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Overview of resistance and prevention to Fusarium head blight in barley

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Abstract

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Barley grains are highly susceptible to fungal contamination. Fungal infection of its kernels occurs in the field and is often associated with *Fusarium* species, which are phytopathogenic fungi. These fungi cause variety of diseases such as Fusarium head blight (FHB). FHB is one of the most studied diseases, which is responsible for worldwide losses in small-grain cereals. Losses are manifested as reduction in yield and quality of the grain, and the presence of mycotoxins in grain. Moreover, mycotoxins produced by the FHB pathogens are one of the most important groups of anti-nutritional substances found in feed. They are hazardous to animal and human health. Cases of mycotoxicosis caused by ingestion of barley contaminated with FHB mycotoxins have necessitated the need for resistant barley cultivars. That can limit mycotoxin production by the dominant causal pathogen, *Fusarium graminearum.* Various inoculation methods have been used to decrease the severity of the disease. Resistant cultivars and proper management of prevention methods could reduce damage from FHB. This review examines the progress of FHB resistance in barley, as well as, prevention methods. A combination of cultural practices, planting resistant varieties, chemical control, biological control and harvesting strategies is required. Combining these aspects leads to quality grain production and protects human and animal health.

Keywords: barley; Fusarium head blight; resistance; prevention

Introduction

Fungi of the genus *Fusarium* can cause FHB, which is one of the most harmful cereal diseases (Schöneberg et al., 2016). This disease has become one of the most important cereal diseases worldwide and likelihood of FHB has increased over the past century (Agriopoulou et al., 2020). FHB is also referred as fusarium ear blight, scab, or head fusariosis. It describes a disease of small-grain cereals such as wheat, barley and maize (Xu et al., 2005). Besides yield losses, infections lead to accumulation of different mycotoxins in the grains and grain deformation, and reduced quality (Martin et al., 2017).

The infection can be recognized by necrotic patches and bleaching of the florets and discoloured kernels (tan, orange, brown, pink, or red) scattered throughout the head. Infected grains cause technological problems concerning quality and safety of barley products (Hoheneder et al., 2022).

Barley is most susceptible to FHB during warm and wet conditions. There is evidence that climate change is associated with increased frequency and severity of FHB epidemics (Nopsa et al., 2014). FHB is a fungal disease favoured by humid conditions during flowering and early stages of kernel development. The favourable conditions for the infection are temperatures between 16°C-20°C and high humidity (Musa et al., 2007). FHB development starts after primary infection when spores released from crop residues, transported by wind and rain, are deposited on florets (Bai & Shaner, 2004). Once established in the ear, the infection progresses throughout the spike, causing progressive blighting (Oliveira et al., 2013). During the infection process, *F. graminearum* produces the mycotoxin deoxynivalenol (DON) that accumulates in grains. According to some authors (Nesvadba et al., 2006) there are insignificant correlations between ear infection percentage and DON content and between the percentage of fusaria in a laboratory test and DON content. By contrast, other authors (Špunarová et al., 2005) reported significant correlations between FHB severity and DON accumulation.

Fodder barley contaminated with DON can result in feed refusal, diarrhea, vomiting, and growth depression in farm animal. The contamination of barley grains for human consumption may also cause health problems, since mycotoxins remain in the final product (Malachova et al., 2012).

The most effective means to reduce loss caused by FHB is to cultivate crops with high levels of genetic resistance. More than 25000 germplasm accessions have been screened, however, they exhibited only partial resistance to FHB (Chamarthi et al., 2014). The resistance in plants against pathogens can be due to constitutive or induced biochemicals or structural components (Kushalappa & Gunnaiah, 2013). Several secondary metabolites such as phenolic compounds, either in active forms or passive as glucoside conjugates, have also been associated with constitutive resistance (Kumaraswamy et al., 2011).

The cultivation of resistant varieties is the most sustainable and cost effective way to control yield losses and contamination with mycotoxins. Genetic improvement of barley's resistance to FHB has the potential to provide economical and effective control of this disease (Sakr & Kurdali, 2023).

The lack of FHB resistant barley genotypes makes it difficult to achieve complete control of FHB when inoculums is present and the environmental conditions are conducive for infection. Integrated field prevention strategies are required to mitigate FHB and DON contamination in barley, which include crop rotation with non-susceptible hosts, fungicide application, and deployment of moderately resistant cultivars (Huang et al., 2018).

This review summarizes the control of FHB through resistant cultivars and methods for disease prevention.

Resistance of barley to FHB

Plant resistance to FHB is economically important because of the negative effects the disease has on cereal yield and grain quality. The investigations concerning FHB is evolving as new species continue to be identified and examined for their contribution to the disease complex.

It is necessary to develop new varieties of plants resistant to FHB, for this purpose it is indispensable to carry out inoculation in order to trace the effect of a given microorganism on a given plant species. Assessment of FHB resistance is often not possible through natural infection because disease intensity varies over time due to environmental changes. FHB can be completely absent depending on environmental conditions (Mesterhazy et al., 2003). Furthermore, the implementation of resistant genotypes is very important in terms of efficiency, environmental friendliness and sustainability of production (Mengesha et al., 2022). Hoheneder et al. (2022) found that only artificial inoculation provoked ecologically stable and sufficient disease pressure for genotype selection against the influence of weather conditions.

Parry et al. (1995) established that to have a consistent differentiation of FHB resistance levels there is a need to be involved inoculation methods. As a result, inoculation techniques have been developed to quantify resistance and to screen breeding material for FHB resistance. In addition to the current sources and methods of artificial inoculation, researchers should explore other means by which experimental crops can be cultivated in fields and greenhouses. In Table 1 are summarized some of inoculation methods to FHB.

Controlling most plant diseases is to identify the inoculum source and the mode through which it is transferred to the host plant and then make it unavailable for disease incitement (Bateman, 2005).

Geddes et al. (2008) reported three methods of artificial inoculation, including point or spray, inoculation in the greenhouse and grain spawn in a field nursery. They evaluated nineteen barley genotypes, which represent various levels of resistance to FHB. The genotypic differences for FHB symptoms were detected for the all three-inoculation methods. However, it was observed that indoor spray inoculation is the most reproducible method. It can mimic natural infection while controlling environmental influences and provided the greatest discrimination of FHB resistance.

Table 1. Inoculation methods to FHB in cereals

Grain	Method of inoculation	Type resistance	References
Wheat	Point inoculation	Type II	Burlakoti et al.,(2010; Engle et al., (2003)
Barley	Spray inoculation	Type I and Type II	Miedaner et al., (2003); Burlakoti et al., (2010)
Maize, oat, barley and wheat	Soil-surface inoculation	Type I, II, III, IV и V	Imathiu (2008); Bateman (2005)
Wheat	Bilateral Floret Inoculation (BFI) Basal Rachis Internode Injection (BRII)	Type V	Wang et al., (2021)

In a later study, Khanal et al. (2021) investigated forty-eight spring barley genotypes to see if reactions of barley genotypes to artificial FHB inoculation correlate to natural FHB infection. These genotypes were evaluated for DON concentration under natural infection. The genotypes were also evaluated for FHB severity and DON concentration under field nurseries with artificial inoculation of *Fusarium graminearum* by the grain spawn method. Additionally, these genotypes were also evaluated for FHB severity under greenhouse conditions with artificial inoculation of *Fusarium graminearum* by conidial suspension spray method. DON concentration under natural infection was positively correlated with DON concentration and FHB incidence in the artificially inoculated nursery with grain spawn method. Nine barley genotypes were found to contain low DON under natural infection. The results showed that artificial inoculation with the grain spawn method has a similar response to DON accumulation as natural infection, and it can be used to effectively screen for low DON.

With the studies conducted on FHB resistance in barley, artificial inoculation highlights genotypic differences when the inoculums dose and pathogen isolates are well adapted to the chosen inoculation method in a way to reproduce increased disease pressure (Imathiu et al., 2014).

Due to the complex interaction between individual genotypes, quantitative FHB resistance in barley is still little exploited and not fully understood. In this connection, Hoheneder et al. (2022) assessed quantitative resistance to FHB in seventeen spring barley genotypes in the field in southern Germany. They used spray inoculation of plants with *Fusarium culmorum* and *Fusarium avenaceum.* This increased disease pressure and provoked genotypic differentiation. To normalize effects of variable weather conditions they used a disease ranking of the genotypes based on quantification of fungal DNA contents and multiple *Fusarium* toxins in harvested grain. This allowed for assessment of stable quantitative FHB resistance of barley in several genotypes. Strong quantitative resistance to one *Fusarium* species could probably indicate sufficient resistance to other species. Only artificial inoculation could induce provoked ecologically stable and sufficient disease pressure for genotype selection against the influence of climatic conditions.

This is in line with previous studies (Geddes et al., 2008) that genotype selection is less conclusive without artificially increased disease pressure because the local dose of natural inoculum cannot be controlled and occurs randomly in the field.

Due to the quantitative inheritance of FHB resistance, continuous effort is required to identify breeding lines and incorporate them into crossing schemes and to enhance FHB resistance. These lines identified could be used as new resistance sources or released as cultivars if they have acceptable resistance to other diseases and good grain quality (He at al., 2016).

Chrpová et al. (2011) demonstrated the importance of barley breeding for FHB resistance in the Czech Republic, where in recent years most spring barley cultivars were significantly affected by the disease. They studied forty four varieties of spring barley for two years after artificial inoculation with *Fusarium culmorum* under field conditions. The greatest effect on the DON content is due to the environmental conditions while the visual symptoms of the disease depend largely on the cultivars. They determined the resistance of barley to FHB based on the DON content under field conditions. However, no correlation between FHB severity and DON accumulation was confirmed in any of those cases. Therefore, it is necessary to find a suitable tool for evaluating infestation in plants in order to assess the resistance of barley cultivars in a more accurate manner than symptomatic evaluation. The varieties should be selected to be exploited in a way to improve FHB resistance.

On the other hand, Huang et al. (2018) established that plant architecture and flowering traits should be taken into full consideration when breeding barley for FHB resistance. It has to be mentioned that short plants tend to have higher infection levels on the heads due to their proximity to higher spore concentrations at the soil level and more humid microenvironment compared to plants of tall stature. Moreover, densely arranged spiklets on the rachis may also facilitate fungal spread within spikes.

In a way to reduce, the risk of FHB and mycotoxin contamination in barley Yoshida et al. (2007) examined the effect of the timing of *Fusarium graminearum* infection on FHB severity and mycotoxin accumulation between flowering types of barley. Barley has two flowering types, chasmogamous (open flowering), and cleistogamous (closed-flowering). The most critical time for *Fusarium graminearum* infection and mycotoxin accumulation differs with cultivar, and probably is associated with the flowering type. Late infection, even without FHB symptoms, also has implications for the risk of mycotoxin contamination.

Genetic mapping studies have revealed that resistance to FHB and the accumulation of pathogen-produced mycotoxins are highly influenced by plant morphological traits and environmental conditions (Huang et al., 2018). Agronomic and morphological traits have been found to be associated with FHB resistance in barley, which has been elucidated by genetic studies (Massman et al., 2011). Generally, high stature, late heading, lack of laterals, lax and nodding spike, hulless, and lodging resistance are often associated with FHB resistance (Choo, 2006).

Breeding for resistance is the most economical and environmentally safe way to manage the disease (Bai & Shaner, 2004). Complete resistance to FHB in barley has not yet been found (Choo, 2006). Breeding lines are usually tested for two types of resistance: type I, resistance to infection by spray inoculation of the pathogen; type II, resistance to spread of disease within the class in single-class inoculation.

Type II resistance is very high in barley, and the FHB research in barley is mainly focused on type I resistance (Bai & Shaner, 2004). Coloured barley is considered to have more resistance than yellow barley, but among coloured barley, genotypes range from highly resistant to highly susceptible to FHB (Choo, 2006). The ranking of genotypes based on types of resistance has been inconsistent over locations and years (Chamarthi et al., 2014).

Black grain colour is associated with higher resistance to *Fusarium* in barley.

The safety of barley is essential to ensure that human and animal lives are not endangered. Mycotoxins produced by the barley-infecting *Fusarium graminearum* pathogen pose serious risk. It is therefore of the utmost importance to breed barley varieties that are able to limit the accumulation of mycotoxins produced from *Fusarium graminearum* (Figlan & Mwadzingeni, 2022).

In certain instances, the resistance incorporated into a cultivar against FHB may be race-specific, though in most cases it is race non-specific. It is always important to adopt a clear resistance breeding strategy so that broad-spectrum and durable resistance may be incorporated into the cultivar (Figlan & Mwadzingeni, 2022).

When using traditional breeding techniques, it is critical to select effectively in the early generations for FHB resistance; otherwise, the promising gene combinations are lost irretrievably. The selection efficiency increases when the breeding method can be used to select successfully in the early generations of selection (Janick, 2010). However, the limitations of traditional plant breeding require integration of new and more sophisticated methods for cultivar improvement to fast-track *Fusarium graminearum* resistance breeding.

Methods of prevention to FHB in barley

FHB is one of the most noxious cereal diseases causing severe reduction in yield and quality of grain. Because of the large worldwide economic losses caused by FHB on grain crops, prevention strategies are needed. For the past few decades, multidisciplinary studies have been conducted on prevention in a way to reduce the losses caused by FHB (Powell &Vujanovic, 2021). The strategies of prevention (Figure 1) include planting resistant cultivars, crop rotation, chemical, and biological control, and as well as is very important harvesting under suitable conditions.

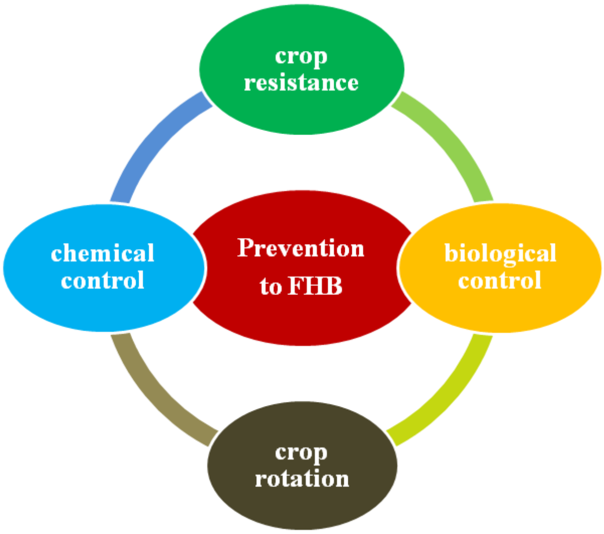

Fig. 1. Shematic depicture of prevention strategies to FHB

Irrigation management is also important because of reducing FHB intensity. Growers will benefit most when multiple practices are used together, rather than individually. In addition, very important for the best prevention is that they should never rely on a single prevention practice to control FHB.

Warm and humid weather during flowering favors the development of the disease, resulting in damage kernels, yield loss, altered quality and mycotoxin accumulation in the grain. For example, *Fusarium graminearum* prefers warmer climates, while *Fusarium culmorum,* the other major species, occurs in cooler climates. Over the past decade, *Fusarium graminearum* has become more widespread in parts of Europe, including the Netherlands, England and Wales, and Germany (Gilbert, & Haber, 2013).

Most practices aimed at mycotoxin prevention are essentially crop prevention practices whose goal is to reduce infection or fungal growth by toxigenic fungi (Munkvold, 2003).

The most effective, durable and environmentally safe strategy for prevention the disease and associated mycotoxin contamination is the use of resistant varieties against complex *Fusarium* species (Abdissa et al., 2022). The development of resistant cultivars is not completely finished. That means that resistant cultivars still can be infected, but disease progression is often greatly reduced, as is DON accumulation (McMullen, M., et al., 2012). The host response to infection and disease development varies widely. FHB is extremely difficult to predict and control, so a multi-pronged approach is most effective.

Crop rotation

Fusarium graminearum does not grow as well on residues of some crops (e.g. soybean) compared to wheat, and barley. For example there is some evidence that planting wheat after soybean may help to reduce the level of local inoculum . In addition to cultivar selection and fungicide application, tillage affects FHB disease severity and DON accumulation. Properly crop rotation is very crucial to reduce of infected crop residues, rotating away from cereals particularly maize crops to non-host crops. This will allow enough time for the infested residue to decompose before the next cereal crop to be planted. (Islam et al., 2022).

Seed quality

To reduce FHB the most important is to use high-quality seed. That means the seeds should be healthy, without signs of damage that could facilitate pathogen penetration. If the seeds are of susceptible crop species must be tested for the presence of mycotoxins and only seed with non-detectable levels of *Fusarium* species is to be used for seeding purposes (Moya-Elzondo and Jacobsen, 2016). Although infected seed can cause seedling blight, it typically does not directly give rise to head blight symptoms in one growing season. The fungus will move from the infected seed to the root, crown, and stem base tissues of the plant that develops from the infested seed, therefore, creating potential sources of infested residue that can influence subsequent crops. To prevent the FHB epidemic is also very important modification of planting dates to avoid having all cereal fields flowering at the same time (Regasa, 2023).

Chemical control

Control and suppress of FHB can be achieved by the timely application of fungicides to wheat and barley (McMullen et al., 2012).

Pirgozliev et al. (2003) showed that FHB and DON concentration could be strongly influenced by fungicide treatments applied at mid anthesis and by the choice of cultivar. The successful reduction of FHB severity and DON concentrations is the timely application of triazole-based fungicides.The use of a moderately resistant variety combined with the use of a triazole fungicide for suppression of FHB provide significantly greater reduction in DON than either method alone (Palazzini et al., 2017).

The timing of fungicide application is also critical for FHB control.

Application of fungicides containing prothioconazole at the beginning of flowering has been shown to significantly suppress FHB disease. As a result, grain yields increased and the content of DON in cereals dropped significantly (Haidukowski, 2012).

From another side Japanese study recommended that applications should happen at 20 days after anthesis in a way to reduce Fusarium-damaged kernels and mycotoxin contamination (Yoshida et al.,2012).

According to Gilbert & Haber (2013) prevention in such short interval before harvest is controversial.

Although unable to prevent infection later in the growing season, seed treatment helps prevent seedling blights caused by FHB and other seed and soil-borne pathogens. Prior to planting a cereal crop, the seed have to be treat with a fungicide. Seed treatment is the most effective way to protect the grain crops against FHB (Mengesha et al., 2022). The chemical treatment of seed helps to prevent seedling blight caused by *Fusarium* species. Fungicide seed treatments are designed to mitigate external or internal microorganisms from seeds or soil, resulting in healthy seedlings and plants (Beres et al., 2016). The damage from the pathogens can be more severe when the seed had not been treated (Turkington et al., 2016).

In addition, FHB control-using fungicides involve some disadvantages mainly costs, bio- and eco-hazards, and relatively short lifetime due to fungicide resistance.

They are not the ideal means of combating pathogenic fungi. The results of field trials with fungicides are often conflicting (Gilbert & Haber, 2013). An effective control that damages the environment less than chemicals is desirable. These findings prompted the search for organisms to identify antagonists of *Fusarium* spp. Bacteria, for example, predominate among such antagonists, but fungi and yeasts have also been identified. One study shows that biocontrol agents can be used most effectively as part of an integrated program to reduce, rather than completely replace, the chemical load on the environment (Palazzini et al., 2017; Xue et al., 2009).

Biological control

Biological control methods for prevention use microorganisms that are antagonistic to FHB and have the ability to inhibit FHB and its related toxins. These biological control agents can be applied to residues from previous crops or directly to wheat ears to suppress perithecia formation (Zhao et al., 2014). Using the least susceptible varieties will help to reduce the risk of FHB and perhaps the potential for buildup of *Fusarium graminearum.* Producers should select varieties that exhibit some level of FHB resistance. The results indicate that barley growers to minimizing DON should both plant moderately resistant varieties and apply fungicide if there is scab risk (Cowger et al., 2019). The use of resistant cultivars against *Fusarium* species still remains the most effective and environmentally safe strategy for managing the disease and associated mycotoxin contamination (Abdissa et al., 2022).

Conclusions

FHB is the most serious disease affecting wheat and barley crops throughout the cereal-growing regions. However, in FHB-endemic regions, it remains the case that few cultivars with even moderate resistance to FHB are available and the disease continues to inflict notable losses on cereal producers.

The effective prevention is still challenging due to the emergence of fungicide-tolerant strains of *Fusarium graminearum* as well as the lack of highly resistant wheat and barley cultivars. To safeguard crops from FHB the researches must be open to science.

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