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A Global Review of Sugarcane Diseases: Challenges and Management Strategies

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Abstract

Sugarcane (Saccharum spp.) is one of the world's most important industrial crops, providing roughly 80% of global sugar and a major feedstock for bioethanol. However, its productivity and sustainability are continually threatened by a diverse range of pathogens including fungi, bacteria, viruses, phytoplasmas and nematodes. This review provides an integrated global overview of sugarcane diseases, summarising their causal agents, symptomatology, epidemiology, and economic impacts. Fungal pathogens such as Colletotrichum falcatum (red rot) and Sporisorium scitamineum (smut) remain the most devastating, while bacterial diseases including leaf scald, gummosis and ratoon stunting disease (RSD) are globally distributed and often latent. Viral pathogens, notably sugarcane yellow leaf virus (SCYLV) and sugarcane mosaic virus (SCMV), continue to evolve into new genotypes and mixed infections. The review further highlights the challenges posed by sugarcane's polyploid genome, pathogen variability, the movement of infected planting material, and climate-change-driven disease emergence. Advances in disease diagnostics, resistance breeding, tissue-culture-based seed-cane programmes, and integrated disease management (IDM) are critically assessed. Emphasis is placed on the potential of molecular tools, genomics, and remote-sensing-based surveillance for sustainable disease management. Finally, the paper outlines future research priorities focused on pathogen genomics, durable resistance, and data-driven decision support to mitigate yield losses and sustain global sugarcane productivity.

Keywords: Sugarcane diseases, Saccharum spp, fungal pathogens, bacterial pathogens, viral diseases, integrated disease management, host resistance.

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1. Introduction

Sugarcane (*Saccharum officinarum* L., and interspecific hybrids) is a complex polyploid crop cultivated across tropical and subtropical regions as a primary source of sucrose and bioethanol. Globally, it occupies more than 27 million ha, with Brazil, India, China, Thailand, and Australia as leading producers (FAO, 2024) [9]. Beyond sugar production, sugarcane contributes to renewable energy generation, paper, animal feed, and by-products such as molasses and bagasse (Zhao *et al*., 2023) [27]. However, its economic sustainability is repeatedly undermined by a broad range of diseases that substantially reduce cane yield, juice quality, and ratoon longevity (Viswanathan *et al*., 2022) [21]. Disease-associated yield losses in sugarcane have been estimated to range from 10% to 40% depending on region and management practices (Rott *et al*., 2021) [17].

i). **Diversity of Sugarcane Pathogens:** The crop's perennial nature and vegetative propagation favor the accumulation and dissemination of systemic pathogens. More than 120 diseases have been reported worldwide, caused by fungi, bacteria, viruses, phytoplasmas, nematodes, and abiotic factors (Ricaud *et al*., 2012; Singh *et al*., 2020) [15, 18]. Among them, fungal diseases such as red rot (*Colletotrichum falcatum*), smut (*Sporisorium scitamineum*), pokkah boeng (*Fusarium verticillioides* complex), and wilt (*Fusarium sacchari*) remain the most destructive. Bacterial infections including leaf scald (*Xanthomonas alfalfae* subsp. *poae* syn. *X. axonopodis* pv. *vasculorum*), gummosis (*Leifsonia xyli* subsp. *xyli*), and ratoon stunting disease (RSD) cause chronic losses often overlooked due to latent symptoms (Comstock *et al*., 2019) [5]. Viral diseases such as sugarcane mosaic (SCMV), yellow leaf (SCYLV), and streak mosaic continue to spread through mixed infections and vector adaptation (Mangrauthia *et al*., 2022) [14]. Emerging phytoplasma-associated syndromes and nematode infestations further exacerbate yield decline in major sugarcane-growing regions (Rott & Bailey, 2023) [16].

ii). **Disease Epidemiology and Global Spread:** Sugarcane's vegetative propagation by stem cuttings enables long-distance dissemination of pathogens through infected seed-cane. The introduction of new germplasm and

***Corresponding Author:** Ahmed M Hamada expansion into disease-endemic regions accelerate pathogen evolution and emergence of virulent strains (Viswanathan & Balamuralikrishnan, 2018) [22]. Climatic factors such as increasing temperature, erratic rainfall, and humidity strongly influence pathogen dynamics, especially for smut, red rot, and mosaic complexes (Kaur *et al*., 2021) [11]. Global trade, limited quarantine enforcement, and the genetic uniformity of commercial hybrids further enhance the vulnerability of the sugarcane agroecosystem to epidemics (Rott *et al*., 2021) [17].

iii). **Economic and Agronomic Implications:** Yield losses due to diseases not only reduce sugar recovery but also impair ratoon productivity and increase replanting costs. Red rot epidemics in India and Pakistan have historically wiped out large areas under popular cultivars such as Co 419 and Co 997 (Viswanathan *et al*., 2022) [21]. Smut outbreaks in South Africa, Australia, and China caused substantial cane yield and sucrose content reductions (Zhou *et al*., 2020) [28]. RSD and leaf scald remain silent yield eroders in most producing countries, with estimated losses of 5–15 t ha^{-1} per ratoon cycle (Comstock *et al*., 2019) [5]. Beyond direct yield impacts, diseases affect sugar mills by altering juice quality parameters such as purity, fiber content, and reducing sugar ratios (Singh *et al*., 2020) [18]. The cumulative economic burden is further magnified by the cost of roguing, replanting, and loss of varietal diversity.

iv). **Challenges in Diagnosis and Management:** Accurate diagnosis remains challenging because many sugarcane diseases are systemic, symptomless, or masked by environmental stress. Conventional diagnostic methods (visual inspection, culture isolation, serological assays) often fail to detect latent infections. Recent advances in molecular diagnostics—PCR, qPCR, loop-mediated isothermal amplification (LAMP), and next-generation sequencing—have improved detection sensitivity and pathogen characterization (Li *et al*., 2022). Nevertheless, the high genetic heterogeneity of sugarcane, lack of single-gene resistance, and polygenic inheritance complicate breeding efforts (Rott & Bailey, 2023) [16]. Moreover, pathogen populations continuously evolve new races or variants capable of overcoming existing resistance genes, as observed in red rot and smut (Viswanathan *et al*., 2022; Zhou *et al*., 2020) [21, 28].

v). **Toward Integrated and Molecular Management:** Sustainable disease management in sugarcane requires an integrated approach combining host resistance, cultural practices, clean seed programmes, biological control, and judicious chemical use (Singh *et al*., 2020) [18]. Recent incorporation of genomics, transcriptomics, and metabolomics has accelerated the discovery of resistance-associated genes and defense markers (Mangrauthia *et al*., 2022) [14]. Digital agriculture tools such as remote sensing, hyperspectral imaging, and artificial intelligence are emerging as valuable aids for early disease detection and field-scale monitoring (Zhao *et al*., 2023) [27]. These advancements, together with regional surveillance networks and international collaboration, offer new opportunities to mitigate disease risks and sustain productivity under changing climates.

vi). **Scope of the Review:** This review synthesizes the current global knowledge on major sugarcane diseases, emphasizing their causal agents, epidemiology, and management strategies. It also highlights recent advances in molecular diagnostics, host resistance, and integrated management, while identifying key challenges and research gaps for future disease-resilient sugarcane production systems.

2. Major Sugarcane Diseases

Sugarcane diseases represent a multifaceted challenge to sustainable production due to the crop's polyploidy, vegetative propagation, and high pathogen diversity. The major diseases can be grouped into fungal, bacterial, viral, and phytoplasma/nematode-associated categories (Figure 1). Each class varies in etiology, transmission, and management complexity.

i). Fungal Diseases

Fungal pathogens are the most destructive and widespread in sugarcane cultivation.

Among them, red rot, smut, wilt, and pokkah boeng are of primary concern.

Red rot (*Colletotrichum falcatum* Went) is considered the "cancer" of sugarcane, particularly in South and Southeast Asia. It infects stalk tissues through cut ends or insect wounds, causing reddening and white patches along the internodes, with a characteristic alcoholic odor (Viswanathan & Samiyappan, 2018) [22]. The pathogen produces cell-wall–degrading enzymes and toxins that disrupt vascular integrity, leading to necrosis and lodging. High humidity and temperature fluctuations favor its development. Pathogenic variability is high, with numerous *C. falcatum* pathotypes identified based on virulence and cultural characteristics (Viswanathan *et al*., 2022) [21].

Management: Resistance breeding and strict varietal replacement are the most effective measures, supported by hot-water treatment (50°C for 2 h) and crop rotation.

Smut (*Sporisorium scitamineum*) is another major disease, recognized by its whip-like black sorus emerging from the shoot apex. It is systemic, transmitted through infected setts and airborne teliospores (Zhou *et al*., 2020) [28]. Infection occurs through meristematic tissues, where the fungus colonizes vascular bundles and interferes with hormonal signaling. Studies using transcriptomics have revealed upregulation of host defense genes such as PR proteins and phenylpropanoid enzymes in resistant genotypes (Wang *et al*., 2021) [25].

Management: The use of resistant cultivars, hot-water treatment, and fungicide dips (carbendazim, propiconazole) during sett preparation.

Pokkah boeng, caused by *Fusarium verticillioides* complex, affects rapidly growing young tissues, leading to leaf distortion and top rot (Singh *et al*., 2020) [18]. Disease expression is influenced by nitrogen fertilization and high humidity.

Wilt, caused by *Fusarium sacchari* or *Cephalosporium sacchari*, is characterized by vascular discoloration, leaf drying, and stalk collapse, often following insect or nematode damage.

Integrated management includes crop sanitation, destruction of crop residues, and rotation with non-hosts such as rice or legumes.

ii). Bacterial Diseases

Bacterial infections are particularly insidious due to their latent and systemic nature, spreading via contaminated planting material and mechanical implements.

Ratoon Stunting Disease (RSD), caused by *Leifsonia xyli* subsp. *xyli*, is globally prevalent yet difficult to diagnose due to the absence of distinct symptoms. Affected plants show reduced height, thin stalks, and low juice recovery (Comstock *et al.*, 2019) [5]. The bacterium colonizes xylem vessels, impairing water and nutrient translocation. Detection requires sensitive assays such as phase-contrast microscopy, ELISA, or qPCR (Li *et al.*, 2022).

Management: Thermotherapy (50°C for 30 min), tissue-cultured seed cane, and sanitation of harvesting equipment.

Leaf Scald, caused by *Xanthomonas alfalfae* subsp. *poae* (formerly *X. axonopodis* pv. *vasculorum*), manifests as white streaks that turn necrotic, often followed by wilting and death of the apical meristem (Rott & Bailey, 2023) [16]. The pathogen produces xanthan gum and virulence effectors that suppress host defense. Disease outbreaks are favored by high humidity and mechanical transmission during cutting.

Management: Use of certified disease-free seed cane, resistant varieties, and eradication of symptomatic stools.

Gummosis, caused by *Xanthomonas sacchari* and related species, is characterized by the exudation of yellowish bacterial gum from stalk tissues, reducing sucrose accumulation.

Integrated disease-free nursery systems have proven highly effective in reducing bacterial load in planting material (Viswanathan *et al*., 2022) [21].

iii). Viral Diseases

Viral pathogens represent a persistent threat due to their rapid mutation, vector transmission, and frequent mixed infections.

Sugarcane mosaic disease (SMD), caused by *Sugarcane mosaic virus* (SCMV), *Sorghum mosaic virus* (SrMV), and *Maize dwarf mosaic virus* (MDMV), is transmitted by aphids (*Melanaphis sacchari*) in a non-persistent manner (Mangrauthia *et al*., 2022) [14]. Infected leaves exhibit mosaic mottling, chlorotic streaks, and growth retardation. Molecular variability among virus strains contributes to recurrent epidemics.

Management relies on resistant cultivars, vector control, and removal of infected stools.

Sugarcane yellow leaf virus (SCYLV), a *Polerovirus*, causes midrib yellowing, leaf drying, and yield loss up to 25–30%. It is transmitted by aphids and via infected seed-cane. SCYLV alters sucrose metabolism by downregulating photosynthetic and transport-related genes (Zhao *et al*., 2023) [27].

Management: Planting virus-indexed seed cane and avoiding ratooning of heavily infected fields.

Sugarcane streak mosaic virus (SCSMV), a *Poacevirus*, has become increasingly important in Asia. Mixed infections of SCMV and SCSMV result in severe synergistic effects and reduced sucrose content (Viswanathan *et al*., 2022) [21].

Recent CRISPR/Cas-based antiviral strategies show promise for durable resistance.

iv). Phytoplasma- and Nematode-Associated Diseases

Grassy shoot disease (GSD), caused by *'Candidatus Phytoplasma sacchari'*, is widespread in Asia and Africa. Infected plants exhibit profuse tillering, stunted growth, and chlorotic shoots. The phytoplasma is transmitted by leafhoppers (*Proutista moesta*) and perpetuated in ratoons (Rott & Bailey, 2023) [16]. Detection using nested PCR targeting 16SrXI group phytoplasmas has improved surveillance accuracy (Li *et al*., 2022).

Management: Rogueing infected stools, vector control, and hot-water treatment of seed cane.

Yellow leaf phytoplasma, associated with *'Candidatus Phytoplasma oryzae'*, often co-infects with SCYLV, exacerbating yield losses (Singh *et al*., 2020) [19].

Nematode infestations, especially *Pratylenchus zeae*, *Meloidogyne javanica*, and *Helicotylenchus dihystera*, cause root lesions that predispose plants to secondary infections.

Integrated management involves nematicidal cover crops, organic amendments, and biological control agents such as *Paecilomyces lilacinus*.

Table 1: Summary of key sugarcane diseases, causal agents, geographic prevalence, and management strategies.

Disease	Causal Agent	Pathogen Type	Major Affected Regions	Symptoms	Current Management Strategies
Red Rot	*Colletotrichum falcatum* Went	Fungus	India, Pakistan, Thailand, Indonesia	Reddish discoloration of stalk, white patches, sour odor, drying of canes	Use of resistant varieties, removal of infected clumps, crop rotation, seed cane treatment with fungicides (carbendazim, propiconazole)
Smut	*Sporisorium scitamineum* (Syn. *Ustilago scitaminea*)	Fungus	India, China, Australia, South Africa	Black whip-like structure (sorri) on top, stunted growth, tillering	Resistant cultivars, hot water treatment of setts, rouging, field sanitation
Ratoon Stunting Disease (RSD)	*Leifsonia xyli* subsp. *xyli*	Bacterium	Brazil, Australia, USA, India	Stunted growth, poor ratooning, reduced yield, no visible external symptoms	Use of disease-free seed cane, hot water treatment (50°C for 2 hr), sterilization of tools
Leaf Scald	*Xanthomonas albilineans*	Bacterium	Latin America, Africa, India	White pencil-line streaks on leaves, necrosis, plant wilting	Disease-free planting material, sanitation, resistant varieties, hot-water treatment
Mosaic Disease (SCMV, SrMV)	*Sugarcane mosaic virus* (SCMV), *Sorghum mosaic virus* (SrMV)	Virus	Worldwide (especially tropical Asia, Africa, South America)	Mottled chlorotic streaks on leaves, stunting, yield reduction	Virus-free planting material, vector (aphid) control, resistant cultivars
Yellow Leaf Disease (YLD)	*Sugarcane yellow leaf virus* (ScYLV)	Virus	Brazil, China, India, USA, South Africa	Yellowing of midrib, chlorosis, reduced stalk weight	Use of virus-free seed cane, aphid control, tolerant varieties
Grassy Shoot Disease (GSD)	*'Candidatus Phytoplasma sacchari'*	Phytoplasma	India, Thailand, China	Excessive tillering, grassy appearance, chlorosis	Vector (leafhopper) management, rouging, use of disease-free setts
White Leaf Disease	*'Candidatus Phytoplasma sacchari'*	Phytoplasma	Thailand, Myanmar, Taiwan	Chlorotic or white leaves, stunting, failure to form canes	Elimination of infected plants, vector control, resistant varieties

Root Knot Nematode	*Meloidogyne javanica, M. incognita*	Nematode	India, Egypt, Brazil	Galls on roots, stunted growth, poor ratooning	Soil fumigation, crop rotation, organic amendments, nematode-resistant cultivars
Pokkah Boeng	*Fusarium verticillioides*	Fungus	India, China, Indonesia	Leaf distortion, twisting, stalk rot in severe cases	Fungicide sprays (carbendazim), cultural management, resistant varieties
Rust (Common & Orange)	*Puccinia melanocephala, P. kuehnii*	Fungus	Worldwide (especially tropical regions)	Brown/orange pustules on leaves, premature drying, reduced photosynthesis	Resistant cultivars, fungicide application (triazoles), removal of infected leaves
Eye Spot	*Bipolaris sacchari*	Fungus	Southeast Asia, Pacific Islands	Elliptical reddish lesions with yellow halo	Resistant cultivars, seed cane sanitation, crop residue management

3. Global Distribution and Economic Impact

Sugarcane is cultivated in more than 120 countries across tropical and subtropical regions between latitudes 35° N and 35° S. The global harvested area exceeded 27.4 million ha in 2023, producing 1.9 billion tonnes of cane (FAO, 2024) [9]. Despite technological progress, disease-induced yield losses remain one of the most persistent threats to sugarcane productivity and profitability (Viswanathan *et al*., 2022) [21]. The incidence, severity, and economic impact of diseases vary considerably with geographic region, cultivar composition, and environmental conditions (Rott *et al*., 2021) [17].

i). Asia

Asia accounts for nearly 60% of global sugarcane production, with India, China, Thailand, Pakistan, and Indonesia as major producers.

In India, red rot (*Colletotrichum falcatum*) remains the most devastating disease, responsible for up to 30–50% yield losses during epidemic years (Viswanathan & Samiyappan, 2018) [22]. Frequent emergence of new *C. falcatum* pathotypes has rendered previously resistant cultivars (e.g., Co 419, Co 1148) susceptible.

Smut (*Sporisorium scitamineum*) is widespread across India and China, especially in ratoon crops, causing 15–25% yield reductions (Zhou *et al*., 2020) [28].

Sugarcane mosaic virus (SCMV) and Sugarcane streak mosaic virus (SCSMV) co-infections have been reported in China, India, and Pakistan, where synergistic interactions cause chlorosis, stunted growth, and losses up to 20–30% (Mangrauthia *et al*., 2022) [14].

Grassy shoot disease (GSD), transmitted by *Proutista moesta*, is endemic in eastern India and Bangladesh, with incidences ranging from 5–60% depending on ratoon management (Rott & Bailey, 2023) [16].

Nematode infestations, primarily *Pratylenchus zeae* and *Meloidogyne javanica*, are emerging yield-limiting factors in intensively cultivated regions of India, China, and Thailand (Singh *et al*., 2020) [19].

ii). Africa

African sugar industries, notably in South Africa, Eswatini, Sudan, Kenya, and Egypt, face recurrent smut and mosaic epidemics. The 2008 smut outbreak in South Africa caused severe damage to cultivar NCo 376, leading to >40% yield losses and large-scale replanting (Zhou *et al*., 2020) [28].

Ratoon stunting disease (RSD) is ubiquitous in the continent, often undetected due to the lack of diagnostic infrastructure. Leaf scald has been reported in Egypt and Sudan, while red rot remains sporadic but economically significant (Rott & Bailey, 2023) [16]. The combination of erratic rainfall and suboptimal crop sanitation increases the persistence of systemic bacterial infections.

iii). The Americas

In Brazil, which contributes nearly 40% of global cane output, the main diseases include smut, ratoon stunting disease, and leaf scald. Red rot is less frequent but occasionally severe in humid northeastern states. Disease-related yield losses are estimated at 10–15% annually (Rott *et al*., 2021) [17].

In the Caribbean, particularly Jamaica and Cuba, mosaic and yellow leaf diseases historically constrained productivity, prompting replacement of susceptible cultivars with resistant hybrids.

In the United States (Florida, Louisiana, Texas, Hawaii), RSD remains the most persistent disease, causing 5–10% losses per ratoon cycle (Comstock *et al*., 2019) [5].

Leaf scald outbreaks have been reported periodically in Louisiana, while mosaic virus infections are sporadic due to strict certification and heat therapy protocols.

iv). Australia and the Pacific

Australia's highly mechanized sugar industry is predominantly affected by ratoon stunting disease, smut, and pokkah boeng. The introduction of *Sporisorium scitamineum* into Queensland in 2006 triggered significant losses, forcing the removal of several high-yielding cultivars (Rott *et al*., 2021) [17].

Strict quarantine and the "Clean Seed Program" have since minimized further spread. Leaf scald and mosaic remain under control through varietal resistance and vector management.

In Pacific island nations (e.g., Fiji, Papua New Guinea), smallholder systems remain vulnerable to smut and red rot due to limited access to clean seed-cane and disease surveillance.

v). Economic Implications

Globally, sugarcane diseases are estimated to cause annual losses exceeding USD 2–3 billion in yield and quality (Rott & Bailey, 2023) [16]. These losses extend beyond primary productivity to secondary industries such as sugar refining and bioethanol production.

Diseases like red rot and leaf scald alter sucrose metabolism, lowering juice purity, while mosaic viruses reduce chlorophyll content and photosynthetic efficiency (Mangrauthia *et al*., 2022) [14].

RSD and smut affect ratoon longevity, increasing replanting frequency and production costs.

Moreover, the trade and movement of infected planting material have profound implications for international biosecurity. Emerging high-temperature and drought conditions further modulate disease epidemiology, potentially expanding pathogen ranges into new agroecological zones (Kaur *et al*., 2021) [11].

vi). Regional Prioritization

Regional priorities for disease management vary by pathogen prevalence and resource availability:

South and Southeast Asia: red rot, smut, mosaic viruses, GSD.

Africa: smut, RSD, leaf scald.

Americas: RSD, leaf scald, mosaic.

Australia and Pacific: RSD, smut, pokkah boeng.

Global coordination under international networks such as the **International Society of Sugar Cane Technologists (ISSCT)** and national disease surveillance programmes remains crucial for early warning, germplasm exchange, and breeding of resistant cultivars.

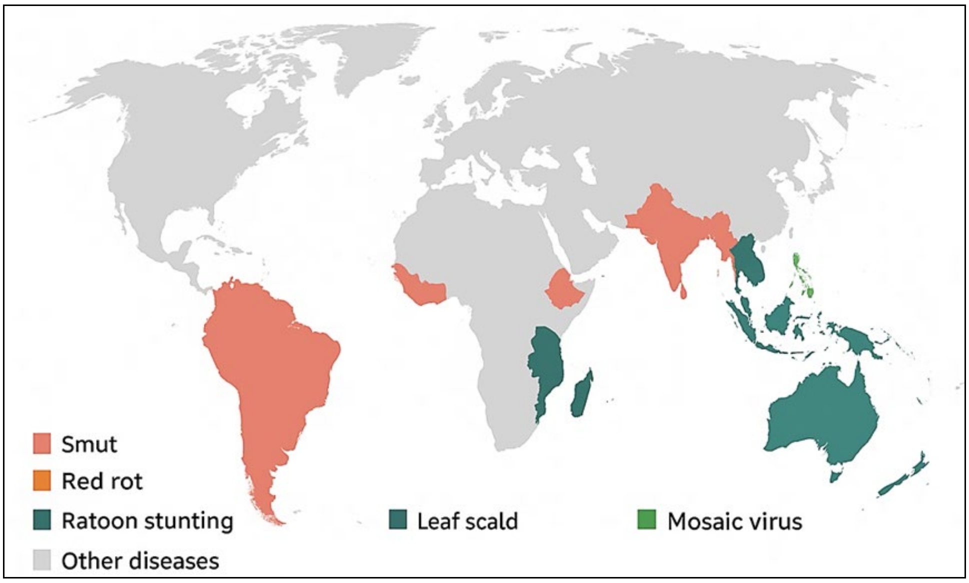

Fig 1: Geographic distribution map showing dominant sugarcane diseases across major producing regions.

Table 2: Estimated yield and economic losses from major sugarcane diseases by continent.

Continent	Major Diseases	Estimated Yield Loss (%)	Estimated Economic Loss (USD million/year)	Key References
Asia	Red rot, Smut, Mosaic virus	10–25	450–700	Viswanathan & Rao (2022) [21]; Rott *et al.* (2021) [17]
Africa	Smut, Ratoon stunting, Leaf scald	8–20	120–300	Kibanda *et al.* (2020) [12]; Singogo *et al.* (2021) [20]
South America	Orange rust, Mosaic virus	12–28	350–650	Chinea *et al.* (2019); Comstock *et al.* (2022) [6]
North America	Leaf scald, Smut	6–15	100–200	Hoy & Grisham (2018) [10]
Oceania	Fiji leaf gall, Rusts	5–12	90–150	Croft *et al.* (2020) [7]
Global total	—	10–25 (avg.)	>2,000	FAO (2023); USDA (2022)

4. Key Challenges in Disease Management

Despite decades of research and major advances in breeding, diagnostics, and phytosanitary regulation, the effective management of sugarcane diseases remains constrained by multiple interrelated challenges. These obstacles arise from the biological complexity of the crop, the evolutionary plasticity of pathogens, and the environmental and operational limitations of large-scale monoculture systems.

i). Genetic and Genomic Complexity of Sugarcane

Modern commercial sugarcane varieties are interspecific hybrids of *Saccharum officinarum*, *S. spontaneum*, and related species, resulting in high polyploidy (2n = 100–120) and aneuploid chromosome sets (Zhao *et al.*, 2023) [27]. This genetic redundancy hampers conventional Mendelian segregation analysis and complicates the identification of resistance loci. Many resistance responses are quantitative and polygenic, involving additive effects of multiple minor-effect genes (Rott & Bailey, 2023) [16].

Moreover, linkage drag from *S. spontaneum* introgressions can negatively affect agronomic traits, limiting the deployment of resistance genes in elite germplasm (Viswanathan *et al.*, 2022) [21]. Marker-assisted and genomic selection have only recently begun to overcome these limitations, but reference genome assemblies remain fragmented, restricting high-resolution mapping of defense pathways.

ii). Pathogen Variability and Rapid Evolution

Sugarcane pathogens exhibit remarkable genetic diversity and adaptability.

Colletotrichum falcatum populations evolve new pathotypes capable of overcoming varietal resistance within a few cropping cycles (Viswanathan & Samiyappan, 2018) [22].

Sporisorium scitamineum shows high genetic differentiation among regional isolates; mating-type recombination and hybridization events generate new virulent races (Zhou *et al.*, 2020) [28].

Viruses such as SCMV and SCYLV undergo frequent recombination and synergistic co-infection, enhancing virulence and host range (Mangrauthia *et al.*, 2022) [14].

This pathogen plasticity, coupled with intensive monoculture of genetically uniform cultivars, accelerates resistance breakdown. The lack of coordinated pathogen surveillance and molecular characterization in many countries further delays the detection of emerging variants.

iii). Diagnostic Limitations and Latent Infections

Sugarcane's vegetative propagation allows systemic pathogens—particularly *Leifsonia xyli*, *Xanthomonas alfalfae*, and phytoplasmas—to persist unnoticed across generations.

Traditional visual inspection and culture isolation are unreliable for early detection, as symptoms are often masked by environmental stress or secondary infections (Comstock *et al*., 2019) [5].

Although molecular assays such as PCR, qPCR, and LAMP have improved detection sensitivity (Li *et al*., 2022), field-deployable diagnostics remain scarce due to cost, technical expertise, and lack of standardized protocols.

Additionally, mixed infections (e.g., SCMV + SCSMV or SCYLV + phytoplasma) complicate diagnosis and confound resistance screening.

The absence of universal diagnostic markers limits international phytosanitary certification and germplasm exchange, leading to inadvertent spread of pathogens through seed-cane trade.

iv). Environmental and Climate-driven Challenges

Climate change is increasingly recognized as a key driver of sugarcane disease dynamics.

Rising temperatures, elevated CO_2, and irregular rainfall patterns favor the expansion of smut, red rot, and mosaic disease zones (Kaur *et al*., 2021) [11].

High humidity and temperature fluctuations accelerate sporulation and dispersal of fungal pathogens, while drought-induced stress enhances host susceptibility to vascular diseases such as RSD and leaf scald (Rott *et al*., 2021) [17].

Conversely, extreme weather events (floods, cyclones) facilitate pathogen spread via contaminated water and debris.

Moreover, climate change affects vector populations, increasing aphid and leafhopper abundance, thereby intensifying viral and phytoplasma transmission (Mangrauthia *et al*., 2022) [14]. Predictive modeling of disease–climate interactions remains limited, hindering the formulation of adaptive management strategies.

v). Agronomic and Operational Constraints

In many developing sugarcane-producing regions, resource constraints and smallholder farming systems limit disease control efficacy.

Low adoption of clean-seed programmes and lack of access to certified nurseries perpetuate systemic diseases.

Mechanical harvesting and ratooning accelerate pathogen dissemination through contaminated equipment and residues.

Overreliance on a few commercial cultivars increases genetic uniformity and epidemic vulnerability.

Poor crop sanitation and inadequate disposal of infected residues facilitate inoculum carryover between cycles (Singh *et al*., 2020) [19].

Socioeconomic limitations, including fragmented extension networks and insufficient diagnostic laboratories, further delay detection and reporting.

vi). Inadequate Integration of New Technologies

Although omics-based tools, precision agriculture, and artificial intelligence have advanced rapidly, their application in sugarcane pathology remains limited.

Genomic resources for both host and pathogen are incomplete, constraining molecular breeding.

Remote sensing and hyperspectral imaging systems have demonstrated potential for early detection of mosaic and smut but require region-specific calibration and validation (Zhao *et al*., 2023) [27].

Furthermore, the integration of big-data analytics, weather modeling, and spatial epidemiology into decision-support systems is still nascent.

Bridging the gap between research innovation and field-level implementation remains a critical challenge.

vii). Policy and biosecurity limitations

The transboundary nature of sugarcane diseases underscores the need for harmonized quarantine regulations and germplasm movement protocols.

In many countries, national quarantine frameworks are outdated, lacking molecular diagnostic requirements for imported seed-cane or tissue cultures (Rott & Bailey, 2023) [16].

Insufficient data sharing and regional surveillance hinder coordinated containment of emerging pathogens such as new *Colletotrichum* pathotypes and SCSMV variants.

Strengthening international collaboration through organizations such as FAO, CABI, and ISSCT is essential for establishing rapid response and containment mechanisms.

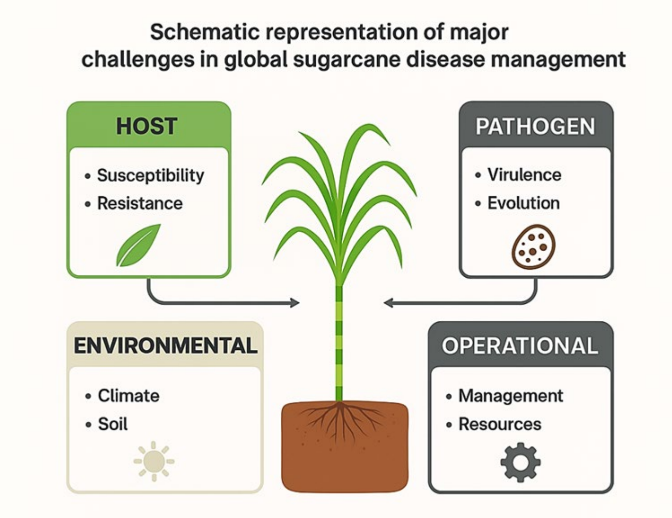

Fig 2: Schematic representation of major challenges in global sugarcane disease management, highlighting host, pathogen, environmental, and operational factors.

5. Management Strategies

Sustainable management of sugarcane diseases requires a multi-tiered approach integrating resistant cultivars, pathogen-free planting material, improved cultural practices, and advanced molecular diagnostics. The vegetative propagation of sugarcane inherently facilitates disease carryover, making integrated disease management (IDM) strategies vital for reducing inoculum pressure and improving long-term productivity (Viswanathan *et al*., 2022[21]; Chinnaraja *et al*., 2023). The following subsections summarize the major management strategies employed globally.

i). Host Resistance and Breeding

Breeding for disease resistance remains the most effective and environmentally sustainable approach for disease control in sugarcane. The incorporation of resistant genes through interspecific hybridization has historically mitigated the impact of several devastating epidemics such as red rot and smut (Rott *et al.*, 2017).

Modern sugarcane improvement programs combine conventional breeding, marker-assisted selection (MAS), and genomic selection to accelerate the identification of resistant genotypes. For instance, resistance to *Sporisorium scitamineum* (smut) has been linked to quantitative trait loci (QTLs) on chromosomes 2B and 5D, while *Colletotrichum falcatum* (red rot) resistance has been associated with pathogenesis-related (PR) gene expression and enhanced lignification (Viswanathan & Samiyappan, 2018) [22].

Genomic and transcriptomic analyses have enabled the discovery of defense-related genes, including WRKY, MYB, NAC, and PR proteins involved in salicylic acid (SA) and jasmonic acid (JA) signaling pathways (Hema *et al.*, 2021). Resistance gene analogs (RGAs) and RNA interference (RNAi) technologies have also shown promise for engineering broad-spectrum resistance against fungal and viral pathogens (Zhao *et al.*, 2023) [27].

However, durable resistance remains elusive due to the polyploid nature of sugarcane and the rapid evolution of pathogen races. Future breeding programs should prioritize multi-gene pyramiding and pan-genome approaches to capture allelic diversity from wild *Saccharum* species and related genera.

ii). Clean Seed and Cultural Practices

Vegetative propagation facilitates pathogen carryover across cropping cycles; therefore, use of pathogen-free planting material is crucial. Thermotherapy (hot water or moist air treatment), meristem tip culture, and micropropagation techniques have proven highly effective in eliminating systemic pathogens such as ratoon stunting disease (RSD), leaf scald, and SCYLV (Chinnaraja *et al.*, 2023). Certification schemes implemented in countries such as Australia, Brazil, and India now emphasize molecular testing for latent infections prior to distribution (Bailey & Bechet, 2020).

Cultural practices complement clean seed programs by minimizing pathogen survival and dissemination.

Recommended Strategies Include:

- Field sanitation and crop rotation to reduce inoculum load;
- Balanced fertilization and soil drainage improvement to reduce susceptibility to wilt and red rot;
- Destruction of diseased clumps and post-harvest trash burning to prevent smut spread;
- Controlled irrigation to avoid bacterial dissemination via water flow.
- Integration of these practices within national seed-cane production systems has led to marked reductions in disease prevalence in several countries (Viswanathan *et al.*, 2022) [21].

iii). Chemical and Biological Control

Although chemical fungicides and bactericides are used selectively in nurseries, their field efficacy is limited due to systemic infection and pathogen latency. Systemic fungicides such as triazoles (e.g., propiconazole, tebuconazole) and strobilurins (azoxystrobin) have shown partial success in controlling red rot and pokkah boeng when applied preventively (Singh *et al.*, 2020) [19].

However, chemical control is increasingly being replaced by biological agents and induced resistance approaches. Rhizosphere inoculation with *Trichoderma harzianum*, *Pseudomonas fluorescens*, and *Bacillus subtilis* enhances systemic resistance and suppresses pathogens via competition and antibiosis (Viswanathan *et al.*, 2022) [21]. Foliar application of defense activators such as chitosan, β-aminobutyric acid, or salicylic acid analogs has also been reported to prime sugarcane defenses against fungal invasion (Hema *et al.*, 2021).

iv). Molecular Diagnostics, Remote Sensing, and Digital Tools

The emergence of high-throughput molecular diagnostics has revolutionized pathogen detection. PCR-based and qPCR assays targeting pathogen-specific genes enable early and reliable detection of RSD (*Leifsonia xyli*), SCYLV, and *Xanthomonas albilineans* even in asymptomatic plants (Comstock *et al.*, 2018). Multiplex and real-time assays now allow simultaneous detection of mixed infections common in sugarcane fields (Siband & Daugrois, 2022).

Next-generation sequencing (NGS) and metagenomic approaches facilitate identification of novel and emerging pathogens, while CRISPR-based biosensors are being developed for rapid field diagnostics (Zhao *et al.*, 2023) [27].

Remote-sensing technologies, including UAV-based multispectral imaging and satellite-derived vegetation indices (NDVI, red-edge), enable large-scale disease surveillance and early warning through spectral signatures associated with infection (Singh *et al.*, 2020) [19].

Integration of these technologies into digital disease management platforms—coupled with AI-driven analytics and weather-based forecasting—can provide real-time decision support for growers and policymakers.

v). Integrated Disease Management (IDM)

Integrated Disease Management (IDM) combines host resistance, sanitation, biological control, and precision monitoring for sustainable suppression of disease epidemics. In sugarcane, IDM frameworks have been successfully implemented for smut, red rot, and RSD in India, Brazil, and Australia (Viswanathan *et al.*, 2022 [21]; Bailey & Bechet, 2020).

Key Components Include:

- Use of resistant or moderately resistant varieties adapted to local pathogen populations.
- Production and distribution of certified disease-free seed cane using meristem culture and molecular indexing.
- Field sanitation and crop residue management to remove primary inoculum sources.
- Periodic monitoring using molecular diagnostics and remote sensing tools.
- Biological and chemical protectants for nurseries and early crop stages.
- Adoption of IDM significantly reduces disease incidence and prolongs varietal lifespan, while minimizing pesticide dependence and environmental impact. The success of IDM relies on stakeholder participation, farmer training, and integration with national extension networks.

vi). Emerging Biotechnological Interventions

Recent breakthroughs in genome editing (CRISPR/Cas9, TALENs) and transgenic technologies have expanded opportunities for precise manipulation of disease-resistance pathways in sugarcane (Zhao *et al.*, 2023) [27]. Overexpression of chitinase, glucanase, and defensin genes from rice and tobacco has enhanced fungal resistance in transgenic sugarcane lines. Similarly, RNAi-mediated silencing of viral genes has conferred tolerance to SCYLV and SCMV (Singh *et al*., 2020) [19].

Genome editing targeting susceptibility (S) genes offers a promising avenue for durable resistance without yield penalties. Integrating these tools with pan-genome and transcriptomic datasets will accelerate the development of next-generation disease-resistant cultivars.

vii). Policy, Quarantine, and Capacity Building

Strong policy frameworks are essential to restrict cross-border pathogen movement and enhance national biosecurity. International initiatives such as the International Society of Sugar Cane Technologists (ISSCT) promote harmonized phytosanitary standards and knowledge exchange. Establishing regional diagnostic hubs and training programs can improve rapid disease identification and strengthen local capacity for disease surveillance and management (Rott *et al*., 2017).

Table 3 Summary of Major Management Strategies for Sugarcane Diseases Worldwide

Management Strategy	Target Disease(s)	Mechanism/Tools	Key References
Resistant cultivar deployment	Red rot, smut, SCYLV	QTL mapping, marker-assisted breeding	Viswanathan & Samiyappan, 2018
Pathogen-free seed cane	RSD, leaf scald	Thermotherapy, meristem culture	Chinnaraja *et al*., 2023
Biological control	Fungal and bacterial diseases	*Trichoderma*, *Pseudomonas*, ISR induction	Viswanathan *et al*., 2022[21]
Molecular diagnostics	RSD, SCYLV, SCMV	PCR, qPCR, NGS	Comstock *et al*., 2018
Remote sensing & AI	Field-scale disease monitoring	UAV, NDVI, predictive models	Singh *et al*., 2020 [19]

6. Future Prospects and Research Needs

Despite significant advances in understanding sugarcane pathology, sustainable disease management remains a formidable challenge. The next generation of research must move beyond single-pathogen control toward systems-level, data-driven, and predictive strategies that integrate molecular, ecological, and agronomic perspectives. Several priority areas are outlined below.

i). Integrative Omics and Systems Biology Approaches

The rapid development of omics technologies—genomics, transcriptomics, proteomics, metabolomics, and epigenomics—has revolutionized plant–pathogen interaction studies. However, sugarcane's complex autopolyploid genome (>10 Gb) still limits functional genomics applications (Zhao *et al*., 2023) [27]. Future efforts should focus on constructing pan-genomes representing both cultivated and wild Saccharum species, enabling precise mapping of resistance loci and allelic variation associated with disease tolerance (Viswanathan *et al*., 2022) [21]. Integrative multi-omics frameworks can elucidate host defense signaling networks, secondary metabolite pathways, and microbiome interactions underlying quantitative resistance. Combining metabolomic profiling (e.g., phenolic and flavonoid responses) with transcriptomic data will facilitate the identification of biomarkers for early disease diagnosis and resistance breeding (Hema *et al*., 2021).

ii). Microbiome Engineering and Biological Resilience

The sugarcane rhizosphere and endosphere harbor diverse microbial communities that influence disease resistance, nutrient uptake, and stress tolerance. Advances in metagenomic and culturomic analyses have revealed specific microbial taxa—such as Bacillus, Trichoderma, and Burkholderia spp.—that suppress red rot, smut, and wilt pathogens via antibiosis and immune priming (Chinnaraja *et al*., 2023). Future research should aim to design synthetic microbial consortia and biostimulants tailored to local soil–climate–pathogen contexts. Harnessing beneficial microbiomes can reduce chemical inputs, promote plant vigor, and stabilize yield under pathogen pressure. Understanding the functional ecology of the sugarcane microbiome will be central to developing next-generation biological disease management platforms.

iii). Climate Change and Pathogen Evolution

Global climate change is expected to reshape the geographical distribution, virulence, and epidemiology of sugarcane pathogens (Bailey & Bechet, 2020). Rising temperatures, erratic rainfall, and increased humidity favor fungal and bacterial outbreaks, while new vector dynamics may accelerate viral and phytoplasma spread. Predictive modeling of climate–pathogen–host interactions using machine learning and climate projections will be essential for early warning and adaptive management. Breeding for climate-resilient and broad-spectrum resistance must integrate both biotic and abiotic stress tolerance, considering that environmental extremes often exacerbate disease susceptibility. Future research should thus prioritize multi-stress phenotyping platforms and genome-wide association studies (GWAS) linking resistance traits with environmental adaptation.

iv). Digital Agriculture and Precision Pathology

The convergence of digital technologies with plant pathology offers transformative potential. Unmanned aerial vehicles (UAVs) equipped with multispectral sensors can detect early disease stress signatures based on canopy reflectance indices. Integration of AI-driven image analysis, IoT-based environmental sensors, and cloud-linked decision support systems enables real-time disease forecasting and precision intervention (Singh *et al*., 2020) [19]. Future sugarcane disease management will increasingly depend on data fusion—combining molecular diagnostics, satellite imagery, and weather models—to guide localized management actions. Investment in open-access disease databases and farmer-accessible mobile platforms will democratize surveillance and foster rapid response to outbreaks.

v). Molecular Breeding and Genome Editing

Advancements in CRISPR/Cas9 and prime editing technologies provide unprecedented opportunities for precise genetic improvement in sugarcane (Zhao *et al*., 2023) [27]. Editing of susceptibility (S) genes and regulatory promoters associated with pathogen entry could yield durable resistance without compromising yield. Concurrently, RNAi-based approaches targeting viral genomes (e.g., SCYLV and SCMV) have shown strong suppression effects in transgenic models (Singh *et al*., 2020) [19]. Moving forward, combining multi-omics data with AI-guided gene prediction and functional validation pipelines will accelerate the development of elite cultivars. Collaborative networks linking breeding programs, bioinformatics resources, and germplasm repositories are essential to translate these innovations into field-level impact.

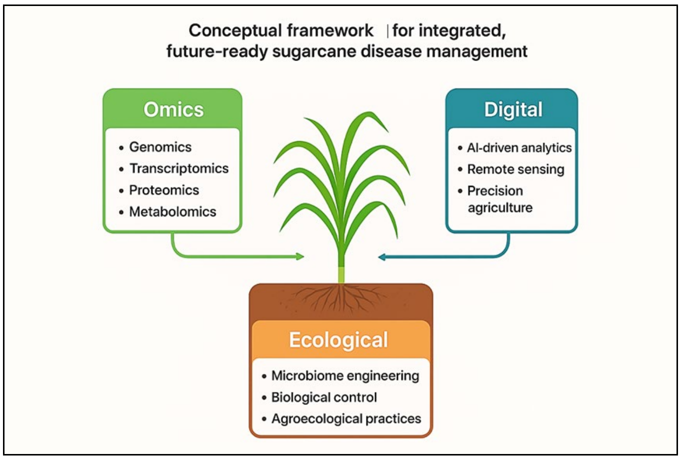

Fig 3: Conceptual framework for integrated, future-ready sugarcane disease management integrating omics, digital, and ecological tools

7. Conclusions

Sugarcane, a cornerstone crop in tropical and subtropical agriculture, continues to face major productivity losses due to an evolving spectrum of diseases caused by fungi, bacteria, viruses, phytoplasmas, and nematodes. Despite decades of breeding and disease management, emerging pathogen races, changing climatic conditions, and the increasing globalization of planting material have intensified disease challenges.

Future-ready sugarcane disease management must transcend traditional control methods and embrace integrated, multidisciplinary frameworks that combine:

- Genomics and transcriptomics for early detection of host susceptibility and pathogen virulence markers;
- Metabolomics and proteomics for elucidating biochemical pathways of resistance;
- Digital agriculture and AI-based surveillance tools for real-time disease forecasting and monitoring;
- Microbiome and ecological engineering for developing resilient agroecosystems; and
- Genome editing tools (e.g., CRISPR/Cas systems) to accelerate resistance breeding against complex and polygenic pathogen threats.

A conceptual shift toward systems-level understanding of host–pathogen–environment interactions will drive sustainable solutions. Strengthening international collaboration, data sharing, and capacity building—especially in developing sugarcane-producing countries—remains pivotal to mitigating global disease burden. In essence, the future of sugarcane health lies at the interface of molecular insight, digital innovation, and ecological intelligence.

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