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MORALITY BEFORE KNOWLEDGE

Sporisorium scitamineum: A comprehensive mini-review on biology, pathogenicity, and management

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ABSTRACT

Background: Sugarcane smut disease, caused by *Sporisorium scitamineum*, is one of the most destructive fungal diseases affecting sugarcane production in Indonesia. Although the national plantation area has expanded in recent years, productivity and sugar recovery rates remain low, hindering the achievement of sugar self-sufficiency. Understanding pathogen characteristics and improving disease management strategies are therefore critical to strengthening national sugarcane sustainability. **Methods:** This study employed a descriptive qualitative approach based on secondary data obtained from the Central Bureau of Statistics (BPS), the Ministry of Agriculture, and peer-reviewed scientific literature published within the last 5–10 years. The analysis covered national cultivation trends, pathogen morphology, and recent advances in chemical and biological control strategies. **Findings:** Indonesia's sugarcane plantation area increased from 429,959 ha in 2018 to 494,764 ha in 2023; however, sugar recovery rates remain low (6.5–7.5%). Morphologically, *S. scitamineum* produces characteristic black whip-like structures containing brown teliospores, which disperse through wind, water, and infected planting materials. Disease control strategies include seed-cane treatment with systemic fungicides (e.g., *flutriafol, propiconazole, triadimefon*) and hot-water treatment. Biological control agents such as Trichoderma spp., Streptomyces spp., and Bacillus spp. demonstrate more than 70% suppression of pathogen growth. Recent developments emphasize integrated management combining genetic resistance, chemical protection, biological control, and molecular technologies. **Conclusion:** Effective management of sugarcane smut in Indonesia requires an integrated and sustainable approach that combines agronomic, chemical, biological, and molecular strategies. Strengthening disease control systems is essential to improving productivity and supporting national sugar security. **Novelty/Originality of this article:** This study provides an updated synthesis linking national production trends with pathogen biology and integrated control innovations. By connecting macro-level agricultural data with micro-level pathogen characteristics and emerging molecular approaches, it offers a comprehensive framework for sustainable smut disease management in Indonesia.

KEYWORDS: disease control; *Sporisorium scitamineum*; sugarcane; teliospore; whip smut.

1. Introduction

Sugarcane smut, caused by *Sporisorium scitamineum*, is a systemic fungal disease that poses a significant threat to global sugarcane production. The disease is characterized by the development of elongated, black whip-like structures emerging from the growing points of infected plants. In Indonesia, this disease is locally known as "luka api," as its symptoms resemble tissues scorched by fire. Several commonly cultivated varieties exhibit high susceptibility to this pathogen. Kristini et al. (2022) identified the Bululawang (BL)

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variety—released in 2004/2005—as one of the most vulnerable varieties to smut infection. Similarly, Hanif (2020) found that PS 862, HPI 2, HPI 3, PS 091416, and PS 090401 also show susceptibility ranges from highly susceptible to moderately susceptible. The dominance of susceptible varieties becomes a major production constraint, especially in East Java where the Bululawang variety accounts for 70–80% of total cultivation (Radar Jember, 2019).

Historically, *S. scitamineum* was first documented in 1877 in Natal, South Africa, before spreading to major sugarcane-growing regions worldwide (Bhuiyan et al., 2021). As sugarcane cultivation expanded into tropical regions, the pathogen encountered conducive climatic conditions and genetically diverse hosts, enabling rapid adaptive evolution. The adaptive nature of fungi has been well recognized; Bazzicalupo (2022) notes that most fungal pathogens possess the capacity to adjust to new hosts and environments, although the rate of adaptation varies among species. Once *S. scitamineum* becomes established in a new environment, it produces abundant teliospores capable of long-distance dispersal through wind, rain splash, planting material, and mechanical transmission, facilitating its spread across regions and production systems.

The impact of sugarcane smut on crop productivity can be severe. Under high inoculum pressure, the disease may cause up to 80% yield loss and may result in complete crop failure when unmanaged. In Indonesia, high infection rates are particularly common in plantations managed by PTPN X, PTPN XI, and smallholder farmers, where susceptible varieties such as Bululawang, PS 921, and M 44251 remain widely cultivated. These infection levels are further exacerbated by inadequate disease monitoring systems, lack of routine seedling sanitation, and limited access to resistant cultivars. Such conditions create a cycle of reinfection that continues across planting seasons, contributing to chronic losses in production.

Various disease-management strategies have been explored, with chemical control being the most widely used approach. Fungicide-based seedling treatments have demonstrated high levels of effectiveness. Mesfin et al. (2022) reported that soaking sugarcane sets in triadimefon 25% and propiconazole 25% solutions significantly reduced infection rates. Varma et al. (2020) similarly found that a mixture of azoxystrobin + tebuconazole (0.1%) suppressed the spread of smut by 88.11%. More recent evaluations by Osman et al. (2025) demonstrated that fungicides such as Montoro, Hattrick, and Trust provided effective protection throughout the planting season. Sealy (2025) further emphasized that most commercial fungicides show protective potential, though there remains limited understanding of how sugarcane plants develop defense responses following fungicide application.

Biological control has also emerged as a promising complementary strategy. Several biological control agents (BCAs), including Trichoderma spp., Streptomyces spp., and Bacillus spp., have shown substantial antagonistic effects against *S. Scitamineum*. Tegene et al. (2021) documented that Trichoderma isolates inhibited pathogen growth by up to 90%, while Deni (2024) reported that Streptomyces sp. S2Ss suppressed fungal growth by 73% in vitro. Parallel to these findings, sugarcane breeding programs in Indonesia have begun developing varieties with improved smut tolerance, though most breeding objectives still prioritize yield improvement over disease resistance. As a result, the availability of truly resistant varieties remains limited.

Despite being recognized globally as a major sugarcane disease, information on *S. scitamineum* in Indonesia remains relatively scarce. The pathogen is not yet categorized as a high-priority disease requiring intensive surveillance, resulting in limited national-scale data on its genetic diversity, epidemiology, and distribution patterns. Significant knowledge gaps persist, including limited evaluation of resistant varieties, insufficient understanding of host–pathogen interactions under local agroclimatic conditions, and inadequate characterization of pathogen variability across regions. Addressing these gaps is essential for developing effective, sustainable disease management strategies. Moreover, strengthening the scientific foundation surrounding *S. scitamineum* in Indonesia will support future researchers in refining current knowledge and expanding insights into pathogen ecology, host resistance, and disease mitigation.

Information regarding Sporisorium scitamineum at the national level remains limited, as this pathogen is not yet classified as a major disease requiring intensive monitoring. In addition, there are constraints in evaluating resistant varieties, understanding the infection process of *S. Scitamineum*, and studying its biodiversity within local environments while also presenting it as a stepping stone for future readers to correct and add some additional information based on it. Therefore, further comprehensive research is essential to strengthen national surveillance data and support the development of effective and sustainable disease management strategies.

2. Methods

2.1 Research design

This study employs a qualitative descriptive approach based on secondary data and a comprehensive literature review to analyze the status, impacts, and management strategies of sugarcane smut disease (*S. scitamineum*) in Indonesia. This approach is particularly suitable for synthesizing existing knowledge and identifying patterns across diverse sources of information. It also allows for a comprehensive understanding of the disease from biological, environmental, and management perspectives without relying on primary field data.

2.2 Data sources

Secondary data were obtained from official institutions such as the Central Bureau of Statistics (BPS), the Ministry of Agriculture, the Ministry of Environment and Forestry, and national research agencies involved in sugarcane development. These data include information on cultivation area, production levels, climate conditions, yield recovery, and national agricultural policies. The use of data from these authoritative sources ensures the reliability and validity of the information analyzed in this study.

2.3 Literature review procedure

The literature review was conducted systematically through academic databases such as Google Scholar, SINTA, and Scopus using keywords related to sugarcane smut, disease management, varietal resistance, and national production. Literature selection followed strict criteria, including publication within the last 5–10 years, relevance to sugarcane smut disease, and full-text availability to ensure recency and reliability. In addition, duplicate records were removed and only peer-reviewed articles and reputable reports were included to maintain the quality of the reviewed sources.

2.4 Data analysis and analytical framework

Data analysis in this study employed content analysis, involving the processes of reducing, categorizing, and synthesizing information derived from scientific publications, research reports, and policy documents. The findings were systematically organized into thematic categories, including pathogen biology, epidemiology, environmental influences, host susceptibility, and management strategies. This analytical framework enabled comparisons across national and international studies and facilitated the identification of patterns, relationships, and research gaps within the existing literature. Through this integrated approach, the study ensures a structured and comprehensive interpretation of the collected data.

3. Results and Discussion

3.1 The state of sugar production in Indonesia

Indonesia, as a tropical country, possesses high potential for the cultivation of various agricultural commodities, including sugarcane (*Saccharum officinarum L.*). According to Goodstats (2024), the total area used for sugarcane cultivation in Indonesia is approximately 502,800 hectares, with East Java being the largest contributor at 239,700 hectares, followed by Lampung with 145,600 hectares, and Central Java with 56,000 hectares. The Ministry of Agriculture (2023) further reports that around 400,000 hectares of land have been optimized for national sugarcane production. Most sugarcane plantations in Indonesia are managed by private estates, while the rest are owned by state-owned enterprises (PTPN) and smallholder farmers. Cultivation systems include monoculture, polyculture, and crop rotation, depending on agroecosystem conditions and land management strategies (Artikanur et al., 2024).

Table 1. Harvested area and sugarcane production in Indonesia, 2018–2023

Year	Harvested area (ha)	Sugarcane production (metric tons)
2018	429,959	2,170,947
2019	411,435	2,227,046
2020	420,505	2,130,719
2021	445,207	2,350,809
2022	483,901	2,405,907
2023	494,764	2,610,658

(Ministry of Agriculture Republic of Indonesia, 2023)

Table 1 illustrates the national development of sugarcane cultivation areas in Indonesia, showing a generally increasing trend over the period 2018–2023. In 2023, Indonesia produced approximately 2,610,658 tons of sugarcane; however, only about 7.61% was processed into white sugar. The sugar recovery rate remains relatively low, ranging from 6.5% to 7.5% (Rianditya & Hartatik, 2022). According to DataIndonesia (2024), national sugar production reached approximately 2.27 million tons. Despite the increase in cultivated area and production volume, domestic sugarcane output remains insufficient to meet national sugar demand, resulting in continued reliance on imports. Hermawan et al. (2025) reported that national sugar production during 2024–2025 has not yet achieved self-sufficiency, mainly due to policy constraints, field conditions, and inefficiencies in sugar mill processing (PG). Similarly, Aulia (2024) noted that domestic production fulfills only about 30–35% of total demand, while the remaining 65–75% is met through imports.

Sugar production over the past five years has been significantly influenced by government policies, both positively and negatively, particularly in relation to domestic production and import regulation. However, some policies appear to be ineffective or not fully implemented as intended. Table 2 presents several key policies and their observed impacts based on current conditions. One notable example is the government's plan to eliminate sugar imports by 2025; however, in practice, Indonesia continues to import sugar from major producing countries such as China, Brazil, and Thailand.

Countries such as Brazil, India, China, and the United States are among the major global producers of sugar, primarily derived from sugarcane and sugar beet (USDA, 2025). Global sugar production exceeds 180 million tons annually, with Brazil being the largest producer and exporter. Indonesia, in contrast, remains highly dependent on sugar imports, mainly from Brazil and Thailand. According to BPS (2024), during the period 2017–2024, Brazil was the largest source of Indonesia's sugar imports, totaling approximately 3.4 million tons, followed by Thailand, Australia, and India.

Table 2. Government policy on sugar production in the last 5 years

Year	Regulation	Description & impact	Source
2019	Sugar self-sufficiency roadmap	The government introduced a roadmap targeting sugar self-sufficiency by 2025, focusing on land expansion and revitalization of sugar mills (PG).	Ministry of Agriculture (2019)
2020	Increase of raw sugar import quotas	To stabilize domestic supply and meet industrial demand during COVID-19, the government increased raw sugar import allocations.	USDA (2025); Ministry of Trade (2020)
2021	Regulation on raw and refined sugar import licenses	Tightened import licensing for consumption and industrial sugar, prioritizing state-owned enterprises and refineries.	Ministry of Trade Regulation No. 19/2021
2022	National commodity balance policy (*Neraca Komoditas*)	Introduction of a commodity balance system to regulate imports based on production, consumption, and stock levels.	Presidential Regulation No. 32 of 2022
2023	Sugar outlook and expansion policy	Confirmation of approximately 400,000 ha of productive sugarcane land and expansion targets up to 700,000 ha.	Ministry of Agriculture (2023)
2023	Import reduction target (No sugar imports by 2025)	The Government plans to eliminate sugar imports by 2025 and strengthen domestic production capacity.	Antara News (2024); Ministry of Agriculture (2023)
2024	Sugar mill revitalization and bioethanol integration	Revitalization of aging sugar mills and integration of sugarcane into bioethanol programs (E10–E20).	Ministry of Agriculture (2024); CRIF Asia (2024)
2024	Price regulation and HPP adjustment	Adjustment of the farmer benchmark price (HPP) to improve farmer incentives and increase sugarcane production.	Ministry of Trade (2024); Bapanas (2024)

Brazil is also recognized as the world's leading sugar exporter. Trade data from the Observatory of Economic Complexity (OEC, 2024) indicate that Brazil's sugar exports reached approximately USD 18.6 billion, while Indonesia's sugar imports were valued at around USD 1.65 billion. Despite government efforts to achieve self-sufficiency, domestic production remains insufficient to meet national demand, reinforcing the country's reliance on imports.

3.2 Climate condition in Indonesia

Indonesia is a tropical country located along the equator, characterized by consistently high temperatures and relatively high humidity throughout the year. The country's climate is largely influenced by monsoonal wind circulation, resulting in two main seasons—the rainy season and the dry season. The transition between these seasons occurs periodically but varies across regions depending on geographical location, altitude, and topographic conditions. This variation contributes to Indonesia's diverse microclimatic patterns, which significantly influence agricultural systems, particularly in terms of cropping patterns, productivity, and land management (Badan Meteorologi, Klimatologi, dan Geofisika [BMKG], 2023).

BMKG (2023) reported that the average annual temperature in Indonesia ranges between 25–28°C, with annual rainfall reaching 2,000–3,000 mm in most regions. Highland and mountainous areas generally have lower temperatures and higher rainfall compared to lowland and coastal areas. In addition to geographical factors, global climatic phenomena such as El Niño and La Niña also have a significant influence on national climate patterns. El

Niño tends to cause prolonged droughts, while La Niña increases rainfall intensity and the risk of flooding in several regions. The impacts of global climate change are becoming increasingly evident, marked by shifting seasonal patterns, temperature anomalies, and unpredictable rainfall intensity (Ministry of Environment and Forestry of the Republic of Indonesia, 2022).

Indonesia's tropical climate generally supports the growth of various food and plantation crops such as rice, oil palm, coffee, and sugarcane. However, fluctuations in rainfall and uneven water distribution often pose challenges to maintaining stable crop productivity. Therefore, adjusting planting calendars, implementing efficient water management, and using drought-tolerant varieties are essential strategies to maintain food security and ensure the sustainability of crop-based industries in Indonesia.

The average temperature in most sugarcane-growing areas of Indonesia ranges between 25°C and 28°C, with annual rainfall between 1,500–3,000 mm depending on the region. Highland and coastal regions show marked differences in humidity and temperature, influencing crop growth duration and sucrose accumulation. BMKG (2023) reported that coastal lowlands such as those in East Java and Lampung—key sugarcane centers—tend to have longer dry periods, which favor sugar concentration in cane juice but can reduce stalk growth if water stress is severe. Conversely, excess rainfall during the wet season can trigger lodging, waterlogging, and disease outbreaks, including smut disease caused by Sporisorium scitamineum, due to favorable conditions for teliospore germination and dispersal.

In response to these challenges, integrated climate-smart agricultural practices are being promoted to optimize sugarcane cultivation. Techniques such as adjusting planting calendars, adopting efficient irrigation systems, and utilizing drought-tolerant or flood-tolerant sugarcane varieties have proven effective in mitigating climate-related risks. Furthermore, site-specific nutrient management and the use of soil moisture monitoring systems have helped farmers better regulate water usage and maintain plant health. The Ministry of Agriculture (2023) emphasizes that sugarcane production sustainability depends not only on land expansion but also on improving climate adaptability through resilient farming systems and precision agriculture technologies.

The relationship between climate variability and the prevalence of smut disease has become an emerging research focus in Indonesia. *S. scitamineum* thrives in warm, humid conditions, particularly during transitional periods between wet and dry seasons (Bhuiyan et al., 2021; Hidayah et al., 2024). Prolonged moisture on sugarcane buds facilitates teliospore germination and infection, whereas dry stress may suppress sporulation but weaken host resistance (Bhuiyan et al., 2021; Hidayah et al., 2024). Thus, climate management—through irrigation timing, drainage improvement, and varietal selection—plays a crucial role in minimizing disease incidence. By integrating climatic data with disease forecasting, Indonesia can develop an early warning system to better prepare for future climate-related disease risks and support national sugar self-sufficiency goals.

3.3 Scitanenium morphology

S. scitamineum is a pathogenic fungus belonging to the division Basidiomycota, class Ustilaginomycetes, and family Ustilaginaceae (Bhuiyan et al., 2021). This fungus is known to cause "sugarcane smut", characterized by the appearance of a black whip-like structure at the top of the sugarcane plant. S. scitamineum infects the host systemically and can attack sugarcane at any stage of its growth cycle. Infection by *S. scitamineum* leads to several symptoms, including stunted growth, narrow and chlorotic leaves, excessive tillering, and the formation of a black whip at the shoot apex of the plant (Fig. 1) (Rajput et al., 2021).

Fig. 1 sugarcane that already infected with *S. scitamineum* (private documentation)

Microscopic observations of *S. scitamineum* revealed the presence of brown, coccus-shaped teliospores (Fig. 2). Teliospores are formed under stress conditions and are capable of germinating at approximately 30°C under specific water potential levels (Hidayah et al., 2024). These teliospores serve as the primary means of dissemination for *S. scitamineum*. The size of teliospores ranges from 8 to 10 μm, with shapes varying from coccus to elliptical (Shuai et al., 2023). During the sporulation phase, the black whip releases teliospores that can be dispersed by wind over distances of up to 2 km, potentially infecting surrounding sugarcane plants. Furthermore, human activities, such as field operations, agricultural tools, and water movement, also contribute to the spread of *S. scitamineum* (Bhuiyan et al., 2021).

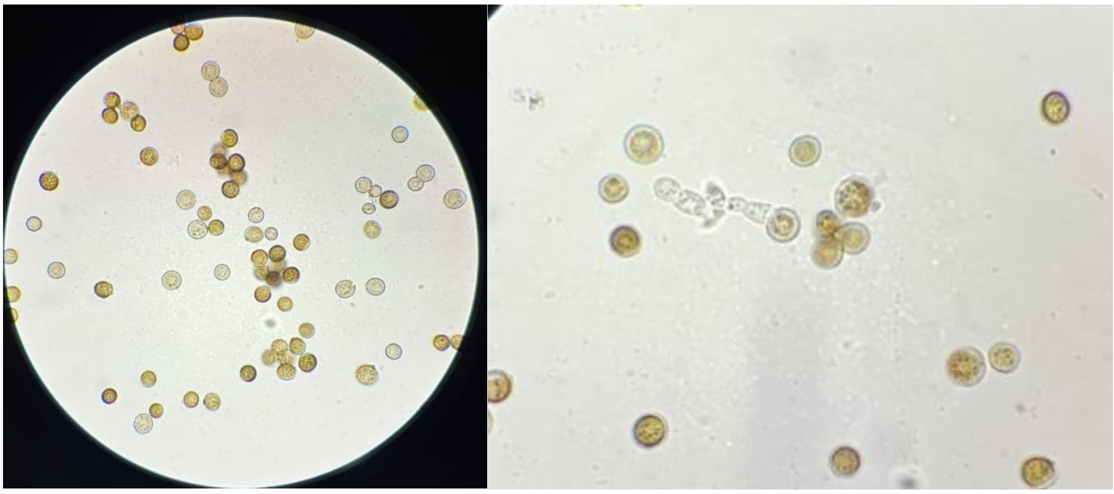

Fig. 2. *S. scitamineum* teliospore's microscopic observation (100x) (private documentation)

Further examination showed that S. Scitamineum's teliospore can be germinated inside a petri dish containing PDA (Potato Dextrose Agar) in a room temperature environment. Figure 3 showed the growth of an already germinated teliospore, its colony having a white cottony texture with an almost purple center while its spore is ellipse in shape with a septate hyphea and a sack-like sporangium containing its spore. The isolate has not been identified with PCR but it's already been tested through Postulate Koch, Deni (2024) experiment showed that germinated teliospore can still effect a young sugarcane around 3 months after it was infected with it.

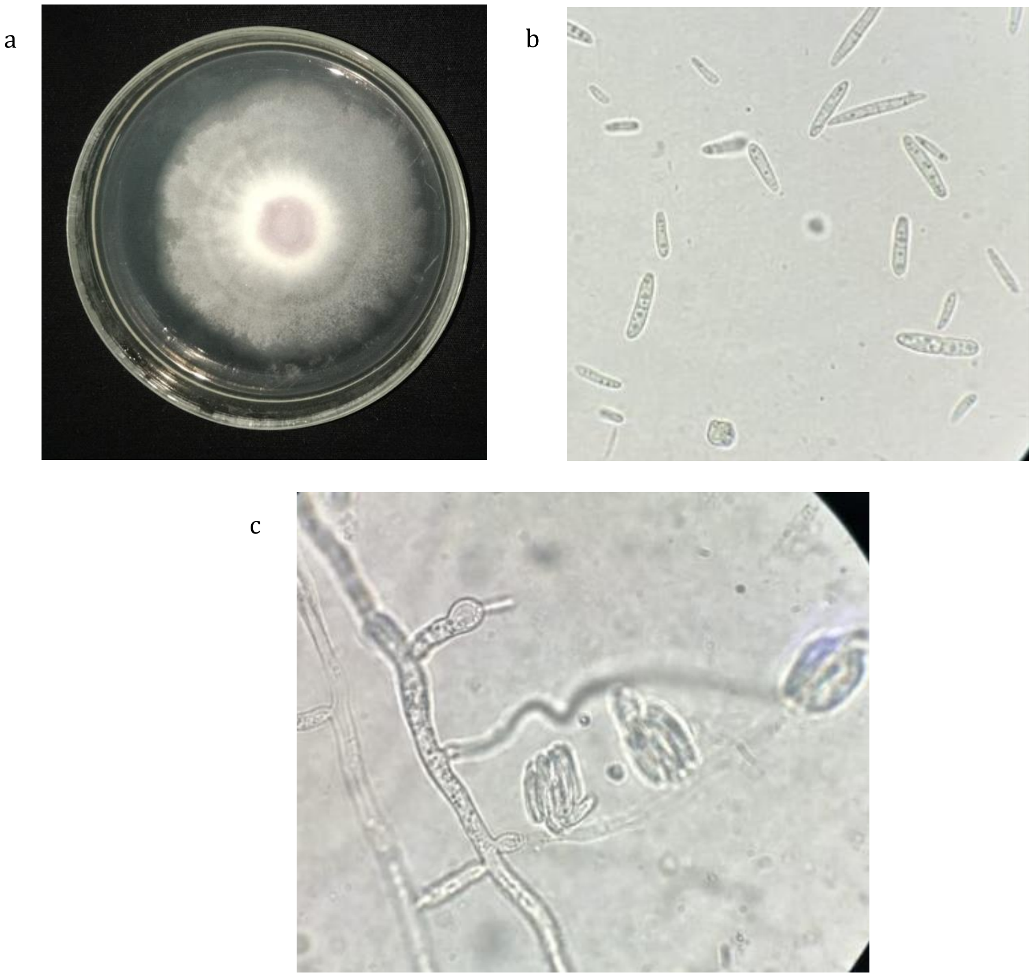

Fig. 3. Morphology of *S. scitamineum*: (a) colony; (b) spores (100×); (c) hyphae and sporangium

3.4 Environmental factors influencing the development of sugarcane whip smut

Whip smut disease, caused by *Sporisorium scitamineum*, is one of the most important diseases of sugarcane, and its spread is strongly influenced by environmental factors. Physiologically, this pathogen thrives under warm temperatures and high humidity, conditions commonly found in tropical regions such as Indonesia. The teliospores of the fungus require optimal temperatures of 25–30 °C and relative humidity above 80% to germinate and infect young plant tissues (Rajput et al., 2021). Under such conditions, spores adhere more easily and penetrate the epidermal tissue of plant buds. In subtropical regions, smut infections generally increase at the onset of the rainy season when humidity is high and temperatures are moderate—conditions that also correspond to the climatic patterns of many sugarcane production centers in Indonesia (Bhuiyan et al., 2021).

In addition to temperature and humidity, rainfall plays a critical role in expanding the infection area because rain splash facilitates the spread of teliospores from plant to plant. Prolonged rainy seasons extend periods of leaf and bud surface wetness, thereby increasing opportunities for primary infection. Conversely, extreme dry seasons may suppress spore germination but also reduce the physiological resilience of sugarcane due to drought stress. Global climate change, which disrupts rainfall patterns, further complicates these dynamics. La Niña events tend to increase humidity and trigger fungal disease outbreaks, whereas El Niño causes prolonged droughts that lower overall sugarcane productivity.

Other environmental factors such as soil type, drainage, and light intensity also have direct correlations with smut development. Poorly drained soils tend to retain moisture, creating ideal conditions for pathogen survival and proliferation. Mesfin et al. (2022) reported that in northern Ethiopia, smut incidence was significantly higher in poorly drained areas compared to sandy soils that dry quickly. Similarly, excessive shading caused by dense planting reduces air circulation and prolongs leaf surface moisture, enhancing the likelihood of secondary infection. Such conditions are commonly observed in smallholder fields in Indonesia, where sugarcane is frequently planted at close spacing to maximize stalk production.

The spread of the pathogen is also heavily influenced by agronomic practices and field sanitation. Planting material from infected sugarcane serves as the primary inoculum source for new fields. Bhuiyan et al. (2021) emphasized that the use of healthy planting material and hot-water treatment prior to planting can reduce infection risk by up to 80%. However, these practices remain underutilized among Indonesian farmers due to limited facilities and cost constraints. Other factors such as crop rotation, residue management, and cleaning of harvesting tools also contribute either to the dissemination or suppression of the disease in the field. Thus, environmental conditions and human practices are closely interconnected in determining the severity of smut outbreaks within a region.

Indonesia's highly diverse agroclimatic conditions lead to significant variation in smut incidence across regions. According to the Ministry of Agriculture (2023), provinces such as East Java and Lampung, which experience long dry seasons and high light intensity, tend to have moderate infection risk, whereas northern Central Java, which is more humid, shows higher disease incidence. This variation underscores the need for climate-based disease risk zoning as a foundation for determining planting schedules and variety rotation. Such an approach has also been implemented in Brazil and India with notable success in reducing the spread of *S. scitamineum* (Hoepers et al., 2024).

The ecological and climatic influences on whip smut highlight the need for a weather-based integrated disease management system. Integrating real-time climate data with field monitoring can help predict infection risks and determine optimal timing for fungicide applications or set treatments. Furthermore, the development of resistant and climate-adaptive varieties is essential for long-term management strategies. Collaboration among institutions such as P3GI, BMKG, and the Ministry of Agriculture is expected to produce disease prediction models tailored to Indonesia's agroclimatic conditions. With such approaches, whip smut disease can be controlled more preventively, efficiently, and sustainably to support the resilience of the national sugar industry

3.5 Sugarcane variety

Indonesia has a wide range of sugarcane varieties cultivated across different regions, each possessing distinct characteristics. Saifudin et al. (2021) reported that the clonal varieties SB 01, SB 03, and SB 12 exhibit resistance to smut disease (*S. Scitamineum*) and sugarcane mosaic virus, as well as tolerance to drought and high sugar yield potential. Furthermore, the study by Wening et al. (2023) indicated that the varieties used in their research showed moderate resistance to smut disease, mosaic virus, and top rot disease caused by Xanthomonas albilineans.

There are 22 superior sugarcane varieties currently used by private sugar estates in Indonesia, each selected based on their high sugar recovery rates, enabling greater white sugar production (Kasiamdari et al., 2019). Indonesia continues to develop new sugarcane varieties each year; however, most breeding efforts primarily focus on improving sugar yield rather than enhancing disease resistance. Sugarcane smut disease can significantly reduce yield and potentially decrease sugar recovery quality (Kristini et al., 2022). In addition, smut infection not only reduces cane tonnage but also lowers Brix, sucrose percentage (Pol), and juice purity (Rajput et al., 2021).

Sugarcane (*Saccharum officinarum L.*) cultivated in Indonesia consists of various varieties developed by both national research institutions and international collaborations. The main institution responsible for variety development is the Pusat Penelitian Perkebunan Gula Indonesia Institute (P3GI) in Pasuruan, which collaborates with PT. Perkebunan Nusantara (PTPN) and Badan Penelitian dan Pengembangan Pertanian (Balitbangtan). Sugarcane varieties in Indonesia are generally classified based on their origin, productivity, sugar yield (recovery), and resistance to major diseases such as sugarcane smut, caused by *S. scitamineum* (Rajput et al., 2021). The commonly used naming systems for varieties include PS (Pasuruan), BL (Bululawang), PSJK (Pasuruan–Jember–Kebun), R (South Africa), and VMC (Philippines). Each variety is designed to adapt to specific environmental conditions such as dry land (upland), irrigated paddy fields, volcanic soils, and coastal alluvial soils (Ministry of Agriculture, 2023). Therefore, the selection of suitable varieties plays a crucial role in determining productivity, pest resistance, and milling efficiency.

Several sugarcane varieties widely cultivated for their high productivity and sugar yield include PSJK 922, PS 891, and PS 892. The PSJK 922 variety, developed by P3GI, has shown a sugar recovery rate of around 9% and performs well in both irrigated and dryland fields (Firdaus, 2021). Meanwhile, PS 891 and PS 892, also developed by P3GI, have demonstrated sugar recoveries exceeding 10% under experimental conditions (Wening & Kuswurjanto, 2023). The Bululawang (BL) variety remains commonly planted by farmers due to its broad adaptability; however, it has low resistance to smut disease (Rianditya & Hartatik, 2022). On the other hand, VMC 76-16 from the Philippines and R-579 from South Africa are known for their higher resistance to *S. scitamineum* (Rajput et al., 2021). The utilization of resistant varieties represents a key strategy in minimizing the spread of sugarcane smut in the field.

Disease resistance is a critical aspect in determining superior sugarcane varieties. *S. scitamineum* infects the growing points and young buds of sugarcane, making varieties with thin leaf sheaths and rapid growth more susceptible. Research by Wening et al. (2023) demonstrated that epidermal thickness and the degree of stem lignification significantly influence plant resistance. Additionally, varieties exhibiting rapid tiller development and thicker cuticular wax layers tend to show higher resistance to infection (Rajput et al., 2021). Conversely, varieties such as Bululawang (BL) often experience severe smut outbreaks, particularly during the humid season and under suboptimal cultivation conditions (Rianditya & Hartatik, 2022). This highlights the importance of variety selection based on physiological and morphological traits, not solely on yield potential.

In recent years, Indonesia's national sugarcane breeding programs have focused on developing high-sucrose and disease-resistant varieties through molecular approaches. Techniques such as RAPD (Random Amplified Polymorphic DNA) and SSR (Simple Sequence Repeat) have been employed to identify resistance genes against S. scitamineum (Ministry of Agriculture, 2023). Moreover, imported varieties such as R-579 and VMC 76-16 have been used as parental lines due to their stable resistance to the pathogen. New varieties such as PSBM 901, Kidang Kencana, and GMP 3, released between 2020 and 2023, have shown strong potential to support Indonesia's sugar self-sufficiency program (Ministry of Agriculture, 2023). However, adoption among farmers remains limited due to the low availability of high-quality seeds and delays in seedling distribution by sugar mills.

Thus, the development and selection of sugarcane varieties in Indonesia are determined not only by productivity but also by disease resistance and environmental adaptability. The continued use of susceptible varieties such as Bululawang contributes to the increasing incidence of smut disease, which can reduce sugar recovery by up to 20% (Rajput et al., 2021). Therefore, the implementation of resistant varieties, strong seed policy support, and collaboration among researchers, industry, and government are crucial for the sustainability of Indonesia's sugar industry. Looking forward, research on genomics-based breeding (CRISPR/Cas), endophytic biological control agents, and molecular biotechnology must be strengthened to develop more adaptive and productive sugarcane varieties in the face of climate change.

3.6 Global status of sugarcane smut disease

Whip smut disease in sugarcane, caused by *S. Scitamineum*, is a cosmopolitan pathogen that affects major sugarcane-producing regions across several continents. Historically, the disease was first reported in Natal, South Africa in 1877 and has since spread to Asia, Latin America, Africa, and Australia, causing variable yield losses depending on host variety and environmental conditions. Literature reviews and field studies have reported that yield losses can range from moderate (around 20–30%) to severe (>50%) in cases of heavy infection, particularly in susceptible varieties and poorly managed fields (Que et al., 2014). Consequently, smut is considered a major threat to sugar recovery and the sustainability of the sugarcane industry in tropical and subtropical countries.

In India, smut remains a significant agronomic constraint across many sugarcane-growing regions. National studies indicate that disease incidence varies among regions and seasons, and is associated with the use of contaminated planting materials, susceptible varieties, and local climatic conditions that favor teliospore germination. Research efforts in India have focused on screening resistant varieties, developing standard inoculation protocols for resistance testing, and integrating cultural practices with set treatments (such as artificial inoculation and hot-water treatment) to minimize disease transmission (Maurya et al., 2024). These approaches have produced variable results but consistently emphasize the importance of combining resistant genotypes with proper seed management for long-term control.

Brazil, as one of the world's leading sugarcane producers and exporters, faces unique smut-related challenges linked to the scale of production and diversity of local isolates. Smut has been reported in Brazil since the mid-20th century, and several Brazilian studies have highlighted the genetic variability of the pathogen and its impact on stalk mortality and juice quality. Breeding efforts and field surveillance programs have become key strategies to suppress disease prevalence. Genotype screening studies in Brazil have revealed significant resistance variability among both local and imported lines, suggesting that local breeding programs incorporating resistance sources are the most effective approach (de Fátima Santos, 2025). Furthermore, due to Brazil's massive production scale, the economic impact of smut often manifests through increased control costs, reduced overall sugar recovery, and the need to replace susceptible varieties.

South Africa holds both historical and practical importance: as the first region to report the disease, it also possesses extensive pathogen diversity and a long record of management experience. Early observations on the biology and epidemiology of smut originated from South African studies, forming the foundation for global taxonomy and disease modeling. Field experience in South Africa and neighboring regions emphasizes the role of contaminated planting material as the primary source of spread, along with the effectiveness of sanitation measures, set treatments, and resistant variety selection in reducing transmission rates. These historical insights have become the basis for management guidelines in other countries that later encountered outbreaks.

From a global economic perspective, sugarcane smut affects not only yield tonnage but also juice quality (reducing Brix/Pol and sugar recovery), control costs, and the loss of elite susceptible varieties, creating the need for varietal replacement and replanting. Reviews and field studies report wide fluctuations in yield losses—from moderate reductions to total crop failure in extreme cases—representing significant economic consequences for both farmers and the sugar industry (Rajput et al., 2021). From a policy standpoint, major sugarcane-producing countries require a comprehensive strategy that includes phytosanitary surveillance, breeding programs for smut resistance, sett treatment protocols (hot-water and/or fungicide application), and support for the adoption of new resistant varieties—in order to minimize economic losses and maintain sugar supply chain resilience.

3.7 Prevention and innovation

The smut disease (*S. Scitamineum*) is one of the most damaging major diseases affecting sugarcane in Indonesia. Infection by this fungus causes abnormal growth, characterized by the emergence of a black whip from the plant's growing point, along with a reduction in plant vigor, stalk weight, and juice quality. In severe cases, yield losses may reach 20–40%, accompanied by a decline in sucrose content and sugar recovery rate. The disease is systemic, as the fungus can survive in setts (seed cane pieces) or in the soil, allowing rapid spread through infected planting material and airborne spores. According to Bhuiyan et al.

(2021), *S. scitamineum* infections are commonly found in major sugarcane-producing regions of East Java, such as Malang and Pasuruan, with varying severity depending on environmental conditions and the variety planted.

Control of sugarcane smut disease is carried out through an Integrated Disease Management (IDM) approach. The main measures include the use of certified healthy planting materials, hot water treatment of setts (at 50–52°C for 30 minutes), and soaking with systemic fungicides such as flutriafol or propiconazole prior to planting. Good field management practices, including the destruction of infected plants, crop rotation, and proper drainage management, have also proven effective in reducing inoculum levels in the field. According to Firdaus (2021), intensive monitoring during the seedling and replanting stages is the most critical phase for preventing systemic disease spread. Furthermore, field sanitation and planting time management adjusted to climatic conditions are essential factors in minimizing infection risk.

Research developments in disease control have been directed toward enhancing varietal resistance and the utilization of molecular technologies for early detection. Breeding programs conducted by P3GI and Balitbangtan focus on the development of disease-resistant clones such as SB 01, SB 03, and SB 12, which exhibit high performance under dry land conditions (Setyobudi et al., 2023). Molecular studies have also identified genetic markers associated with resistance genes against *S. Scitamineum*, enabling faster selection of resistant varieties. According to Rajput et al. (2021), the integration of pathogen genomic analysis and plant gene expression profiling can reveal natural resistance mechanisms, such as increased activity of defense-related enzymes and inhibition of fungal colonization within meristem tissues.

Recent research directions also include the application of biological control agents as an environmentally friendly alternative. Several isolates of Trichoderma harzianum have been reported to significantly inhibit spore germination and mycelial growth of *S. scitamineum* under laboratory conditions (Joshi & Goswami, 2024). This biocontrol approach has begun to be tested in field conditions with promising results, especially when combined with seed treatment and field sanitation practices. In addition, climate-based epidemiological modeling is being developed to predict infection peaks based on temperature and humidity, allowing for more timely and targeted disease control. Through the combination of genetic, biological, and environmental management strategies, the control of sugarcane smut disease is expected to become more sustainable and efficient.

4. Conclusions

The sugarcane smut disease caused by *Sporisorium scitamineum* continues to be a major constraint on sugarcane productivity in Indonesia, particularly in regions dominated by highly susceptible varieties such as Bululawang, PS 921, and M44251. The systemic nature of the pathogen, combined with efficient teliospore dispersal through wind, rain, and infected planting material, enables the disease to persist and spread rapidly across production landscapes. Although chemical fungicides remain an important component of disease suppression, their standalone effectiveness is limited. Evidence increasingly shows that integrated management—combining fungicide treatment, clean seed practices, field sanitation, and the use of biological control agents such as Trichoderma and Bacillus—offers more reliable protection while reducing environmental risks. These integrated strategies are essential given Indonesia's ongoing challenges related to climatic extremes, inconsistent disease surveillance, and continued reliance on susceptible cultivar types.

Moving forward, achieving sustainable control of *S. scitamineum* will require a stronger emphasis on developing and disseminating resistant varieties, supported by advances in molecular breeding and improved access to high-quality planting material. Expanding research on biological control agents, pathogen diversity, and host–pathogen interactions is also crucial for designing long-term solutions adapted to local agroecosystems. Furthermore, strengthening national monitoring systems and integrating climate-based risk assessment can enhance early detection and targeted intervention. By addressing these scientific and structural gaps, Indonesia can increase the resilience of its sugarcane production systems, improve sugar yield and recovery rates, and more effectively progress toward national sugar self-sufficiency.

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