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The Role of Viruses in Sugarcane Yield Reduction: A Case Study on *Sugarcane Yellow Leaf Virus*

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Abstract This study systematically explores the role of viruses, particularly *Sugarcane yellow leaf virus* (SCYLV), in sugarcane yield reduction. Key findings reveal that SCYLV significantly impacts the physiological functions of sugarcane, leading to decreased photosynthetic efficiency, impaired nutrient uptake and transport, and stunted growth. SCYLV infection not only directly damages plant tissues but also predisposes sugarcane to secondary infections and environmental stresses, further exacerbating yield losses. The prevalence of SCYLV has led to significant yield reductions and varietal degeneration in various regions, including Florida, Réunion Island, and India. To mitigate the impact of SCYLV on sugarcane production, several management strategies have been employed, including the use of virus-free seed cane, breeding for resistant varieties, and employing chemical and biological control methods. These strategies have shown positive results under different conditions and in various regions. Future research should focus on advancing the understanding of the mechanisms of SCYLV resistance, further exploring the application of RNA interference technology and multi-target resistant transgenic lines, and improving early detection and diagnostic tools to enhance disease management. This study aims to advance the understanding of SCYLV resistance mechanisms and improve management strategies to reduce the impact of SCYLV on sugarcane yield and promote sustainable sugarcane production.

Keywords Sugarcane (*Saccharum* spp.); *Sugarcane yellow leaf virus* (SCYLV); Yield; Virus management; Resistance breeding

1 Introduction

Sugarcane (*Saccharum* spp.) is a vital crop globally, providing approximately 80% of the world's sugar and a significant portion of bioethanol (Yang et al., 2019). Cultivated in tropical and subtropical regions, sugarcane is a major economic driver in many countries, supporting both local economies and global markets. The crop's high biomass yield and adaptability to various climates make it a preferred choice for sugar and biofuel production. However, sugarcane cultivation faces numerous challenges, including diseases caused by viruses, which can significantly impact yield and quality (Viswanathan, 2018).

The yield of sugarcane is crucial for the economic viability of the crop. High yields ensure the profitability of sugarcane farming, which in turn supports the livelihoods of millions of farmers and workers in the sugar industry. Yield reductions can have severe economic consequences (Lu et al., 2021), affecting not only the farmers but also the entire supply chain, from processing mills to global sugar markets. Diseases such as *Sugarcane yellow leaf virus* (SCYLV) have been identified as major threats to sugarcane yield, causing significant losses in various regions (Lehrer et al., 2009; Boukari et al., 2019; Sood et al., 2021; Viswanathan, 2021).

This study is to comprehensively examine the role of viruses, particularly SCYLV, in reducing sugarcane yield. It will assess the prevalence and impact of SCYLV on sugarcane yield in different regions, and evaluate the effectiveness of various management strategies in mitigating the impact of SCYLV. By synthesizing findings from multiple studies, this study expects to provide a detailed understanding of how SCYLV affects sugarcane yield and to propose evidence-based recommendations for managing this disease to sustain sugarcane production.

2 Overview of Plant Viruses

2.1 General characteristics of plant viruses

Plant viruses are typically small, obligate intracellular parasites that rely on host cellular machinery for replication. They possess a wide range of genetic material, including single-stranded or double-stranded RNA or DNA. For instance, the *Sugarcane yellow leaf virus* (SCYLV) is a member of the *Polerovirus* genus within the Luteoviridae family, characterized by a monopartite, single-stranded positive-sense RNA genome approximately 6 kb in size. The virions are composed of 180 coat protein units and are 24 nm-29 nm in diameter (Holkar et al., 2020).

2.2 Transmission mechanisms

Plant viruses can be transmitted through various mechanisms, including mechanical means, seed transmission, and vectors such as insects. SCYLV, for example, is primarily transmitted by the sugarcane aphid, *Melanaphis sacchari*, in a circulative and non-propagative manner (Lehrer et al., 2006; Holkar et al., 2020). Other aphid species, such as *Ceratovacuna lanigera*, *Rhopalosiphum rufiabdominalis*, and *R. maidis*, have also been reported to transmit SCYLV (Holkar et al., 2020). The virus is phloem-limited, meaning it is restricted to the plant's vascular system, which complicates its detection and management (Holkar et al., 2020; Shabbir et al., 2022).

2.3 Impact on crop yields

The impact of plant viruses on crop yields can be severe, leading to significant reductions in both quantity and quality of the produce. SCYLV, for instance, has been shown to cause substantial yield losses in sugarcane. In Hawaii, SCYLV-infected plants exhibited a 26% reduction in sugar yield when harvested after 11 months, although yields did not decrease when plants were harvested after two years (Lehrer et al., 2009). In India, SCYLV has led to yield reductions of up to 50% in severe cases, with juice yield reductions of 40%-50% (Viswanathan et al., 2021). The virus can also cause varietal degeneration, reducing the vigor and productivity of subsequent vegetative generations or ratoons (Bagyalakshmi et al., 2019; Viswanathan et al., 2021).

Field studies have demonstrated that SCYLV prevalence can vary significantly depending on soil type and crop season. For example, in Florida, SCYLV prevalence rates were found to be higher in organic soils compared to mineral soils, with yield reductions in ratoon crops varying from non-significant to 27% depending on the cultivar and soil typeC (Boukari et al., 2019). The slow spread of SCYLV via aphids, typically a few meters per year, suggests that planting virus-free seed cane can be an effective strategy to limit the impact of SCYLV on sugarcane production (Lehrer et al., 2006).

3 *Sugarcane Yellow Leaf Virus* (SCYLV)

3.1 Discovery and history

Sugarcane yellow leaf virus (SCYLV) is a significant pathogen affecting sugarcane crops worldwide (Madugula and Umadevi, 2018). It was first identified as the causal agent of sugarcane yellow leaf syndrome (YLS), a disease characterized by yellowing of the leaf midrib, followed by leaf necrosis and potential growth suppression (Madugula and Gali, 2017; Schenck and Lehrer, 2000). SCYLV was first detected in Réunion Island in 1997, where it was found to cause substantial yield losses in certain sugarcane cultivars (Rassaby et al., 2003). In India, the virus was recorded in the late 1990s and reached epidemic status by 2005, severely impacting cane productivity (Viswanathan, 2021).

3.2 Biological characteristics

SCYLV is a member of the *Polerovirus* genus within the Luteoviridae family. The virus has a monopartite genome consisting of single-stranded positive-sense RNA approximately 6 kb in size, which includes six open reading frames (ORFs) expressed by sub-genomic RNAs (Holkar et al., 2020). The virion is composed of 180 coat protein units and measures 24-29 nm in diameter (Holkar et al., 2020). SCYLV is phloem-limited, meaning it primarily infects the phloem tissues of the plant, and it has a limited natural host range, mainly infecting sugarcane, grain sorghum, and Columbus grass (Schenck and Lehrer, 2000; Holkar et al., 2020).

3.3 Transmission and spread

SCYLV is primarily transmitted by the sugarcane aphid, Melanaphis sacchari, in a circulative and non-propagative manner (Boukari et al., 2019; Holkar et al., 2020). Other aphid species, such as Ceratovacuna lanigera, Rhopalosiphum rufiabdominalis, and Rhopalosiphum maidis, have also been reported to transmit the virus (Boukari et al., 2019; Holkar et al., 2020). The virus is not transmitted mechanically, which underscores the importance of aphid vectors in its spread (Paray et al., 2011; Holkar et al., 2020).

The initial multiplication of SCYLV in a virus-free plant occurs exclusively in very young sink tissues. When a single leaf is inoculated, only the meristems and subsequently formed new leaves become infected, while older leaves remain virus-free. The spread of SCYLV within plantation fields via aphids is relatively slow, typically in the range of a few meters per year, with no indication of long-distance transfer. This slow spread suggests that it may be possible to produce and use virus-free seed cane for planting high-yielding but YLS-susceptible cultivars (Boukari et al., 2019).

In field conditions, the prevalence of SCYLV can vary significantly depending on the cultivar, location, and crop season. For instance, in Florida, virus prevalence ranged from 83% to 100% in plots planted with infected seed cane, while healthy sugarcane became progressively infected over multiple crop seasons (Boukari et al., 2019). The impact of SCYLV on yield can also vary, with some cultivars showing significant yield reductions while others remain unaffected (Rassaby et al., 2003; Boukari et al., 2019).

4 Symptoms and Diagnosis

4.1 Visual symptoms in infected plants

Sugarcane yellow leaf virus (SCYLV) infection manifests primarily through yellowing of the leaf midrib, which can progress to leaf necrosis and growth suppression in severe cases (Figure 1) (Holkar et al., 2020). The visual symptoms are not always consistent across all cultivars, as some may show symptoms sporadically or not at all despite being infected (Fitch et al., 2001). In Réunion Island, leaf yellowing was observed at harvest, particularly when sugarcane was no longer irrigated, with 10%-59% of symptomatic stalks attributed to SCYLV presence. Additionally, the severity of yellowing symptoms was directly related to the extent of SCYLV infection (Rassaby et al., 2003).

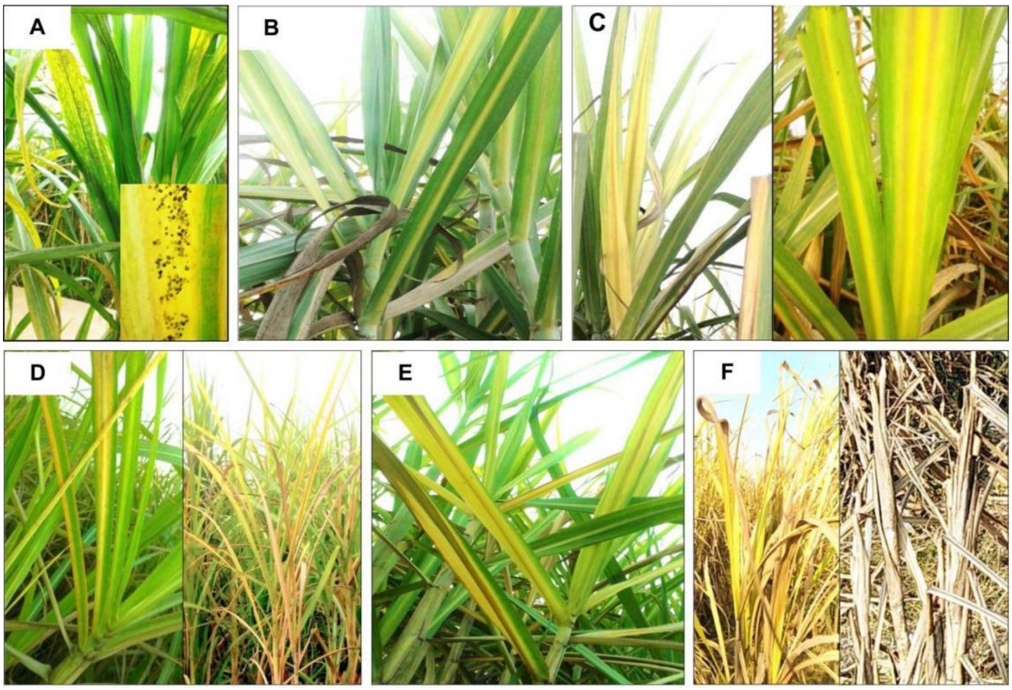

Figure 1 Symptoms of yellow leaf disease in sugarcane and natural occurrence of aphid colonies (Adopted from Holkar et al., 2020)
Image caption: (A) Aphid (*Melanaphis sacchari*) infesting sugarcane and reported vector of *Sugarcane yellow leaf virus* (SCYLV) in India; (B) Matured leaves with mild yellowing of midrib; (C) Young leaves showing mild midrib yellowing and matured leaves showing initial discoloration of leaf lamina; (D) Young leaves showing bright midrib yellowing and matured leaves showing extensive discoloration of lamina with necrosis; (E) Severe necrosis of leaf area in matured leaves; (F) Plant showed extensive stunting with complete drying (Adopted from Holkar et al., 2020)

4.2 Laboratory diagnostic methods

Several laboratory techniques are employed to diagnose SCYLV, including Tissue Blot Immunoassay (TBIA), Reverse Transcription-Polymerase Chain Reaction (RT-PCR), and Quantitative Real-Time RT-PCR (qRT-PCR). RT-PCR and qRT-PCR are particularly effective, revealing SCYLV presence even in cultivars previously thought to be immune based on TBIA results (Eiden et al., 2010; Zhu et al., 2010). These methods can detect varying virus titres, with qRT-PCR providing a semi-quantitative measure of virus load, which is crucial for understanding the correlation between virus titre and yield reduction (Zhu et al., 2010). Additionally, Double Antibody Sandwich-ELISA (DAS-ELISA) is used for virus quantification in both nursery and field trials, aiding in the identification of resistant genotypes (Burbano et al., 2021).

4.3 Field detection techniques

Field detection of SCYLV involves both visual inspection and laboratory confirmation. Visual symptoms such as leaf yellowing can be an initial indicator, but laboratory methods like RT-PCR and TBIA are essential for accurate diagnosis. In field trials, virus-free plants are often produced through meristem tip culture and monitored for reinfection by viruliferous aphids to ensure the effectiveness of the virus-free status. Field trials in Florida demonstrated that planting virus-free seed cane significantly limits SCYLV prevalence and its impact on yield, highlighting the importance of starting with healthy planting material (Boukari et al., 2019). Additionally, combining symptom phenotyping with precise virus titration in field trials helps in screening for SCYLV resistance among different genotypes (Filloux et al., 2018; Burbano et al., 2021).

By integrating visual inspection with advanced laboratory techniques and strategic field management, effective diagnosis and control of SCYLV can be achieved, thereby mitigating its impact on sugarcane yield.

5 Impact on Sugarcane Physiology

5.1 Effects on photosynthesis

Sugarcane yellow leaf virus (SCYLV) significantly impacts the photosynthetic efficiency of sugarcane plants. Infected plants exhibit notable reductions in photosynthetic rate, stomatal conductance, transpiration rate, chlorophyll fluorescence ratio, and leaf chlorophyll content (Bagyalakshmi et al., 2019). These physiological impairments hinder the plant's ability to convert light energy into chemical energy, thereby reducing overall plant vigor and productivity. The reduction in photosynthetic activity is a critical factor contributing to the decline in sugarcane yield observed in SCYLV-infected plants.

5.2 Nutrient uptake and transport

SCYLV infection also affects the nutrient uptake and transport mechanisms within sugarcane plants. The virus is phloem-limited, meaning it resides and spreads within the plant's phloem tissue, which is responsible for the transport of nutrients and sugars (Holkar et al., 2020). This localization disrupts the normal flow of nutrients, leading to deficiencies that can further exacerbate the physiological stress on the plant. The impaired nutrient transport can result in stunted growth and reduced biomass, as observed in various studies (Lehrer et al., 2009; Boukari et al., 2019).

5.3 Growth and development impairments

The growth and development of sugarcane plants are severely impaired by SCYLV infection. Infected plants show reduced germination rates and early shoot growth, leading to a lower number of stalks per stool and decreased biomass. The virus causes a significant reduction in the number of stalks, biomass, and sugar yield, particularly when plants are harvested after shorter growth periods (Lehrer et al., 2009). Additionally, the presence of SCYLV can lead to varietal degeneration, where the overall vigor and productivity of the sugarcane cultivar decline over successive planting cycles (Amata et al., 2016; Bagyalakshmi et al., 2019). This degeneration is marked by poor growth, reduced juice yield, and overall diminished plant health.

6 Yield Reduction Mechanisms

6.1 Direct damage to plant tissues

Sugarcane yellow leaf virus (SCYLV) directly impacts sugarcane by infecting and damaging plant tissues, leading to significant reductions in growth and yield. Infected plants often exhibit stunted growth, reduced biomass, and lower sugar yields. For instance, a study conducted in Hawaii found that SCYLV-infected plants had a 30% reduction in the number of stalks per stool, a 29% reduction in biomass, and a 26% reduction in sugar yield when harvested after 11 months (Lehrer et al., 2009). Additionally, symptomatic plants showed significant reductions in physiological parameters such as photosynthetic rate, stomatal conductance, and chlorophyll content, which are critical for plant growth and sugar production (Bagyalakshmi et al., 2019).

6.2 Secondary infections and stresses

SCYLV infection can predispose sugarcane plants to secondary infections and additional stresses, exacerbating yield losses. The virus can interact synergistically with other pathogens, leading to more severe disease symptoms and greater yield reductions. For example, mixed infections of SCYLV with other viruses such as Sugarcane mosaic virus (SCMV) and Sugarcane streak mosaic virus (SCSMV) have been shown to cause significant varietal degeneration, with reductions in juice yield by up to 36% (Bagyalakshmi et al., 2019). Furthermore, the presence of SCYLV can lead to increased susceptibility to environmental stresses, such as drought, which further diminishes plant vigor and productivity (Asinari et al., 2020).

6.3 Long-term field impacts

The long-term impacts of SCYLV on sugarcane fields can be profound, affecting both the current and subsequent crop cycles. Field studies have shown that SCYLV prevalence can increase over time, leading to cumulative yield losses. For instance, in Florida, SCYLV prevalence in virus-free plots increased progressively over three crop seasons, with yield reductions in ratoon crops varying from nonsignificant to 27% depending on the cultivar and soil type (Boukari et al., 2019). Additionally, the slow spread of SCYLV via aphid vectors can result in gradual but persistent infection of neighboring plants, further compounding yield losses over multiple growing seasons. The use of virus-free seed cane and SCYLV-tolerant cultivars has been recommended to mitigate these long-term impacts and sustain sugarcane production (Sood et al., 2021).

7 Case Study: Management Practices and Outcomes

7.1 Case study introduction

Sugarcane yellow leaf virus (SCYLV) is a significant pathogen affecting sugarcane production globally. The virus is primarily transmitted by aphids and has a limited natural host range, mainly infecting sugarcane, grain sorghum, and Columbus grass (Holkar et al., 2020). The impact of SCYLV on sugarcane yield and quality has been documented in various regions, including Florida, Réunion Island, and India, where it has caused substantial yield losses and varietal degeneration (Rassaby et al., 2003; Lehrer et al., 2009; Viswanathan, 2021).

7.2 Management strategies implemented

Several management strategies have been employed to mitigate the impact of SCYLV on sugarcane production:

1) Use of Virus-Free Seed Cane: Planting virus-free seed cane has been a critical strategy. In Florida, virus prevalence varied from 83% to 100% in plots planted with infected seed cane, but healthy plants of two sugarcane cultivars were only infected at low levels after three crop seasons (Figure 2). Field trials demonstrated that planting healthy seed cane significantly reduced SCYLV prevalence and limited its impact on yield (Boukari et al., 2019). Similarly, in Argentina, the use of healthy planting material was recommended to manage SCYLV (Asinari et al., 2020). Virus prevalence varied from 83% to 100% in plots planted with infected seed cane.

2) Breeding for Resistance: Developing and planting SCYLV-resistant cultivars is another effective approach. Genome-wide association studies by Yang et al. (2019) have identified resistance loci (Figure 3), providing valuable genetic resources for breeding resistant sugarcane cultivars. In India, screening parental clones and pre-release varieties for disease resistance has been a practical strategy (Viswanathan, 2021).

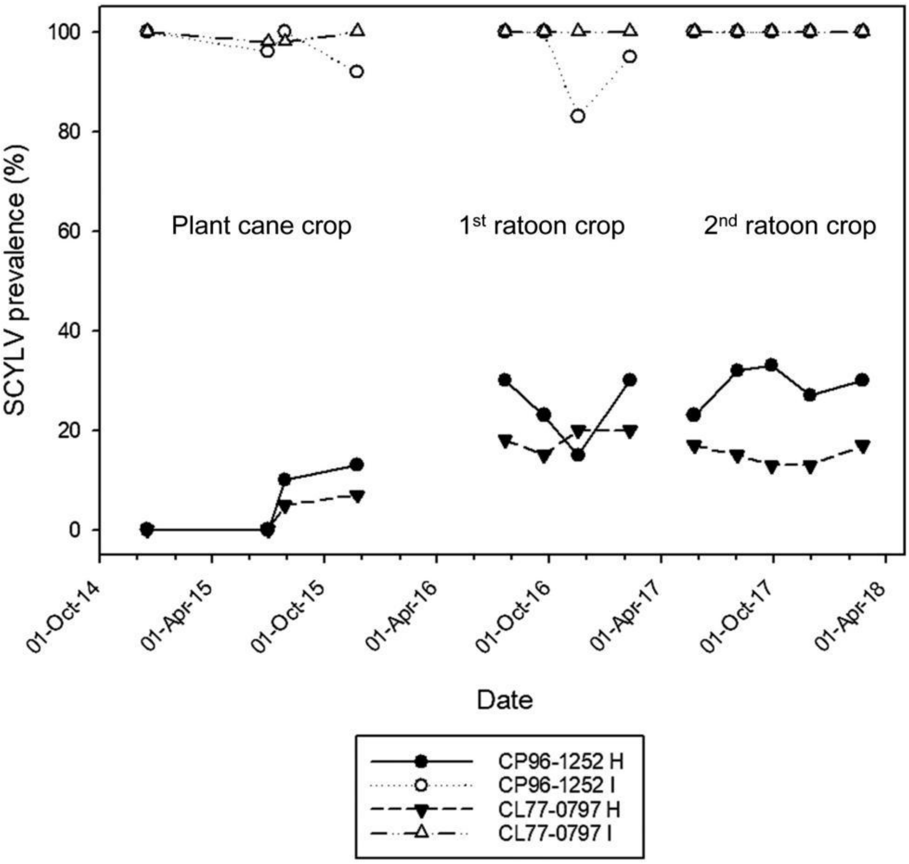

Figure 2 Progress of prevalence of *Sugarcane yellow leaf virus* (SCYLV) in two sugarcane cultivars grown on organic soil during three crop seasons (Adopted from Boukari et al., 2019)

Image caption: Each data point represents the percentage of infection for a total of 60 leaves (10 leaves per plot) (Adopted from Boukari et al., 2019)

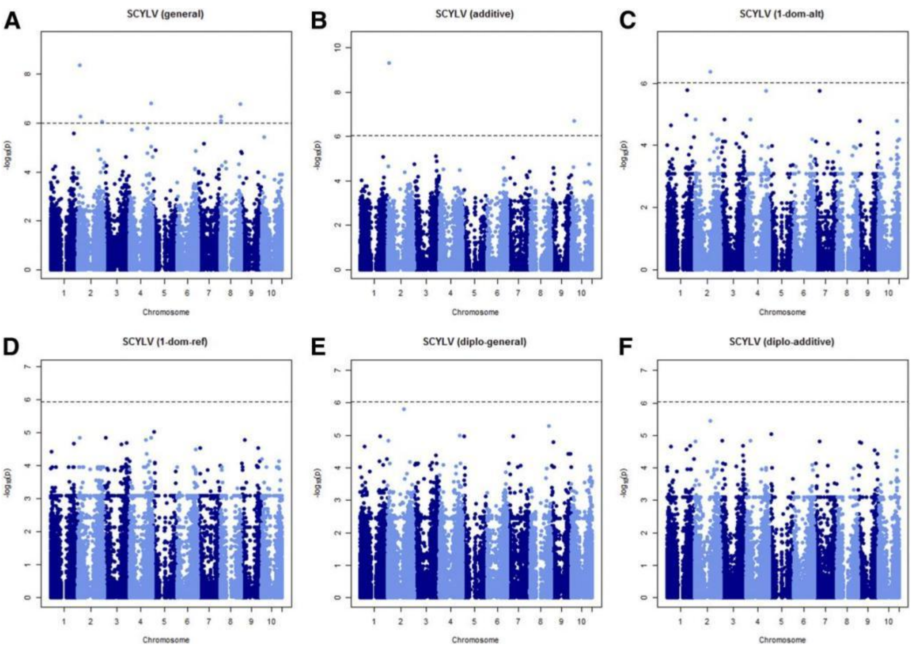

Figure 3 Significant marker-trait associations identified in the sugarcane diversity panel (full set) for disease reactions to *Sugarcane yellow leaf virus* (SCYLV) (Adopted from Yang et al., 2019)

Image caption: (A) General model; (B) Additive model; (C) 1-dom-alt model; (D) 1-dom-ref model; (E) Diplo-general model; (F) Diplo-additive model (Adopted from Yang et al., 2019)

3) Tissue Culture and Molecular Diagnostics: Virus elimination through tissue (meristem) culture combined with molecular diagnostics has been successful in rejuvenating popular sugarcane varieties and increasing cane yield by 30%-35% under field conditions in India (Viswanathan, 2021).

4) Field Management Practices: Implementing good agricultural practices, such as timely irrigation and proper fertilization, can help mitigate the effects of SCYLV. In Réunion Island, significant yield losses were observed in non-irrigated fields, highlighting the importance of maintaining optimal field conditions (Rassaby et al., 2003).

7.3 Results and analysis

The outcomes of these management strategies have been varied but generally positive. In Florida, planting virus-free seed cane resulted in low SCYLV prevalence after three crop seasons, effectively limiting the virus's impact on sugarcane production (Boukari et al., 2019). Similarly, in Réunion Island, significant yield reductions were observed in SCYLV-infected plants, but proper management practices helped mitigate these losses (Rassaby et al., 2003). Breeding programs have successfully developed SCYLV-resistant cultivars, showing improved yield and disease resistance in various field conditions (Yang et al., 2019). In India, screening for disease resistance and using virus-free planting material have led to increased cane yield and reduced varietal degeneration (Viswanathan, 2021).

Additionally, tissue culture and molecular diagnostics have proven efficient in eliminating SCYLV from infected plants, leading to varietal rejuvenation and increased productivity (Viswanathan, 2021). Surveys and field trials have provided valuable insights into the prevalence and impact of SCYLV. For instance, a survey in northern Argentina revealed high infection rates and significant sugar content loss in SCYLV-infected plants, emphasizing the need for continuous monitoring and management (Asinari et al., 2020).

8 Control and Prevention Strategies

8.1 Breeding for resistant varieties

Breeding for resistant sugarcane varieties is a crucial strategy in managing *Sugarcane yellow leaf virus* (SCYLV). Genome-wide association studies have identified numerous DNA markers and candidate genes associated with resistance to SCYLV, providing valuable resources for marker-assisted selection in breeding programs (Yang et al., 2019; Pimenta et al., 2020; Pimenta et al., 2021). The integration of RNA interference (RNAi) technology has also shown promise in developing virus-resistant sugarcane varieties. However, the high mutation rate and recombination within SCYLV strains necessitate a multi-target RNAi strategy to effectively combat the virus (Khalil et al., 2018). Additionally, the expression of the *PAC1* gene in transgenic sugarcane has demonstrated potential in developing virus-resistant plants, although further field evaluations are necessary to confirm agronomic performance (Wang et al., 2022). The use of transgenic lines with SCYLV resistance has shown reduced infection rates, highlighting the potential of genetic transformation methods in breeding programs (Gilbert et al., 2009).

8.2 Agronomic practices

Agronomic practices play a significant role in controlling the spread of SCYLV. Planting virus-free seed cane is a fundamental practice to limit the impact of SCYLV on sugarcane production. Field trials have shown that planting virus-free seed cane can significantly reduce the prevalence of SCYLV, thereby minimizing yield losses (Boukari et al., 2019). Regular monitoring and screening of sugarcane nurseries for SCYLV infection can help in early detection and management of the disease (Meixin et al., 2014). The use of apical meristem propagation to produce virus-free clean seedcane has been suggested as an effective method to minimize the spread of SCYLV (Sood et al., 2021). Additionally, understanding the interactions between SCYLV, sugarcane genotypes, and aphid vectors can inform the development of resistant cultivars and improve cultural practices to manage the disease (Bertasello et al., 2021).

8.3 Chemical and biological controls

Chemical and biological controls are also important components of an integrated management strategy for SCYLV. The use of insecticides to control aphid vectors, such as *Melanaphis sacchari*, can help reduce the spread of SCYLV. However, the effectiveness of chemical control is limited by the presence of multiple aphid vectors and the persistent nature of the virus (Khalil et al., 2018). Biological control methods, including the use of natural predators and parasitoids of aphid vectors, can provide an environmentally friendly alternative to chemical control (Bertasello et al., 2023). Additionally, the development of sugarcane cultivars that exhibit resistance to aphid feeding behavior can indirectly reduce the transmission of SCYLV (Bertasello et al., 2021). Combining chemical and biological control methods with resistant cultivars and cultural practices can provide a comprehensive approach to managing SCYLV in sugarcane production.

By integrating breeding for resistant varieties, agronomic practices, and chemical and biological controls, it is possible to develop a robust management strategy to mitigate the impact of SCYLV on sugarcane yield and production.

9 Concluding Remarks

This study has comprehensively examined the role of viruses, particularly *Sugarcane yellow leaf virus* (SCYLV), in reducing sugarcane yield. Key findings highlight the significant impact of SCYLV on sugarcane physiology, leading to reduced photosynthetic efficiency, impaired nutrient uptake and transport, and stunted growth. SCYLV infection not only directly damages plant tissues but also predisposes sugarcane to secondary infections and environmental stresses, further exacerbating yield losses. The prevalence of SCYLV has been documented in various regions, including Florida, Réunion Island, and India, where it has caused substantial yield reductions and varietal degeneration. Effective management strategies, such as using virus-free seed cane, breeding for resistant varieties, and employing chemical and biological controls, have shown promising results in mitigating the impact of SCYLV on sugarcane production.

The successful management of SCYLV and other plant viruses requires an integrated approach that combines multiple strategies. Breeding for resistant varieties provides a long-term solution by developing sugarcane cultivars with inherent resistance to SCYLV. Agronomic practices, such as planting virus-free seed cane and maintaining optimal field conditions, are crucial for reducing the initial infection rates and limiting the spread of the virus. Chemical controls, including the use of insecticides to manage aphid vectors, and biological controls, such as employing natural predators of aphids, offer additional layers of protection. The integration of these strategies, supported by continuous monitoring and field trials, ensures a comprehensive approach to managing SCYLV and sustaining sugarcane production.

Future research should focus on advancing our understanding of the genetic mechanisms underlying SCYLV resistance in sugarcane. Genome-wide association studies and the identification of resistance loci are essential for the development of more effective breeding programs. Additionally, the application of RNA interference (RNAi) technology and the development of transgenic lines with multi-target resistance should be explored further. Research should also investigate the interactions between SCYLV and other pathogens, as well as the virus’s impact under different environmental conditions. Improved diagnostic tools and techniques for early detection of SCYLV in field conditions are needed to enhance disease management. Meanwhile, long-term field studies are necessary to evaluate the effectiveness of integrated management strategies and their impact on sugarcane yield and quality over multiple growing seasons.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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