Review Article

A Review of:Epidemiology and management practices of fungal and bacterial diseases of pearl millet [*Pennisetum glaucum* (L.) R. Br.]

ABSTRACT

Economic significance of pearl millet has recently received more attention than ever, especially in light of the great nutritional value of gluten-free diets for people with celiac disease. The most major diseases afflict pearl millet include smut, ergot, rust, leaf blast, and green ear disease/downy mildew, despite many new varieties being created throughout the years. Nevertheless, to effectively control them and maximize the crop's economic production, diseases like leaf blast, rust, smut, bacterial leaf spot, stripe, and strike also require early attention. Result, comprehensive data has been gathered in this review within the categories of a etiology, epidemiology, and management practices. The goal of this review is to know the status of pearl millet diseasesis adequately understood, and their correct present management approaches and the need for prospects is underlined.

Key words: Pearl millet, Fungal diseases, Bacterial diseases, Epidemiology, Management

1.INTRODUCTION

Pearl millet remains the main food and economic source for millions of people in the third world. Consumption of "fura," or large balls made of flour, parboiled grains, or fermented drinks, is widespread [1]. India contributes 44% of the world's total millet production to the production of pearl millet. Pearl millet crop is viewed as a species with high hardiness levels due to its excellent drought resilience and low need for soil fertility [2]. For rural residents in the drier parts of the country, it is their primary dietary energy source. From the vantage points of production, consumption, and trade, it is notable that the Ministry of Agriculture and Farmers Welfare of the Government of India has categorized it as "Nutri-Cereals" [3]. It is a plentiful source of many good nutrients, including iron, zinc, folic acid, beta-carotene, and protein. The grain can be used to combat malnutrition brought on by a deficiency in minerals since it has a moderately high content of the vitamins thiamine, riboflavin, and niacin [4, 5]. In addition to being rich in nutrients, it provides a cheap alternative for addressing micronutrient shortages in areas where millet is consumed and has the potential to be used to produce recipes that are very rich in nutrients [6, 7, 8]. It is also utilized for a sizable number of non-food uses, including producing alcohol, animal feed, poultry, and cow feed, and feed for other species [6, 9]. Pearl millet generally contains more protein and fat than sorghum, and its energy content is highest among grains. Bajra is a top cereal for fiber content as well [10].

Unfortunately, the crop suffers substantial losses as a result of several biotic factors. The most major productivity constraints imposed by biotic factors on producing pearl millet are diseases caused by fungi, bacteria, and viruses. Many diseases have been noted in areas where pearl millet is extensively grown. A brief review of the status of fungal and bacterial diseases of pearl millet has been listed here [11].

2. Fungal Diseases

2.1 Downy mildew

One of the main biotic yield-reducing factors is the downy mildew of pearl millet, which is caused by *Sclerospora gruminicola* (Sacc.) Schroter. This is the most significant disease of pearl millet in worldwide [12]. The most significant ailment affecting pearl millet is downy mildew, brought on by the fungus *Sclerospora graminicola* in Asia and Africa [13, 14, 15, 16]. In Asian nations like India, ergot is this crop's second-most dangerous disease [17, 18]. Other serious fungal diseases negatively impact its output other serious fungal diseases negatively impact its output as rust, blast, and smut, as well as bacterial and viral infections [19, 20, 18].

2.1.1 Epidemiology

The two distinct types of symptoms that are brought on by the diseases are downy mildew and green ears. Downy mildew symptoms can appear on the first leaf, although they typically appear on the second and third leaves. Chlorosis of the leaf lamina, which appears as these signs, travels from the infected leaf's base upward. As the plant grows, the chlorosis spreads to the higher leaves the entire lamina on the third or fourth leaf. The abaxial surface of the leaves develops abundant asexual sporulation when the relative humidity is over 95%, and the temperature is moderate, giving the leaves a downy appearance. Plants that have been severely harmed continue to develop slowly and don't produce panicles. Half-leaf symptoms, which have a distinct border between the diseased (basal) region and the non-diseased parts at the tip of the leaf, define the disorder. Because the disease has systemic disease manifestations, if symptoms occur on one leaf, they will also appear on all succeeding leaves and the panicle [21, 22].

The signs of the green ear appear on panicles and are caused by transforming floral elements into leafy structures. The oospore, which has thick walls, a black-walled exosporium, and an adherent oogonial membrane, gave rise to the name "*Sclerospora*" [23, 24]. Oospore germination is thought to occur best at a temperature of 28.2°C. The significance of oospores in the study of disease epidemiology is demonstrated by the significant association between the density of oospores in the soil and the occurrence of disease [25]. The oospores play a vital part in the disease's propagation, just as the spores transferred by seeds are essential to developing downy mildew [26, 27]. Oospores, naturally present in the soil, are the primary source of inoculums and usually infect plants' underground areas when they are in the seedling stage [28].

2.1.2 Management techniques

It is vital to sterilize moist soil for more than two hours to ensure the complete removal of all oospores in the soil because the diseases are spread via oospores found in soil and seed. Oospores can be killed more effectively by steam sterilization [29]. Pre-sowing seed treatment is preferable to fungicide treatment with Thiram and Captan. Metalaxyl has been found to have extremely powerful *in vitro* and *in vivo* activity [30]. Downy mildew disease is effectively controlled by other strobilurin fungicides and oomyceticides [31, 32, 33]. Pearl millet seeds were treated with BABA (Beta amino butyric acid), which increased seedling vigor, protected them from downy mildew, and revealed a 23% increase in disease incidence compared to the control [34]. Raw cow's milk and *Gliocladium virens* seed and soil treatments have been recommended as natural control options *G. virens* controls downy mildew [21]. To increase disease control and seedling vigor, some researchers advise combining biopolymers with fungicide/oomyceticide and using them as seed treatments. In this regard, biopolymers from various plants, including *Acacia arabica*, neem, drumstick, papaya, atrocarpus, and mimosops, have been researched and recommended for use in treating pearl millet seeds along with a half-dose of Metalaxyl, which is very effective in preventing pearl millet downy mildew [35]. *Artemisia pallens, Helianthus annuus*, *Murraya koenigii, Tagetes erecta*, *Citrus sinensis*, *Thuja occidentalis*, *Ocimum basilicum*, *Agave americana*, *Parthenium hysterophorus*, *Dalbergia latifolia*, *Zingiber officinale* are other plants with methanolic extracts that have antisporulant activity against *S. graminicola* [36].

In view of the emergence of metalaxyl resistance, a search for substitute systemic fungicides is currently under progress. Researchers came to the conclusion that acylanilide-series fungicides are the best at preventing downy mildew as a result of the findings. Yet a cost-benefit analysis reveals they are not worthwhile [36, 33]. Therefore, the most recent and effective way to prevent the spread of this deadly pathogen is to cultivate resistant varieties including PHB 10, WCC 75, ICMH 451, Mallikarjuna, ICTP 8203, HB 5, HB-1, and PHB 14. Sometimes, resistance is created in pearl millet by menadione sodium bisulfite treatment of the seeds, which causes the crop's protective enzymes to be amplified before seeding [37]. The use of antagonists has grown over the past few decades because chemical therapies are either environment friendly nor short-lived. *Trichoderma hamatum* treatment of seeds resulted in significantly increased germination rates and stronger pearl millet seedlings [38]. *Bacillus* spp. Treatment of seeds has also been demonstrated to be a practical preventative approach [39]. Treatment with chitosan nanoparticles (CN), made from low molecular weight chitosan, can make pearl millet resistant to *Sclerospora graminicola* [40].

2.2 Ergot

Ergot is a fungus called *Claviceps fusiformis* Lov. Even high-yielding hybrids are particularly vulnerable to declining due to this disease. Losses of between 58 and up to 75% in terms of grain, seed production, seed quality, germination, and seedling emergence have been reported [41]. When an ergot-infected grain is consumed, it can poison pearl millet's consumers, including people, birds, chicks, and animals. Affected organisms exhibit symptoms such nauseousness, vomiting, giddiness, and tiredness [42, 22].

2.2.1 Epidemiology

Between September and October, which are rainy season months, the diseases first appear in the host's inflorescence. Between the glumes of the damaged ear head tissue, sticky, sugary exudates that resemble honeydew are visible. The first indication of infection appears after 8 to 10 days after flowering. A severe infection would make the entire ear head dark to black and mushy and sticky. Honeydew would also flow on the leaves, including many conidia, which are asexual spores. Dark brown to black sclerotia develop during roughly 14–20 days following the appearance of honeydew. Instead of grains, these sclerotia can be seen sticking out from the florets [13, 42].

The disease is disseminated via sclerotia-infected seeds, as well as by soil- and airborne conidial inoculums. Insects that spread the sclerotia inoculum are another factor in the disease's enduring nature. Mature sclerotia may contaminate the grain or fall to the ground during harvest and threshing. These sclerotia serve as the disease's main inoculum in the following year's crop [12].

The ascospores that are produced when the sclerotia germinate might lead to infection in otherwise healthy ear-heads of pearl millet. The sclerotia in semi-arid regions have been found to release asexual spores, commonly known as conidia, after germination. Insects, wind, and raindrops distribute these conidia over the area [43, 12].

2.2.2 Management techniques

The ergot disease is difficult to manage and control. In addition to developing disease-resistant lines, several other management strategies using cultural, chemical, and biological interventions have been documented. Plowing the field deeply during the warm summer months is indicated to lower the main inoculum load of the pathogen. This practice burries the sclerotia to the depth that their germination is prevented. The primary inoculum can be cut down by using seed that is derived from disease-free crops. Hybrids with the characteristics of quick pollination have been shown to be an effective bio-cultural control measure against the disease [42]. Spraying the ear head with fungicides like Cuman-L (200 ppm), Ziram (0.1-0.15%), and Aureofungin has been tried by several researchers with varying degrees of success. 8-hydroxyqunoline has been proven to be 90% effective in controlling the disease.

2.3 Smut

Tolyposporium penicillariae syn. *Moesziomyces penicillariae* is a fungus that causes smut disease, mostly affecting the plant's flowers. Five to thirty percent of harvest loss is attributed to this disease [44, 16]. Senegal was the first country to report the disease, followed by India [16].

2.3.1 Epidemiology

The ovaries in the inflorescence of infected flowers transform into a black powdery mass (sori), signaling the onset of pearl millet smut. The projecting sori between the glumes of a typical grain are often and more significant than the seed they surround, measuring 3–4 mm in length and 2–3 mm in width. Initially, sori is present as a glossy green, but as it ripens, it changes color, moving from green to brown to black. Tiny, dark spores supplant the seed. At maturity, the slimy coating on the sorus bursts and releases the spores within. When mature, spores released into the air cause disease in otherwise healthy panicles [45, 42].

The spore balls are dense, spherical clusters of teleutospores and range in shape from angular to circular, are brown, and are 7-12 m in diameter. There is no way to isolate individual teleutospores. Germination of a teleutospore is promoted at a temperature of 30 degrees Celsius. Teliospores produce a four-celled promycelium that produces lateral and terminal sporidia upon germination. Variable teleutospore development and chainlike sporidia formation on branching hyphae characterize spore balls [42]. In the field, the pathogen's teleutospore (resting spores) and infected seeds or soil are the principal sources of inoculum. Airborne sporidia are responsible for primary infection, which occurs when badly contaminated grains are utilized for planting. Creating a dense mycelialnetwork germinate spores when conditions are right. During the blooming stage, teleutospores from pro mycelia and sporidia germinate and infect the floral organs [45]. After sporidia have landed on the ovaries, it takes 14 days to develop the spore and another 21-28 days for the sori to mature [46].

2.3.2 Management techniques

In order to avoid the germination of fungal spores, thorough ploughing must be performed after the spores have been buried deep in the soil. Intercropping pearl millet with other crops, such as mung bean, is another method that helps reduce the risk of infection. The disease may be efficiently managed in the field with just four sprays of Capatafol, Thiram, or Captan at a 3mg/L concentration. [47] have reported in-vitro evaluation of fungicides against smut pathogen and found thiram providing relatively best inhibition of diametric growth of *T. penicillariae*.

Compared to the field's control, soil treatment with *Gliocladium virens* and raw goat milk and cow milk treated seeds provide up to 60% better protection [48]. It is regarded as a key element of a comprehensive plan for smut control for farmers with insufficient access to resources. Resistance cultivars have recently been created and advised, including DC 7, MPP 7131, and MPP 7108.

2.4 Rust

Rust of pearl millet appears in the later stage of crop growth, mainly during the seed developing stage, commonly occurring after the grain-filling stage, producing a minor reduction in grain production. Rust of pearl millet emerges in the later stage of crop growth. *Puccinia penniseti* Zimm. The pathogen that causes this disease. This disease manifests on the leaf as reddish-orange pustule that can range from circular to oval. The pustules initially appear on the distal half of the leaf, and later they extend over both sides of the leaf. The pustules that have matured burst, releasing rusty spores in the process. There is a possibility that the symptoms will occur not only on the stem but also on other plant sections. Plants with severe rust damage have a rusty, brownish-red appearance [42].

2.4.1 Epidemiology

On pearl millet crops, the first signs of the disease manifest as uredinia pustules that are round and range in color from reddish brown to reddish-orange. The infected leaf eventually dies, starting at the tip and working down. It generates teliospores and uredospores on the crop, the same as other species of Puccinia, and furthermore, on alternate hosts such as *Solanum melongena*, it yields aecial spores [45]. On pearl millet crop *P. substriata* var. *indica* and *Puccinia substriata* var. *penicillariae* generates basidial, uredinial, and telial phases because to its macrocyclic structure. In the latter phases, telia take the role of uredinia and become sub-epidermal, black, and ovoid. The pustules produce a cluster of spores known as urediniospores. These spores are responsible for the spread of rust disease throughout the crops. After some time, pustules darken in color and appear as a type of spore called a teliospore. The leaves become wilted starting at the top and the way down. If the disease incidence is particularly high, additional rust pustules may emerge on the stems, ultimately resulting in the plants' death. The teliospore has a number of tough exterior layers, which allow it to survive for an extended amount of time in the soil. The complete its life cycle, the fungus must first go through the spermatogonial and aecial stages on another host, such as solanum [42].

2.4.2 Management techniques

Chemical treatment involves Propiconazole, Hexaconazole, Copper oxychloride, Carbendazim, Mancozeb, Azadirachtin [49, 50]. At the initial stages, spray with fungicides like Wettable sulfur or Mancozeb is recommended. The fungicide Triadimefon has also performed satisfactorily against pearl millet rust under field conditions and recorded the most minor rust severity. Also, rust of pearl millet can be managed greatly with *Trichoderma viride* [51] and *T. harzianum* [52] spray and is significantly superior to other chemical treatment methods.

Also, cultural practices like adjusting the sowing date so the crop does not flower during September when high rainfall and high relative humidity favour the disease spread are also helpful. To eradicate collateral hosts, the seeds are immersed in the common salt solution, and the floating sclerotia are removed. Furthermore, growing resistant varieties like PHB 10, 14; Co 2, 3, and Bajra are practiced.

2.5 Helminthosporium leaf spot

Helminthosporium bipolarissetariae causes this disease. Little, brown spots or oval to oblong or rectangular patches on leaves are the symptoms of the disease. Lesions may grow and clump together. Lesions typically have a more or less noticeable dark brown border and are tan or greyish-brown. Seedling blight and significant loss could result from an early infection. The collateral hosts, stray crops, crop leftovers, and possibly some seed-borne hosts are how this pathogen perpetuate. Conidia carried by air may aid in the secondary transmission of the diseases [42, 7].

2.5.1 Epidemiology

Many ovals to oblong leaf spots that are brown or have a grey core with brown edges are among the tough leaf spot's field symptoms. Leaf spots on older leaves are characterized by many consolidated spots that cause tip-burn and withering. Before the seed ripened, most plants perished [53].

2.5.2 Management techniques

Practices including deep ploughing, clearing, and removing crop remain from the field, cleaning the infected plants from the field, and burning crop residues are advised to treat this disease [22].

2.6 Cercospora leaf spot

This disease is brought on by the fungus *Cercospora penniseti*, and it typically has a little economic impact.

2.6.1 Epidemiology

Pearl millet may have circular lesions with dark brown edges and pale tan to grey or white cores that are dotted with rows of black conidiophores as the symptoms of leaf spots. Stems can also develop lesions. Thus, it has little economic significance. This pathogen survives on crop debris, stray plants, side hosts, and seed. Airborne spores may cause secondary spread [42, 7].

2.6.2 Management techniques

Practices including deep ploughing, clearing field bunds after the crop season is finished, removing crop remains from the field, uprooting the infected plants from the field, and burning crop residues are advised to treat this disease [12].

3. BACTERIAL DISEASES

3.1 Bacterial leaf spot

The bacterium that causes bacterial leaf spots is *Pseudomonas syringae* [54]. A plant's entire leaf canopy may sustain damage. Although the pathogen primarily affects the leaves, the stem might also show streaks. This bacterium is soil-dwelling and survives by consuming crop residue. When rains strike surfaces and facilitate the movement of bacterial cells to new infection sites, the disease travels to new locations [12].

3.1.1 Epidemiology

The first signs of bacterial spots on leaves are minor, elliptical, or irregularly shaped spots with a straw-colored centre and a black ring. These spots gradually unite to form huge bands. The patches initially have a light, yellowish-brown appearance, but very quickly, they darken to a considerably darker brown. After the disease has progressed to a more severe level, the leaf has split along the stripe. Every leaf of a plant may sustain damage. The predominant attack site for this disease is the leaves, which can also occasionally appear on the peduncle. This bacterium pathogen survives on crop residue in the soil. When rain splashes onto surfaces, the disease is spread secondarily because the bacterial cells are more easily transported to new infection sites. A wet, chilly atmosphere between 12º and 25º degrees Celsius is necessary for disease to thrive [22].

3.1.2 Management techniques

Deep ploughing in the summer, clearing, removing crop bundles, disease plants, and crop residues from the field, burning crop residues, and controlling irrigation water from entering neighboring fields are all examples of field maintenance. In addition to the practices mentioned above, prompt removal of volunteer weeds, wild crop species, collateral, and alternate hosts can help control diseases like ergot because they serve as reservoirs for pathogens and sources of inoculums [12].

3.2 Leaf bacterial stripe

The pathogen responsible for bacterial leaf stripe is *Pseudomonas avenae*. It also goes by the name "bacterium *Acidovorax avenae* subsp. *avenae*" and has been reported seed-borne in graminaceous species [55, 56, 57]. It was first identified in 1909 as the cause of oats' (*Avenae sativa* L.) leaf blight, a disease that affects many species when there is a lot of rainfall and heat [58, 59, 60, 61].

3.2.1 Epidemiology

The formation of the stripes with a water-soaked, reddish-brown look may be seen on the pearl millet growing leaves [62]. The lamina's damaged area almost always seems straw in color. Occasionally, it will even get to the leaf's tip. Hydathodes are also thought to act as the bacterium's point of entry of the pathogen. Although the stripes occasionally reach to the leaf's border, they always leave the midrib and centre of the leaf unaffected [63]. A light brown color darkening can be visible throughout the length of the affected culms and leaf sheeth. The discoloration frequently begins 5 to 7 cm above the base and extends to the leaf sheath. This pathogen is believed to spread internally between plants in latently infected plants and through farm equipment in rice [55, 64]. If agricultural waste products are in the soil, the pathogen can survive there. Since they make it simpler for bacterial cells to reach new infection sites, rain splashes may be to blame for the secondary spread of disease [58, 64].

3.2.2 Management techniques

Both cultural and chemical strategies are used to control the disease. The primary inoculum load of the pathogen is reduced as part of cultural control. It is advised that fields be deeply tilled in the warm summer months to bury the sclerotia as deeply as possible to prevent the sclerotia from sprouting. Using seeds from disease-free crops will reduce the amount of the initial inoculum. A successful bio-cultural control strategy against the disease has been demonstrated by hybrids with rapid pollination traits [65].

3.3 Leaf streak

Caused by the bacterium *Xanthomonas axonopodis* pv. *pennamericanu.*

3.3.1 Epidemiology

Thin, water-soaked, transparent leaf stripes that are 2-3 mm wide and 2-15 mm long are the disease's first visible symptoms. These stripes might appear as early as the seedling's second leaf stage. The lesions become opaque with red rims with oval patches. Moreover, these lesions may enlarge into more prominent regions. In more extreme cases, these lesions may unite to form extensive, uneven streaks and blotches that cover the majority or the entire leaf blade. If agricultural waste products are in the soil, the pathogen can survive there. This disease is most prone to spread in temperatures between 26^o and 30^o C. When temperatures are low in the spring, the disease manifests more severely. It manifests less severely when it's hot and dry in the summer [12].

3.3.2 Management techniques

The primary inoculum can be reduced by using seeds that came from disease-free crops. Quick pollination hybrids have proven to be an efficient biocultural control strategy against the disease [65].

4. CONCLUSION

The need for more food has increased with the population, but the demand for pearl millet is predicted to drop as the crop's output is severely constrained by bacterial, fungal, and other unanticipated diseases. This risk might be reduced if yield stability could also be increased by including drought, insect, and disease resistance or tolerance. The current assessment underscores that because farmers find it difficult to treat broad areas with pesticides, the chemical control is neither economical and environment friendly nor practical to the farmer. As a result, the development of biological and environmentally friendly control measures is urgently needed.

The concern is also expressed over the impact of host-associated microbial communities, the impact of climate change, the incidence and prevalence of disease symptoms, and crop losses. Furthermore, this review emphasizes the need for more significant and focused studies to comprehend the progression of the less well-studied bacterial diseases, their pathogenicity, and disease management in light of the unpredictability of climate change and the emergence of new pathogens like stem rot of pearl millet (*Klebsiella aerogenes*). More thorough research is required to be ready for any forthcoming future disasters.

COMPETETING INTRESTS

Authors have declared that no competing interests exist.

AUTHORS' CONTRIBUTIONS

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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