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Review Article

Spot blotch: A journey from minor to major threat of wheat

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Abstract

In the recent times, the rapidly changing climate has transformed the host-pathogen-environment interactions considerably, leading to minor pathogens, such as *Bipolaris sorokiniana,* emerging as a major threat. *B. sorokiniana* attacks leaves, stem, sheath, root and grains of wheat which causes significant yield loss. However, lack of precise forecasting models, limited resistant cultivars and inadequate knowledge of new technologies for disease management serves as limitations in the proper management of the disease. In this article, we discuss the pathogen biology, its host range, host pathogen interactions, trend of severity, prevalence area, changing weather condition, newly reported resistant line/germplasm, gene and some other ecological sound approaches of the management.

Keyword: Cereals, disease resistance, management, taxonomy, Wheat.

1. Introduction

From time immemorial, cereals have been the most reliable source of energy and nutrition, making it the staple food of majority of people throughout the world. However, the cereals are prone to a multiple number of the pathogens, among which *Bipolaris sorokiniana* (Sacc.) Shoemaker (1959) [teleomorph, *Cochliobolus sativus* (S. Ito & Kurib.) Drechsler ex Dastur] is a notable one. It is known as a cereal pathogen as its host range mainly comprises of cereals and grasses that belong to Gramineae family, although infections on other agronomical crops and dicots have been reported (Gupta *et al*., 2018a; Acharya *et al*., 2011; Ghazvini, 2018)**.** The warmer parts of the continents are generally dominated by this pathogen, while the pathogen is most devastating in India in the wheat growing belts of Punjab, Uttar Pradesh, Bihar and West Bengal (Acharya *et al*., 2011). *Bipolaris sorokiniana* generally produces a wide array of symptoms, *viz*., leaf spot/blotch/blight, black point and common root rot in infected hosts (Kumar *et al*., 2019; Al-Sadi *et al*., 2021). Although a number of published works are available on the pathogen, a preview of the prevalence, disease severity, increasing losses, and recent changes in adaptability of the pathogen to warmer climatic conditions is the need of the hour.

This review aims at drawing attention of the researchers towards the growing significance of *Bipolaris sorokiniana* and identifying the recent as well as ecologically sound management practices. The review describes the latest taxonomy, significance, host range, symptomatology and epidemiology of the pathogen. The host–pathogen interactions and pathogen variability has been discussed briefly, to develop a deeper understanding of the pathogen. Finally, the effective management strategies have been summarised, which would aid in minimising the impact of the pathogen on its hosts.

1.1 Taxonomical position

Bipolaris sorokiniana (Sacc.) Shoemaker, 1959 has had a number of synonyms over the years. According to Shoemaker (1959), *Bipolaris* is merely the generic name for the species *Helminthosporium* having the characteristic fusoid, straight, or curved conidia featured with the bipolar germination. The pathogen that causes spot blotch was initially a part of the former genus *Helminthosporium*, but it was separated later (**Fig. 1**) (Kumar *et al.*, 2020).

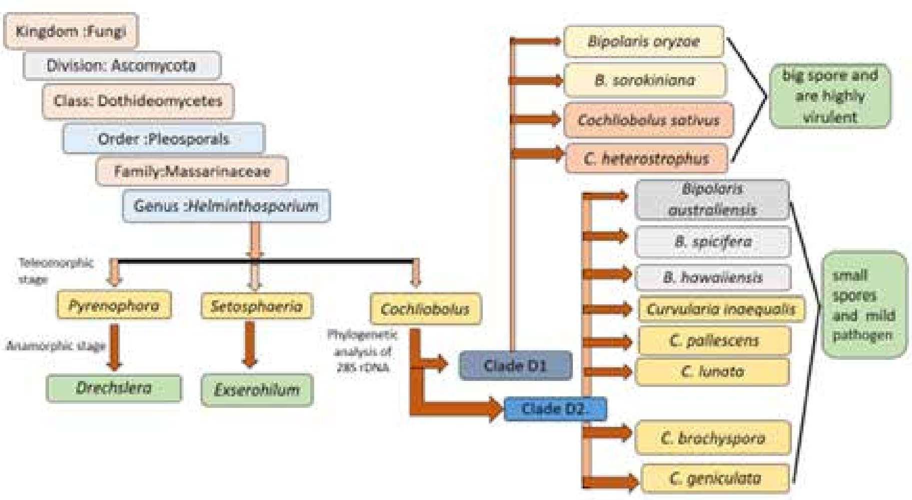

Fig. 1. Taxonomic position of *Bipolaris sorokiniana*

Through the analysis of gene sequences of rDNA internal transcribed spacer (ITS) region, Manamgoda *et al.* (2011) reported that *B. sorokiniana* and *C. sativus* represented the two stages of the same taxon. It was stated that anamorph and teleomorph of the same taxon can develop independently on different substrates or sometimes in different area. International Code of Botanical Nomenclature (ICBN) further supported this statement by mentioning that two separate binomials for two forms of the same pleomorphic fungus can be considered.

Kumar *et al.* (2020) also supported *B. sorokiniana* as the accepted nomenclature as *Cochliobolus* is prevalent in South Asia but dominated by *B. sorokiniana.* Moreover, the pathogen germination is bipolar, which makes *Bipolaris sorokiniana* as the preferable name as compared to *Cochliobolus*. The genus *Bipolaris* belongs to Division Ascomycota, Sub-Division Loculoascomycete, Class Dothideomycetes, Order Pleosporales and Family Pleosporaceae (Gupta *et al.*, 2018b). Some of the synonyms of *B. sorokiniana* that are reported and mentioned in various literatures have been described in (Table 1).

Table 1. Synonyms of *Bipolaris sorokiniana*

Synonym	Reference
Bipolaris californica (Mackie & G.E. Paxton)	Gornostaĭ [as 'californicum'], in Azbukina *et al.* (eds), Vodorosli, Gribyi Mkhi Dal'nego Vostoka (Vladivostok): 80 (1978).
Helminthosporium californicum	Mackie & G.E. Paxton, Phytopathology 13: 562 (1923)
Ophiobolus sativus	Ito & Kurib, Trans. Sapporo nat. Hist. Soc. 10: 138 (1929)
Drechslera sorokiniana (Sacc.)	Subram. & B.L. Jain,Curr. Sci. 35: 354 (1966)
Cochliobolus sativus (S. Ito & Kurib.)	Drechsler ex Dastur, Indian J Agr Res 12: 733 (1942)
Helminthosporium sativum	Pammel, C.M. King & Bakke, B. Iowa. State. Coll. 116: 180 (1910)
Helminthosporium acrothecioides	Lindf, Sevensk bot. Tidskr. 12: 562 (1918)
Helminthosporium sorokinianum	Sacc. in Sorok, Trans. Soc. Nat. Univ. Kazan 22: 15 (1890)

2. The yield loss associated with spot blotch of wheat

Bipolaris sorokiniana has devastating effect on the different wheat growing zones, especially in the areas with warmer temperature and high humidity (Table 2). Gupta *et al.* (2018a) also mentioned that the warmer temperature in the countries like Eastern India, Bangladesh, the Terai of Nepal, Latin America, China and Africa are most favourable for the occurrence of spot blotch disease and are responsible for huge yield loss. The same was reported by Chowdhury *et al.* (2013), who also added that the probability of the disease to flare up into an epidemic was probable in the near future. Also a relationship developed between disease severity and yield loss by Devi *et al.* (2018).

Table 2. Yield losses by *B. sorokiniana* in different regions of India in the last decade

Sl. No	Place	Crop	Yield loss in percentage/infected area in ha	Reference
1	India	Wheat	15.5%	Dubin and van Ginkel, 1991
2	Eastern Gangetic Plains	Wheat	18-22%	Singh *et al.*, 1997
3	Bihar	Wheat	7 to 30% and 3 to 23% loss in 1000-grain weight	Kumar and Rai, 2018
4	Eastern Gangetic Plains	Wheat	9 million hectares	CIMMYT, 2013
5	Warmer countries	Wheat	15-25%	Gupta *et al.*, 2018a
6	Trans-Himalayan Ladakh region of India	Barley	6% to 53%	Vaish *et al.*, 2011
7	Eastern Gangetic Plains	Wheat	10-50%	Chowdhury *et al.*, 2013
8	Eastern Gangetic plains	Wheat	More than 15%	Chowdhury *et al.*, 2021

3. Host range

Although wheat and barley (Pokharel *et al.*, 2021) are the most adversely affected, *Bipolaris sorokiniana* has been reported to infect a large number of crops. It has been reported in cereals, grasses, as well as dicots, which is enlisted in Table 3.

Table 3. Different hosts of *Bipolaris sorokiniana*

Host(s)	References
Wheat (*Triticum aestivum* L.)	Biswas and Das, 2018
29 crop species including *Avena sativa, Hordeum vulgare, Zea mays, Oryza sativa* and several grasses	Acharya *et al.*, 2011
Avena sativa, Hordeum vulgare, Zea mays, Oryza sativa, Linum usitatissimum and wild canary grass	Naresh *et al.*, 2015
Avena sativa, Hordeum vulgare, Brassica compestris, Glycine max, Lens culinaris, Vigna radiata, Sesamum indicum, Vigna mungo, Sorghum bicolor, Zea mays and *Pennisetum amaricanum*	Iftikhar *et al.*, 2009
Triticum aestivum, Hordeum vulgare, Avena sativa, Sorghum bicolour and a large number of other grasses	Bahadar *et al.*, 2016
Solanum lycopersicum, Abelmoschus esculentus, Zea mays convar. saccharata var. rugosa, Allium schoenoprasum, Musa acuminata, Solanum melongenae, Capsicum annum, Ipomoea batatas, Cenchrus purpureus, Spinacia oleracea, Eleusine indica.	Ismail *et al.*, 2020
Hordeum vulgare	Ghazvini 2012
Avena sativa, *Brassica campestris, Glycine max*, *Lens culinaris*, *Pennisetum amaricanum*, *Sorghum bicolour*, *Vigna radiate*, *Vigna mungo* and *Zea mays*	Yashwant *et al.*, 2017

4. Pathogen biology

The pathogen, *B. sorokiniana* was reported to exhibit differences in conidia and conidiophore on the basis of shape, size and septation by several researches. The mycelial growth as observed on PDA media is black-mat, black-fluffy, ash-mat, brownish ash-fluffy, blackish ash-mat, whitish ash-mat, greenish ash-fluffy and pinkish white-mat coloured growth depending on the isolates (Momtaz *et al.*, 2019). The size of the conidia ranges from 40–120 and 15–28 µm (Acharya *et al.,* 2011).

The best medium for the highest vegetative growth (7.4 cm) of *B. sorokiniana* was reported as supplementation of mustard leaf extract with PDA, whereas the highest sporulation (45×10^4 spores/ml) was obtained by the wheat leaf extracts with PDA (Nur *et al.*, 2019). However, sexual reproduction of *C. sativus* has been rarely reported (Sultana *et al.*, 2018b). *Cochliobolus sativus* (Previously known as *Ophiobolus sativus*) known as ascogenous state of the pathogen was first observed in the presence of opposite mating types on natural media under *in vitro* condition (Dastur, 1942). However, this perfect stage was reported from nowhere in natural condition except Zambia (Raemaekers, 1988).

5. Disease symptoms

Bipolaris sorokiniana produces more or less same kind of symptoms in its cereal host mainly on the wheat and barley. The three main symptoms that can be observed in case of *B. sorokiniana* attack are discussed in following sections:-

5.1 Spot blotch

The first visually identifiable symptoms are in the form of small lesions of 1-2 mm size which starts to grow on leaves (Acharya *et al.*, 2011). Brown coloured lesions appear, surrounded by yellow halos in the initial stages (Fig 2) (Gupta *et al.*, 2018a; Gupta *et al.*, 2018b). They gradually increase in size and cover the whole leaf area by coalescing together, resulting in leaf blight (Kumar *et al.*, 2020). After abundant conidia production on old lesions under humid conditions due to result of toxin production a chlorotic streak sometimes formed on the border of the leaves (Bockus *et al.*, 2010).

5.2 Seedling infection and common root rot

According to Al-Sadi and Deadman (2010) and Al-Sadi (2021) dark brown lesions are formed on coleoptiles, basal stem, crowns, sub-crown as well as on roots on infected plants. Under extreme conditions, the seedling may die immediately after emergence. Plant shows common root rot infection which results in fewer tillers and reduced grain production.

5.3 Black point

B. sorokiniana, when infects cereal seeds, exhibits brown to dark brown areas on basal end of the lemmas of infected grains, resulting in 'black point' or 'kernel blight'. Black point adversely affects the seed germination and seedling emergence (Al-Sadi 2021; Neupane *et al.*, 2010; Ghosh *et al.*, 2018; Li *et al.*, 2019b; Chakraborty *et al.,* 2021). Early and severe floral infection is the main cause of seedling death. Pathogen penetrates through the ovary wall and seed coat which leads to embryo abortion as well as shrivelled and fewer grains (Han *et al.*, 2010; Acharya *et al.*, 2011).

Fig 2. Symptoms produced by *Bipolaris sorokiniana* on infected wheat leaves; a) Initial infection in the form of small lesions; b) Lesions coalesce to give a blighted appearance

6. Variability of the pathogen

Variability is the inheritable difference in pathogenicity and other physiological abilities in a pathogen, which determine the extent of damage. For this reason, the genetic analysis of the existing pathogen population is used to understand the host-pathogen relationship, nature of virulence and the development of suitable management strategy.

Mann *et al.* (2014) isolated and tested 60 monosporic *B. sorokiniana* isolates from Brazil and other countries by using polymerase chain reaction (PCR) with universal rice primers (URP) for molecular characterization and identification of the variability among the pathogen. They observed a significant variation between isolates as well as phenotypic variations in terms of colony morphology. Mahto *et al.* (2012) broadly classified the 48 isolates of *C. sativus* into three groups i.e., white, light grey, and dark grey. They also observed that the isolates collected from the plains were more aggressive in nature than the isolates of hills, which indicated the dependence of host responses on the different agro climatic zone. Sultana (2018a) identified BS-24 as the highest spore producer and BS-33 having maximum PDI among the 169 isolates collected. According to the study conducted by Chauhan *et al.* (2017), it was concluded that among the 13 isolates collected from different part of the country, BS-2 isolates were capable of producing maximum lesions and highest necrotic area (8.5 mm²) in susceptible genotype, Sonalika whereas, BS-10 produced least number of lesions on the same susceptible genotype and BS-5 (1.0 mm²) produced the least necrotic area. This reflects the influence of pathogen variability on host responses under similar environmental conditions.

7. Host–pathogen interactions

Successful host pathogen interaction between the *B. sorokiniana* and the susceptible host can initiate the disease under favourable conditions (Fig 3). Acharya *et al.* (2011) mentioned *B. sorokiniana* to be an opportunistic hemi-biotrophic pathogen, which leads a biotrophic life prior to infection but can turn necrotrophic in the host body. Generally, the infection starts with the landing and germination of the spore, followed by germ tube production. The germ tube then modifies into appressorium which helps in the penetration of the infection peg (Acharya *et al.* 2011; Domiciano *et al.*, 2013). The duration of the onset of different event in pathogenesis has been studied by Sahu *et al.* (2016). They reported that the pathogen needs at least 48 hours from landing of the spore to conidia production. They also observed that initial spots occur on the leaf surface by 4 days post inoculation (DPI) and become severe by 7 DPI on the susceptible cultivar, Sonalika, at the average temperature of 18°C. After production of the conidia, it is generally dispersed into the air causing secondary infections (Acharya *et al.*, 2011).

This host pathogen interaction is fairly complex in nature. The cross talk of pathogenicity factors of the pathogen and the defence of the host to overcome these obstacles play a major part, and described in following sections.

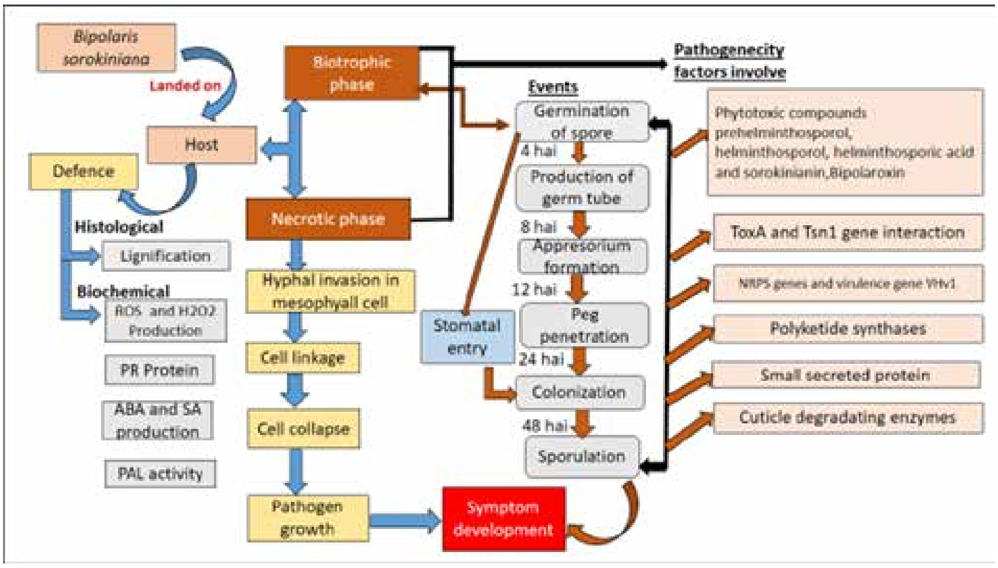

Fig. 3. Infection process of Bipolaris sorokiniana on susceptible host under favourable conditions

7.1 Pathogenicity factor

For increasing the chances of infection, the pathogen relies on different pathogenicity factors which impact the plant and aid in successful disease development. Wu *et al.* (2021) identified a fungal virulence factor ToxA, previously reported from Australia, USA, India and Mexico, which interact with the *Tsn1* in wheat plant and evoke a susceptible reaction in host. By analysing 196 Mexican isolates of *B. sorokiniana* using PCR technique, they identified 20 such isolates that are able to induce necrotic reaction on the Glenlea genotype which had *Tsn1* gene. *ToxA-Tsn1* system was referred by an example of inverse Gene-for-gene relationship by Navathe *et al.* (2020). According to them, among the 110 isolates of *B. sorokiniana* collected from India, 77 isolates had *ToxA* positivity and 81 wheat cultivars among 220 cultivars showed *Tsn1* gene presence. It was also revealed that seedlings having *Tsn1* gene showed necrotic spots with yellow halo against the *ToxA*-containing isolates of the pathogen. The same *ToxA*-Tsn1 reaction was reported by Friesen *et al.* (2018), thus the presence of the *Tsn1* sensitive gene helps in successful disease development by ToxA positive isolates.

Among the different phytotoxic compounds that act as important pathogenicity factor, prehelminthosporol ($C_{15}H_{22}O_2$) is found to be the most active and abundant phytotoxin formed by the *Bipolaris sorokiniana.* According to Liljeroth (1998) a concentration of Helminthosporium of 30 µg ml^{-1} or higher quantity can significantly increase the rate of nuclear disintegration in the cells and can cause the leakage of ATP. They mentioned that filtered solution of the fungus can inhibit seedling growth (21 – 73%) by direct cell damage or the parasitism of the barley roots, thus causing double trouble.

Jahani *et al.* (2014) reported bipolaroxin, a sesquiterpene toxin belonging to family Eremophilane isolated from *B. sorokiniana*, to be responsible for producing symptoms on wheat, barley, sorghum, maize, oats, *Phalaris minor*, and *Cynodon dactylon* even at low concentration of 30ng ml^{-1}. They observed that the isolates with low toxin producing ability had lower virulence towards plant as compared to those with higher toxin production. This led to the conclusion that the toxin produced by pathogen and their interaction with the host makes a plant susceptible or resistant.

Non-Ribosomal Peptide Synthetases (NRPSs) produced by the pathogen helps in the biosynthesis of non-ribosomal peptide (NRPs) which act as a determinant of pathogenicity (Gupta *et al*., 2018b). They also mentioned the presence of 25 NRPS genes in the highly virulent isolate ND90Pr of *C. sativus* (anamorph *B. sorokiniana*). An association of NRPS with *VHv1* gene was also reported which is an important pathogenicity determinant. They further mentioned the presence of polyketide synthases (PKSs) in the virulent isolate ND90Pr (pathotype 2), which helps in the synthesis of polyketides, but the role of these polyketides in pathogenicity is not clear.

7.2 Host defence

During the course of penetration by the pathogen, different defence mechanisms are triggered in the host. Cell lignification, which is the primary line of defence, act as a physical barrier around *B. sorokiniana* in infected host (Tronchet *et al*., 2010). The biosynthesis of lignin is regulated by ROS signalling molecules and mediated by the formation of glycosylated monolignols from L-phenylalanine, a derivative of shikimate biosynthetic pathway in the plastid (Denness *et al*., 2011; Jacobo-Velázquez *et al*., 2015; Marschall and Tudzynski, 2016). Poudel *et al.* (2019) pointed that H_2O_2 production was higher in the resistant genotypes than susceptible ones. They also reported that H_2O_2 associated lignin production significantly reduced the number of appressoria and penetration pegs formation, which led to disease resistance. Yusuf *et al.* (2016) and Eisa *et al.* (2013) came to similar conclusions when studying the association between H_2O_2 and lignification in determining the lesion area in infected plants. Janni *et al.* (2013) however reported a different defence mechanism whereby polygalacturonase-Inhibiting Protein (PGIP) produced by the host inhibits the EndoPolygalacturonase (EPG) produced by *B. sorokiniana*. This acts as an elicitor and strengthens the host cell wall.

The wheat genes *TaPIEP1, RD22, TLP4* and *PR1a* have reportedly been responsible for encoding pathogen-induced ethylene responsive factor which helps in activating plant defenses against the pathogen. These genes are linked to abscisic acid (ABA) and salicylic acid (SA), which plays a crucial role in signal mediated plant defence (Dong *et al*., 2010; Zhang *et al*., 2012). Pathogenesis mediated SA accumulation in resistant plant regulate the production of a wide range of phenols and other secondary metabolites which inhibit the growth of the *B. sorokiniana* (Eisa *et al*., 2013).

Chorismate, which is also a derivative of Shikimate pathway, initiates the synthesis of pathogen-induced SA that helps in the defence of plant mainly in the biotrophic phase, whereas JA-and ET-signalling pathways control the resistance against the necrotrophic phase (Dempsey *et al*., 2011). On the other hand, expression of PAL1 and PAL2 increased in 12–24 hpi and 12 and 48 hpi respectively in Yangmai 6 variety of wheat.

8. Epidemiology

The study of epidemiology is a pre-requisite for developing an understanding of the disease severity as well as formulating disease management strategies. Sultana (2018a) indicated that the adoption of warmer temperatures by the *B. sorokiniana* in the South Asia during 20^{th} century has resulted in the development of highly virulent isolates in high ganges river flood plain agro-climatic zones. Only few regional forecasting models are developed so far (Devi *et al*., 2012; Viani *et al*., 2017; Devi *et al*., 2017; Tamang *et al*., 2021). Studies on the relationship between disease development and related weather condition are enlisted in Table 4.

Table 4. List of epidemiological conditions for disease development

Epidemiological conditions	Reference
The optimum temperature for growth and sporulation was at 28°C	Naresh *et al.*, 2015
High relative humidity favourable for infection and pathogen growth	Acharya *et al.*, 2011
B. sorokiniana survive in moderate to warm temperatures (18°C to 32°C).	Kumar *et al.*, 2020
Higher humidity (especially above 90%), rain and relatively lower temperatures (< 30°C) after heading increase the severity of black point disease	Li *et al.*, 2019a; Li *et al.*, 2019b
20°C to 30°C, high humidity (90-100%) and long periods of leaf wetness (more than 12 to 18 hours) are favourable for disease development	Patsa *et al.*, 2020
30°C, 15°C and 25°C were ideal for maximum conidial germination (92.04%), Maximum length of unipolar germ tube (26.28 µm) and maximum width of unipolar germinated germ tube (4.49 µm) formation respectively.	Patsa *et al.*, 2018.
Colony growth was slower in dark condition and colonies were dark black at 25 °C. In light condition, whitish fluffy colony, round mycelial growth formed and the rate of growth was also higher.	Bashyal *et al.*, 2010

9. Management of the disease

For the successful management of the disease, an integrated approach is always the most preferred one because it increases the chances of disease control, helps in managing the loss below economic threshold level and minimizes the environmental pollution caused by excessive protective and eradicant chemicals. As *B. sorokiniana* has emerged as a major pathogen in the recent years, new and reliable technologies are also being developed for its management (Kumar *et al.*, 2021; Chakraborty *et al.*, 2021).

9.1 Induced host resistance

In terms of disease management, prevention is always better than cure. So, the scientists have shifted their focus in making the plant resistant against the disease, prior to attack by the pathogen. Plant resistance can be triggered externally by combined application of methyl jasmonate (150 mg L^{-1}) and *Trichoderma harzianum* strain UBSTH-501. This not only increases the indole acetic acid (IAA) in the rhizosphere, but also enhances the activities of defense related enzymes *viz*., catalase, ascorbate peroxidase, phenylalanine ammonia lyase and peroxidase against *B. sorokiniana* (Singh *et al.*, 2019).

Salicylic acid signalling enhances the expression of phenylpropanoid pathway regulating genes which leads to phenol accumulation and helps in inducing resistance against spot blotch (Sahu *et al.*, 2016). Sharma *et al.* (2018) showed that salicylic acid and syringic acid helps in induced resistance of the host plant against the pathogen. External application of sillicon decreases the number of necrotic cells which thus reduces the spot blotch symptoms. Devi *et al.* (2019) studied the role of different inducer chemicals in management of spot blotch of wheat. They observed that $CuSO_4$ (10^{-4} M and 10^{-5} M) and salicyclic acid (10^{-4} M) significantly reduced disease incidence as well as increased grain yield in treated plants.

9.2 Resistance by breeding

Breeding of the plant for the development of resistant variety is an age-old technique of disease management. Along with the conventional breeding methods, the identification of resistance gene and their incorporation in the desired germplasm using molecular approaches is gaining popularity.

Sajjid *et al.* (2015) screened sixty wheat advanced lines/varieties from Punjab and Pakistan, out of which 12 lines, namely, 8C006, 8C007, 9C033; 9C035, 9C036, 7C002; 088186, 088195; 076395, 076309, V 07142 and V 05068 were identified as tolerant against *B. sorokiniana.* Singh *et al.* (2017) identified one genotype KARAWANI/4NIF3/SOTY/NAD63/CHRIS as immune, while 31 genotypes were resistant, 75 were moderately resistant, 52 were moderately susceptible and 17 were susceptible to *B. sorokiniana.* Deepsikha *et al.* (2017) reported HD2888, HS375, PDW291, VL804, VL829, WH1021 and WH1105 to be highly resistant to spot blotch.

Kumari *et al.* (2018) reported seven varieties of wheat (IC564121, IC529684, IC443669, IC443652, IC529962, IC548325 and EC178071-331) to be highly resistant to *Bipolaris sorokiniana*, which could be used for identification of novel resistance gene. Singh *et al.* (2018) studied sixty-two wheat genotypes, and reported 8 genotypes (HD-2967, HD-3043, HP-1102, HS-277, JAUW-598, PBW-660, PBW-692 and VL-907) to be resistant, 24 were moderately resistant while others were reported as moderately susceptible and susceptible against *B. sorokiniana*. Mahapatra *et al.* (2020a) studied the performance of 117 wheat genotypes in different zones of the country. They reported that PBW 665 from North-eastern plain zone, HI 8726(d), GW 1280(d), HI 1500, HI 8730 and MP 1259 from Central zone, Raj 4240, C 306 and K 8027 from North-Eastern Plain Zone, and NIDW 295, AKAW 4731, MACS 6222, HI 8728 and HI 8725 from peninsular zone could be used for zone specific research breeding programmes against *Bipolaris sorokiniana.* F_2 and backcross generation of resistant varieties like Chirya-3, Mayoor, Shanghai-4, Suzhoe 128-OY, Suzhoe 1-58, Longmai and Chuanmai 18 were developed by crossing them with two susceptible varieties Sonalika and HD-2329. It was revealed that Chirya-3 and Mayoor is governed by two dominant genes (Khan *et al.*, 2010). Ghazvini (2014) identified four putative loci on chromosomes 1H, 3H, 5H, and 7H which were associated with highly resistant spot blotch lines TR 251. In a recent study, Zhang *et al.* (2020) made a genetic linkage map of a spot blotch resistance gene namely, Sb4 and pointed its delimitation in a 7.14-cM genetic region on 4BL between markers B6811 and B6901 in linkage map by the crossing between GY17' and 'Zhongyu1211.

9.3 Biological control

Biological control of the pathogen is a common phenomenon in nature and is generally mediated by four types of mode of action i.e., direct parasitism, competition for food, direct effect by producing toxic or antimicrobial compound and indirect toxic effect by producing volatile compounds. Some of the effective biological control agents and their mode of action against *B. sorokiniana* are enlisted in Table 5.

Table 5. Biocontrol agents and their mode of action against *B. sorokiniana*

Bio control agent	**Mode of Action**	**Reference**
Bacillus amyloliquefaciens, B. megaterium, Trichoderma harzianum, and *Epicoccum sp.*	Antagonistic effect	El-Gremi *et al*., 2017; Mahapatra *et al*., 2020
B. vallismortis	Antifungal compound	Kaur *et al*., 2015; Kaur *et al*., 2017
Bacillus subtilis TE3 strain	Colonizing the wheat phyllosphere and the antimicrobial compounds production	Villa-Rodríguez *et al*., 2019
B. safensis and *Ochrobactrum pseudogrignonense*	Promotes defense enzymes such as chitinase, β-1,3 glucanase, Phenylalanine Ammonia Lyase and peroxidase	Sarkar *et al*., 2018
Nocardiopsis dassonvillei	Produce siderophores and hydrogen cyanide, enhances growth of wheat through the production of Indole-3-Acetic Acid.	Allali *et al*., 2019
Lysobacter enzymogenes C3 and *Rhizoctonia solani BNR*-8-2	Production of chitinases, β-1,3-glucanases and antibiotics	Eken and Yuen, 2014
Chaetomium globosum	Production of secondary metabolites Chaetoviridin A, which inhibits the growth of *B. sorokiniana.*	Yue *et al*., 2018
Chaetomium globosum	Direct antagonism and induced systemic resistance by acting as Plant Growth-Promoting Fungus (PGPF)	Moya *et al*., 2016; Aggarwal, 2011
Mycorrhiza *Glomus fasciculatum*, *Pseudomonas fluorescens* sh4	Singly or in combination, reduces the pathogen growth by direct antagonism or host growth promotion	Hashemi *et al*., 2013

9.4 Use of botanicals

For reducing the dependency on environmentally harmful fungicides, the scope of botanical extracts as alternatives has been studied. Botanicals are not only effective against the pathogen, but are also devoid of any negative impact on environment and ecology. Some of the efficient botanicals have been identified for controlling the *B. sorokiniana* attack. Naz *et al.* (2018) reported that aqueous and methanolic leaf extracts (1.2% w/v) of *Jacaranda mimosifolia* resulted in 96 to 97% inhibition against *B. sorokiniana*. In a study conducted with clove oil, ginger oil, eucalyptus oil, til oil and neem oil by Debsharma *et al.*, (2021), clove oil exhibited strongest efficacy (55.27%) @3000 ppm concentration, although all the botanicals inhibited the pathogen. The efficacy of garlic clove extract was reported by Magar *et al.* (2020) and Hasan *et al.* (2012) to be 52.85% and 67.50% respectively, against *B. sorokiniana*. Prashanth *et al.* (2017) obtained 100% inhibition in spore germination with garlic clove extract. Bahadar *et al.* (2016) reported 97% fungal growth inhibition with methanolic extract of flowering buds of *Eucalyptus camaldulensis.* Tiwari and Singh (2021) studied the efficacy of *Allium sativum, Allium cepa, Ginger Zingiber officinale, Eucalyptus globulus, Azadirachta indica* and *Nigella sativa* oil extract against *B. sorokiniana*. Eucalyptus leaf extract showed 78.82% (highest) @10% solution while others also showed the inhibition against the target pathogen.

9.5 Chemical management

Along with the different eco-friendly management practices some chemicals and molecules have been proved to be highly effective against *B. sorokiniana* infection on wheat and other host. Along with the traditional fungicides, some combinations of fungicides with plant extract and other bio control agents are also used, which are enlisted in Table 6.

Table 6. Chemicals with effective concentrations for maintaining *B. sorokiniana*

Chemical group	Chemical name	Effective dose	Remarks	Reference
Triazole	Propiconazole	1.5 mL/L	Increased spike yield 97.74 gm	Gupt *et al.*, 2020
		1ml/l	Spot blotch reduce upto 60.18%	Mahapatra and Das 2013; Patsa *et al.,* 2020
		0.1%	87.77 % mycelial growth inhibition isolated from barley	Kavita *et al.,* 2017
Inorganic copper compound	Copper oxychloride	400 ppm	Inhibited 83% growth of mycelium of the fungus after 10 days *in vitro* condition	Angdembe *et al.*, 2019
Inducers	Salicylic acid	300 ppm	Maximum mycelial growth inhibition of 70-80%	Adhikary *et al.*, 2016
		10^{-4} M	Total yield 39.17 q/ha which is 9.17 quintal more than untreated plot	Devi *et al.*, 2018
Inorganic copper compound	$CuSO_4$	10^{-4} M	Total yield 37.92 q/ha which is 7.92 q/ha more than untreated control	Devi *et al.*, 2019
Strobilurin + Triazole	Azoxystrobin and Tebuconazole	120 g/L +200 g/L	18% higher yields than the control	Pittner *et al.*, 2019

10. Conclusion and future aspects

History has proven that minor diseases transform into major threats with the passage of time. Disease outbreak is regulated by different factors like favourable weather condition, availability of susceptible host and increased pathogens virulence, *B. sorokiniana* being no exception. A number of effective and reliable disease control measures have been developed, but their proper integration is the need of the hour. If extensive research is performed on identifying other rapid management strategies for reducing the extent of the pathogen in the near future, then our effort for drawing attention of the researchers through this article would be fruitful.

Conflict of interest

The authors declare that they have no conflict of interest

Author contribution

All the authors are equally contributed for this review article. SM made the concept of the article, DD and SC wrote according to the concept.SM finally edited and correspond to the journal.

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