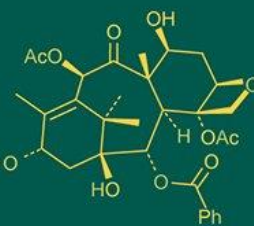
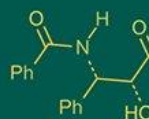
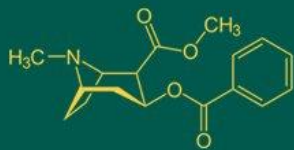


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Sustainable disease management strategies in major fodder crops: Advances, challenges, and future perspectives

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Abstract

Fodder crops are essential for sustainable livestock production, providing nutritious forage that supports milk, meat, and draught animal production. However, their productivity and quality are significantly affected by diseases caused by fungi, bacteria, viruses, phytoplasma, and nematodes, resulting in reduced biomass, forage quality, digestibility, seed yield, and farm profitability. Major fodder crops such as sorghum, maize, and Napier grass are susceptible to diseases including anthracnose, rust, downy mildew, leaf blight, powdery mildew, smut, wilt, root rot, and viral mosaics. Disease incidence is further aggravated by climate change, continuous monocropping, and the emergence of new pathogen races.

Sustainable disease management relies on Integrated Disease Management (IDM), combining resistant cultivars, disease-free planting material, crop rotation, balanced nutrition, biological control, cultural practices, and judicious fungicide use. Recent advances in molecular diagnostics, genomics-assisted breeding, artificial intelligence, remote sensing, and precision agriculture have strengthened disease detection and management while reducing reliance on chemical pesticides. This review summarizes the major diseases of economically important fodder crops, their symptoms and management strategies, and highlights emerging technologies, research gaps, and future priorities for developing climate-resilient and sustainable forage production systems.

Keywords: Fodder crops; plant diseases; integrated disease management; forage production; biological control; disease resistance; sustainable agriculture; precision agriculture; artificial intelligence; molecular diagnostics

Introduction

Livestock production is a cornerstone of global agriculture, contributing to food security, nutrition, employment, and rural livelihoods. Sustainable livestock productivity depends on the continuous supply of high-quality fodder, yet India faces a significant shortage of green and dry fodder due to increasing livestock demand, limited cultivable land, and climate variability ^[1]. Major fodder crops, including sorghum (*Sorghum bicolor*), maize (*Zea mays*), and Napier grass (*Cenchrus purpureus*), provide nutritious forage and contribute to soil fertility, carbon sequestration, and sustainable crop–livestock farming systems. However, diseases remain a major constraint to fodder production, reducing biomass yield, forage quality, and livestock productivity ^[2].

Fungal, bacterial, viral, phytoplasmal, and nematode pathogens adversely affect fodder crops by reducing plant growth, nutritional quality, and, in some cases, contaminating forage with mycotoxins. Disease development is influenced by environmental factors and climate change, increasing the need for climate-resilient management strategies ^[3]. Integrated disease management (IDM), incorporating resistant cultivars, healthy planting material, crop rotation, biological control, balanced nutrition, cultural practices, and judicious pesticide use, offers sustainable disease control ^[4]. Recent advances in molecular diagnostics, genomics, remote sensing, unmanned aerial vehicles (UAVs), artificial intelligence, machine learning, and precision agriculture have further strengthened disease detection and management ^[5].

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[5]. This review summarizes the major diseases of economically important fodder crops, their epidemiology, integrated management strategies, emerging technologies, and future research priorities for sustainable forage production [6].

1. Diseases of sorghum (*sorghum bicolor*)

Sorghum (*Sorghum bicolor* L. Moench) is one of the most important cereal fodder crops cultivated in tropical and subtropical regions because of its rapid growth, high biomass production, drought tolerance, and excellent nutritional value. It is a major source of green fodder, silage, and dry forage for livestock [7]. However, sorghum productivity is frequently constrained by several diseases caused primarily by fungi, although bacterial and viral pathogens also contribute to crop losses under favorable environmental conditions. Disease outbreaks reduce green fodder yield, nutritional quality, digestibility, and seed production, thereby affecting the profitability of fodder production systems [8].

1.1 Anthracnose

Anthracnose, caused by *Colletotrichum sublineola*, is one of the most destructive fungal diseases of sorghum in tropical and subtropical production regions [9].

Symptoms

The pathogen infects leaves, stems, panicles, and grains during crop development. The initial symptoms appear as small reddish-brown or tan lesions that gradually enlarge into elongated necrotic spots. As the lesions mature, numerous black fruiting bodies (acervuli) develop on the infected tissues, which serve as a characteristic diagnostic feature [10]. Progressive infection causes lesion coalescence, extensive leaf blight, premature senescence, stem discoloration, lodging, and poor grain development. Severe infection considerably reduces photosynthetic efficiency and biomass accumulation [11].

Disease management

Effective management requires an integrated approach. Cultivation of resistant cultivars remains the most economical and environmentally sustainable strategy. The use of certified disease-free seeds, crop rotation with non-host crops, destruction of infected crop residues, and maintenance of optimum plant spacing help reduce primary inoculum and canopy humidity [12]. Under severe disease pressure, foliar application of systemic fungicides, such as azoxystrobin or propiconazole, at the recommended concentration effectively suppresses disease development [13].

1.2 Downy mildew (crazy top)

Downy mildew, caused by *Peronosclerospora sorghi*, is a systemic disease that significantly affects sorghum productivity in several tropical countries, including Brazil. [14]

Symptoms

The earliest symptoms appear as pale yellow or chlorotic streaks running parallel to the leaf veins. Under humid conditions, white downy fungal growth develops on the lower surface of infected leaves during early morning hours [15]. Severely infected plants become stunted with narrow

leaves, while the floral structures are transformed into leafy proliferations known as "crazy top." Such plants produce little or no grains and contribute significantly to yield losses [16].

Disease management

Integrated management involves cultivating resistant varieties, treating seeds with systemic fungicides, such as metalaxyl, before sowing, and promptly removing infected plants to prevent secondary spread. [16] Crop rotation with non-host crops and avoidance of continuous sorghum cultivation further reduces inoculum levels. Where disease incidence is high, foliar sprays of metalaxyl combined with mancozeb provide additional disease suppression [17].

1.3 Grain mold

Grain mold is a disease complex caused by several fungal genera, including *Fusarium*, *Curvularia*, *Alternaria*, *Aspergillus*, and *Cladosporium*. The disease commonly develops when warm temperatures coincide with high humidity during the grain maturation period [18].

Symptoms

Infected grains exhibit discoloration accompanied by fungal growth that may appear pink, gray, black, or white, depending on the pathogen involved. Diseased grains become shrivelled, lightweight, and exhibit poor germination. Besides reducing seed quality, grain mold also lowers fodder quality and market value [19].

Disease management

The cultivation of tolerant cultivars, timely harvesting immediately after physiological maturity, rapid drying of harvested grains, and proper storage under low-moisture conditions significantly reduce disease severity. In fields with a history of severe grain mold, preventive fungicide application during flowering has been reported to minimize disease incidence [20].

1.4 Rust

Rust, caused by *Puccinia purpurea*, is an economically important foliar disease that develops predominantly in cool and humid weather. The disease interferes with photosynthesis, thereby reducing forage biomass and grain production [21].

Symptoms

The disease is characterized by numerous reddish-brown pustules on both leaf surfaces. As the infection progresses, these pustules rupture and release large numbers of urediniospores. In the later stages, black telial pustules replace the uredinial stage. Severe infection accelerates leaf senescence, resulting in poor biomass accumulation and a reduced forage quality [22].

Disease management

Disease management includes the cultivation of resistant cultivars, removal of volunteer sorghum plants, maintenance of balanced fertilizer application, and adequate crop spacing to improve air circulation [15]. Early fungicide application using propiconazole or tebuconazole effectively limits disease development under favorable environmental conditions [23].

2. Diseases of fodder maize (*Zea Mays* L.)

Fodder maize (*Zea mays* L.) is among the most extensively cultivated forage crops worldwide because of its rapid growth, high biomass production, superior digestibility, and excellent nutritional value. These pathogens reduce photosynthetic efficiency, interfere with plant growth, decrease forage digestibility, and ultimately lower biomass yield. As fodder maize is harvested mainly during the vegetative stage, maintaining healthy foliage is essential for obtaining maximum forage production and nutritional quality^[24].

Major diseases affecting fodder maize include Turcicum leaf blight, Maydis leaf blight, banded leaf and sheath blight, rust, downy mildew, charcoal rot, Fusarium stalk rot, smut diseases, gray leaf spot, ear rot, bacterial stalk rot, and viral diseases^[25].

2.1 Turcicum leaf blight (northern corn leaf blight)

Turcicum leaf blight, caused by *Exserohilum turcicum* (syn. *Setosphaeria turcica*), is one of the most economically important foliar diseases of maize. It is prevalent in both tropical and temperate regions and may cause severe yield losses when favorable environmental conditions persist for a prolonged period^[26].

Symptoms

Disease development begins with the appearance of small, water-soaked lesions on lower leaves. These lesions gradually enlarge into long, elliptical, cigar-shaped spots with gray or tan centers and dark margins^[27]. As the disease progresses, adjacent lesions merge, resulting in extensive blighting of foliage. Severe infection causes premature leaf senescence, reduces photosynthetic activity, lowers forage digestibility, and significantly decreases the production of biomass^[28].

Disease management

Integrated disease management includes the cultivation of resistant hybrids, destruction or deep incorporation of infected crop residues, crop rotation with non-host crops, optimum plant spacing to improve air circulation, balanced fertilization and continuous disease surveillance^[29]. In areas with high disease pressure, the timely application of fungicides, such as azoxystrobin, propiconazole, tebuconazole, and pyraclostrobin, effectively suppresses disease progression^[30].

2.2 Maydis leaf blight (southern corn leaf blight)

Southern corn leaf blight is caused by *Bipolaris maydis* and is widely distributed in tropical and subtropical maize-growing regions^[31].

Symptoms

The initial symptoms appear as small, tan-colored lesions surrounded by reddish-brown margins on older leaves. These lesions rapidly enlarge and coalesce under favorable environmental conditions, resulting in extensive necrosis and premature drying of the foliage. Severe infections reduce photosynthesis, forage digestibility, and overall crop productivity^[32].

Disease management

Management involves growing resistant cultivars, using certified disease-free seeds, practicing crop rotation, removing infected crop residues, maintaining balanced nutrient application, and applying triazole or strobilurin

fungicides whenever the disease severity exceeds the economic threshold level^[33].

2.3 Banded leaf and sheath blight

Banded leaf and sheath blight, caused by *Rhizoctonia solani* f. sp. *sasakii*, is one of the most destructive diseases of maize in several Asian countries, including India. The pathogen infects leaves, leaf sheaths, stems, and ears, causing considerable reductions in both fodder yield and grain production^[34].

Symptoms

Initially, the disease develops near the soil surface as irregular, water-soaked lesions on the lower leaf sheaths. These lesions rapidly enlarge and form alternating light- and dark-brown concentric bands, which are characteristic of the disease^[35]. Under humid conditions, abundant white fungal mycelium and brown sclerotia develop on the infected tissues. Advanced infection spreads upward through the plant canopy, resulting in severe leaf blight, weakened stems, and poor ear development^[36].

Disease management

Integrated management includes crop rotation, removal of infected residues, optimum crop spacing, balanced fertilizer application, proper drainage to prevent waterlogging, and biological control using *Trichoderma harzianum* and *Pseudomonas fluorescens*. When necessary, fungicides such as validamycin, propiconazole, hexaconazole, and azoxystrobin can be applied to reduce disease severity^[37].

2.4 Common rust

Common rust, caused by *Puccinia sorghi*, is one of the most widely distributed foliar diseases in maize^[38].

Symptoms

Small, circular, cinnamon-brown pustules developed on both surfaces of infected leaves. As the disease progressed, the pustules ruptured and released large numbers of urediniospores^[28]. Later in the season, dark-brown to black telial pustules appeared. Severe infection accelerates leaf senescence, decreases photosynthetic activity, and reduces forage yield and quality^[39].

Disease management

Cultivation of resistant hybrids remains the primary management strategy. Additional measures include crop rotation, removal of volunteer maize plants, balanced fertilizer application, regular disease monitoring, and timely application of triazole or strobilurin fungicides under severe disease conditions^[40].

2.5 Polysora rust

Polysora rust, caused by *Puccinia polysora*, is an important disease in tropical maize-growing regions and is often more destructive than common rust under warm and humid conditions^[41].

Symptoms

The disease is characterized by numerous small orange-to-light-brown pustules that develop primarily on the upper leaf surface. As the infection progresses, the epidermis ruptures, releasing abundant urediniospores that facilitate rapid disease spread. Heavy infection leads to premature leaf drying, reduced biomass accumulation and deterioration of forage quality.^[42]

Disease management

Management relies on resistant hybrids, timely sowing, removal of volunteer plants, field sanitation, balanced nutrient management, and fungicide application at the initial stages of disease development.^[42]

2.6 Downy mildew

Downy mildew is caused by several species, including *Peronosclerospora sorghi*, *P. philippinensis*, and *Sclerophthora rayssiae* var. *zeae*. The disease primarily affects seedlings and young plants and often results in severe yield reduction under favorable environmental conditions^[43].

Symptoms

Early symptoms include chlorotic longitudinal stripes parallel to the leaf veins, followed by stunted growth and reduced tillering. During humid mornings, white downy fungal growth develops on the lower leaf surfaces. Severely infected plants remain dwarfed, produce malformed ears, and may become sterile^[44].

Disease management

Integrated disease management includes the cultivation of resistant hybrids, use of certified disease-free seeds, seed treatment with metalaxyl, removal of infected plants, elimination of alternate hosts, crop rotation, and maintenance of proper field drainage to minimize the development of disease^[45].

3. Diseases of hybrid napier grass (*Cenchrus purpureus*)**3.1 Leaf Blight**

Causal Organism *Bipolaris maydis* and related species

Symptoms

Initially, small brown lesions appear on leaves, which gradually enlarge into elongated necrotic patches. Lesions eventually merge, resulting in extensive leaf blighting and premature drying^[46].

Disease management

Disease-free planting material, balanced fertilization, field sanitation, proper spacing, and fungicide application effectively reduce disease incidence^[47].

3.2 Helminthosporium leaf spot

Causal Organism *Helminthosporium* spp.

Symptoms

Small oval lesions enlarge into elongated brown spots with dark margins. Under severe infection, extensive blighting reduces photosynthetic efficiency and forage production^[48].

Disease management

Removal of infected foliage, balanced nutrient management, resistant cultivars, and protective fungicides effectively suppress disease development^[49].

3.3 Rust

Causal Organism *Puccinia* spp.

Symptoms

Orange to reddish-brown pustules develop on leaf surfaces, causing chlorosis, premature drying, and deterioration in forage quality^[50].

Disease management

Resistant cultivars, removal of infected leaves, proper crop

spacing, and systemic fungicides provide satisfactory disease control^[51].

4. Diseases of lucerne (*Medicago sativa*)**4.1. Anthracnose**

Anthracnose, caused primarily by *Colletotrichum trifolii*, is one of the most destructive fungal diseases of lucerne (*Medicago sativa*). Although other *Colletotrichum* species may also be associated with the disease, *C. trifolii* is considered the principal causal organism.

Symptoms

The disease initially appears as small water-soaked lesions on the stems, which gradually enlarge into sunken, oval or diamond-shaped brown lesions surrounded by dark margins. As the lesions expand, they girdle the stems, causing them to bend into the characteristic "shepherd's crook" shape^[51]. Infected stems subsequently wilt, dry, and become straw coloured. Under severe disease conditions, the pathogen spreads to the crown region, leading to crown rot, plant mortality, and progressive thinning of the crop stand.

Management

Effective management of anthracnose involves an integrated disease management approach. Cultivation of resistant cultivars and the use of certified disease-free seed serve as the primary preventive measures. Crop rotation with non-leguminous crops for a minimum of two years helps reduce inoculum levels in the soil. Removal of infected crop residues, maintenance of good field sanitation, and minimizing plant stress caused by drought or nutrient deficiencies further reduce disease incidence. Under high disease pressure, fungicides such as chlorothalonil or strobilurin-based compounds may be applied to suppress disease development.

4.2. Root and crown rot

Root and crown rot is a destructive disease complex of lucerne caused by several soil-borne pathogens, including *Phytophthora medicaginis*, *Fusarium* spp., *Rhizoctonia solani*, and *Pythium* spp. Disease severity is generally greater under poorly drained soil conditions and prolonged soil moisture.

Symptoms

Infected seedlings often exhibit poor germination and damping-off symptoms during the early stages of crop establishment. As the disease progresses, roots become brown to black and undergo extensive decay, while crown tissues become soft, discoloured, and necrotic. Affected plants display yellowing, wilting, reduced vigour, and stunted growth, eventually leading to plant death. In older stands, continuous mortality of infected plants results in gradual thinning of the field.

Management

Management strategies focus on minimizing favourable conditions for soil-borne pathogens. Cultivation of resistant varieties, establishment of crops in well-drained soils, and avoidance of waterlogging or excessive irrigation are essential preventive measures. Seed treatment with recommended fungicides before sowing protects seedlings from early infection, while crop rotation with non-host crops instead of continuous lucerne cultivation helps reduce pathogen populations in the soil.

4.3. Rust

Rust of lucerne is caused by *Uromyces striatus* and is commonly observed under humid environmental conditions. The disease adversely affects both forage yield and nutritional quality by reducing the photosynthetic efficiency of infected plants.

Symptoms

The disease is initially characterized by the appearance of numerous small orange-brown pustules on leaves and stems. As the infection advances, these pustules rupture and release large quantities of rusty-coloured spores, facilitating rapid dissemination of the pathogen. Severe infection leads to premature drying and shedding of leaves, thereby reducing forage quality and overall biomass production.

Management

Effective management includes the cultivation of resistant varieties and the removal of volunteer plants and infected crop residues that serve as sources of inoculum. Maintaining optimum plant spacing improves air circulation within the crop canopy and discourages disease development. Where disease incidence becomes severe, foliar application of fungicides such as Propiconazole or Mancozeb provides effective disease suppression.

4.4. Downy mildew

Downy mildew, caused by *Peronospora trifoliorum*, primarily affects young lucerne plants during cool and humid weather. The disease is particularly damaging during the early stages of crop growth, where severe infections impair plant establishment and reduce forage productivity.

Symptoms

Initial symptoms appear as pale yellow patches on the upper surface of leaves, while a greyish-violet downy fungal growth develops on the lower surface under humid conditions. As the disease progresses, infected leaves become curled, distorted, and may fall prematurely. Young seedlings are highly susceptible and frequently become severely stunted when disease pressure is high.

Management

Management of downy mildew includes the use of healthy seed and cultivation of resistant cultivars. Overhead irrigation should be avoided to reduce leaf wetness, while proper plant spacing enhances field aeration and minimizes disease development. Where disease severity is high, application of suitable fungicides provides effective control.

4.5. Common leaf spot

Common leaf spot, incited by *Pseudopeziza medicaginis*, is among the most widespread foliar diseases of lucerne.

Symptoms

The disease is characterized by the development of small, circular, dark-brown to black lesions on the leaves. As infection progresses, the lesions enlarge and may coalesce to form larger necrotic areas. Severely infected leaves gradually turn yellow and fall prematurely, reducing the photosynthetically active leaf area and ultimately lowering forage yield.

Management

Management involves cultivating resistant cultivars and adopting crop rotation with non-host crops to minimize pathogen survival. Removal of infected crop debris after harvest and maintenance of balanced nutrient management further reduce disease incidence. Where disease pressure is severe, application of appropriate fungicides helps limit disease development^[52].

5. Diseases of cowpea (*Vigna unguiculata*)

Cowpea (*Vigna unguiculata*), an important fodder and grain legume, is affected by a wide range of fungal, bacterial, viral, and nematode pathogens across the seedling, vegetative, and reproductive stages of growth.

5.1. Damping off

Causal organism: Damping-off, one of the most destructive diseases at germination and early seedling stages, is caused by a complex of soil-borne fungi, chiefly *Pythium aphanidermatum* and *Rhizoctonia solani*.

Symptom

The disease occurs as pre-emergence damping-off, where infected seeds decay before emergence causing gaps in the field, and post-emergence damping-off, where seedlings develop reddish-brown, water-soaked collar lesions that enlarge, constrict the stem, and cause collapse and death. *Rhizoctonia*-induced lesions stay confined to the collar, while *Pythium* produces soft, watery lesions extending upward.

Management

Use of certified pathogen-free seed, seed treatment with *Trichoderma viride* or *Pseudomonas fluorescens* (10 g/kg seed) or fungicides such as carbendazim/thiram (2 g/kg seed), good field drainage, avoidance of excess irrigation, crop rotation, and spot drenching with carbendazim (1 g/L) or *Trichoderma* formulations in disease-prone fields together provide effective control^[53].

5.2. Stem Rot (Southern Blight)

Causal organism: Stem rot or southern blight is caused by *Sclerotium rolfsii* Sacc.

Small water-soaked lesions appear at the collar region and enlarge to girdle the stem, causing yellowing, wilting, and plant collapse. Abundant white cottony mycelium develops around the stem base under humid conditions, along with numerous spherical sclerotia that are white initially and later turn brown the most characteristic diagnostic feature.

Management

Crop rotation with cereals, deep summer ploughing to expose sclerotia, removal of infected residues, seed treatment with *Trichoderma harzianum* or *T. viride*, and organic amendments such as vermicompost, neem cake, coir-pith compost, and panchagavya reduce disease incidence; need-based fungicide application can be adopted where pressure is high^[54].

5.3. Charcoal rot

Causal organism: Charcoal rot is caused by *Macrophomina phaseolina* (Tassi) Goid., a soil- and seed-borne fungus that survives as microsclerotia for years.

Symptoms

Seedlings show poor vigour, hypocotyl rot, and root decay, while mature plants develop greyish-black sunken lesions on the lower stem and roots. Numerous minute black microsclerotia form within infected tissue, giving a charcoal-like appearance; stems become brittle and may split, and plants wilt suddenly and die.

Management

Crop rotation, destruction of infected residues, deep summer ploughing, maintenance of optimum soil moisture, seed treatment with carbendazim or thiram, biological seed and soil treatment with *Trichoderma harzianum*, *T. viride*, or *Pseudomonas fluorescens*, balanced fertilization, and avoidance of drought stress together reduce disease severity [55].

5.4. Fusarium wilt and root rot

Causal organism: Fusarium wilt is caused by *Fusarium oxysporum* f. sp. *tracheiphilum*, while root rot is associated with *F. oxysporum*, *F. solani*, *F. equiseti*, and *F. proliferatum*. These soil- and seed-borne pathogens survive as chlamydospores in debris and soil and colonize vascular tissue, becoming severe at warm soil temperatures (25–30°C) under continuous cultivation of susceptible varieties.

Symptoms

Older leaves first show yellowing and temporary wilting during the hottest part of the day that initially recovers in the evening but later becomes permanent; leaves dry but remain attached, and plants become stunted with fewer branches and pods. Splitting infected stems reveals brown vascular discoloration, the characteristic symptom, while root rot causes brown, decayed roots that reduce water and nutrient uptake.

Management

Disease-free/resistant seed, seed treatment with carbendazim, thiram, or captan, biological treatment with *Trichoderma harzianum*, *T. viride*, *Pseudomonas fluorescens*, and *Bacillus* spp., two-to-three-year cereal rotation, residue removal, deep ploughing, and balanced fertilization reduce inoculum; recent studies have demonstrated rhizosphere bacteria such as *Priestia megaterium* suppress Fusarium under greenhouse conditions [56].

5.5. Cercospora leaf spot

Causal organism: Cercospora leaf spot, caused by *Cercospora canescens*, is among the most widely distributed foliar pathogens of cowpea.

Symptoms

Small circular to irregular reddish-brown lesions appear first on older leaves, enlarging to a light grey or ash-coloured centre with dark reddish-brown margins and grey fungal sporulation under humid conditions. Coalescing lesions cause extensive leaf blighting, premature defoliation, and reduced yield; lesions may also occur on petioles, stems, and pods.

Management

Certified disease-free seed, residue destruction, rotation with non-legumes, adequate spacing, seed treatment, foliar sprays

of mancozeb (0.2%) or carbendazim at 10–15 day intervals, and resistant cultivars provide effective and sustainable control [57].

6. Conclusion

Fodder crops are fundamental to sustainable livestock production, but their productivity and forage quality are significantly constrained by diseases caused by fungi, bacteria, viruses, phytoplasmas, and nematodes. These diseases reduce biomass, digestibility, and nutritional value, may contaminate fodder with mycotoxins, and result in substantial economic losses. Climate change, intensive cultivation, and the emergence of new pathogen races further increase disease risks [58]. This review summarizes the major diseases affecting important fodder crops, including sorghum, maize, pearl millet, oat, berseem, cowpea, barley, lucerne, and hybrid Napier grass, highlighting their symptoms, epidemiology, and integrated management strategies. Sustainable disease control relies on Integrated Disease Management (IDM), combining resistant cultivars, disease-free planting material, crop rotation, balanced nutrition, biological control, disease surveillance, and judicious fungicide use [59].

Recent advances in molecular diagnostics, genomics-assisted breeding, artificial intelligence, remote sensing, unmanned aerial vehicles (UAVs), precision agriculture, and digital decision-support systems have significantly improved disease detection and management, enabling timely and site-specific interventions while reducing pesticide use and production costs. Future efforts should focus on developing climate-resilient cultivars, affordable diagnostic tools, advanced disease forecasting systems, and eco-friendly biological control technologies. Strengthening research, technology transfer, farmer awareness, and collaboration among researchers, extension agencies, policymakers, and farming communities will be essential for achieving resilient and sustainable fodder production systems [60].

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