REVIEW

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Among the food grains, wheat is one of the most important cereal crops grown all over the world. The total acreage under wheat crop production in the world is 222.21 million hectares with the total production of 781.31 million metric tonnes. The total production of wheat grains harvested in India during crop season of 2022-23 was 112.74 million tonnes from an area of 34.50 mha and the country is regarded as second largest producer of wheat in the world. Wheat production in India has increased many folds from 6.4 mt in 1950 to 112.74 mt during 2022-23. The achievements in wheat production in India have been perhaps the most important and unparallel in the history of developing world. Since the initiation of the 'Green Revolution' in the mid-sixties, India achieved remarkable increase in production and productivity of wheat. The most serious constraints to the wheat production in India are biotic stresses (diseases) such as rusts, spot blotch, powdery mildew, Karnal bunt, loose smut, flag smut and head scab etc. The expected onslaught of climate change is also a worrisome aspect so it is very important to keep different biotic stresses under check for harvesting maximum yield potential of wheat varieties. In India, among foliar and head diseases of wheat *viz*., Fusarium head blight or head scab is likely to become most important disease in South Asia in near future due to global climate change and changing tillage practices. Most wheat cultivars currently grown in India are susceptible to FHB. Control of the disease has been difficult, because of the complex nature of the host/pathogen/environment interaction. Detailed systematic study is required on pathogen aspects and interaction with the host for devising eco-friendly management of disease for sustaining global wheat production.

Keywords: Climate change, *Fusarium graminearum*, Fusarium head blight, resistance, management, wheat

INTRODUCTION

Fusarium head blight (FHB) or head scab (Fig.1A) is one of most destructive diseases of bread wheat (*Triticum aestivum* L.) and durum wheat (*Triticum durum* Desf.) worldwide. The disease was reported first time in England in 1884. *Fusarium* spp. caused reduction in yield and quality of wheat in countries where warm and humid climate prevails.Recently outbreaks of *Fusarium* head blight (FHB) or head scab of wheat caused by *Fusarium* spp., has been reported from Canada, Europe, Asia, Australia and South America. *Fusarium* head blight or head scab of wheat has been found associated with more than 17 *Fusarium* spp. Among predominant species causing FHB, *F. graminearum* and *F. culmorum* have been reported to be the most pathogenic (Schluter *et al.* 2006). *Fusarium* species produce mycotoxins and are responsible for many diseases of crop plants. FHB of wheat is a serious constraint for wheat production as disease caused significant yield reduction in different countries. Conservation tillage and minimum tillage adoption resulted in increase in FHB incidence in USA (Dill-Macky and Jones, 2000). Currently head scab is of minor importance to India but the disease is likely to increase due to global climate change and the preference of farmers for reduced tillage practices in the northern plains of India.

PATHOGENS AND SYMPTOMS

Fusarium head blight has been associated with up to 17 causal organisms, of which *Fusarium graminearum* Schwabe (teleomorph *Gibberella zeae* [Schwein] Petch) is the principal pathogen (Figs.1 B &C) responsible for head blight in many countries of the world. Other related species such as *F. culmorum* (Smith) Sacc*., F. avenaceum*

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(Fries) Sacc., *F. verticillioides* (Sacc.) Nirenberg (syn. *F. moniliforme* J. Sheld), *F. oxysporum* Schlect., *F. poae* (Peck) Wollenw and *Microdochium nivale* (Fries) Samuel & Hallett also contribute to the head blight complex. In India, *F. avenaceum* and *F. graminearum* causing ear blight and scab of wheat on such varieties as Sonalika, Kalyan Sona, Safed Lerma and Lerma Rojo were first reported in samples received from Siang District of Arunachal Pradesh. *Fusarium graminearum* causing head scab of wheat was also observed on varieties viz., Sonalika, Agra Local, HW 517, HW 741, HW 1042, E 9382, E 2670 and C 306 at IARI, Regional Station, Wellington. Several *Fusarium* spp. (*M. nivale*, *F. compactum* (Wollenw) Gordon, *F. verticillioides*, *F. subglutinans*, *F. oxysporum* and *F. pallidoroseum* (Cke) Sacc. were also found associated with head scab complex in the Gurdaspur area of Punjab. In addition to these, *F. semitectum*, *F. compactum* have also been associated with head scab of wheat.

Six *Fusarium* species *viz*., *F. graminearum*, *F. verticillioides*, *F. oxysporum*, *F. equiseti*, *F. solani* and *F. semitectum* were isolated from head scab infected samples. *F. graminearum* was found in most of the samples collected from Lahaul valley, Punjab as well as from Wellington (Saharan *et al.* 2003). *Fusarium graminearum* is the predominant causal agent of head blight of small grain cereals in the United States, Europe and India (O'Donnell *et al*. 2000). Initial infections appear as small, water-soaked spots at the base or middle of the glume, or on the rachis. Water soaking and discoloration then spreads in all directions from the point of infection. A salmon-pink fungal growth may be seen along the edge of the glumes or at the base of the spikelet.

DISEASE CYCLE

Fusarium head blight is a monocyclic disease with a complex life cycle. During overwintering or

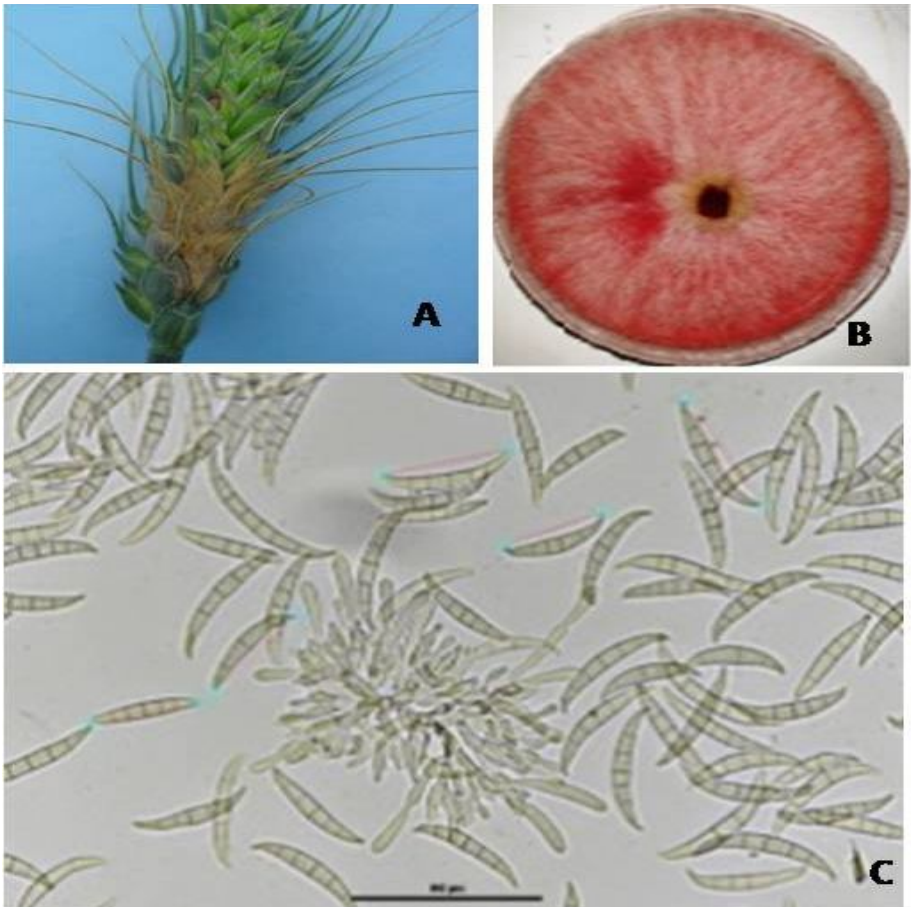

Fig. 1:(A) *Fusarium* head blight (FHB) or head scab disease symptom of wheat, (B) Mycelial growth and (C) Macroconidia of *Fusarium graminearum*

oversummering, the pathogen survives in crop debris, either as ascospores within sexual structures called perithecia or as asexual spores (macroconidia or microconidia) for species with only an anamorph stage. These spores serve as the primary source of infection. Whereas both gramineous and non-gramineous weeds can also act as hosts and sources of inoculum.

During optimal weather conditions, when wheat is at the susceptible stage of anthesis, the inoculum is transported by wind or rain and settles on exposed spikelets. On the surface of the spikelet tissue, the spores undergo germination and form germination tubes. Fungal hyphae then spread across the ovary, palea, and lemma, initiating mycotoxin production without penetrating the spikelet tissue. Subsequently, the pathogen penetrates the host tissue, leading to a biotrophic infection characterized by intercellular growth within the spikelet. Eventually, the infection switches to a necrotrophic stage, involving inter- and intracellular growth both laterally and vertically within the spike. During this pathogenic stage, mycotoxins accumulate in spike tissue and kernels, resulting in reduced crop yield and quality. Interestingly, mycotoxins play a role in disabling plant defense mechanisms and protecting the fungus from other microorganisms, thus facilitating infection. Boenisch and Schãfer (2011) conducted a study revealing that *F. graminearum* forms lobate appressoria and infection cushions during FHB pathogen infection in wheat tissue. These structures are also involved in trichothecene biosynthesis, which contributes to the production of mycotoxins. Overall, FHB is a complex disease with various stages of infection and mycotoxin production, impacting wheat yield and quality. Understanding the dynamics of its life cycle and pathogenesis is essential for developing effective strategies to manage and control FHB in agricultural settings.

MYCOTOXINS AND SOCIO-ECONOMIC IMPLICATIONS OF FHB

Fusarium species involved in FHB produce a wide range of mycotoxins, mainly trichothecenes, zearalenone, fusaric acid, fumonisins, and emerging toxins, i.e., enniatins, beauvericin, moniliformin, and fusaproliferin. When mammals consume food and feed contaminated with the mycotoxin deoxynivalenol (DON), it can lead to immunotoxic and neurotoxic consequences (Desjardins, 2006). Nivalenol toxin has been found to be more harmful to humans and animals compared to DON. Covarelli *et al*. (2015) stressed that exposure to these toxins can cause intestinal disorders, vomiting, skin dermatitis, hemorrhagic lesions, and immune system problems.

Based on a comprehensive evaluation of various economic and scientific factors, the ascomycete *F. graminearum*, which thrives in temperate climate conditions, is currently recognized as one of the top four significant fungal pathogens affecting plants. Throughout its evolutionary history, various forms of FHB have been devastating numerous wheat-growing areas worldwide. However, in recent times, FHB has witnessed a rise in prevalence across North America, Asia, Europe, and South America, leading to a significant escalation in economic losses. The dynamic nature of the environment and the growing concern of global warming have contributed to the escalation of the *Fusarium* head blight (FHB) epidemic. Variations in temperature and humidity in the atmosphere play a pivotal role in the dissemination of FHB infection. The FHB epidemic has been associated with significant production losses ranging from 10% to 70% during outbreak years. In the United States alone, between 1993 and 2001, the FHB epidemic resulted in a reported financial loss of 7.6 billion US dollars.

VARIATIONS IN *FUSARIUM* SPP./ ISOLATES CAUSING HEAD SCAB OF WHEAT IN INDIA

Among head scab infected wheat ear heads collected from Dalang Maidan, Lahaul valley of Himachal Pradesh and Wellington, Nilgiris hills, Tamil Nadu, dominance of *F. graminearum* was observed. Twenty-nine *Fusarium* isolates were identified as *F. graminearum* based on morphological, cultural and molecular approaches. Pathogenic variation among 29 *F. graminearum* isolates was observed on wheat varieties (UP 2338, PBW 343, Sonalika, HD 2967, HD 3086, HD 29, MACS 5049, HS 645, VL 1013). After 7 and 14 days of inoculation, isolates from Wellington (Fg-W10 and Fg-W24) were

found highly pathogenic while isolates Fg-W7 and Fg-W26 were found least pathogenic. Out of 23 SSR markers designed using whole genome sequence of *F. graminearum* PH-1 strain, 21 SSRs amplified *F. graminearum* isolates. Cluster analysis separated the isolates into two main groups. Group A consisting two isolates one from Wellington (Fg-W27) and another from Lahaul Spiti (Fg-L2). Group B contained all other 27 isolates. This study has shown that there is considerable pathogenic and genetic variability among *F. graminearum* isolates obtained from infected wheat ear heads from different geographic regions of India (Kumar *et al*., 2021)

EPIDEMIOLOGY

FHB is highly influenced by environmental conditions particularly during and after anthesis. *Fusarium graminearum* produces ascospores and macroconidia which are formed in perithecia and sporodochia, respectively. Ascospores released and transported by wind and infect flower parts are considered the main source of inoculum for epidemics (Osborne and Stein, 2007). Warm temperatures and high humidity are favourable conditions for blighting of ear heads in 2 to 4 days after infection. Perithecia and sporodochia are fruiting structures of the fungus which over winter in crop debris. The relationship between crop debris and FHB epidemics has been well documented (Dill-Macky and Jones, 2000). Minimum soil temperatures for perithecia production are 6°C to 10°C with an optimum in the range 15°C to 20°C (Gilbert *et al*., 2008). High relative humidity and soil moisture content are favourable for perithecia formation; therefore, humid weather during August and September favour FHB epidemics in the following growing season. In the spring, ascospores and macroconidia are released from the fruiting bodies. The optimum temperatures for production of ascospores is 29°C for *F. graminearum*. Kaur *et al.* (2007) reported high humidity for 48 h immediately after inoculation conducive for the proper development of disease.

MANAGEMENT

The effective management of FHB presents numerous challenges stemming from various factors. Firstly, the intensification of maize cultivation and the adoption of reduced tillage practices have contributed to an increased frequency of FHB epidemics over the past few decades. Secondly, the visible symptoms of FHB on wheat spikes appear at a later stage of pathogenicity, making it impractical to apply fungicides at this point as the kernels have already been contaminated by *Fusarium* mycotoxins. To minimize the likelihood of an outbreak of FHB, it is necessary to implement measures that target three key areas: (a) reducing the amount of available inoculum for dispersal, (b) preventing the spread of inoculum, and (c) averting spikelet infections in the presence of inoculum. Various control strategies can be employed to accomplish these goals, including the implementation of cultural control practices, cultivation of resistant cultivars, and the application of fungicides or biological antagonists. Moreover, the conventional approach to disease control using fungicides entails several disadvantages. These include high costs, potential negative impacts on biodiversity and the environment, relatively short effectiveness due to the development of fungicide resistance, and limited accessibility for small-scale farmers. These factors collectively make the management of FHB a challenging task.

CULTURAL MANAGEMENT

Traditional disease control methods relying on fungicides come with a set of drawbacks. These drawbacks encompass high expenses, potential negative effects on biodiversity and the environment, limited efficacy due to the emergence of fungicide resistance, and restricted accessibility for small-scale farmers. These factors collectively contribute to the complexities associated with managing FHB. To address these challenges, tillage practices can be employed to bury crop residues and facilitate their decomposition. Additionally, the application of fertilizers or the use of green manures can enhance residue breakdown and reduce the population of *Fusarium* by promoting microbial competition. Other approaches, such as removing residues from the field (e.g., baling straw) or destroying them on-site (e.g., burning), can also aid in reducing inoculum levels. Cultural

control techniques are most effective when integrated with disease forecasting models. This integration allows for the assessment of the potential benefits for future crops while considering the costs associated with implementing control measures. Additional strategies with moderate or limited effectiveness in managing FHB of wheat include the following practices: disease forecasting, early planting, the cultivation of early maturing cultivars, utilizing cultivars with agronomic traits that discourage FHB infection, weed control, effective irrigation management, and optimizing crop nutrition.

CHEMICAL CONTROL

Numerous fungicides have been extensively evaluated worldwide to assess their effectiveness in mitigating FHB of wheat. Paul *et al*. (2018) conducted a study where the application of DMI fungicides on wheat anthers during the Feekes 10.5.1 growth stage proved to be the most successful in reducing FHB index and DON levels. Salgado *et al*. (2014) and Palazzini *et al*. (2007) reported successful reductions in FHB severity, DON concentrations, and subsequent yield and quality losses through the timely use of triazole-based fungicides. Cromey *et al*. (2001) observed a reduction of up to 90% in FHB incidence and a 14% increase in yield through the application of tebuconazole on FHB-infected wheat plants. Additionally, meta-analyses of fungicide trials in the USA revealed that metconazole, prothioconazole + tebuconazole, and prothioconazole were the top three fungicide treatments resulting in the greatest yield and test weight improvements. However, certain fungicides used to combat FHB have been found to indirectly elevate DON concentrations in grains. This is particularly true for fungicides belonging to the quinone inhibitor (QoI) class. The timing of fungicide application is critical, as fungicides are most effective when applied within a week of early anthesis. However, achieving optimal timing can be challenging due to uneven flowering among tillers across fields and unpredictable weather conditions. Moreover, the erratic nature of FHB epidemics can reduce fungicide efficacy. Although certain fungicides have demonstrated successful FHB and DON reduction, no fungicide has been reported to completely eradicate the disease in infected crops, and even the most effective fungicides have limitations. Therefore, fungicides are most effective when used in combination with other control strategies, such as cultural methods.

BIOCONTROL

Fungicides are not the optimal solution for managing pathogenic fungi. Field trials of fungicides frequently yield inconsistent results, and there is a need for more effective control methods that have a lesser environmental impact compared to chemical agents. An attractive approach is to integrate microbiome methodologies into modern global breeding programs. Currently, there is growing recognition of the significance of interactions between plant pathogens and the plant microbiome, particularly focusing on pathogenic and mycotoxigenic *Fusarium* species. In the context of microbiome research, there is a rising interest in employing biological control as a means to combat plant pathogens.

Throughout the years, various biocontrol agents (BCAs) have been investigated, including bacterial BCAs like *Bacillus* sp., *Pseudomonas* sp., and *Actinobacter* sp., as well as fungal BCAs such as *Trichoderma* spp., *Clonostachys rosea*, and *Sphaerodes mycoparasitica*. These studies have unveiled the immense potential of BCAs in mitigating the impact of Fusarium head blight (FHB). However, there is a limited availability of commercially viable BCA products that can be utilized in conjunction with existing FHB management strategies. Among the BCAs explored in the past two decades, *Trichoderma* spp. and *Gliocadium roseum* have been the most extensively researched for their application in FHB treatment on a global scale.

FUNGAL ANTAGONIST

The application of fungal biological control agents to combat plant pathogens has seen significant potential growth due to several factors. Fungi exhibit a high reproductive rate, both sexually and asexually, along with a short generation time. They also possess target-specific properties, enhancing their effectiveness. Additionally, fungi

have the ability to survive in the environment even in the absence of a host, transitioning from parasitism to saprotrophism and ensuring long-term sustainability. Many fungal species have developed mechanisms that enable them to effectively protect plants from diseases caused by pathogenic fungi.

Luongo *et al*. (2005) conducted bioassay on 135 candidate antagonists, which included *Chaetomium globosum*, *Acremonium strictum*, *Aspergillus repens*, *Aureobasidium pullulans*, *Botrytis cinerea*, *Cladosporium cladosporioides*, *C. herbarum*, *Clonostachys rosea*, *Clonostachys rosea*, *Cryptococcus albidus*, *C. laurentii*, *Epicoccum nigrum*, *Fusarium aquaeductuum*, *F. equiseti*, *F. flocciferum*, *F. oxysporum*, *F. poae*, *F. sambucinum* , *F. solani*, *Gliocladium nigrovirens*, *Idriella bolleyi*, *Penicillium brevicompactum*, *P. commune*, *P. echinulatum*, *P. waksmanii*, *Scopulariopsis brevicaulis*, *Sporobolomyces* sp., *Trichoderma aureoviride*, *T. harzianum*, *T. koningii*, *T. polysporum*, *T. pseudokoningii*, *T. strictipilis*, *T. viride*, *Trichothecium roseum*, and *Ulocladium atrum* against 2 pathogenic *Fusarium* species (*F. culmorum* and *F. graminearum*) infecting *Fusarium* head blight. The outcomes of bio-assays conducted in controlled environments showed variability among different *Fusarium* species and host substrates when tested with various antagonists, including yeasts, *Trichoderma* spp., and non-pathogenic *Fusarium* spp. However, Clonostachys rosea isolates consistently exhibited the ability to suppress sporulation of *F. culmorum* and *F. graminearum* on wheat straw.

Saharan *et al*. (2007) conducted a study on the efficacy of different isolates of biocontrol agents in inhibiting the mycelial growth of *F. graminearum* and *F. semitectum* using a dual culture method to see the inhibition of mycelial growth. The biocontrol agents used in the study were *Gliocladium virens*, *T. harzianum*, *T. viride*, and *Pseudomonas fluorescens*. All the biocontrol agents significantly reduced the mycelial growth of *F. graminearum* collected from Wellington, Tamil Nadu. Maximum inhibition of mycelial growth was observed in the W18 isolate of *F. graminearum* with *T. viride*-M and in DBN3 isolate of *F. semitectum* with *T. viride* 5-2. And also, disease severity was reduced by seed treatment with *P. fluorescens* (Biomonas), *T. viride* (Bioderma), *T. viride* 5-2, and *T. harzianum*. He *et al*. (2009) conducted an experiment to identify the biocontrol agents that can both control the FHB and deoxynivalenol (DON) production. The microorganisms were evaluated using five different assays, including co-culture and dual-culture assays, an indirect impedance assay, a wheat floret assay, and two assays specifically assessing deoxynivalenol (DON) production. Among them, *Paenibacillus polymyxa* W1-14-3 and C1-8-b exhibited the most significant inhibition of F. graminearum and reduction in DON production in greenhouse experiments. In comparison to a control treatment, these microorganisms reduced disease severity by 56.5% and 55.4%, *F. graminearum* colonization of wheat heads by 58.8% and 62.4%, DON production by 84.8% and 89.4%, and increased the weight of 100 kernels by 56.6% and 66.9%, respectively.

Panwar *et al*. (2014) evaluated bioefficacy of biocontrol agents *T. harzianum* isolated Th-M and Th-P and *T. viride* isolate Tv against *F. graminearum in vitro* and under greenhouse conditions for their efficacy of foliar spray. Biocontrol agents were tested against 7 isolates of *F. graminearum* and found *T. harzianum* (M) to be an effective agent in reducing the radial growth of all *F. graminearum* isolates, followed by *T. viride*. Foliar application of *T. harzianum* (M) and *T. viride* alone and in combination significantly reduced the disease severity as compared to control. Maximum reduction in disease severity was achieved with combined application of *T. harzianum* and *T. viride*. Rojas *et al*. (2020) showed that healthy wheat spikes and leaves collected in areas with high FHB incidence harbor fungal isolates that reduce disease severity and pathogen biomass inside the spikes. They conducted an in-planta screening method using detached spikelets to observe the performance of 15 fungal strains against *Fusarium* infection. The results were validated in greenhouse spike inoculation assays. Isolates *Sarocladium strictum* C113L, *Anthracocystis floculossa* P1P1, *A. floculossa* F63P and *Penicillium olsonii* ML37 were identified as potential biocontrol agents of FHB in wheat.

BACTERIAL ANTAGONIST

Numerous bacterial genera, such as *Agrobacterium*, *Alcaligenes*, *Arthrobacter*, *Bacillus*, *Enterobacter*, *Erwinia*, *Pseudomonas*, *Rhizobium*, *Serratia*, *Stenotrophomonas*, *Streptomyces*, and *Xanthomonas*, have been identified as having the ability to protect plants against fungal and bacterial pathogens. These bacteria employ diverse mechanisms that contribute to limiting the development of plant pathogens. These mechanisms include colonization of infection sites and competitive exclusion of the pathogen, antagonistic activity through the secretion of potent antimicrobials like antibiotics or cell wall lytic enzymes, and the induction of plant resistance.

Palazzini *et al*. (2007) conducted an experiment in which a total of 354 bacterial strains were screened using a two-step selection process, considering environmental parameters such as temperature and water activity in the interaction between the pathogen and antagonist. Among the tested strains, 22 strains (6%) exhibited the ability to inhibit the growth of *F. graminearum*. These 22 selected strains demonstrated a reduction in the production of deoxynivalenol (DON) by 60-100% on irradiated wheat grains. The greenhouse evaluation of these strains' effectiveness in controlling Fusarium head blight (FHB) and DON production revealed that nine strains (40.9%) significantly reduced disease severity by 49-71% ($P < 0.05$). Furthermore, the DON content in spikes produced by plants in the greenhouse trial was significantly decreased by 32-100% compared to the control. Five strains even lowered mycotoxin content to undetectable levels. Based on this study, two strains, *Brevibacillus sp*. BRC263 and *Streptomyces sp*. BRC87B, were identified for potential combination testing in the control of FHB.

Chan *et al*. (2009) reported a substance produced by *Bacillus subtilis* D1/2, a bacterium isolated from cultivated soil, which was found to inhibit *F. graminearum*. The antifungal activity of the bacterium was primarily due to specific extracellular lipopeptides known as fengycins, which were identified and isolated. The addition of casamino acids to the culture medium enhanced the synthesis of these lipopeptides. Furthermore, when wheat spikes were treated with these substances, it was observed that the progression of Fusarium head blight was slowed down.

In a test conducted by Khan and Doohan (2009) to identify potential disease control agents, *Pseudomonas fluorescens* strains MKB 158 and MKB 249, as well as *Pseudomonas frederiksbergensis* strain 202, demonstrated significant reductions in both the severity of Fusarium head blight (FHB) symptoms caused by *F. culmorum* on wheat and barley and the associated decrease in 1000-grain weight. Khan and Doohan (2009) conducted a comparison between a biological control agent (*Pseudomonas fluorescens* strain MKB 158) and chitosan, a biochemical derived from crabshells, in their effectiveness against Fusarium head blight (FHB) disease in wheat and barley. Both the biological control agent and chitosan exhibited equal efficacy in reducing the contamination of grain by deoxynivalenol (DON), a mycotoxin produced by *F. culmorum*.

Tan *et al*. (2021) investigated the efficacy of chemical and biocontrol agents against *F. graminearum* in wheat ears. Thus, one fungicide comprising prothioconazole + spiroxamine and two bacterial biocontrol strains, *Streptomyces rimosus* LMG 19352 and *Rhodococcus* sp. R-43120 were tested for their efficacy to reduce FHB symptoms and mycotoxin (deoxynivalenol, DON) production by *F. graminearum* in the presence or absence of *F. poae*. The fungicide and both actinobacterial strains were found to reduce FHB symptoms and concomitant DON levels in wheat ears inoculated with *F. graminearum*. The chemical- and biocontrol efficacy was significantly reduced when *F. poae* was co-inoculated with *F. graminearum*. This reduced efficiency was linked to a suppression of the plant's intrinsic defense system and increased levels of DON.

Followed by fungal and bacterial biocontrol agents studies have also been conducted on plant extract with significant impact on pathogen. One such significant study was conducted by Abbas *et al*. (2022) with methanolic extract of medicinal

plant *Zanthoxylum bungeanum* (M20 extract) as a new preventive management strategy against FHB of wheat. This M20 extract was mainly composed of four flavonoids: quercetin, epicatechin, kaempferol-3-O-rhamnoside, and hyperoside. The *in vitro* bioassay, which measured the percent inhibition of fungal growth, showed that co-inoculation of four *F. graminearum* strains with the M20 extract inhibited the fungal growth up to 48.5%. After biocontrol treatments, *F. graminearum* DNA level was reduced up to 85.5% compared to that of wheat heads, which received *F. graminearum* mixture only. Moreover, DON production was decreased in wheat heads by 73% after biocontrol treatment; meanwhile, in wheat heads inoculated with *F. graminearum* conidia, an average of 2.263 ± 0.8 mg/kg DON was detected.

RESISTANCE

Infection of FHB is impacted by the developmental stage of the wheat plant. The timing of flowering can influence susceptibility to *Fusarium* infection. Wheat's resistance to FHB can be categorized into two types: passive resistance and active resistance. Passive resistance is characterized by morphological and phenological features, while active resistance involves physiological attributes. Morphological and phenological features associated with passive resistance include plant height, wheat awns, narrow and short floral opening, and the duration of retained anthers. Tall plant height aids in keeping wheat spikes away from rain droplets splashed with the disease-causing agents, which are carried in the soil surface and crop residues. Wheat awns have the ability to trap the disease-causing agents, thereby increasing natural infection. Conversely, their absence reduces the chances of infection. A narrow and short floral opening minimizes the exposure of florets to the disease-causing agents, enhancing resistance. Retained anthers and pollen have the potential to trap the disease-causing agents and facilitate spore germination and fungal penetration.

No wheat cultivar released thus far has exhibited complete resistance or immunity to FHB. This is primarily due to the complexity of FHB resistance, which is a trait influenced by multiple genes and environmental factors. Evaluating FHB resistance requires significant resources and time, and results can be affected by environmental variations, necessitating repeated assessments across different environments. The use of molecular markers offers potential for identifying FHB resistance genes (QTL) in breeding populations. While several QTLs associated with FHB resistance have been identified, one notable QTL on 3BS has shown a significant impact on resistance.

It has also been discovered that the presence of additive interaction involving at least three minor genes that contribute to FHB resistance in Frontana wheat. It has been recommended the use of cotton webs as an effective method for inoculation to determine FHB resistance in wheat lines. Saharan *et al*. (2004) also confirmed the efficiency of the cotton web approach for assessing FHB resistance in wheat lines. Based on the studies on agronomic parameters such as plant height, awn character, high spikelet density, and delayed flowering date, their relationship with FHB resistance have been investigated. Different mechanisms have been identified and categorized into five types: Type I refers to resistance against primary infection, Type II relates to resistance against spread within the plant, Type III represents resistance against kernel infection, Type IV involves yield tolerance, and Type V denotes resistance against mycotoxin production. Subsequently, two additional types have been proposed: Type VI, which pertains to resistance against later blighting, and Type VII, which signifies resistance against blighting above the point of inoculation. These mechanisms contribute to FHB resistance in various wheat genotypes.

Most wheat cultivars currently grown in India are susceptible to FHB (Saharan, 2020). Control of the disease has been difficult, because of the complex nature of the host/pathogen/environment interaction. Resistance to the FHB pathogen had been observed both in soft (SWW) and hard (HWW) winter wheat germplasm native to the U.S. Cultivar Truman (SWW), a full-sib of the cultivar Bess, has also shown resistance to FHB. Cultivars, Freedom (SWW), Roane (SWW), T154 (HWW), Bess (SWW), Century (HWW),

Heyne (HWW), Lyman (HWW), Everest (HWW), Harry (HWW), Atlas66 (SWW), and Husker (HWW) have been reported for high disease resistance.

To incorporate resistance genes into Indian wheat cultivars, resistant lines such as Sumai 3 and Frontana were included in breeding programs involving cultivars DBW 16, PBW 502, PDW 274, and PDW 286 (Gupta *et al*., 2013). HSRBW-2 (durum wheat) and HSRDW-2 (bread wheat) were registered as resistant stocks (Kumar *et al*., 2018). Utilizing Sumai 3 and Frontana, the Indian Institute of Wheat and Barley Research in Karnal, Haryana, developed seven scab-resistant lines: HSRBW 1, HSRBW 3, HSRBW 4, HSRBW 5, HSRDW 1, HSRDW 3, and HSRDW 4 (Kumar *et al*., 2018). Additionally, after evaluating approximately 5000 genotypes, several Indian lines, including AKDW 2997-16, DBW 62, PBW 396, PDW 311, UAS 415, UP 2747, UP 2798, VL 926, VL 821, and WH 1021, were identified as moderately resistant. Kumar *et al*. (2021) conducted a study to evaluate the resistance of a collection of 164 wheat genotypes to *Fusarium* head blight (FHB). Only two genotypes, HI 1636 and HD 3377, exhibited a disease score of 2 or higher based on spikelet data recorded 21 days after inoculation, indicating moderate resistance.

CONCLUSION

Among the most serious biotic stresses to wheat production in India, foliar and head diseases of wheat *viz*., Fusarium head scab or head scab is likely to be affected most in near future by global climate change and changing tillage practices. As number of resistant sources are very limited for FHB in Indian genotypes so far screened and most of the varieties grown in India did not possess adequate level of resistance to these diseases. Thus there is dire need to explore more number of resistant sources from indigenous and exotic germplasm including wild relatives of wheat. Resistant sources identified should be incorporated in the released cultivars of wheat which are high yielding but have not adequate level of multiple resistance to these diseases.

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