initial disease symptoms include water-soaked lesions on spikelets which later appear whitened or bleached. Thereafter, white or pinkish mycelia (Figure 3a) and pink or orange spore masses (Figure 3b) appear on the margin of the glumes of infected spikelets. Small purple-like or black spherical structures (perithecia) are produced (Figure 3c) which then sporulate and further infect healthy host tissue. Infected kernels may appear shrivelled, shrunken and discoloured with a light-brown or pinkish-white appearance. These Fusarium-damaged kernels (FDKs) are often associated with high mycotoxin concentrations, reduced seedling emergence and reduced seedling vigour, making them unusable as food, feed or seed.

**Economic and social importance of FHB**

According to Dean et al., FHB is currently ranked the fourth most scientifically and economically important plant fungal disease globally. Economic impacts (direct or indirect) caused by FHB are due to yield loss (production of FDKs), mycotoxin contamination, reduced animal productivity and human health costs. In the USA, yield and quality losses due to FHB disease on wheat and barley in the 1990s amounted to more than USD3 billion (which equates to ZAR10.5 billion based on the average annual exchange rate in the aforementioned years). Losses in Canada have ranged from USD50 million (ZAR183.5 million) to USD300 million (ZAR1.1 billion) annually since the early 1990s. According to Scott et al., a disease incidence of more than 70% was reported near Winterton in KwaZulu-Natal, South Africa.

FHB-infected grain can result in allergic reactions as well as breathing problems for handlers. In non-ruminants (e.g. pigs), feed refusal and reduced feed consumption have been reported as side effects of DON-contaminated feed ingestion. Ruminants (e.g. cattle) are reported to have a higher tolerance to DON concentrations than non-ruminants. Moreover, adult beef cattle have a higher tolerance to DON concentrations than calves and pregnant cows. DON has been reported to result in abortions, stillbirths and weak piglets, thus affecting pig markets.

In addition to crop losses and mycotoxin production, the disease also leads to the selective loss of albumin and gluten proteins on contaminated grains. This results in yield and quality (economic) losses due to a reduction in the market grade of grains intended for feed, malting, baking, milling, trade (exports), biofuel and brewing industries.

Chemical and physical methods for the detoxification of mycotoxin-contaminated grains have been previously studied. In a review by Jard et al., various techniques of mycotoxin decontamination are discussed which can be achieved by either adsorption or transformation. Current regulations, however, prohibit both the decontamination of grains with mycotoxin levels above the acceptable limits and the chemical treatment of products intended for human consumption. Moreover, obtaining an economical or commercially feasible method for the detoxification of contaminated grains has been unsuccessful thus far.

**Management strategies**

**Agronomic practices**

Certain agronomic practices have been reported to contribute to the reduction of FHB incidence and severity. The most effective cultural control strategies that result in reduced pathogen inoculum and thus reduced FHB incidence and severity in succeeding seasons include: crop rotation with non-host crops; residue management; and tillage practices. Other practices that are of moderate or low efficacy in the control of FHB include: disease forecasting; early planting; the use of early maturing cultivars; the use of cultivars with agronomic traits that are unfavourable for FHB infection; weed control; irrigation management; and optimising crop nutrition. Post-harvest storage practices such as increasing the combine’s fan speed, reducing moisture and temperature in the silos, and sorting and discarding broken and damaged kernels have also been reported to be effective in reducing FHB and DON contamination in grain batches. Because damaged kernels are lightweight and thus easily blown away, they can be separated by increasing the combine’s fan speed.

Environmental conditions can affect the efficacy of agronomic practices in the control of FHB. For example, the occurrence of rainy weather can encourage the dispersal of ascospores, thus resulting in FHB infections. Nevertheless, agronomic practices can lower the amount of inoculum present in the field and thus lower FHB infections on host plants.
Chemical control

In most parts of the world, several fungicides have been tested for their efficacy in reducing FHB on wheat.1,3 According to Haidukowski et al.,14 the use of certain fungicides resulted in reductions of 77% and 89% in disease severity and mycotoxin contamination of infected grains, respectively. Fungicides in the demethyltransferase inhibitor (DMI) class are widely used to control FHB and DON contamination on grain crops.15,16 In a study by Paul et al.,16 the application of DMI fungicides on wheat anthers at Feekes 10.5.1 growth stage was the most effective treatment in reducing FHB index and DON.

According to Salgado et al.,50 and Palazzini et al.,66 past research has reported on the successful reduction of FHB severity and DON concentrations and consequently reduced yield and quality losses from the timely application of triazole-based fungicides. Cremeys et al.17 observed a reduction up to 90% in FHB incidence and a 14% yield increase through the application of tebuconazole on FHB-infected wheat plants. Moreover, meta-analyses of fungicide trials conducted in the USA showed that metconazole, prothioconazole + tebuconazole, and prothioconazole were the best three fungicide treatments resulting in the highest increase in yield and test weight.51,52 Some fungicides used to control FHB have been reported to indirectly increase DON concentrations in grains.53,54 These include fungicides of the quinone inhibitor (QoI) class.34 In a study by Paul et al.,34 the application of QoI fungicides on wheat anthers at either Feekes 9 or Feekes 10.5 growth stages increased mean DON concentrations compared to the non-treated checks. Previous research reports that the use of azoxystrobin resulted in the reduction of FHB caused by Microdochium nivale var. nivale (Fries) Samuels and Hallet, and M. majus (Wollenw.) Glyn & S.G. Edwards, no reduction of F. graminearum and F. culmorum and high DON concentrations on harvested grains.53,54 This could be attributable to the non-toxicity of M. nivale as mycotoxin production has been associated with increased virulence in Fusarium species.53,54 Moreover, azoxystrobin could have slowed down and not prevented the disease53 and also attacked other competitive microorganisms on wheat ears, thus encouraging the development of FHB51,52.

The timing of fungicide application is crucial as fungicides are most effective when applied within a week of early anthesis.1,50 Achieving this timing can be difficult due to the uneven flowering of tillers across cultivation fields as well as rainy weather.50 Moreover, the erratic nature of FHB epidemics can reduce fungicide efficacy.32 Regardless of the successful reduction of FHB and DON provided by certain fungicides, no fungicide has been reported to completely eradicate the disease on infected crops and even the best fungicides are not fully effective.7 Therefore, fungicides are best used in combination with other control strategies (such as cultural methods).1

Biological control

Several bacterial, fungal and yeast strains have been reported to provide effective reduction of FHB severity and/or DON concentrations in infected grains.13,63,64 These were reviewed by Legrand et al.65 and presented in appropriate tables. Biological control agents (BCAs) can be applied as residue, seed, spikellets and/or post-harvest treatments.46 According to Schmale and Bergstrom29, BCAs have been reported to be potentiated with the ability to provide extended protection of spikes even after flowering, when most control strategies (e.g. fungicides) cannot be applied. Mycotoxin-binding and bio-transforming microorganisms can also be used to reduce mycotoxin contamination in grains by binding the mycotoxins or by converting them to less toxic metabolites, respectively.41 Unfortunately, the development of effective and safe detoxifying agents for use in grains intended for human consumption has been unsuccessful thus far.40

Bacteria as antagonists

Strains of Bacillus spp.,18,42 Pseudomonas spp.,43 Streptomyces spp.,18 and Lactobacillus plantarum44 have been tested against F. graminearum. These bacteria were isolated from various environments, applied on anthers and/or residues of host plants, and employed various mechanisms of biological control (such as antibiotics, competition and mycoparasitism) against F. graminearum.19

In a study by Pan et al.,67 Bacillus megaterium reduced FHB incidence and severity, and DON production under field conditions by 93%, 54% and 89.3%, respectively. Furthermore, a study by Palazzini et al.16 reported that Streptomyces sp. RC 87B reduced F. graminearum inoculum by 85% and 100% after 45 days and 90 days, respectively, when applied on wheat stubble. In a later study, Palazzini et al.67 reported that B. velezensis RC 218 and Streptomyces albidoflavus RC 87B effectively reduced FHB incidence (up to 30%), severity (up to 25%) and deoxynivalenol accumulation (up to 51%) on durum wheat under field conditions.

Fungi and yeasts as antagonists

In a study by Xue et al.,69 significant reduction in mycelial growth (52.6%), spore germination (~100%), perithecial production (~99%), FHB index (58%), DON concentration (21%) and number of FDKs (65%) was obtained by using Clonostachys rosea strain ACM941 as a BCA against FHB under laboratory, greenhouse and field conditions. Resultantly, C. rosea strain ACM941 is believed to be a promising BCA of FHB. Other fungal species that have been tested against FHB include Trichoderma spp.,49 and Microsphaeropsis spp.79 According to Gilbert and Haber49, there are only a few yeast strains that have been reported to be effective against FHB compared to bacteria and fungi. Field trials of three strains of Cryptococcus spp. showed a reduction in FHB severity by as much as 50–60%.70 Reduction in FHB severity by Cryptococcus spp. was also observed in other similar studies.18,19,21,27,23

Breeding for resistance

Many researchers believe that genetic resistance is the best, most cost-effective strategy that could provide meaningful, consistent and durable FHB control.51,74 According to Mesterházy et al.,75 wheat resistance to FHB is not Fusarium species-specific, making it achievable by breeding for resistance to Fusarium species in general. Although there are variations in the susceptibility of different host plant species to FHB, there are no wheat or barley varieties that possess immunity against FHB.76

Recent wheat breeding programmes for FHB resistance focus on mapping quantitative trait loci (QTL) that confer a response on two or more types of FHB resistance17,18, such as the Fhb1 derived from the Chinese wheat cultivar Sumai 3.24,76 A list of wheat cultivars that have been evaluated for FHB resistance in China, the USA, Japan and Brazil are presented by Shah et al.77 These landraces provide moderate to high resistance to FHB and some of them have been used as parents in breeding programmes.77

Nonetheless, resistance breeding programmes have been slow, resulting in only a few partially resistant cultivars being produced thus far.13 This could be attributable to FHB resistance in small grains being complex and inherited quantitatively.13 Consequently, there are no resistant cultivars commercially available in most parts of the world, including South Africa.12 However, partially resistant cultivars can be used to reduce disease incidence and severity.75

Priming using resistance inducing chemicals

The use of resistance inducing chemicals such as jasmonic acid, ethylene and salicylic acid to enhance induced systemic resistance and systemic acquired resistance in wheat as means to control FHB has been previously studied.10,12 According to past research, salicylic acid signalling is believed to be responsible for basal resistance to FHB whereas jasmonic acid signalling reduces further infection by the pathogen.48,65 In a study by Palazzini et al.,48 salicylic acid signalling was induced early (12 hours) after the inoculation of wheat spikes with F. graminearum whereas jasmonic acid signalling was induced later (after 48 hours). Nevertheless, further research (such as formulation development, optimum concentration and application timing) is required for resistance-inducing chemicals to be employed in FHB management programmes.12

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Management of Fusarium head blight of wheat
Integrated control strategies

As much as some control strategies provide certain levels of reduction in FHB severity and mycotoxin concentration, no single control strategy will provide significant control of FHB, especially under environmental conditions favourable for disease development. Therefore, the use of integrated disease management strategies is considered the best way to control FHB on cereal crops due to the increased reduction of FHB severity and DON concentrations that could be achieved.

In a study to test the efficacy of an integrated approach to FHB control, McMullen et al. observed that the use of crop rotation, crop rotation + tolerant cultivar, crop rotation + tolerant cultivar + fungicide application resulted in 50%, 80% and 92% reductions in FHB, respectively. In a similar study, the combination of ploughing, a moderately resistant variety and triazole fungicide application at heading resulted in a 97% DON reduction study, the combination of ploughing, a moderately resistant variety and triazole fungicide application at heading resulted in a 97% DON reduction.

Way forward

Regardless of some reported efficacies, the inconsistency and lack of durability of BCAs are, and the residual and resistance development concerns associated with fungicides are major limitations in the development of FHB management strategies. Moreover, the use of agronomic practices in FHB management is not always feasible and/or economical in commercial farming systems. Some researchers believe that improving host genetic resistance could provide more meaningful, durable and consistent protection against FHB and its mainly produced mycotoxin, DON. Therefore, future research can be aimed at improving host resistance to FHB either by resistance breeding or by the use of resistance inducers. The isolation and testing of more effective natural antagonists of F. graminearum that can be integrated with other management strategies could help improve FHB control and reduce the risks associated with fungicide use.

Conclusion

FHB remains a major threat to wheat production worldwide. Although some strategies have provided some level of disease reduction, the current dependency on fungicides in FHB management practices poses concerns regarding fungicide resistance as well as environmental, human and animal health. Therefore, further research in the development of more effective and more reliable FHB management strategies is necessary.

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Competing interests

We declare that there are no competing interests.

Authors’ contributions

S.P.N.S.: Wrote the initial draft of the manuscript, implemented the comments after editing and revised the manuscript. K.S.Y.: Student supervision, project leadership and management, funding acquisition and editing of manuscript. N.C.M.: Student co-supervision, funding acquisition and proofreading of the final draft.

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