Major Diseases of Small Millets and Their Management Strategies

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Abstract

Small millets, also known as coarse cereals comprises finger millet, foxtail millet, proso millet, kodo millet, barnyard millet, little millet and browntop millet etc. Small millets are considered as super grains since ancient times owing to their excellent attributes viz., climate resilience, richness of minerals (Ca, Zn and Fe etc.), fibers and vitamins etc. Superior nutritional and agroecological traits of millets are capturing global importance as smart foods and smart crops which can serve as potential alternative for staple food grains and contributing to global food and nutritional security. Small millets are being widely cultivated in semi-arid regions like India as rainfed crops. Despite their admirable characteristics, small millets production accounts only 2% of worlds cereal production. This is due to the genetic potential of small millets is hindered by various biotic and abiotic stresses resulting in substantial yield and economic losses. Among the biotic stresses, diseases caused by fungal pathogens such as blast (*Magnaporthe* spp.), leaf spot or leaf blight (*Helminthosporium* spp.), rusts, and smuts are the predominant constraints in cultivation of small millets in major millet growing areas. Addressing these challenges on global scale needs better understanding of the disease, causal organism along with their symptomatology and epidemiology for

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devising effective management strategies. This book chapter accentuates on predominant diseases of small millets, their symptoms, modes of survival, and spread along with integrated mitigation practices as well as novel approaches which can be exploited for managing diseases in millets resulting in increased production and productivity of millets.

Keywords

Diseases · Small millets · Management · Host plant resistance · Epidemiology

5.1 Introduction

Millets are the coarse cereal crops with small seeded grains that are relatively less cultivated globally than commercial cereal crops like rice, wheat, and maize. Though millets are known to cultivating since ages majorly by the subsistence farmers under rainfed conditions in Asian and African countries, they lagging behind to receive attention from the breeders, consumers, and growers compare to other food crops. Millets are categorized into two groups viz., major millets (include sorghum and pearl millet) and minor or small millets comprised of finger millet (*Eleusine coracana* L. Gaertn), foxtail or Italian millet (*Setaria italica* L.), barnyard millet (*Echinochloa frumentacea* L.), Proso millet (*Panicum miliaceum* L.), kodo millet (*Paspalum scrobiculatum* L.), little millet (*Panicum sumatrens* L.), and browntop millet (*Brachiaria ramosa* L. Stapf). Small millets are mostly grown in semiarid tropics of Asia and Africa and these can be easily grown in diverse agro-ecological climates where cereals couldn't able to produce substantial yield. With the growing health concerns and to sustain in the world of increasing population, agricultural sustainability is of prime importance which consists of food and nutritional security for which small millets will serve as an ideal solution. Small millets are regarded as nutri-cereals owing to their significant nutritional and agro-ecological characteristics. They are fat-rich, good source of minerals viz., iron (Fe), zinc (Zn), magnesium (Mg) and calcium (Ca), vitamins, dietary fiber content and richness of essential amino acids like cysteine and methionine etc. Owing to their remarkable nutraceutical attributes and climate resilience, millets are capturing global attention over cereals in recent times which were hitherto predominant (Anju Jr and Sarita 2010). Small millets as smart foods and smart crops can serve as potential alternative for staple food grains and has capability for contributing to global food and nutritional security.

Despite their admirable significance, the small millets production accounts only 2% of worlds cereal production where Asia holds 40% of global millet production which is majorly contributed by India and China. In India, millets occupy 13.8 m ha (138 lakh ha) of area with production of 173 lakh ton which accounts 80% of Asia's and 20% of global millet production (FAOSTAT 2021). Millets are known for their climate resilience and enduring capacity towards drought and are comparatively less prone to pest and diseases. However, changing climate scenario has increased the exposure to various biotic and abiotic deterrents that limit millet production as well as productivity. Among the various biotic constraints, diseases caused by fungal pathogens are wide spread and destructive. Fungal disease recorded on small millets includes blast, leaf blight/brown spots, smuts, rusts, downy mildew, leaf spot etc. In addition to the fungal diseases, small millets are also occasionally/sporadically attacked certain bacterial (viz., *Xanthomonas* spp., *Pseudomonas* spp., etc.) and viral pathogens (like *ragi mottle streak virus*, *sugarcane mosaic virus*, etc.) which are of low economic importance to the millet cultivation under natural conditions.

The genetic potential of small millets is affected by the attack of these diseases under varying climatic conditions resulting in substantial yield losses. Albeit many pathogens attack small millets, not all cause significant losses, only some diseases on specific millets occur in severe form while others show negligible effect unless prevalence of vulnerable conditions. Addressing these challenges on global scale needs better understanding of the disease, causal organism along with their symptomatology and epidemiology for devising effective management strategies. Hence, attempts have been made in this chapter to compile the available information by accentuating on major diseases of small millets which are of regular occurrence, their symptoms, modes of survival, and spread along with revised mitigation practices helping in disease control and improving millets production and nutritional quality.

5.2 Diseases of Small Millets

Small millets are known to cope up against abiotic and biotic stresses; nevertheless, under favorable conditions, some of the diseases cause heavy losses and can damage entire crop (Kumar and Singh 2010). All the small millets don't exhibit same level of resistance to biotic factors which varies with genus to genus and also depends on prevailing environmental conditions. Among the biotic constraints, a variety of diseases caused by fungal, bacterial, and viral pathogens became huge economic importance over the time which can devour the crop if left uncontrolled. Various diseases possibly occur on all (seven) small millets are enlisted in the Table 5.1 along with their causal organisms and nature of disease. Although enlisted table comprised of many fungal, bacterial, and viral diseases, the number and intensity of fungal diseases are predominant over the other pathogens which comes about frequently in severe form.

Here, fungal diseases have been categorized into three groups based on their nature of infection or survival and spread of pathogen which includes foliar/airborne diseases (diseases that affect foliar parts, i.e., leaves and stems etc. and spread inoculum through air), soilborne diseases (diseases that affect stem near soil line, root, sheath etc. and survival inoculum in soil) and complex or mixed carrier disease (includes the diseases that affect different (reproductive) plant parts like flowers, grains, and dispersal of inoculum occurs by various agents like seed or air or insects etc.). Among the three categories, foliar diseases are abundant and increasing over the time with emergence of new pathotypes/races or species under diverse environmental conditions. Potential fungal diseases of millets are blast, banded sheath

Table 5.1 List of small millet diseases along with their causal organisms and host range

S. No.	Disease	Causal organism	Host(s)	Reference
Fungal diseases				
(1)	*Foliar/air borne diseases*			
1.	Blast	*Pyricularia grisea* (Cooke.) Sacc. (PS: *Magnaporthe grisea* (Herbert) Barr)	Finger, Barnyard, Proso and Little millet	Viji et al. (2000)
		Pyricularia setariae Y. Nisik. (PS: *Magnaporthe setariae*)	Foxtail millet	Richardson (1990)
2.	Leaf spot/Leaf blight (*Helminthosporium* spp.)	*Drechslera nodulosum* (Sacc.) Subram & Jain (PS: *Cochliobolus nodulosus*)	Finger and Little millet	Sivaesan (1987)
		Bipolaris setariae (PS: *Cochliobolus setariae*)	Foxtail and Browntop millet	Ramesh et al. (2021a, b)
		Bipolaris panici-miliacei	Proso millet	Hyung (1997)
		Exserohilum crusgalli	Barnyard millet	Nagaraja et al. (2007a, b)
	Alternaria leaf blight	*Alternaria alternata* (Fr.) Keissl.	Little and Kodo millet	Praveen et al. (2021)
	Cercospora leaf spot	*Cercospora eleusinis*	Finger millet	Munjal et al. (1961)
3.	Rust	*Puccinia substriata* Ellis & Barthol. (Syn: *Uredo paspali-scrobiculati* Syd.)	Kodo millet	Sydow and Butler (1906)
		Uromyces eragrostidis	Finger millet	Channamma et al. (1996)
		Uromyces setariae-italicae Yoshino	Foxtail millet	Lu et al. (2000)
		Uromyces linearis Berk. & Broome	Little and Proso millet	Cummins (1971)
4.	Smut			
	Grain smut	*Melanopsichium eleusinis* (Kulk.) Mundk. & Thirum. (Syn: *Ustilago eleusines* Kulk.)	Finger millet	Mundkur and Thirumalachar (1946)
		Ustilago crameri	Foxtail and Proso millet	Pall et al. (1980)
		Ustilago panici-frumentacei Bref.	Barnyard millet	Vasudeva (1954)
		Macalpinomyces sharmae Vanky (Syn: *Tolyposporium sharmae*)	Little millet	Jain et al. (2006)

(continued)

Table 5.1 (continued)

S. No.	Disease	Causal organism	Host(s)	Reference
	Head smut	*Sorosporium paspali-thunbergii* (Henn.) S.Ito (Syn: *Sorosporium paspali* Mc Alp.)	Kodo millet	Viswanath and Seetharam (1989)
		Sporisorium destruens (Schltdl.) Vánky (Syn: *Sphacelotheca destruens*)	Proso millet	Sinha and Upadhyay (1997)
		Ustilago crus-galli Tracy & Earle	Barnyard millet	Pall et al. (1980)
		Ustilago crameri	Foxtail millet	Kumar (2011)
	Kernel smut	*Ustilago paradoxa*	Barnyard millet	Viswanath and Seetharam (1989)
5.	Downy mildews	*Sclerophthora macrospora* (Sacc.) Thirum. (Syn: *Sclerospora macrospora* Sacc.)	Finger millet	Venkatarayan (1947)
		Sclerospora graminicola (Sacc.) J. Schröt.	Foxtail and Proso millet	Sinha and Upadhyay (1997)
6.	Udbatta disease	*Ephelis oryzae* Syd. (PS: *Balansia oryzae* (Syd.) Naras. & Thirum.)	Foxtail, Kodo, Proso and Little millet	Das et al. (2016)
7.	Sheath rot	*Sarocladium oryzae* (Saw.) Gams & Hawksw.	Kodo millet	Das et al. (2016)
(2)	*Soil borne diseases*			
8.	Banded sheath blight	*Rhizoctonia solani* Kuhn. (PS: *Thanatephorus cucumeris*)	Finger, Foxtail, Barnyard, Proso, Kodo and Little millet	Nagaraja et al. (2007a, b)
9.	Foot rot	*Sclerotium rolfsii* (PS: *Pellicularia rolfsii*)	Finger millet	Coleman (1920)
(3)	*Complex/mixed carrier diseases*			
10.	Grain mold	*Fusarium moniliforme*, *Curvularia lunata*, *Alternaria alternata*, *Phoma sorghina*, *Aspergillus* spp.	Finger millet	Das et al. (2016)
11.	Ergot or Sugary disease	*Claviceps paspalis*	Kodo millet	Ramakrishnan and Sundaram (1950)
Bacterial diseases				
1.	Bacterial leaf spot	*Xanthomonas eleusinae*	Finger millet	Rangaswami et al. (1961)
		Pseudomonas albo-precepitans Rosen.	Foxtail millet	–

(continued)

Table 5.1 (continued)

S. No.	Disease	Causal organism	Host(s)	Reference
2.	Bacterial leaf stripe	*Pseudomonas eleusinae*	Finger millet	Billimoria and Hegde (1971)
		Pseudomonas syringae Van Hall pv. *panici*	Proso millet	Ramakrishnan (1971)
3.	Bacterial leaf streak	*Xanthomonas axonopodis* pv. *coracanae*	Finger millet	–
		Pseudomonas avenae	Foxtail, Barnyard and Proso millet	Nagaraja et al. (2007a, b)
		Xanthomonas spp.	Kodo millet	Nema et al. (1978)
4.	Bacterial leaf blight	*Xanthomonas axonopodis* pv. *coracanae*	Finger millet	Desai et al. (1965)
Viral diseases				
1.	Ragi mottle streak disease: *Ragi mottle streak virus*		Finger millet	Mariappan et al. (1973)
2.	Ragi severe mosaic: *Sugarcane mosaic virus*			Subbayya and Raychaudhuri (1970)
3.	Ragi streak disease: *Eleusine* strain of *Maize streak virus*			Anonymous (1975)
4.	*Wheat streak virus*, *Sugarcane mosaic virus* and *Eleusine virus 2*		Barnyard millet	Sill and Agusiobo (1955)
5.	*Wheat streak virus*, *Rice dwarf or stunt virus* and *Maize leaf streak virus*		Proso millet	

Note: *PS* perfect stage, *Syn* synonym(s)

blight, grain mold, ergot, rust, smut, anthracnose, downy mildew, foot rot, and sheath rot etc. Fungal pathogens incite various plant parts like root, stem, leaves, peduncle or grain and adversely affect yield and quality of the produce. Hence, in this chapter more importance was given to the fungal diseases which were presented with detailed information while the bacterial and viral diseases were included in a context to describe their role and symptomatology by respective pathogens under favorable conditions along with the revised management strategies framed in sustainable manner.

5.2.1 Major Fungal Diseases of Small Millets

5.2.1.1 Blast

Blast caused by *Pyricularia* spp. is one of the serious threats and most destructive disease that occur widely in major millet growing regions of world. Blast of millets is the major production constraints under natural conditions especially in finger and foxtail millet cultivation causing considerable economic losses with varying damage. In India, the finger millet blast was first reported from Tanjore delta of Tamil Nadu by McRae (1920). While foxtail millet blast was recorded by Nishikado from Japan in 1917, but in India, it was reported from Tamil Nadu in 1919, latter it has also been recorded from Maharashtra, Andhra Pradesh (Sinha and Upadhyay 1997), and Uttarakhand (Kumar 2013). The disease is prevalent in all the major millet growing areas and spreading to new location as well with emerging pathotypes showing varying intensities depending on the cultivar, favorable conditions, and production practices.

Causal Organisms

Pyricularia grisea (Cooke.) Sacc. [Perfect stage: *Magnaporthe grisea* (Herbert) Barr] causing blast in finger and proso millet whereas *Pyricularia setariae* Y. Nisik. infects foxtail millet.

Kulkarni and Patel (1956) grouped *P. setariae* into four physiological races on the basis of pathogenicity, cultural, physiological, and morphological characters of the fungus. However, Gaikwad and D'Souza (1987) concluded that *P. setariae* that infects foxtail millet is different from the isolates that infect rice, pearl millet, and finger millet.

Host Range

Finger millet, proso millet, foxtail millet, pearl millet, rice and wheat etc., Nagaraja et al. (2016) described that *P. grisea* isolated from finger millet possess the potential to infects rice crops but not vice-versa. Likewise, *P. setariae* isolated from foxtail millet shows the ability to infect finger millet, pearl millet, wheat, and *Dactyloctaenium aegyptium* (Viswanath and Seetharam 1989).

Economic Importance

Ragi blast is economically one of the most important diseases, while blast of proso and foxtail millet are relatively of minor occurrence. The disease occurs almost every year in finger millet during rainy season and losses varies with the time of onset of the disease, severity, cultivar, and climatic conditions. During late 1970s to 1980s, incidence of finger and neck blast by *M. grisea* was increased 1% which resulted in a corresponding enhancement of yield losses by 0.32% and 0.084% for neck and finger blast, respectively. However, grain yield losses in finger millet ranged from 6.75% to 87.5% (Rao 1990). In its severe form, foxtail millet blast can lead up to 30–40% loss of economic yield (Nagaraja et al. 2007b) while mean yield loss of ragi blast ranged from 28% to 36% and may go up to 90% in endemic areas with frequent disease (Ramappa et al. 2002).

Epidemiology

The crop is susceptible to the blast disease during all stages of its growth, i.e., seedling (vegetative) to grain formation (reproductive) stage. Especially, young seedlings more prone to the blast both in the nursery and field conditions with favorable weather (Kumar and Singh 2010). Moderate temperature (25–30 °C) with high relative humidity (>90%) and cloudy days in following days coupled with intermittent rainfall creating continuous leaf wetness for more than 10 h are congenial for rapid development and spread of the disease. Continuous rains at the time of heading may lead to development of finger blast causing huge yield losses in both finger and foxtail millet. Also, excessive application of nitrogen fertilizers observed to enhance the blast incidence (Prakash et al. 2007).

Diagnostic Symptoms

Blast pathogen can infect all the stages of plant in both finger and foxtail millet in which young seedlings/germlings are more prone for the attack resulted in formation of dark patches with burnt appearance in nursery under severe infection (Rachie and Peters 1977). In finger millet, *P. grisea* attack at different stages of the crop lead to formation of symptoms like leaf blast, neck blast, and finger blast while in foxtail millet, *P. setariae* attacks the leaf lamina producing leaf blast symptoms (Nagaraja et al. 2007a, b).

On leaf lamina, pathogen produce typical symptoms of water-soaked, spindle, or diamond shaped lesions which are initially surrounded by chlorotic halo. Typical leaf blast symptoms are the formation of elliptical or diamond-shaped lesions containing greyish center with dark brown margins (Plate 5.1). Under severe infection, adjacent lesions enlarge and may coalesce to form large necrotic areas which gives the crop burnt appearance from far. The pathogen infects and develops lesions on the leaf, peduncle, and finger depending on the stage of the crop. The most damaging stage of finger millet blast is neck blast where the pathogen attacks the neck region, which significantly reduces number and weight of grain per spikelet that leads to spikelet sterility (Rath and Mishra 1975). In this, neck portion of 2–4 in. below the ear immediately turns initially brown and later to black, where olive grey fungal growth can be observed in the blackened portion under high humid climate. In finger blast where the pathogen attacks fingers, i.e., attacks usually the apical portions running towards the base (Plate 5.1a). Infection of finger blast result in shriveled and blackened seeds which makes unfit for seed purpose and human consumption because of loss of minerals and vitamins.

Disease Cycle

The pathogen harbors in glumes, straw as well as on some graminaceous weeds. Anitha et al. (2005) described that the blast pathogen is seed-borne with presence of inoculum in the pericarp and endosperm (Viswanath and Seetharam 1989). Blast fungal life cycle is complex due to its nature of disease which show sensitivity to the weather conditions, survival, and spread inoculum in different ways. During off-season, i.e., in the absence main host, it survives on the graminaceous weeds as collateral hosts who provides the primary inoculum for onset of infection. Further, the fungus spreads mainly by airborne conidia and occasionally through seeds.

Characterization of the Pathogen

For proper diagnosis of the disease, the understanding of the pathogenic characteristics is needed as much of knowing symptomatology and disease cycle. Blast caused by the *Pyricularia* spp. is identified based on its above-described

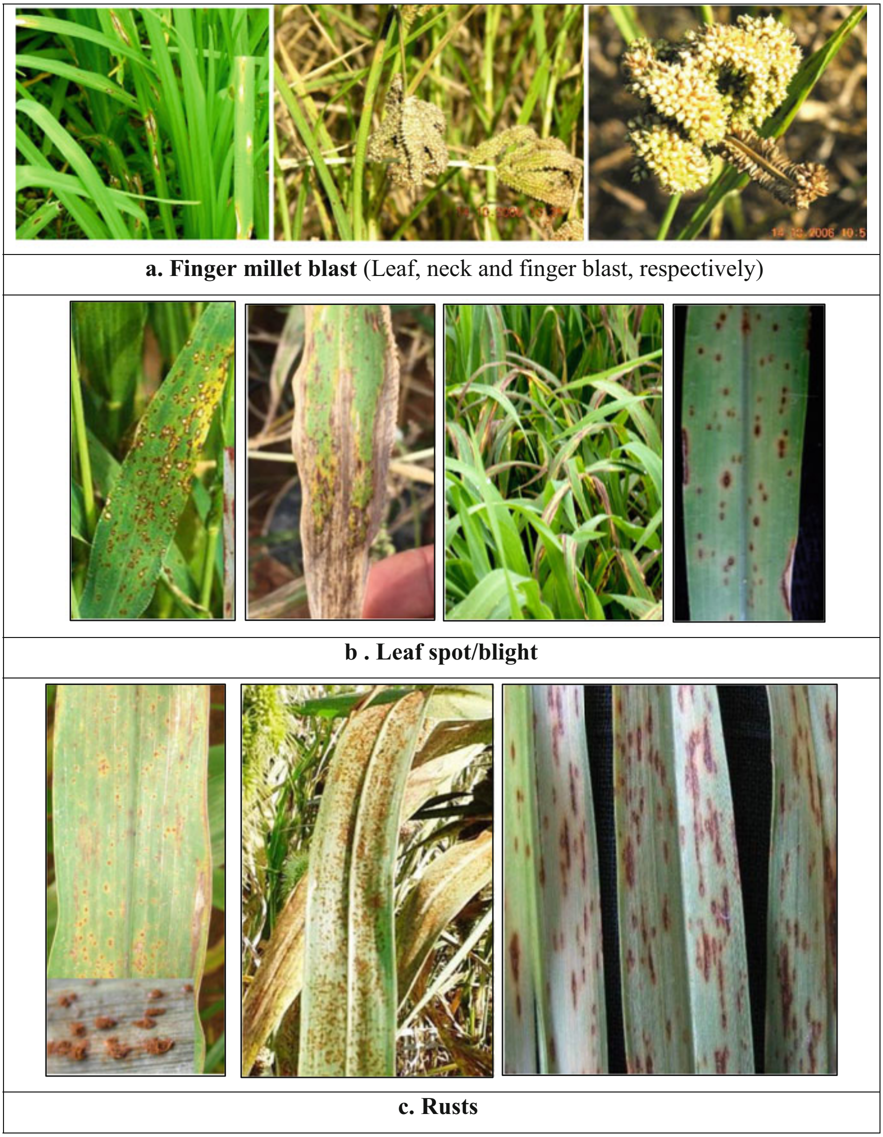

Plate 5.1 Diagnostic symptoms of major diseases of small millets (compiled from Nagaraja et al. 2016; Das et al. 2016; Kumar and Singh 2010). (**a**) Finger millet blast (leaf, neck and finger blast, respectively), (**b**) leaf spot/blight, (**c**) rusts, (**d**) grain smut, (**e**) head smut, (**f**) downy mildews, (**g**) foot rot or wilt of ragi, (**h**) udbatta disease of kodo millet, (**i**) banded sheath blight, (**j**) sheath rot of kodo millet

d. Grain smut

e. Head smut

f. Downy mildews

Plate 5.1 (continued)

	
g. Foot rot or wilt of ragi	**h. Udbatta disease of kodo millet**
	
i. Banded sheath blight	**j. Sheath rot of kodo millet**

Plate 5.1 (continued)

symptoms in the field while in vitro, pathogen characterized based on morphological and molecular attributes. Morphological characterization includes studying mycelial characteristics on agar plates, viz., appearance, color, and amount of melanin pigment produced as well as the microscopic conidial characters. Molecular characterization of pathogen includes amplification of targeted genomic regions such as *ITS*, *beta tubulin*, *TEF*, *LSU* etc. and also by studying the DNA polymorphism using various molecular markers (Longya et al. 2020).

5.2.1.2 Leaf Spot/Leaf Blight

Leaf blights are also known as leaf spots/brown spots/seedling blights are among the common diseases occurred on small millets after the blast. Leaf blights in small millets are caused by different pathogens like *Helminthosporium* spp., *Alternaria alternata,* and *Cercospora eleusinis* in different millets respective to their host range. Among them, leaf blights caused by *Helminthosporium* spp. are gaining importance because of their increasing severity, distribution, and change in virulence to the new hosts by adapting to different agro-ecological regions. Leaf blight is a serious threat in all the small millet crops yet it is more damaging in the finger millet which was first noticed by Butler (1918) in India. Ramesh et al. (2021a, b) stated that, leaf blight caused by *Bipolaris setariae* was found to be most important and destructive disease in browntop millet.

Causal Organisms

Drechslera nodulosum (finger millet and little millet), *Bipolaris setariae* (foxtail and browntop millet), *B. panici-milliacei* (proso millet), *Exserohilum crusgalli* (barnyard millet).

The genus *Helminthosporium* belongs to phylum *Ascomycota*, class *Dothidiomycetes*, subclass *Pleosporomycetidae*, order *Pleosporales* and family *Pleosporaceae*. It produces hyphae, conidiophores, and conidia. Hyphae are septate, conidiophores are brown to dark brown, erect, parallel-walled, and ceasing to elongate when the terminal conidium is formed. Conidia are multicellular (six or more-celled), large (9–40 μm), solitary, club-shaped and pale to dark brown in color, and are placed along the sides of the conidiophores and their wider end is towards the conidiophore. *Helminthosporium* differs from *Bipolaris*, *Drechslera,* and *Exserohilum* by forming parallel walled, erect conidiophores (Alcorn 1988).

Host Range

Leaf spots/blight pathogens attack all the small millets at all stages of the crop. Several other hosts are infected by the leaf blight pathogen includes *Setaria italica*, *Eleusine indica*, *Dactyloctenium aegyptium*, *Echinochloa frumentacea*, *Panicum miliaceum*, *Pennisetum typhoides*, *Sorghum vulgare,* and *Zea mays* (Mitra 1931; Pall et al. 1980).

Epidemiology

Warm humid regions having temperature ranges from 15 to 30 °C during cropping season are congenial for the development of symptoms. Under humid conditions, growth of pathogen on the older spots can be observed. Moderately high temperature and high relative humidity (R.H) are favorable for leaf blight disease (Nagaraja et al. 2007a, b).

Symptomatology

The characteristics symptom on leaf lamina is appearance of brown to dark brown spots. These spots are generally oval in shape and measure 8–10 mm in length and 1–1.5 mm in breadth. Later, these spots coalesce to give the brightening appearance of leaf, especially towards tip which would ultimately be killed prematurely. The disease also affects culm especially at nodal joints. Symptoms are also seen on leaf sheath, especially in older plants, where, in the center of the lesion, the wooly growth of the fungus may be observed under high humid conditions. The area at the juncture of leaf sheath and leaf blade is usually affected resulting in dark brownish discoloration. In neck infection dark tan lesions are seen initially, which may enlarge and extend up and down (Plate 5.1). In severe conditions, the neck may break and hang on to the plant. The pathogen may attack ear head, fingers as well as grains. The affected grains may not develop fully and shrivel, resulting in heavy crop losses (Kumar and Singh 2010).

Disease Cycle

The pathogen survives in soil for over 18 months and the spores on grains are reported to be viable for a year (Vidhyasekaran 1971; Nagaraja et al. 2007a, b). The fungus also remains viable on the stubbles and plant debris. Secondary spread is through air borne conidia. The optimum temperature of 30–32 °C congenial for initiation of infection, however disease can occur in 10–37 °C (McRae 1922). High humidity and intermittent rains during the period of ear emergence and before grain formation causes heavy ear infection results in substantial yield loss. Under severe infections, young seedlings/germlings may get killed within 3 days after infection while elder plants get killed 15 days after infection.

Characterization of Pathogen

Diagnosis of the disease done primarily based on the typical leaf blight symptoms produced in the field on the leaf sheath or by the observation of fungal growth in vitro based on the morphological characteristics viz., mycelial color, texture, pigmentation on reverse side of the Petri plate, conidial morphology includes shape, size, and hilar end structure. Molecular characterization of *Helminthosporium* spp. carried using molecular regions like *ITS*, *LSU*, *SSU* and *gpdh* (glyceraldehyde-3-phosphate dehydrogenase) gene sequences and DNA profiling etc. (Ramesh et al. 2021a).

5.2.1.3 Rusts

Rusts caused by diverse species of *Puccinia* and *Uromyces* in small millets are of minor economic importance unless disease triangle is fulfilled which is the rare possibility. The disease occurs every season and in most of millet growing areas prevailing congenial conditions yet they don't cause considerable economic losses (Butler 1918). Out of seven small millets, rusts are economically important diseases on foxtail millet which is caused by *Uromyces setariae-italica*, which was first recorded by Yoshino from Japan. On foxtail millet, it occurs regularly and in severe form but doesn't result in heavy yield losses. In India, foxtail millet rust is prevalent in predominant millet growing states like Karnataka, Maharashtra, Tamil Nadu, Madhya Pradesh, Bihar, and Andhra Pradesh.

Causal Organism

U. setariae-italica (foxtail millet), *Uromyces eragrostidis* (finger millet), *Puccinia substriata* (kodo millet), and *U. linearis* (little and proso millet). The rust fungus produced both uredial and telial stages. Uredospores are yellowish-brown, stalked, oval to globose, echinulate with 3–4 germ pores, while teliospores are dark brown colored, single celled, pedicellate, oblong to globose by possessing smooth and thick walls which gets more concentrated towards apex rather on its base.

Host Range

Finger millet, foxtail millet, kodo millet, pearl millet and little millet etc. Various pathogens infecting small millets are harboring on graminaceous hosts as collateral hosts.

Epidemiology

Low temperature and high relative humidity are favorable for initiation of rust disease. With the congenial weather conditions prevailing during December and January, rust appears early in the season, i.e., within 20–25 days after sowing and the severity of rust increases with the plant ages (Viswanath and Seetharam 1989).

Symptomatology

The disease has potential to affects the crop at all growth stages; however, the damage is severe only when infection starts before flowering. Disease starts as small, brown uredosori on both the sides of the leaf. Mature and broken pustules arranged linearly on the upper surface of the leaves; however, pustules cover entire leaf blade rather than linear form. Infection can be observed on the most foliar plant parts like leaf sheath, culms, and stem. The disease is relatively more severe on the upper leaves in contrast to middle and lower leaves. Under severe infection, premature drying of leaves and poor grain set are commonly observed in field. Morphology of spore production is different in all the rusts which includes production of light yellow black teliospores in *U. setariae-italica* and *U. linearis*, respectively. *P. substriata* develops small brown, oval spots on upper surfaces of leaf. The teliospores are dark brown colored, single celled, stalked, oblong to globose shaped with smooth and thick walls (Kumar and Singh 2010).

Disease Cycle

The uredospores perpetuate, spread, and infect the host and reproduce by forming uredia in 7–10 days. Collateral hosts such as most graminaceous weed species possibly play an important role in its disease cycle by aids in perpetuation. Early infection of rust appears within 20–25 days of sowing depending on prevalence of inoculum and favorable weather while the intensity increases as the plants grow older. The dark telial pustules develop at the time of crop maturity (Nagaraja et al. 2007a, b).

Characterization of Pathogen

Genus level characterization of rust pathogens can be done based on the microscopic analysis of the uredospores and teliospores based on their color, size, shape, echinulations, presence or absence of stalk, septations, etc.; however, the species demarcation is difficult based on morphological characteristics. Hence, molecular features are of increasing importance owing to their consistency, easy application, and conserved throughout the genus. Molecular regions targeted for species differentiation are majorly based on *ITS*, *LSU*, *SSU* regions, etc.; nevertheless the extraction of genomic DNA is challenging which need to be taken care (Bai et al. 2021).

5.2.1.4 Smuts

Small millets possess potential to cope up with biotic factors; however many pathogens have emerged as threat to the millet cultivation. Among them, smut pathogens are one of the large groups causing varying damaging symptoms at different intensities depending on the genotype and favorable conditions. Smut pathogens belonging to different genus viz., *Ustilago* spp., *Melanopsichium* spp., *Sporisorium* spp., etc. are known to attack all the small millets and produce different kinds of symptoms like grain smut, head smut, and kernel smut. Among the smuts, the grain smut is common on finger, foxtail, and barnyard millet, while head smut is common in kodo, barnyard and proso millet (Das et al. 2017). Generally, smuts of small millets are of minor importance owing to their sporadic nature of occurrence and low economic losses, these smuts can be controlled by practicing clean cultivation as well as seed treatment with fungicides.

Grain Smut

Grain smuts are the most commonly occurring smut diseases compared to the other smuts in small millets. These are common in finger, little, barnyard, foxtail, and proso millet inciting by different genus. Ragi grain smut was first reported by Kulkarni (1922) from Kolhapur. Later, its occurrence was recorded by many scientists such as Coleman (1920), McRae (1924), Narasimhan (1934), Mundkur (1939), and Venkatarayan (1947) in Mysore state province.

Causal Organism

Melanopsichium eleusinis (finger millet), *Macalpinomyces sharmae* (little millet), *Ustilago panici-frumentacei* (barnyard millet), and *Ustilago crameri* (foxtail and proso millet).

Economic Importance

Although the grain smut is negligible important, Mantur (1994) stated that they possess the ability to appear in epidemic form with an infection of 200 grains per ear. Recent studies showed the change of virulence in grain smut pathogens, known summer diseases have appeared to infect during *Kharif* also. Losses caused by *U. crameri* ranges 8–50% of the grain yield (Nagaraja et al. 2007a, b) and 75% of grain infection (Sundararaman 1921). Jain and Tripathi (2002) investigated yield loss due grain smut in little millet showed 9.80–53.55% reduction in grain yield and 6.40–38.90% of panicle length.

Epidemiology

Low temperature and high relative humidity are congenial conditions for rapid development and spread of the disease. The fungus attack majority of the grains in an ear by producing sori in flowers and basal parts of palea; however, terminal portion of the spike may escape the infection. The sori are pale greyish and measure 2–4 mm in diameter. On maturation, the sori rupture and produce dark powdery (dusty) mass of spores. The spores are dark brown colored, angular to round with smooth walls measuring 7–10 μm diameter (Das et al. 2017).

Symptomatology

The symptoms of grain smut can be observed at grain formation stage, i.e., within few days after flowering. The affected ovaries initially turn into velvety greenish smut sori without increase in size than the normal grain. Eventually, the glumes are pushed apart by the transformed spore balls (sori) which are several times bigger in size. The sorus remains enclosed by thin and delicate membrane, which later easily get ruptured exposing the sorus. The greenish outer tunica of the sorus gradually turns pinkish green and finally to dirty black on maturation (Thirumalachar and Mundkur 1947). With the wind, loosened spores are easily blown away leaving nothing inside the glumes. Occasionally, infected grains of some crops develop late in season, remain greenish, and slowly increase in size which release spores upon pressing (Sharma and Khare 1987).

Disease Cycle

Grain smuts are majorly externally seed and airborne pathogens. Infection of flowers occurs through secondary inoculum, i.e., air borne spores. Very limited systemic research has been done on grain and head smuts. Soil borne infection has also been observed. Fungus serves are dormant dikaryotic mycelium in the seed tissues which serves as primary inoculum to the following season (Wang 1943).

Head Smut

Head smut in small millets are relatively minor importance with low economic losses unless left uncontrolled under conditions of fulfilling disease triangle. It is more common in countries like Europe, Australia, Eastern Asia etc. In India, it is known to occur widespread on kodo, barnyard and proso millet which have been consistently reported from Karnataka, Madhya Pradesh (Pall et al. 1980), Tamil Nadu and Uttarakhand (Kumar et al. 2007).

Causal Organism

Sorosporium paspali-thunbergii (Henn.) S.Ito [Syn: *Sorosporium paspali* Mc Alp.] infecting kodo millet, *Sporisorium destruens* (Schltdl.) Vánky [Syn: *Sphacelotheca destruens*] infecting proso millet and *Ustilago crus-galli* Tracy & Earle causing head smut of barnyard millet.

Teliospores of *S. paspali* produced on loose spore ball like masses. Gradually, spore ball split into individual spores with little pressure. The individual spores are globose, angular to roughly pear shaped, dark to yellowish brown with thick smooth wall. The spore germinates by producing septate, single or branched hyphae constricted at septum, which bears lateral and terminal sporidia.

Economic Importance

S. paspali became endemic but its distribution and severity vary with environment and cultivar. Viswanath (1992) reported 30–40% loss in grain yield due to *S. paspali*. Jain and Yadava (1997) observed that loss in yield ranges 13.15–32.98% vary with smut incidence.

Epidemiology

Head smut is externally seed borne which appear sporadically late in the crop season when the crop is about to mature. Temperature range 20–25 °C is optimum for initiation and colonization of infection.

Symptomatology

Diagnostic symptom of head smut is the transformation of entire panicle into single sorus in which the inflorescence is deformed and turn to smut ball. Head smut causing pathogen infects only ovaries of the plant. In addition, head smut also produces some of characteristic symptoms viz., gall-like swellings on stem, nodes of young shoots and in the axils of the older leaves. Sometimes, twisted, deformed clusters of leafy shoots with aborted ears may also develop. The affected ovaries manipulated into hairy, round and grey sac which initially does not increase in size. The gall-like swellings are covered by a hairy rough membrane of host tissue (Mundkur 1943) which on rupturing expose the spore mass carried by wind.

Disease Cycle

The disease is mainly externally seed borne; hence the initial seedling infection starts by penetration of germ tube from seedborne teliospores through the cell wall. After entering into the seedling tissue, the hyphae spread inter and intra-cellularly and become systemic infection which eventually enters the meristematic tissues and finally infects the ear by the time of crop maturation (Kumar and Singh 2010).

Kernel Smut

Kernel smut is a minor disease affecting barnyard millet occasionally in unprotected cultivation. It was first noticed in Italy while in India, Viswanath and Seetharam (1989) reported the incidence of kernel smut from Bihar, Maharashtra, and Tamil Nadu.

Causal Organism

Ustilago paradoxa Syd., P. Syd. & E.J. Butler

Chlamydospores produced by *U. paradoxa* are smooth, olive brown in color and round which measures up to 7–11 μm in diameter.

Symptomatology

Fungi cause infection at the time of flowering which further convert floral parts into fungal bodies resembles greenish swollen bodies. Infection occurs in scattered manner with only few grains gets affected in an ear, i.e., up to 25 grains/ear by forming smut sori of 1.5–4 × 1–2 mm (Nagaraja et al. 2016).

Characterization of Pathogen

Diagnosis of the smut diseases under field conditions can be easily done because of their unique dusty appearance of reproductive parts but the characterization to the genus level is only possible with the microscopic studies of teliospore bodies based on their size, color, shape, septation, arrangement in sori, echinulations etc.

However, the proper species distinction is possibly through molecular analysis using molecular markers like RAPD, RFLP, SSR, SNP etc. Another challenging aspect of smut characterization is the genomic DNA isolation from spores which is different from regular CTAB protocols and needed to be taken care of during the characterization (Ladhalakshmi et al. 2012; Goswami et al. 2022).

5.2.1.5 Downy Mildews

This disease is also referred as crazy top/green ear disease. Downy mildew is a one of the major threats of finger and foxtail millet occurring widely in predominant millet growing regions of world. In India, green ear of ragi was first reported by Venkatarayan (1947) in erstwhile Mysore state, followed by Tamil Nadu and Uttarakhand (Kumar et al. 2007), whereas downy mildew of foxtail millet was reported from many parts of India such as Karnataka, Tamil Nadu, Maharashtra, Bihar, Andhra Pradesh, and Kashmir (Rangaswami and Mahadevan 1999). The disease has potential to be destructive leading to total crop failure owing to underdevelopment of the affected ears result in substantially yield losses ranges up to 50% (Pall et al. 1980).

Causal Organism

Sclerophthora macrospora (Sacc.) Thirum. [Syn. *Sclerospora macrospora* Sacc.] infecting finger millet whereas, *Sclerospora graminicola* (Sacc.) J. Schröt. infects foxtail millet.

Host Range

Finger millet, foxtail millet, pearl millet, maize, *Eleusina indica* (Ulstrup 1955), wheat, oat, *Eragrostis pectinacea,* and *Digitaria marginata*.

Epidemiology

Moderately high temperature (25–30 °C) and high relative humidity is highly favorable for disease development. Temperature around 22–25 °C during night enhance the production of sporangia and facilitates the release of zoospore from sporangia. Raghavendra and Safeeulla (1973) reported the internal and external seed borne nature of the pathogen.

Symptomatology

Early symptom of downy mildew affected plant is the chlorosis of seedling leaves. Characteristic symptoms of downy mildew affected plants are stunting with shortened internodes and profuse tillering. Also, pale yellow translucent lesions are observed on infected leaves. Whitish bloom of sporangiophores and sporangia are prominently noticed on the leaf surface under humid conditions. Plants with mild infection may develop ears, but malformed into green leafy structures giving "green ear" symptom. While the fungus usually invades the entire ear, sometimes only a portion of the ear is involved, the remainder producing normal grains. On maturation, chlorotic patches can be seen on the upper surface of leaf with corresponding downy fungus growth on the lower surface (Kumar and Singh 2010; Nagaraja et al. 2016).

The downy mildew of finger millet generally doesn't show the characteristic symptom, i.e., white cottony growth under-side of leaves. Hence, the disease can only be identified after the formation of ears (reproductive stage of plant). Eventually, partial/whole ear including palea, lemma, and glumes change into leafy-like structures. The proliferation takes place first in the basal spikelet and spreads towards tip. On maturation, the whole ear shows a bush-like appearance with typical "green ear" symptom (Thirumalachar and Narasimhan 1949).

Disease Cycle

The downy mildew fungus is an obligate parasite and found to be both internally and externally seed borne (Raghavendra and Safeeulla 1973) with broad host range. Pathogen life cycle in small millets was elaborated by Safeeulla (1955). Here, the primary inoculum is mainly soil or seed borne oospores. Disease severity is influenced majorly by temperature and soil moisture content and time of sowing. It requires an optimum soil temperature of 20–21 °C with minimum of 12–13 °C and maximum of 30 °C for initiation of infection by the pathogen. Early sown crop in contrast to late/timely sown crop is more prone to attack by downy mildew pathogens. High relative humidity and high soil moisture content favors rapid development of the disease (Nagaraja et al. 2007a, b). Recently high incidence of downy mildew was observed in two popular finger millet varieties viz., GPU 28 (blast resistant) and PR 202 (blast susceptible) in the farmers field of Tumkur district in Karnataka.

Characterization of Pathogen

Diagnosis of the diseases under field conditions is easy due to their unique above-briefed symptoms of downy fungal growth on lower side of leaves and corresponding chlorotic patches on upper leaf surface as well as formation of green ear symptom. Being an obligate pathogen, downy mildew fungus can't be cultured on artificial media to study their morphological characteristics. However, microscopic examination of the pathogen can be done by observing the conidia, conidiophores, oogonia and oospore etc. Morphological characterization is carried for the genus-level identification based on the conidiophore branching pattern, kind of germination, production of sporangia/conidia etc.; morphological classification is further confirmed and extended to species-level distinction by genomic DNA isolation and amplification of conserved molecular regions viz., *ITS*, *LSU,* and *cox2* genes (Kara et al. 2020). Nevertheless, the challenges in characterization of downy mildew pathogen are not scarce in which genomic DNA isolation is the primary concern that needs to be carried from the fungal filaments or spores scraped from infected leaves.

5.2.1.6 Foot Rot or Wilt of Ragi

Earliest report of the foot rot/wilt disease was done by Coleman in 1920 from Mysore state. Afterwards, it was reported from different parts of India where finger millet is cultivated. In ragi, losses may reach up to 50% under field conditions with congenial weather (Basta and Tamang (1983). The disease has been reported mostly from Karnataka, Tamil Nadu, Gujarat, and Odisha. Due to the sporadic nature, it was considered of as minor disease but recent studies have shown increased incidence of the disease under irrigated conditions.

Causal Organism

Sclerotium rolfsii Sacc. [Perfect Stage: *Athelia rolfsii* (Curzi) C.C. Tu & Kimbr.] or *S. rolfsii* (Perfect state: *Pellicularia rolfsii*). Imperfect stage is prevalent mostly in both the field and laboratory conditions while perfect stage can be seen rarely under favorable situation where fertile sporophores are also produced.

Host Range

S. rolfsii has broad host range (Aycock 1966) but among the small millets, finger millet is the only host reported so far.

Epidemiology

Fungus overwinters as sclerotia in soil which acts as the primary source of inoculum. Sandy loam soils with low moisture upsurge the disease incidence. The disease development is favored by warm temperature and high relative humidity which exists during monsoon season.

Symptomatology

Generally, plants are attacked at inflorescence or seed formation stage. Infection occurs just above the soil line in the collar region of the plant. The affected area is water-soaked initially which late turns brown or dark brown which finally shrinks which cause wilting of the entire plant. The cottony white growth of the fungus is evident on different plant parts which become roundish ultimately turning into velvety mustard seed like sclerotial bodies.

Disease Cycle

The fungus survives as sclerotia in soil which is the source of primary infection. The sclerotia germinates with the on the onset of rainy season to produce basidia and each basidia produce four haploid basidiospores. The fungus attacks the collar region of the plant which becomes infected leading to the death of the entire plant. At the end of the cropping season due to lack of available nutrients and onset of unfavorable climatic conditions, fungus forms as mass of tightly packed mycelia called sclerotia. These bodies can be seen easily on the plant which are old and about to die. These sclerotia get accumulated in soil with plant debris and move through rain water from field to field.

Characterization of the Pathogen

Diagnosis of finger millet foot rot can be done based on their symptoms which appear initially at soil line as water-soaked lesions and observation of sclerotial bodies on sheath with coalesced patches. Systemic studies on characterization of

S. rolfsii are vast in various food crops based on morphological attributes like mycelial morphology, pattern of sclerotial production while molecular confirmation is based on analysis of molecular gene regions like *ITS*, *LSU*, *SSU*, *beta-tubulin*, *TEF*, *rpb2*, etc. (Mahadevakumar et al. 2016).

5.2.1.7 Banded Sheath Blight (BSB)

Earliest report of banded sheath blight (BSB) was on finger millet at Vellayani, Kerala, India (Das and Girija 1989). Thereafter, reports on prevalence of disease in severe forms were also reported from experimental plots of Birsa Agricultural University, Ranchi (Dubey 1995). Since then, the disease has been observed commonly on all small millet growing areas of hot and humid climatic regions.

Causal Organism

Rhizoctonia solani (Basidial state: *Thanatephorus cucumeris*)

The fungus produces dull (cream) white mycelial colony which later turn light brown in color. *R. solani* is identified by its characteristic branching at right angle and constrictions on the point of branching.

Host Range

Similar to *S. rolfsii*, *R. solani* has the wide host range among agriculture and horticultural crops. All the small millets viz. finger, foxtail, barnyard, proso, kodo, and little millets are the host for the pathogen.

Epidemiology

Pathogen survives the weather extremities in soil as sclerotia which will act as the primary source of inoculum for next season. Disease is favored by moderate temperature (26 ± 2 °C) and high relative humidity (>80%) (Dubey 1995). Low disease severity is observed on the late maturing varieties due to disease escapes in autumn as the low temperature prevails (Patro 2008).

Economic Importance

BSB generally does not cause high economic losses. However, upon completing disease triangle, disease has the potential to cause huge economic losses. Infection on peduncle results neck rot which deteriorate the grain production due to poor grain filling result in formation of small and shrivelled grains.

Symptomatology

The disease symptoms appear on the lower leaves and leaf sheath as oval to irregular spots. Initially the lesions are light grey to dark brown in color whose center turns white with narrow reddish-brown border. The lesions are distributed throughout the leaf lamina. Under congenial environment, all the lesions may also enlarge and coalesce to cover the entire leaf sheath and lamina appearing as brown colored characteristic bands across the plant leaf. Hence, the entire leaf becomes blighted and dries up. Symptoms are also observed on peduncles, fingers, and glumes. Mycelial growth and sclerotia can also be observed on the lesions under humid conditions (Das et al. 2016).

Disease Cycle

R. solani survives as dormant mycelium which is germinates to produce infective mycelium under prevailing favorable weather (high relative humidity and moderate temperature). Symptoms are visible as small irregular or oval brown spots on lower leaf lamina which later enlarge and coalesce to form bands. Numerous sclerotia are observed on the blighted leaves which subsequently dies. The fungus also spreads from field to field through irrigation water, infected soil and plant debris.

Characterization of the Pathogen

Banded sheath blight can be well diagnosed under favorable field conditions due to their appearance of blight on sheath and presence of sclerotia in severe infections. *R. solani* is well studied pathogens regarding its characterization based on morphological and genomic attributes. Owing to their broad host range, cross-infectivity studies among crops are gaining importance which confirms the anastomosis grouping of *R. solani* and their specificity to the host species (Al-Fadhal et al. 2019; Pralhad et al. 2019).

5.2.2 Minor Fungal Diseases of Small Millets

Apart from the major diseases affecting the production potential of small millets throughout the millet growing areas of world, there are some diseases which are of course not negligible but of relatively minor importance owing to their irregular occurrence and damage to the crop and its produce. Such diseases were also listed in Table 5.1 includes cercospora leaf spot of ragi (*Cercospora eleusinis*), Udbatta diseases (*Ephelis oryzae*) affecting kodo, foxtail, proso and little millet, sheath rot (*Sarocladium oryzae*) of kodo millet, and grain mold in finger millet etc. Albeit, these diseases are less important in small millet cultivation which can be eliminated by protective cultivation, some of them are most destructive in other graminaceous crops like major millets (viz., sorghum, pearl millet) and maize, where it showed to cause huge economic losses especially the grain mold caused by different deuteromycetes and ergot caused by *Claviceps* spp. Among these minor diseases, Udbatta caused by *E. oryzae* are of relative importance due to its effect on kodo and little millet in which affected panicles are transformed into a compact *agarbatti* like shape, hence the name "Udbatta" (Kumar and Singh 2010; Das et al. 2016; Nagaraja et al. 2016).

5.2.3 Bacterial Diseases of Small Millets

Along with fungal diseases, a variety of bacterial diseases has been an inconsistent constraint to the small millet cultivation. Diseases caused by bacterial pathogens are of lesser importance compared to the fungal pathogens unless favored by the prevailing environmental conditions, presence of susceptible cultivar and ample amount of inoculum during cropping season. They have been reported on all the small millets in some millet growing corners yet they failed to establish as major factors under natural conditions. Some of the important bacterial diseases are bacterial leaf spot caused by *Xanthomonas eleusinae* and *Pseudomonas albo-precepitans* in finger and foxtail millet, respectively, bacterial leaf stripe (*Pseudomonas* spp.) in finger and proso millet, bacterial leaf streak (*Xanthomonas* spp. and *Pseudomonas* spp.) in most of small millets and bacterial blight (*Xanthomonas axonopodis* pv. *coracanae*) in finger millet etc.

Systemic studies on bacterial diseases of small millets are very much limited due to which the literature available is scarce. Generally, bacterial entry to the plant tissues takes place mainly through natural opening like stomata or through wounds (physical injury) during inter-cultivation operations or insect damage on leaves, sheath, and roots. In the absence of main host, bacteria survive in infected crop debris/residues left in the soil and also on graminaceous weeds and other crop hosts. Disease development for bacterial pathogens is favored by warm temperature and high humidity (Nagaraja et al. 2007a, b; Das et al. 2017).

5.2.4 Viral Diseases of Small Millets

Unlike other food crops, small millets are less affected by the viral pathogens which might be due to their inherent capacity to sustain in moderately extreme agro-ecological conditions and potential against virus and their transmitting agents. Diseases caused by the viral pathogens are of mere important in the small millet cultivation which occurs once in a while but couldn't able to show consistent infection to the crop. Of all the small millets, viral diseases majorly prevalent in finger, proso, and barnyard millet and has been reported from many parts of the world with less virulent infection. In general, viral pathogens cause symptoms like chlorotic stripe, streak, mosaic or mottling symptoms on leaves while the early infection results sterility of the plant where the plant bears no ear. However, finger millet is reported to be affected by many viral pathogens and cause notable diseases viz., ragi mottle streak disease (*Ragi mottle streak virus*), ragi severe mosaic (*Sugarcane mosaic virus*), and ragi streak disease (*Eleusine* strain of *Maize streak virus*). Likewise, barnyard millet (*Wheat streak virus*, *Sugarcane mosaic virus* and *Eleusine virus 2*) and proso millet (*Wheat streak virus*, *Rice dwarf or stunt virus* and *Maize leaf streak virus*) are also reported to be attacked by viral pathogens in recent past. Transmission of viruses through biotic agents like insect and non-insect vectors serves as inoculum which spread to the healthy fields (Nagaraja et al. 2016; Das et al. 2017).

Despite of their minor effect on small millets, many instances have shown that viruses are potential agents that can lead to enormous crop losses. One such instance in finger millet was reported from Chitradurga and Bangalore districts of Karnataka during *Kharif* 1966 where the farmers have to abandoned their ragi crop due to the severe infection by *sugarcane mosaic virus* which results in infected plants failed to set seed (Joshi et al. 1966).

5.2.5 Mitigation Strategies of Prominent Diseases of Small Millets

5.2.5.1 Cultural Practices

Several agricultural practices such as timely sowing, maintaining optimum plant populations and spacing, timely weeding, balanced use of fertilizers, crop rotation, deep ploughing during summer season, removal of crop residues from the field, cleaning of field bunds after crop season, uprooting the diseased plant from the field and burning, regulating irrigation water from entering into other field etc. will help in reducing chances of disease occurrence. Some of the important cultural practices which helps in millet disease management are as follows:

Methods	Disease managed
Crop rotation	Majorly controls seed and soil borne pathogens viz., downy mildew, ergot, smut, banded blight and sheath rot
Deep summer ploughing	Expose resting spores of the pathogen and controls disease like downy mildew, smut, and a few fungal and bacterial leaf diseases
Adjustment of date of sowing	Early sowing reduces blast and rust severity
Optimization of plant population	High plant population favors disease development, so maintaining optimal plant population helps in managing disease like downy mildew, blast, rust, and grain mold in millets
Use of disease free seeds	Most eco-friendly method for controlling any kind of disease. In millets downy mildew, banded sheath blight, foot rot, ergot and blast can be managed using disease free seeds
Sanitation	This helps in the reduction of primary inoculum and surviving structures of the pathogen. Downy mildew, banded sheath blight, foot rot, ergot, and blast can be controlled by this method
Eradication of alternate and collateral hosts	Their timely removal helps to control diseases like ergot, downy mildew, rust, blast, leaf spots, and bacterial and viral diseases
Fertilizer management	Nutrient can affect the relationship between crop and pathogen in many ways. Regulating the amount of nitrogenous fertilizer reduces incidence of blast and downy mildew
Vector management	A number of viral, bacterial and some of the fungal diseases may get introduced through the visits of their respective vectors to the hosts. For this reason, eradication of such pathogens should include this measure to get the optimum result
Clean cultivation	Practice of clean cultivation like collecting smutted heads in cloth bags and dipping in boiling water to kill the pathogen will reduce the inoculum for the next year and minimize incidence

5.2.5.2 Host Plant Resistance

Exploiting host resistance to control disease is not only economical but also a practical necessity in a low value crop like millets where there is a limitation for

Table 5.2 Disease resistant varieties identified and released for the different sorghum growing areas of India (2000–2018)

Crop	Disease	Resistant or tolerant cultivars
Finger millet	Blast	GPU 26, GPU 45, Chilika (OEB 10), VL 315, GPU 48, PRM 1, Bharathi (VR 762), Srichaitanya, KMR 301, KOPN 235, OEB 526, OEB 532, PPR 2700 (Vakula), VL 352, GNN-6, GN-5, VL Mandua-348, KMR 340, Dapoli-2 (SCN-6), CO 15
Foxtail millet	Downy mildew	Meera (SR 16), SiA 3085, RAU (Rajendra Kauni 1–2)
	Rust	TNAU 196, RAU (Rajendra Kauni 1–2)
	Blast	RAU (Rajendra Kauni 1–2), SiA 3085
	Brown spot, smut and leaf blight	RAU (Rajendra Kauni 1–2)
Barnyard millet	Grain smut	VL Madira
	Blast	Tarini (OLM 203), GNV-3
	Grain smut	Tarini (OLM 203), OLM 217 and GNV-3
	Rust	OLM 217
	Brown spot	Kolab (OLM 36)
	Sheath blight	Kolab (OLM 36), GNV-3
	Head smut	Jawahar Kutki 4 (JK 4)
Proso millet	Brown spot	GPUP 8
	Leaf blight	PRC 1
Kodo millet	Head smut	Jawaharkodo 155 (RBK 155), Jawaharkodo 48 (JK 48), JK 106, JK 65, JK 98, Jawaharkodo 137, JK 13

any additional cash inputs such as fungicides etc. Development of resistance varieties is the best means of combating the disease, which is predominantly grown by resource-poor and marginal farmers. Disease resistant varieties identified and released for the different millets growing areas of India are tabulated in Table 5.2 (www.aicrpsm.res.in).

5.2.5.3 Biological Control

Biological control is an alternative to synthetic chemical pesticides and having several benefits to human beings and ecosystem; they can ensure the protection of plants against biotic and abiotic stresses, production of good quality grains, improve soil fertility, sustainable and safety of environment. The demand for development and application of indigenous bioinoculant products has increased among researchers because of their role in plant growth promotion and crop protection in sustainable farming systems and also for their economic value. Soil-borne diseases of millets (e.g., foot rot in finger millet and Banded sheath blight in small millets), for which adequate host resistance is lacking, use of biocontrol agents are useful. Bio-control agents especially strains of *Trichoderma* and *Pseudomonas* are useful for seed and soil borne diseases of millets and can be applied as seed treatment and soil application.

5.2.5.4 Chemical Control

Disease	Chemical control
Downy mildew	Seed treatment with Ridomyl-MZ at 6 g/kg seed followed by one or two need based spray of Ridomyl-MZ at 3 g/L reduces incidence
Blast	Seed treatment with carbendazim at 1 g/kg of seed. Spray any one of the fungicides viz., Carbendazim (0.2%) or Iprobenphos (IBP) (0.1%) or premixture fungicide (Carbendazim + Mancozeb) (0.1%), Ediphenphos (0.1%) or propiconazole (0.1%) or Tricyclazole (0.1%). First spray immediately after noticing the symptoms. Need based second and third sprays at flowering stage at 15 days interval to control neck and finger infection in finger millet
Grain mold	Spray any one of the following fungicides in case of intermittent rainfall during earhead emergence, a week later and during milky stage. Mancozeb + Captan at 0.2%, thiram + carbendazim at 0.2%, Propiconazole at 0.1%. Two to three sprays should be taken up to reduce the grain mold
Smuts	Seed dressing with sulfur at 4 g/kg seed
Banded sheath blight	Seed treatment with Mancozeb at 2–3 g/kg. Seed and need based spray with the fungicides viz., propiconazole at 1 mL/L orhexaconazole at 2 mL/L or Validamycin at 2 mL/L is highly effective
Rust	Foliar spray of Mancozeb (0.2%), hexaconazole (0.1%), difenconazole (0.1%) and propiconazole (0.1%) for control of disease. Two sprays at 15 days interval immediately after appearance of symptoms is recommend better management of the disease
Leaf spot/leaf blight	Seed treatment with carbendazim at 2 g/kg or mancozeb 0.2% and need based spray

5.2.6 Novel Strategies for Enhanced Control of Small Millet Diseases

Changing climate scenario following the cultivation practices of small millets has resulted in increasing reports of new diseases as well as the enhanced aggressiveness of established pathogens. Besides the unique advantages offered by various existing management strategies, they do carry few limitations under current perspective. Management of small millet diseases under current situation needs not only the conventional approach but also the innovative, cost effective, feasible, efficient mitigation strategies which can be included in the integrated disease management (IDM). By keeping in the view of enhanced cost of cultivation due to agrochemicals, novel ecofriendly strategies need to be explored for controlling the diseases which will serve as best alternative rather than replacement. Such novel green technologies include nanomolecule formulations, endophytes biopriming, use of rhizosphere, phyllosphere-derived bioagents, employing biofumigation techniques, plant immunization approaches (Singh and Gopala 2021), genome assisted breeding methods, genome editing techniques and multi-omics approach etc.

- Germplasm exploitation: Achieving durable plant resistance to diseases is ultimate goal of plant disease management which minimizes the use of chemicals. Analyze the new germplasm and other possible wild relatives for the source of major gene resistance which can be used for breeding into elite cultivars with molecular marker-based breeding methods and development of resistant varieties in relatively short time.
- Use of Microbiome concept: In recent years, use of microbiome in plant disease management has revolutionized by the ways how microbiome interacting with plants and in the environment are perceived which may lead to a switch away from the conventional-driven research and implementation. The potential relevance of microbiome usage in disease management is clear but needs to be exploited by further research (Jeger et al. 2021).
- Use of genomic tools (CRISPR/Cas9) for improved resistance/control: CRISPR/Cas9 system has been utilized vastly in the field of plant pathology and plant breeding for various approaches. This system facilitates genome editing of various organisms precisely using RNA-guided DNA endonuclease activity. It has been exploited to enhance disease resistance in different commercial crops such as rice, wheat, tomato, and grape. Apart from the genome editing of crops, genome editing of fungal and fungi-like pathogens can also provide new insights for plant disease management in eco-friendly manner. Durable management of plant diseases perceives the targeting of multiple plant disease resistance mechanisms with CRISPR/Cas9. The insights gained by probing fungal and oomycete genomes with this system will be powerful approaches (Paul et al. 2021) and will be dual purpose, i.e., for deep understanding the pathogen as well as framing management strategies. CRISPR/Cas9 system has facilitated targeted mutagenesis efficiently and precisely in plants to enhance resistance to fungal diseases.
- Multi-omics approach: It facilitates the comprehensive understanding of the mechanisms underlying ability and nature of plant-mediated effects during interactions of plant tissue and the microbial communities. Multi-omics approach allows to study different plant defense pathways as well as the pathogen response to counteract them by producing various toxic metabolites. There are many pathways apparent in plants needs to be explored for a better understanding and control such as salicylic acid (SA) signaling pathway as prime importance followed by other critical plant hormones such as abscisic acid and jasmonic acid which regulates acquired resistance in plants and mediates the interactions between members of plant microbial communities (Crandall et al. 2020).

5.2.7 Looking into the Future of Small Millet Diseases and Conclusion

With the everyday increasing population of world demands, not only the food security but also the nutritional security are combined to form agricultural sustainability. Updated reports show that the agricultural production needs to be increased 50% by 2050 to meet the growing food and nutritional demand (FAO 2020). Nutritional security is as much important as food security for better quality of life which can be fulfilled by the cultivation of millets on large scale. Erstwhile commercial crops like rice, wheat, sugarcane, maize, etc. have been given more importance owing to their wide distribution and acceptance as daily food. In recent times, millets especially small millets gain huge attention with growing health concerns which are fulfilling by their nutraceutical properties. This results in increasing area of cultivation followed by bringing new problems, i.e., new reports of pests and diseases throughout the predominant millet growing areas which were unseen before on particular crop.

However, systemic research in small millets on many aspects like breeding of new varieties, sequencing of genome, etc. are still underway. With the advent of advanced genomic approaches like next generation sequencing (NGS), genome editing techniques, etc. made identification, cloning, and transfer of resistant (R) genes easy. Using of such approaches in small millets aids in better understanding of the crops and paves way for possible manipulation of crop genome to generate disease-resistant crops which is an ecofriendly perspective. This will make the small millets possibly the ecofriendly alternative for nutraceutical supplement, cost effective due to no use of pesticides, farmer friendly. Also, surveillance of the established diseases and regular monitoring of new diseases aid in achieving the food and nutritional security.

It is concluded that the fungal diseases pose a significant challenge to the small millets production, now and in the future. In this chapter, attempts have been made to briefly summarize the key aspects of some of the most significant diseases of small millets which are threatening its production potential. We acknowledge that, along with major diseases which detailed in chapter, there are many other minor diseases viz., bacterial and viral diseases that also threaten production; however, keeping the space limitations in mind, we have concentrated more onto fungal diseases which are major threat in reality and considered to have the greatest impact on yield. This chapter serves as a reference point for pathologists accompanied in field study in non-exhaustive manner to comprehend the complexity of diseases and to contemplate them in a more holistic manner.

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