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Review Article

Barley diseases and their management: An Indian perspective

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Abstract

Barley is an important coarse cereal, cultivated in Rabi season, particularly in the states of Uttar Pradesh, Rajasthan, Madhya Pradesh, Bihar, Punjab, Haryana, Himachal Pradesh and Jammu & Kashmir. Currently, it covers an area of about 0.66 million hectares under rainfed and irrigated crop. Seventy per cent produce is used for cattle and poultry feed, 25% in industries for manufacturing malt and malt extracts and rest 5% for human consumption. The straw is also used for animal feed, bedding and to cover roofs of houses. Barley grains demand is increasing continuously because of its various uses and high nutritive value. Therefore, a substantial yield gains will be needed over the next several decades. A number of biotic and abiotic factors pose a challenge to increase production of barley. Barley diseases prominently rusts, net blotch, spot blotch, Septoria speckled leaf blotch, stripe disease, powdery mildew, barley yellow dwarf and molya disease are the major biotic constraints in enhancing the barley grain production. Other diseases like black point and smuts, are important from industrial point of view because these deteriorate the quality of malt and beer. This review seeks to provide an overview of different barley diseases and their management.

Keywords: Barley, blotches, diseases, plant pathogens, rusts, smuts

1. Introduction

Barley (*Hordeum vulgare* L. ssp. *vulgare*, 2n=14) is a member of family Poaceae. It is grown in Rabi season, particularly in the states of Uttar Pradesh, Rajasthan, Madhya Pradesh, Bihar, Punjab, Haryana, Himachal Pradesh and Jammu & Kashmir. Barley is considered fourth largest cereal crop in the world after maize, rice and wheat with a share of 7 % of global cereal production. In 2017-18, 1.77 million tonnes of barley was produced in India from 0.66 million ha land area with productivity of 2679 kg/ha (eands.dacnet.nic.in). It is also known as poor man's crop because of its low input requirement and better adaptability to drought, salinity, alkalinity and marginal lands (Verma *et al*., 2012). This cereal is adapted to dry areas characterized by erratic rain and poor soil fertility which are often described as low-input barley (LIB) production systems (Gyawali *et al*., 2018). Barley in India is mainly used as cattle and poultry feed followed by its utilization for malting and beverages. Only 5% of the total production is used for human consumption (Singh *et al*., 2016). In addition, it is also consumed as energy drinks like bournvita, horlicks, and biscuits, prepared from malt extract. In rural areas of India, barley grains are used for preparing sattu and missi roti especially in the tribal areas of hills and plains (Verma *et al*., 2012). Barley is categorized as hulled and hulless barley on the basis of grain type. In hulled barley the lemma and palea are fused to the pericarp whereas in hulless the chaff is easily separated from the grain (Manjunatha *et al*., 2007). Hulless barley is mainly preferred as food for human consumption. Because of its multifarious utilities, nutritive value and ever-increasing industrial demand, a substantial yield gains will be needed over the next several decades. But, a number of biotic and abiotic stresses pose a challenge to increase the production of barley. Like the other cereals, barley also encounter different plant pathogens and succumb to various diseases which result in significant yield reduction and poor grain quality. Mathre (1997) mentioned about 80 different diseases caused by infectious agents in his 'Compendium of Barley Diseases', however, of this number, mainly yellow and brown rusts, covered smut, powdery mildew, net-blotch, spot blotch, speckled leaf blotch, barley stripe, barley yellow dwarf and molya disease are economically important in Indian context (Table 1). Barley diseases like yellow rust, molya and foot/root rot were also prevalent and destructive at higher altitude in Ladakh region of India (Vaish *et al.*, 2011). Diseases occur when a susceptible host is exposed to a virulent pathogen under favourable environmental conditions and they may affect barley yields from 1 to 100% depending on the susceptibility of varieties, virulence level of pathogens, growth stage of crop

Table 1: List of barley diseases and their causal organism

Fungal diseases		Symbol of identified major *R-gene*
Anthracnose	*Colletotrichum cereale*	
Common root rot and seedling blight	*Cochliobolus sativus* (*Bipolaris sorokiniana*)	
Covered smut	*Ustilago hordei*	*Ruh*
Crown rust	*Puccinia coronata* f. sp. *hordei*	
Downy mildew (Crazy top)	*Sclerophthora rayssiae*	
Dwarf bunt	*Tilletia controversa*	
Ergot	*Claviceps purpurea*	
False loose smut	*Ustilago avenae* (*U. nigra*)	
Kernel blight (Black point)	*Alternaria* spp., *Cochliobolus sativus* *Fusarium* spp.	
Leaf (brown) rust	*Puccinia hordei*	*Rph*
Loose smut	*Ustilago tritici* (*U. nuda*)	*Run* (*un*)
Net Type Net Blotch (NTNB)	*Pyrenophora teres* f. *teres*	*Rpt*
Powdery mildew	*Blumeria graminis* f.sp. *hordei*	*Ml (Mla/MILa/Mlo/Reg)*
Pythium root rot	*Pythium arrhenomanes, Pythium graminicola, Pythium tardicrescens*	
Rhizoctonia root rot	*Rhizoctonia solani, R. oryzae*	
Scab (Fusarium Head Blight, FHB)	*Fusarium graminearum*	*fb*
Scald	*Rhynchosporium secalis*	*Rrs (Rh)*
Spot blotch	*Bipolaris sorokiniana* (*Drechslera sorokiniana*), *Cochliobolus sativus* (Teleomorph)	*Rcs*
Spot Type Net Blotch (STNB)	*Pyrenophora teres* f. *maculata*	
Stem (black) rust	*P. graminis* f. sp. *tritici* *Puccinia graminis* f. sp. *secalis*	*Rpg*
Stripe disease	*Drechslera* (*Pyrenophora*) *graminea*	*Rdg (Rhg)*
Septoria speckled leaf blotch (SSLB)	*Septoria passerinii*	*Rsp*
Take-all	*Gaeumannomyces graminis* var *tritici*	
Tan spot	*Pyrenophora tritici-repentis*	
Yellow (stripe) rust	*P. striiformis* f. sp. *hordei*	*Rps*
Bacterial diseases		
Bacterial stripe	*Pseudomonas syringae* pv. *striafaciens*	
Bacterial leaf blight	*Pseudomonas syringae* pv. *syringae*	
Basal glume rot	*Pseudomonas syringae* pv. *atrofaciens*	
Black chaff and bacterial streak	*Xanthomonas translucens* pv. *translucens*	
Nematode diseases		
Cereal root knot nematode (Barley root Knot nematode)	*Meloidogyne naasi, Meloidogyne chitwoodi*	
Molya disease	*Heterodera avenae, Heterodera filipjevi*	*Rha*
Root lesion nematode	*Pratylenchus* spp.	
Stunt nematode	*Merlinius brevidens, Tylenchorhynchus dubius*	
Viral diseases		
Barley mosaic	*Barley mosaic virus* (BMV)	
Barley stripe mosaic	*Barley stripe mosaic virus* (BSMV)	*Rsm* (*sm*)
Barley yellow dwarf	*Barley yellow dwarf virus* (BYDV)	*Ryd*
Barley yellow streak mosaic	*Barley yellow streak mosaic virus* (BYSMV)	
Phytoplasmal diseases		
Aster yellows	*Aster yellows phytoplasma*	

at the time of infection, favourable weather conditions and time of availability of inocula and nutrients. All diseases are not important in different agro-ecological zone of India. Stripe rust is a scourge to barley in cooler and humid areas *i.e.* North Western Plain Zone (NWPZ), whereas, leaf rust like warmer climate as in Central Zone (CZ). Powdery mildew and smuts are of importance in cooler and humid climate. Spot blotch, speckled leaf blotch and net blotch are important diseases in North Eastern Plain Zone (NEPZ) where warm and humid climate exists (Singh, 2017). In barley, the yield losses due to stripe disease were in the range of 20–70% during 1992–1993 (Kumar *et al.*, 1998). Net blotch is second biotic stress, which can lead to losses between 20 and 30%. The losses due to spot blotch and net blotch in barley in Haryana, India were 53% in case of susceptible cultivars (Singh, 2004). The purpose of this review is to provide a brief summary of some of the major diseases impacting barley in India. This updated overview highlights the general importance of the diseases, brief symptomatology, epidemiology, pathogen biology and disease management strategies.

2. The barley rusts

Rust fungi are obligate biotrophic organisms that are completely dependent on living host cells for their nutritional requirement and the most devastating pathogens of crop plants (Cummins and Hiratsuka, 2003; Duplessis *et al.*, 2011). These pathogens have evolved further to many distinct physiologic races or pathotypes. These pathotypes cannot be distinguished morphologically, however, can be determined by testing host response to infection on an established set of differentials carrying different resistance genes or their combinations (Prashar *et al.*, 2014). In addition, molecular marker based methods are also used to differentiate these physiologic forms. There are four barley rust diseases, namely stem, stripe, leaf and crown rust, all caused by members of the genus Puccinia, family Pucciniaceae, order Pucciniales, class Pucciniomycetes, subphylum Pucciniomycotina, Phylum Basidiomycota and kingdom Fungi (Bauer *et al.*, 2006).

Yellow (stripe) rust: Yellow rust of barley caused by *Puccinia striiformis* Westend. f. sp. *hordei* Eriks. & Henn. (Psh), is an important foliar disease of northern India. Yellow rust is a disease that has devastated barley for a long time in southern Asia, eastern Africa, Western Europe, and the Middle East. In 1975, a race of this disease that affects primarily barley was found for the first time in Bogota, Colombia (Dubin and Stubbs, 1986). Severe epidemics of the barley yellow rust have been reported in north-western and central European countries, India, Bangladesh, Nepal, China and Japan (Chen *et al.*, 1995). Since then, the pathogen has spread throughout world. In India, first pathotype that infecting to barley, was identified in 1939 from Nilgiri hills, Tamil Nadu and designated as 4S0 (G). In India, early incidence of yellow rust can cause very heavy losses in the crop and can sometimes prevent the ear head emergence or the grain formation/development (Prakash and Verma, 2009). Yellow rust is principally a disease of barley in cooler climates (2-15°C), where the leaves are wet for prolonged periods (8-10 hours) and provide optimum conditions for infection. The pustules contain yellow to orange-yellow uredospores and form narrow stripes on the leaves (Fig. 1a).

Fig. 1 Barley rust diseases a) Yellow rust b) Leaf rust c) Stem rust d) Crown rust

The stripes continue to enlarge as the fungus is partially systemic. It may also develop on leaf sheaths, necks, and glumes. In conducive conditions (temperature 10-15°C, intermittent rain or dew), pustules erupt within 8-14 days after infection and freshly released uredospores become airborne which facilitate secondary infection and faster disease development (Prashar *et al.*, 2015). Black telia readily develop from uredia as infected barley plants approach maturity. The uredial and telial spore stages of *P. striiformis* f. sp. *hordei* occur on barley and various *Hordeum* species (Marshall and Sutton, 1995). The pycnial and aecial spore stages of Psh are not documented so far. Volunteer plants, autumn-sown barley crops and wild *Hordeum* species can serve as inoculum reservoirs for barley yellow rust (Dubin and Stubbs, 1986; Marshall and Sutton, 1995).

Brown (leaf) rust: Brown rust caused by *Puccinia hordei* Otth., is a sporadic but most common disease of barley. Generally brown rust occurs in all the barley growing areas of India, but this pathogen seldom causes severe epidemics over a wide area. Still, significant yield losses can occur in susceptible cultivars when the inoculum arrives early and levels are high. Under experimental conditions, over 60% yield losses were reported in highly susceptible barley cultivars (Das *et al.*, 2007). The uredia of *P. hordei* are small orange brown pustules, which are scattered mainly on the upper leaf surface but also on the lower side of leaf blades and on leaf sheaths of barley (Fig. 1b). These pustules may be surrounded by chlorotic halos or green islands. In case of severe infection under high inoculum load, symptoms may also appear on stems, glumes, and awns can also be infected. Later in the season, particularly on leaf sheaths but also on stems, heads, and leaf blades, blackish-brown telia are formed usually in stripes and covered by the epidermis (Park *et al.*, 2015). The uredial and telial spore stages of leaf rust pathogen occur on barley and various wild *Hordeum* spp., and the pycnial and aecial spore stages have been reported on alternate hosts of the Liliaceae family, such as *Ornithogalum*, *Leopoldia*, and *Dipcadi* (Clifford, 1985). A temperature ranging from *20-25* and prolonged wet weather are pre-requisite for faster spread of the disease. Under such conditions, new uredia are generally formed within 7 to 10 days after infection and the cycle of spore production is repeated.

Stem (Black) rust: Barley stem rust caused by *Puccinia graminis* Pers. f. sp. *tritici* Eriks. & Henn. (Pgt) and *Puccinia graminis* Pers. f. sp. *secalis* Eriks. & Henn. (Pgs) is primarily a disease of the Central and Peninsular India. It often infects the crop late in the season and, therefore, the losses are minimal. The uredial pustules are much larger, reddish-brown, elongated and develop predominantly on the stem, leaf blade, sheath and occasionally on spike (Fig. 1c). One of the most characteristic features of stem rust that helps to separate it from the other two rusts is that the uredia tear the plant tissue, giving the affected stem and leaf a distinctly tattered appearance. Severe infections with many stem lesions may weaken plant stems and result in breaking of stem from the severe infection point. Late in the season, rust coloured pustules turn into black telia containing teliospores (Bhardwaj *et al.*, 2017). Optimal conditions for infection are a temperature range of 15-28°C and 6-8 hours of free moisture on the leaf surface. Disease spreads rapidly if wet weather persists and temperature remained in the range of 26-30°C. Several cycles of uredospore production occur during the growing season. The uredial and telial spore stages of this pathogen occur on the barley, wheat and other grass hosts. The pycnial and aecial spore stages occur on *Berberis* spp. (barberry) and *Mahonia* spp. which act as alternate hosts. The alternate host species of *Berberis* and *Mahonia* can provide a source of primary inoculum in the form of aeciospores, although this spore is generally disseminated over short distances (Roelfs *et al.*, 1992). In India, the functional alternate hosts (susceptible *Berberis* and *Mahonia* spp.) are absent, therefore, the source of primary inoculum has been remained the Nigiris hills, where it must be surviving on volunteer plants or summer crop in the form of uredospores or some other grasses/ plants in the catchment areas (Bhardwaj *et al.*, 2016). North Indian hills do not play any role in the epidemiology of barley black rust in India.

Crown rust: Barley crown rust caused by *Puccinia coronata* f. sp. *hordei* Jin & Steff. This disease was first observed on barley in the 1950s but the pathogen was not described as a new forma specialis (f. sp.) until 1991 when crown rust appeared in epidemic form in south central Nebraska, U.S.A. (Jin and Steffenson, 1999). Uredial pustules are linear, oblong, orange-yellow in colour and occur mostly on the leaf blades but occasionally occur also on leaf sheaths, peduncles and awns (Fig. 1d). Extensive chlorosis is generally associated with the uredia. Telial pustules are mostly linear, black to dark brown, and are covered by the host epidermis. The Barley crown rust has not been reported from India so far.

Pathotypes of barley rust pathogens: First pathotype of *Puccinia striiformis* f. sp. *hordei*, named G(4S0), was identified from Nilgiri hills in 1939. Subsequently, five other pathotypes viz. Q (5S0), 24 (0S0-1), 57 (0S0), M (1S0) and G-1 (4S0-3) were also described over the years (Nayar et al., 1997; Bhardwaj and Gangwar, 2012). New pathotypes 6S0 and 7S0 of *Puccinia striiformis* f. sp. *tritici*, which were characterized recently, also found virulent on barley genotypes and currently are being used for characterising rust resistance in barley (Gangwar *et al.*, 2016). Most of the Indian Psh pathotypes do infect some wheat cultivars/ accessions and similarly, few Pst pathotypes (70S0-2, 6S0 and 7S0) infect barley host. Chen *et al.* (1995), using random amplified polymorphic DNA (RAPD), demonstrated that the two formae speciales (Pst and Psh) are different but closely related to each other. Line (2002) also observed that some wheat cultivars were very susceptible to Psh and some barley cultivars were very susceptible to Pst. In case of *P. hordei*, five isolates designated as H1, H2, H3, H4 and H5, are being maintained and used for characterising rust resistance in barley. Efforts are going on to design a system for race identification for brown rust of barley. Since, barley and wheat stem rust is caused by the same pathogen (*Puccinia graminis* f. sp. *tritici*), therefore, the pathotypes are also similar. Predominant pathotypes of Puccinia graminis tritici occurring on barley are same as those occurring on wheat in India.

Characterization of rust resistance in barley: As the rust pathogens evolve to neutralize resistance, we must continue to explore the sources of resistance. Screening often must be done using virulent pathotypes identified in the pathogenicity survey. Each year, barley advance lines (NBDSN, EBDSN) are subjected to multi-pathotype testing. The selected /differentiating pathotypes of three barley rust pathogens are used.

The seedlings are grown in aluminum bread pans (29 cm long x 12 cm wide x 7 cm deep size) in a mixture of fine loam and farmyard manure (3:1) that had been sterilized by autoclaving (60^0C) for one hour. These trays are sufficiently large to accommodate 18 barley lines, including a susceptible check to respective rust. For each barley line, about 5-6 seeds are sown in hills. The seedlings are raised in spore-proof chambers (indoors) at 22 ± 2^0C, 50-70% relative humidity and 12-hour daylight. When the seedlings become one week old with fully expanded primary leaves, they are inoculated using a glass atomizer that contained 10 mg uredospores, suspended in 5 ml light grade mineral oil (Soltrol 170)® (Chevron Phillips Chemicals Asia Pvt. Ltd., Singapore). The oil is allowed to evaporate for 5 minutes. Plants are then sprayed with a fine mist of water and incubated overnight in dew chambers at 20 ± 2^0C for black and brown rust and at 16 ± 2^0C temperature for yellow rust. Saturated relative humidity and 12 hours daylight were maintained during the incubation. The plants are then transferred to a glasshouse and grown at 22 ± 2^0C with relative humidity of 40-60% and illuminated at about 15,000 lux for 12 hours for brown and black rusts, whereas, 16 ± 2^0C for yellow rust. Infection types on the test lines are recorded 16-18 days after inoculation (Nayar *et al.*, 1997). Infection types 0 to 2 (small hypersensitive flecks to small-moderate uredial pustules with chlorosis) are considered resistant and infection types of 3 to 3+ (moderate to large uredial pustules without chlorosis) as susceptible. Infection type 33+ classified where both 3 and 3+ pustules are found together. The experiment is repeated to confirm the reaction types.

3. The barley smuts

Loose smut: Loose smut of barley, like wheat, is caused by the fungus *Ustilago tritici* (Pers.) Rostr. {(*U. nuda* (Jens.) Rostr)}. However, the particular isolate of loose smut pathogen that attacks wheat, does not attack barley and vice-versa. Until ear (spike) emergence affected plants often do not exhibit symptoms. Affected ears usually emerge before healthy ones and all the grains are replaced with a mass of dark brown teliospores (Fig. 2a). The teliopores are initially loosely held by a thick membrane that soon breaks releasing the teliospores onto other ears (spikes). Infection occurs under moist conditions at temperatures around 16-22°C. The pathogen survives from one season to next as dormant mycelium within the embryo of barley seeds (internally seedborne). At germination of infected and untreated seeds, pathogen breaks dormancy and begins to grow systemically within the developing barley plant. All floral parts of plant are infected at ear emergence and replaced by massive smut spores (teliospores). Disease spread by wind-blown teliospores from smutted ear to adjacent healthy flowering ears of barley. The teliospores germinate and invade the female parts of barley flowers and eventually colonise the developing embryo. Once the infected seed matures, the pathogen goes dormant until the cycle is repeated with the germination of barley seed.

Fig. 2 Barley smut diseases a) Loose smut, b) covered smut

Covered smut: Covered smut of barley is caused by the fungus *Ustilago hordei* (Pers.) Lagerh. They are recognizable by their blackened ears that emerge from the leaf sheaths. All the ears in a diseased plant and all the grains in a diseased ear are infected. All the infected grains in a diseased ear are transformed into masses of teliospores which are held in place by persistent, tough, greyish-white membrane (Fig. 2b). The covered masses of teliopores are not released from their enclosing membranes until threshing time, unless the membrane is broken accidentally. When the infected ears are broken open during threshing, innumerable teliospores are released. Many of these lodge on healthy kernels and remain dormant until the seed is sown (Externally seedborne). Germination of teliospores take place readily in water or damp soil by the formation of a septate promycelium during which meiosis of the diploid nucleus takes place. A large number of sporidia (basidiospores) are produced which multiply by budding, germinate by germ tubes, or fuse with each other producing dikaryotic condition. As the barley seed begins to germinate the teliopores also germinate and infect the seedling along the epicotyl by dikaryotic infection hyphae. After the pathogen has entered the seedling, its hyphae continue to grow with the shoot and eventually replace the grains by masses of teliopores. A warm, moist, acid soil favours seedling infection. The greatest number of seedlings are infected at a soil temperature range of 10°C to 21°C. Because of routine use of seed treatments with effective fungicides, smut diseases of barley are not common in India. However, if untreated susceptible cultivars are grown in Northern parts of India, then, these diseases especially covered smut can cause considerable yield losses. Additionally, if carried through the malting process, smut spores can negatively affect the beer quality.

4. Foliar diseases of barley

Foliar diseases of barley are one of the main constraints to successful barley production. These diseases destroy green leaf area and thus restrict the barley plant's ability to set and fill grain. The main barley foliar diseases in India are Powdery mildew, netted and spotted forms of net blotches, spot blotch, speckled leaf blotch and stripe disease. Among these diseases, blotches are considered economically very important because of their air borne nature, ability to spread widely and to cause epidemic.

Powdery mildew: Powdery mildew, a common disease of barley, is caused by the fungus *Blumeria graminis* (DC.) Speer f. sp. *hordei* Marchal. The disease is most prevalent in early sown crops with good canopy cover. Symptoms are usually first observed at tillering stage but the disease does not normally persist beyond spike emergence. Losses are minimal in India, but can be as much as 25 percent in heavily infected crops. Both winter and spring barley crops can be affected by powdery mildew, resulting in losses typically ranging from 1% to 14%. Losses exceeding 14% can occur when disease onset is early and inoculum pressure is high. Apart from yield loss, powdery mildew infection can also reduce kernel weight, numbers of tillers and spikes, and root growth (Mathre, 1997). The powdery mildew fungus is a biotrophic pathogen and unique in that it can infect barley without the presence of free moisture. In general, the disease is favoured by cool (15°C -25°C) and humid weather but can also occur in warmer, semiarid environments. Germ tubes from both conidia and ascospores can penetrate the host cuticle directly. The most diagnostic features of the disease are the pathogen signs. They initially appear as fuzzy, whitish tufts of fungal mycelium. Later, powdery or fluffy white pustules of conidial chains develop from the mycelium (Fig. 3).

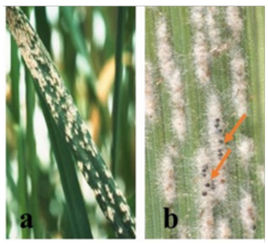

Fig. 3 Powdery mildew sign on leaf (a), Cleistothecia on leaf (b)

Mycelium and conidia may turn gray or even slightly brownish in color with age. Under severe epidemics, the entire spikes of plants can be infected with powdery mildew in addition to the leaves and leaf sheaths. Late in the growing season, the black, globose-shaped cleistothecia (the structure containing the sexual spores) of the fungus will form within the cottony masses of mycelium and conidia. The disease perpetuates on volunteers and grasses from one season to the next.

Net Blotch: Net blotch is an important and destructive foliar disease of barley. The disease occurs in two forms: net form of net blotch (NFNB) and spot form of net blotch (SFNB). The fungi *Pyrenophora teres* Drechs. f. *teres* Smedeg. and *Pyrenophora teres* Drechs. f. *maculata* Smedeg., cause the net (NFNB) and spot form (SFNB) of net blotch of barley, respectively. Generally, only one of the two forms of net blotch will predominate in a given area and this is due to the cultivars grown and also perhaps due to management practices and environment. SFNB develops as small circular or elliptical dark brown spots surrounded by a chlorotic zone of varying width (Fig. 4a).

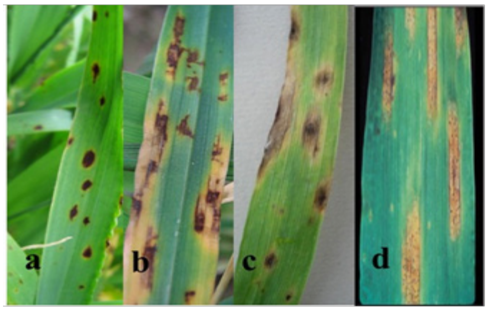

Fig. 4 Leaf blotch diseases- a) Spot Form Net Blotch b) Net Form Net Blotch c) Spot blotch d) Septoria speckled leaf blotch

The diameter of SFNB spots varies from 3mm to 6mm. The net form of net blotch (NFNB) begins as pinpoint brown lesions, later on, elongate and produce fine, dark brown streaks along and across the leaf blades, forming a distinctive net-like pattern (Fig. 4b). Older lesions often are surrounded by a yellow margin, and continue to elongate along leaf veins. The symptoms produced by both forms of net blotch can vary greatly depending on the isolate of the pathogen, genotype and growth stage of the host and environment (McLean *et al.* 2009). Net blotch has the potential to cause total loss in susceptible cultivars under conducive environmental conditions, but, in general, yield losses have been reported from 10-44% in infected barley crops (Steffenson *et al.*, 1991; Jayasena et al., 2007; Murray and Brennan, 2010). The fungus can overseason as mycelium and pseudothecia on host stubble and then produce conidia and/or ascospores that can infect the next season's crop. Moreover, infected volunteer plants of barley or wild *Hordeum* species may also serve as sources of primary inoculum for newly sown crops. Infection by pathogen is favoured by humid periods lasting 10 or more hours and temperatures in the range of 15–20°C. Conidia formed from the lesions on the infected leaves can serve as secondary inoculum and facilitate the spread of disease.

Spot blotch: Spot blotch, caused by *Bipolaris sorokiniana* (Sacc.) Shoemaker {(*Cochliobolus sativus* (Ito and Kuribayashi) Drechs. ex Dastur)} is important foliar disease of barley in India. The pathogen has been described as the most important fungal pathogen of barley (Arabi and Jawhar, 2004; Valjavec-Gratian and Steffenson, 1997). The pathogen has a wide host range and pathogenicity is variable in nature. It has many physiologic races that differ greatly in virulence and ability to attack specific cereals and grasses. Yield losses ranging from 10% to 30% are common in susceptible barley cultivars but can exceed the 30% level under highly favourable environments (Fetch and Steffenson, 1994). Spot blotch damage can reduce grain yield by 10% to 20% when the temperature is between 15 °C and 22 °C during the first two weeks after the appearance of full ears (Steffenson, 1997). The yield loss due to the disease is very significant under warm and humid environmental conditions especially in Uttar Pradesh, Bihar, Jharkhand, West Bengal, Assam and plains of North-Eastern states of India. Extended warm periods (> 16 h) of and moist weather are conducive to epiphytotic development. Incubation period for disease development is 3-6 days, depending on environmental conditions. Early and heavy infection on flag leaf result in the greatest losses in grain yield. Early symptoms are characterized by small, dark brown lesions ranging 1-2 mm long without chlorotic margin. The typical lesions are round to oblong, 2-5 x 15-20 mm restricted in width by leaf veins, dark brown and chlorotic at their margins (Fig. 4c). In susceptible genotypes, these lesions extend very quickly in oval to elongated blotches (2-20mm) that may coalesce into larger irregular patches. Heavily infected leaves dry out and die prematurely. The kernel blight phase (Black point) of this disease may develop if inoculum is available and the environmental conditions are conducive to infection. This fungus also produces toxins (mainly prehelminthosporol), which are capable of causing disease symptoms (Kumar *et al.*, 2002). The sexual state is rare in nature, however, pseudothecia can be produced artificially in the laboratory by inoculating boiled barley grains on mineral salt agar with a suspension of compatible mating types. Pseudothecia are black and globose and have erect beaks, asci are hyaline, 4-10 septate and spirally flexed within the ascus. The pathogen survives on the seeds, crop residue and other grass hosts. Initial leaf infections in the field result from airborne conidia produced either on wild grasses or on crop residue.

Septoria speckled leaf blotch (SSLB): This disease caused by the fungus *Septoria passerinii* Sacc., is an important disease of North Eastern Plains Zone. Yield losses of 23-38 per cent due to SSLB have been reported (Toubia-Rahme and Steffenson, 1999). The disease also affects test weight and kernel weight significantly. Symptoms vary depending upon the growth stage of barley. Lesions on leaves are initially mildly chlorotic, then become grey-green to straw coloured, elongated and often coalesce. On seedlings, lesions sometimes may not contain pycnidia. Necrotic blotches appear irregular and contain very small dot like dark brown pycnidia as the lesions become older (Fig. 4d). The masses of pycnidia on areas killed by the fungus are diagnostic character of the disease and pycnidia often develop in lines parallel to veins. At heading stage, light grey to white rectangular lesions delimited by veins are produced. On mature plants, large grey spots with many pycnidia develop on senescent leaves and sheaths. Pycnidia may develop on the awns but rarely occur on grain (Green and Dickson 1957). Lesions on the upper leaves and glumes significantly reduce photosynthetic activity of the plants as well as yield. The grains may become shrivelled and chaffy at harvest (Tekauz, 2003). Hosts of *Septoria passerinii* include a number of *Hordeum* spp. and wild grasses. Infected plants residue on soil surface or below ground play a pivotal role in over-seasoning of the pathogen. Inoculum is dispersed short distances by rain splash and infested straw which may move from one field to another by wind gusts. After crop maturity, new pycnidia developed between 15 and 30°C but only within existing lesions (Lutey and Fezer, 1960). More than 48 h of continuous moisture may be required for spore germination and leaf infection. Additionally, the incubation period for *Septoria passerinii* is 19 days or longer and therefore, disease is important only in years when favourable conditions persist for long periods. Seasonal rainfall at or above the normal along with low temperatures that lengthened the vegetative phase of growth is associated with severe disease during this period (Green and Dickson 1957).

Stripe disease: Stripe disease is caused by the fungus *Drechslera graminea* (Rabenh.) Shoemaker. The disease occurs only on barley. Unlike spot blotch and net blotch, the stripe disease produces a systemic infection that affects the whole plant. The first symptom of stripe disease is the appearance of small, pale lesions on seedling leaves. If severely infected seeds of a susceptible barley variety is sown, some of the seedlings may be killed by the stripe pathogen. The characteristic long, narrow and yellowish to straw coloured streaks or stripes appear on the leaves as they unfold. Parallel stripes, may extend the entire length of the blade. The light yellow streaks soon turn brown (Fig. 5).

Fig. 5 Barley stripe-initially yellow stripe, later on turn brown

The browning is usually followed by a drying-out and lengthwise splitting of the leaf blade. The streaks extend to the leaf sheath when the leaves are mature. Stripe-affected plants are severely stunted with few tillers and usually spike do not emerge or produce seed. The ears that do emerge are greyish brown, withered, twisted, often barren, and erect. Generally, all the leaves of a diseased plant are affected. Infected plants, shrivel and die prematurely. Large numbers of spores (conidia) of the stripe fungus are produced in the dark grey to olive grey stripes on dead barley leaves. These conidia are carried by air currents or splashing rain to the spikes of healthy barley plants at or soon after flowering. The conidia lodge near the tips of the glumes, germinate and produce mycelial growth in moist weather. The mycelium starts to grow between the hulls and the kernels and may penetrate the embryo. Infection can occur any time before the spike emergence at soft dough stage and under varying temperature and moisture conditions. The pathogen remains dormant as mycelium on or within the dry barley grains until the seed germinates. The stripe fungus then resumes active growth, progressing into the sheath surrounding the first seedling leaf, from that into the next leaf, and continuing until all of the leaves are infected. The spores of the stripe pathogen can remain alive for as long as 34 months. Seed transmission is high at soil temperatures below 12°C. The transmission is reduced or prevented when the temperature is above 15°C.

Root and crown diseases

Rhizoctonia root rot: Barley is highly susceptible to rhizoctonia root rot, caused by *Rhizoctonia solani* Kuhn. AG8 and R. oryzae Ryker & Gooch. *R. solani* AG8 has a wide host range, including wheat and barley. Aboveground symptoms include yellowing and purpling of the leaves and stunting, which can often occur in patches in the field, hence the names rhizoctonia patch, purple patch, bare patch, or barley stunt. Below ground, root tips are brown, and crown root tips are rotted or tapered to a point, hence the name spear tipping. Under extreme conditions, where seedling growth is slowed by cool temperatures, *Rhizoctonia* can also cause damping-off. *Rhizoctonia* can survive on living plants via a green bridge on grassy weeds or volunteers plants (Smiley et al., 1992). Because the fungus has a wide host range, therefore, its survival becomes very easy.

Common root rot and seedling blight: Common root rot is caused by *Bipolaris sorokiniana* (Sacc.) Shoemaker. The pathogen forms brown lesions on the roots and especially on the subcrown internode. These lesions can extend to the crown and leaf sheaths and eventually affected seedlings may killed. Under severe conditions, these lesions become almost black. This pathogen also causes spot blotch on the leaves and kernel blight or black point on seeds. Infected plants are stunted, with reduced tillering and reduced yield. White heads (spikes) can be formed, and heads contain fewer kernels that are small and shrivelled. This pathogen survives in the soil via thick-walled conidia, which can persist in the soil for many years. In most areas, soilborne inoculum from conidia is the primary source of infection. Infection is initiated from conidia in the soil. Conidia germinate in the presence of a host and can infect the emerging coleoptile or primary roots. The fungus can produce phytotoxins, which aid in the pathogenesis and colonization of the root. Seedborne inoculum can be important in more humid areas. The pathogen can survive on roots of grassy weeds and some dicots or on host debris.

Viral diseases

Barley yellow dwarf (BYD): Barley yellow dwarf is important virus disease of barley caused by *Barley yellow dwarf* virus (BYDV). Losses due to this disease can be 100% if infection of the crop occurs on early crop growth stage (Mathre, 1997). BYDV infections cause leaf yellowing and stunting, initially confined to single plants scattered randomly in a field but later developing into distinct circular patches as secondary spread occurs (Fig. 6).

Fig. 6 BYD yellowing on Barley

Barley leaves often turn bright yellow. Other symptoms include upright and stiff barley leaves with serrated leaf borders, reduced tillering and flowering, sterility and failure to fill kernels, which results in fewer and smaller kernels and corresponding yield losses. The viruses that cause barley yellow dwarf (BYD) are hexagonal and typically 25-28nm in diameter. They are composed of two proteins that encapsulate the single-stranded ribonucleic acid (ssRNA) genome. The viruses are restricted to the phloem of host plants. A typical disease symptoms develop due to the death of infected phloem cells which inhibits translocation, and loss of chlorophyll. Spread of BYDV from infected grasses and volunteer cereals to barley and plant to plant is facilitated by at least 25 different species of cereal aphids. The viruses is not transmitted mechanically (by rubbing) and do not multiply in their aphid vectors. Thus, all aphids must acquire the viruses by feeding on infected plants. The viruses move up from aphid's stylet to the gut, where they are transported into hemocoel. The viruses then circulate through the hemocoel to the aphid's accessory salivary gland where they mixed with saliva and can be expelled into the phloem of another plant. The viruses can not be transmitted by an aphid until they travel through the body of the insect. Therefore, usually, an aphid takes the several hours from viruses acquirement to become capable of transmitting them. This duration is called the latent period. A single viruliferous aphid can spread the virus to many plants as it moves and feeds. High light intensity and relatively cool temperatures 15-18°C, generally favour expression of symptoms, such as leaf discoloration which may attract aphid vectors to virus-infected plants.

Nematode diseases

Molya disease: Barley, like most other cereal crops, suffers from damage by parasitic nematodes. Cereal cyst nematode (*Heterodera avenae* Woll.), causing molya disease is a sedentary endoparasite that infects the roots of many crops belonging to family Poaceae including barley. Cereal cyst nematode (CCN) can cause substantial yield losses, particularly in north eastern Rajasthan and adjoining Haryana. Cereal cyst nematodes cause short branching and swelling (knots) on the roots of seedlings of wheat but do not cause distinctive root symptoms on barley, other than a bushier root system (Fig. 7).

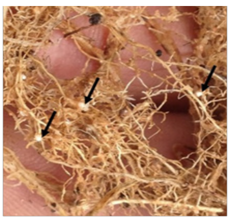

Fig. 7 CCN infected barley roots, white cycts

Aboveground, the plants are severely stunted, usually with a patchy distribution and show symptoms of nutrient deficiency. Juveniles gain entry to the root, and females set up a feeding site in the vascular system of the root. The females become swollen, produce eggs and are transformed into cysts, which protrude through the roots. These cysts are white when young and then turn brown. The eggs are formed within the cyst and the cysts can survive for long periods of time and overwinter. Eggs hatch out the following season. *H. avenae* is widely distributed throughout the world. In addition, a new species was detected in Oregon in 2008, *Heterodera filipjevi* (Smiley *et al*., 2008). Cysts can spread by the movement of soil with wind, transplants, shoes, tubers, machinery, harvesters, and so on. Cereal cyst nematodes have only one life cycle per year. However, each cyst contains several hundred eggs, so populations can increase rapidly on susceptible barley cultivars. The disease is reduced by rotation with a non-host for 1–2 years, including controlling grassy weeds. In general, barley is more tolerant to cyst nematode than wheat or oats.

Management strategies of barley diseases

Disease management is best achieved by knowledge of the pathogens involved and manipulation of the interacting factors. Resistant varieties provide the easiest and most effective option to manage the major diseases. For effective disease management, it is important to use the integrated disease management practices that focus on the factors affecting disease.

Genetic resistance: The principle mechanism of control of the cereal rusts has been through the use of resistant cultivars. There are two types of genes that used for breeding disease resistant barley cultivars. The first is R-genes, these are pathogen race specific in their action, and effective at all plant growth stages. The second is called adult plant resistance genes (APR-genes) because resistance is functional only in adult plants. In contrast to most R-genes, the levels of resistance conferred by single APR-genes are only partial and allow considerable disease development (Ellis *et al*., 2014). The agronomic lifespan of a resistant cultivar is about 4-5 years where an active breeding programme exists. For instance, barley stem rust has been managed successfully in the northern Great Plains of the U.S. and Canada due to deployment of the stem rust resistance gene *Rpg1* in 1942. Since then, this gene has provided durable protection against this disease in widely grown barley cultivars. However, emergence of new races for this resistance gene resulted in some losses in late sown barley (Steffenson, 1992). For the deployment of resistant cultivars, one must be aware of level of resistance in barley cultivars against different diseases and severity of occurrence of diseases in different agro-climatic zones of India. The cultivars grown in North western plain zones are not yielding good in North eastern plain zones due to heavy attack on these by spot blotch pathogen under warmer conditions. Likewise, varieties bred for other zones may suffer badly due to attack of stripe rust in Northern hills and plains zones. In India, barley crop improvement has been obtained through the utilization of genetic resources available as land races of indigenous or exotic origin. Exotic germplasm of barley received from ICARDA has been remained an important base material for the development of barley varieties either as direct or their utilization in the development of new barley varieties. The varieties namely, LSB 2, HBL 113, Dolma, VLB 118, BHS 400 and BHS 380 have been released directly for the cultivation in Northern Hill zone of India. Several barley varieties viz. BHS 169, DL 88, BH 393, NDB 1173 and VLB 56 have been developed by adopting hybridization followed by selection in the segregating generations for targeted traits (Singh *et al.*, 2016). To identify the sources of disease resistance in barley, a rigorous evaluation in greenhouse and multilocational adult plant screening is undertaken. Use of all the prevalent cultures of the pathogens is made in evaluation. Recently, 336 barley genotypes from ICARDA (International Center for Agricultural Research in the Dry Areas) were evaluated against barley yellow rust at ICAR-IIWBR, Shimla. Twelve barley genotypes viz. ARAMIR/COSSACK, Astrix, C8806, C9430, CLE 202, Gold, Gull, Isaria, Lechtaler, Piroline, Stirling, and Trumpf were resistant to barley yellow rust at the seedling and adult-plant stages (Verma *et al.*, 2018). Both seedling and adult plant resistance are considered for the promotion of barley varieties. Substantial diversity for resistance to rusts occurs also in Advance Varietal Trial material. A major challenge for barley breeders is to pyramid multiple disease resistance genes into high yielding, high quality germplasm. Some important targets include: yellow and leaf rust, powdery mildew, net blotch and spot blotch. Singh (2008) reported that barley cultivars RD 2508, RD 2035, DWRUB 52, RD 2552 and RD 2624 have multiple disease resistance in India. The cultivar like DWRUB52, DWRB73, DWRUB64, DWRB91 and DWRB92 are yellow rust resistant and effective in NWPZ and NHZ. Cultivar RD 2035, RD2052 and RD2592 are molya disease resistant (CCN) and recommended in disease affected areas of Rajasthan and Haryana. Resistant/tolerant varieties such as DWRUB52, DWRB73, DWRUB64 and RD2552 are being promoted in NEPZ where foliar diseases (net blotch and spot blotch) are the major constraints.

Innovative approaches: Molecular technologies will facilitate designing better strategies for developing disease resistance in crop plants. Mutation, marker assisted selection (MAS), gene cloning, genomics, recombinant DNA technology, targeted induced local lesions in genome (TILLING) and virus induced gene silencing (VIGS) are now being followed by breeders to develop effective resistance in cultivated crops within a short period of time. TILLING, being a non- transgenic method, is expected to become the most powerful tool for developing disease resistant cultivars (Hussain, 2015).

Rotation and stubble management: Diseases such as spot-type net blotch and net- type net blotch, spot blotch, SSLB are stubble-borne. Crop rotation with a non-host crop will minimise initial inoculum levels for next season's crop. Cultural practices such as incorporating the crop residue into the soil or removing it completely by burning will reduce the abundance of the pathogen and the disease pressure. Molya disease is reduced by rotation with a nonhost for 1–2 years.

Green bridge management: Three major diseases, barley rusts, powdery mildew and barley yellow dwarf virus (BYDV), persist on living hosts. Barley rusts survive on barley volunteers, powdery mildew on barley volunteers and stubble and BYDV on cereal regrowth and perennial grasses. This is also most effective cultural technique for reducing the initial inoculum of many soilborne pathogens. A green bridge of self-sown barley leading into the cropping season provides host material for these diseases and the aphid vector of BYDV and increases the risk of their early onset. Removing this green bridge will greatly reduce the risk of early crop infection.

Seed health: The net-type net blotch (NTNB), loose smut and covered smut are seed-borne diseases. Sowing infected seed can introduce disease into a healthy crop. Therefore clean seed should be used wherever possible. Fungicide treatment can reduce the risk associated with sowing infected seed, particularly for smuts.

Fungicidal disease management: Fungicide seed dressings or fungicides applied in-furrow with fertiliser can be useful in disease protection or suppression of early seedling infection. The selection of fungicide should be determined by the target diseases. The purpose of foliar fungicide application in the crop is to delay disease development and to maintain green leaf area. It reduces disease impact on yield and grain quality. The cost effectiveness of foliar fungicide applications depends on disease severity, susceptibility of the variety, yield potential of the crop, grain quality outlook and the environment where the crop is growing. When susceptible varieties are grown in disease prone areas or high rainfall seasons, fungicide can be cost effective in reducing the disease impact where yield potential is over 2.0 t/ha. For controlling initial load of inoculums or under high incidence of barley rust diseases, fungicides belonging to triazole group such as Azoxystrobin 25% EC (Amistar), Bayleton 25%EC (Triadimefon), Difenoconazole 25% EC (Score), Propiconazole 25% EC (Tilt) and Tebuconazole 25% EC (Folicur) have been found effective at the rate of 0.1 per cent i.e. 1ml in 1litre of water (Bhardwaj *et al.*, 2017). Seed borne diseases particularly covered and loose smuts, can be managed effectively by seed treatment with Carboxin (Vitavax)/ or Carbendazim (Bavistin) @ 2.5 g/kg seed for loose smut and Vitavax and Thiram (1:1)/ or Tebuconazole @1.5 g/kg seed for covered smut. Bayleton, Tilt and Folicur are broad spectrum fungicides, are also effective against foliar diseases like powdery mildew, spot blotch and net blotch besides of rusts (at the rate of 0.1 per cent).

Conclusions

Barley is affected by a number of airborne, seedborne and soilborne pathogens which causes various diseases and considerable loss to grain yield and quality. Among these, brown and yellow rusts, both type of net blotches, spot blotch, Septoria speckled leaf blotch, barley yellow dwarf and molya disease are important in Indian perspective. In general, barley diseases are best managed by adopting integrated disease management strategies. Growing resistant/tolerant cultivars with minimum number of chemical sprays are the best way to manage these diseases. However, It is difficult to manage the soilborne pathogens because of the lack of distinctive symptoms for identification and lack of soil-applied fungicides or nematicides that are effective or economic on a relatively low-value crop such as barley. Genetic resistance or tolerance to most of these generalized wide host range root rotting pathogens is also lacking. Thus, growers must rely on a number of cultural methods to manage these diseases.

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