Review Article

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

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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 celiac disease sufferers. The most major diseases that afflict pearl millet include smut, ergot, rust, leaf blast, and green ear disease/downy mildew, despite the fact that many new varieties have been created throughout the years. Yet, in order 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. As a result, thorough data has been gathered in this review within the categories of a etiology, epidemiology, and management practices. The goal of this review is known the status of pearl millet diseases are properly understood, their correct present management approaches and the need for future prospects is underlined.

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

1.INTRODUCTION

Pearl millet continues to be the main food and economic source for millions of people in the third world nations. 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 levels of hardiness due to its great drought resilience and low needs for soil fertility [2]. For rural residents in the drier parts of the country, it is their main source of dietary energy. 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 nutrients that are good for you, 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 in the production of recipes that are very rich in nutrients [6, 7, 8]. It is also utilized for a sizable number of non-food uses, including as the production of 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 whole grain grains. Bajra is a top cereal for fiber content as well [10].

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

2. Fungal Diseases

2.1 Downy mildew

One of the main biotic yield-reducing factors is downy mildew of pearl millet, which is caused by *Sclerospora gruminicolu* (Sacc.) Schroter. This is the most significant disease of pearl millet in the worldwide [11]. The most significant ailment affecting pearl millet is downy mildew, which is brought on by the fungus *Sclerospora graminicola* in both Asia and Africa [12, 13, 14, 15]. In Asian nations like India, ergot is this crop's second-most dangerous disease [16, 17]. Its output is negatively impacted by other serious fungal diseases as rust, blast, and smut as well as bacterial and viral infections [18, 19, 17].

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 and eventually covers 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, are what 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 [20, 21].

The signs of green ear appear on panicles and are caused by the transformation of 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*" [22, 23]. 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 [24]. The oospores play a vital part in the disease's propagation, just as the spores transferred by seeds are essential to the development of downy mildew [25, 26].

Oospores, which are naturally present in soil, are the main source of inoculums and usually infect plants' underground areas when they are in the seedling stage [27].

2.1.2 Management practices

It is vital to sterilize moist soil for more than two hours in order to ensure the complete removal of all oospores in the soil because the diseases is spread via oospores found in soil and seed. Oospores can be killed more effectively by steam sterilization [28]. A 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 [29]. Downy mildew disease is effectively controlled by other strobilurin fungicides and oomyceticides [30, 31, 32]. Pearl millet seeds were treated with BABA (Beta amino butyric acid), which increased seedling vigour, protected them from downy mildew, and revealed a 23% increase in disease incidence when compared to the control [33]. Raw cow's milk and *Gliocladium virens* seed and soil treatments have been recommended as natural control options *G. virens* controls downy mildew [20]. To increase disease control and seedling vigour, 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 [34]. *Artemisia pallens, Helianthus annuus*, *Murraya koenigii, Tagetes erecta*, *Citrus sinensis*, *Thuja occidentalis*, *Ocimum basilicum*, *Agave americana*, *Parthenium hysterophorus*, *Dalbergia latifolia*, and *Zingiber officinale* are other plants with methanolic extracts that have antisporulant activity against *S. graminicola* [35].

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 [35, 32]. Therefore, the most recent and effective way to prevent the spread of this deadly pathogen is to cultivate disease resistant varieties include 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 [36]. The use of antagonists has grown over the past few decades because chemical therapies are nor environment friendly and short-lived. *Trichoderma hamatum* treatment of seeds resulted in significantly increased germination rates and stronger seedlings for pearl millet as well [37]. *Bacillus* spp. treatment of seeds has also demonstrated to be an effective preventative approach [38]. Treatment with chitosan nanoparticles (CN), made from low molecular weight chitosan, can make pearl millet resistant to *Sclerospora graminicola* [39].

2.2 Ergot

Ergot is a fungus called *Claviceps fusiformis* Lov. Even high-yielding hybrids have shown to be 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 [40]. 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 [41, 21].

2.2.1 Epidemiology

Between September and October, which are rainy season months, the diseases first, appears 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 result in the entire ear head becoming dark to black and becoming mushy and sticky. Honey dew would also flow on the leaves, which would include a lot of conidia, which are asexual spores. Dark brown to black sclerotia develop during a period of roughly 14–20 days following the appearance of honey dew. Instead of grains, these sclerotia can be seen sticking out from the florets [12, 41].

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 crop of the following year [11].

The ascospores that are produced when the sclerotia germinate might lead to infection in otherwise healthy ear-heads of pearl millet. It has been found that the sclerotia in semi-arid regions release asexual spores, commonly known as conidia, after germination. Insects, wind, and raindrops distribute these conidia over the area [42, 11].

2.2.2 Management practices

The ergot disease is difficult to manage and control. In addition to the development of disease-resistant lines, a number of other management strategies using cultural, chemical, and biological interventions have been documented. Plowing the field deeply during the warm summer months is indicated for the purpose of lowering the main inoculum load of the pathogen. This practice burries the sclerotia to depth that their germination is prevented. The primary inoculum can be cut down by using seed that is derived from crops that were disease-free. Hybrids with the characteristics of quick pollination have shown to be an effective bio-cultural control measure against the disease [41]. Spraying the ear-head with fungicides like Cuman-L (200 ppm), Ziram (0.1-0.15%), and Aureofungin has been tried by a number of 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, which mostly affects the plant's flowers. Five to thirty percent of harvest loss is attributed to this disease [43, 15]. Senegal was the first country to report the disease, followed by India [15].

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 larger than the seed they surround, measuring 3–4 mm in length and 2–3 mm in width. Initially, sori present as a glossy green, but as it ripens, it changes color, moving from green to brown to black. The seed is supplanted by tiny, dark spores. At maturity, the slimy coating on sorus bursts and releases the spores within. When mature, spores released into the air cause disease in otherwise healthy panicles [44, 41].

The spore balls are dense, spherical clusters of teleutospores and range in shape from angular to circular, are brown in colour, and are 7-12 m in diameter, and there is no way to isolate individual teleutospores. Germination of a teleutospore is promoted at a temperature of 30 degrees Celsius. Upon germination, teliospores produce a four-celled promycelium that produces lateral and terminal sporidia. Variable teleutospore development and chainlike sporidia formation on branching hyphae characterize spore balls [41]. In the field, the teleutospore (resting spores) of the pathogen and infected seeds or soil is the principal sources of inoculum. Airborne sporidia are responsible for primary infection, which occurs when badly contaminated grains are utilized for planting. To create a dense mycelial network, spores germinate when conditions are right. During the blooming stage, teleutospores from promycelia and sporidia germinate and infect the floral organs [44]. After sporidia have landed on the ovaries, it takes 14 days to develop spore and another 21-28 days for the sori to mature [45].

2.3.2 Management practices

In order to avoid the germination of fungal spores, thorough ploughing must be performed after the spores have been buried deeply 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 concentration of 3mg/L. [46] 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, a soil treatment with *Gliocladium virens* and raw goat milk and cow milk treated seeds provide up to 60% better protection [47]. It is regarded as a key element of a comprehensive plan for smut control for farmers with insufficient access to resources. Resistance cultivars including DC 7, MPP 7131, and MPP 7108 have recently been created and advised.

2.4 Rust

Rust of pearl millet appears in later stage of crop growth, mainly during seed developing stage, commonly occurring after grain-filling stage, producing minor reduction in grain production. Rust of pearl millet emerges in later stage of crop growth. *Puccinia penniseti* Zimm. is the pathogen that leads to this disease. This disease manifests itself on the leaf as a reddish-orange pustule that can range in shape 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 [41].

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 very tip and working its way down. It generates teliospores and uredospores on crop, same as other species of Puccinia, and furthermore, on alternate hosts such as *Solanum melongena*, it yields aecial spores [44]. 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 the rust disease throughout the crops. After a period of time, pustules darken in color and take on the appearance of another 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, which may ultimately result in the death of the plants. The teliospore has a number of tough exterior layers, which allow it to survive for an extended amount of time in the soil. To complete its life cycle, the fungus must first go through the spermagonial and aecial stages on another host, such as solanum [41].

2.4.2 Management practices

Chemical treatment involves use of Propiconazole, Hexaconazole, Copper oxychloride, Carbendazim, Mancozeb, Azadirachtin [48, 49]. At initial stages spray with any of the fungicides like Wettable sulphur or Mancozeb is recommended. The antibiotic Triadimefon has also performed satisfactory against pearl millet rust under field conditions and recorded the least rust severity. Also, rust of pearl millet can be managed to a great extent with *Trichoderma viride* [50] and *T. harzianum* [51] spray and is significantly superior in comparison to other chemical treatment methods.

Also, cultural practices like adjusting the sowing date so that the crop does not flower during September when high rainfall and high relative humidity favour the disease spread are also useful. For eradication of collateral hosts, the seeds are immersed in 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 diseases. Lesions may grow and clump together. Lesions typically have a more or less noticeable dark brown border and are tan or greyish brown in color. 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 purpetuate. Conidia carried by the air may aid in the secondary transmission of the diseases [41, 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 severe leaf spot's field symptoms. Leaf spots on older leaves are characterized by many, consolidated spots that caused tip-burn and withering. Before seed ripened, the majority of the plants perish [52].

2.5.2 Management technique

Practices including deep ploughing, clearing, and removing crop remains from the field, cleaning the infected plants from the field, and burning crop residues are advised for the treatment of this disease [21].

2.6 Cercospora leaf spot

This illness is brought on by the fungus *Cercospora penniseti*, and it typically has 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 of crop debris, stray plants, side hosts, and seed. Airborne spores may cause secondary spread [41, 7].

2.6.2 Management technique

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 for the treatment of this disease [11].

3. BACTERIAL DISEASES

3.1 Bacterial leaf spot

The bacterium that causes bacterial leaf spot is *Pseudomonas syringae* [53]. It's possible that a plant's entire leaf canopy will sustain damage. Although the pathogen primarily affects the leaves, the stem might occasionally show streaks as well. 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 [11].

3.1.1 Epidemiology

The first signs of bacterial spots on leaves are small, 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 site of attack for this disease is the leaves, while it can also occasionally show up 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 with a temperature between 12^0 and 25^0 degrees Celsius is necessary for illness to thrive [21].

3.1.2 Management technique

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 in its control diseases like ergot because they serve as reservoirs for pathogens and sources of inoculums [11].

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 [54, 55, 56]. 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 [57, 58, 59, 60].

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 [61]. Almost always, the lamina's damaged area seems to be 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 [62]. Throughout the length of the affected culms and leaf sheeth, a light brown color darkening can be visible. Frequently, the discoloration begins 5 to 7 cm above the base and extends all the way to the leaf sheath. It is believed that this pathogen spreads internally between plants in latently infected plants and through farm equipment in rice [54, 63]. If there are agricultural waste products 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 [57, 63].

3.2.2 Management techniques

Both cultural and chemical strategies are used to control disease. The primary inoculums 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 seed from disease-free crops will reduce the amount of the initial inoculum. A successful bio-cultural control strategy against the illness has been demonstrated by hybrids with rapid pollination traits [64].

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. As early as the seedling's second leaf stage, these stripes might appear. The lesions become opaque with red rim with oval patches. Moreover, these lesions may enlarge into bigger 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 there are agricultural waste products in the soil, the pathogen can survive there. In temperatures between 26^0 and 30^0 C, this disease is most prone to spread. When temperatures are low in the spring, the disease manifests more severely, and when it's hot and dry in the summer, it manifests less severely [11].

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 illness [64].

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. If yield stability could also be increased by including drought, insect, and disease resistance or tolerance, this risk might be reduced. The current assessment underscores the fact that because farmers find it difficult to treat broad areas with pesticides, the chemical control is neither economical and environment friendly or practical to the farmer. As a result, the development of biological and environmentally friendly control measures is urgently needed.

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 emphasises 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.

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