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Review Article

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A comprehensive exploration with reference to sugarcane red rot caused by *Colletotrichum falcatum*

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ABSTRACT

Red rot disease, of sugarcane caused by Colletotrichum falcatum, poses a significant threat to sugarcane cultivation in India, particularly in the states of Bihar and Uttar Pradesh. This disease has been responsible for the elimination of several popular sugarcane varieties, leading to substantial reductions in cane production and productivity. Incidence rates of red rot disease have been reported to range from 30% to 50% within India, and trace to 50% across various cane-growing regions globally. The impact of this disease extends to crucial cane parameters, including cane weight, brix, pol, sucrose content, and purity, which collectively contribute to significant economic losses. Extensive studies have been conducted to understand the morphological characteristics and pathogenic behavior of Colletotrichum falcatum. In addition, various control methods have been tested both in-vitro and in-vivo to mitigate the disease. These methods include chemical treatments, botanical approaches, biological controls, and heat therapy. Each of these control strategies has been assessed for their effectiveness in reducing disease incidence and severity. Furthermore, research has explored the influence of intercropping and crop rotation on red rot disease and associated cane parameters. The role of micronutrients, temperature, and pH value in influencing disease incidence and severity has also been a focal point of study. Overall, the concerted efforts of researchers in studying various aspects of red rot disease and implementing diverse control methods aim to enhance the resilience of sugarcane varieties against this detrimental pathogen. The ongoing evaluation of resistant varieties, coupled with optimized agricultural practices and environmental management, holds promise for sustaining sugarcane production and minimizing the losses caused by red rot disease in India and other affected regions. The study faced challenges from the high variability of Colletotrichum falcatum and difficulty in standardizing control methods across regions. It contributed by advancing red rot pathology research, evaluating diverse control strategies, and promoting resistant varieties for sustainable management.

Keywords: *Sugarcane, Comprehensive exploration, Red rot, Economic losses, Pathogenic behavior, Control method, Intercropping, weather parameters*

1. Introduction

Sugarcane (*Saccharum officinarum L.*), is a member of the Poaceae family belonging to the genus *Sachharum*.It is a significant agricultural commodity cultivated in tropical and subtropical regions for its sugar content, holding economic importance globally. India and Brazil, out of the 110 countries where sugarcane is grown, account for approximately half of the world's production (1). The sugar industry ranks as the second largest agro-processing industry in the country, making substantial contributions to rural income, employment, and tax revenue (2). Cultivated across approximately 5 million hectares of tropical and subtropical regions, sugarcane sustains the livelihoods of approximately 123.4 lakh farmers and farm workers (3). Agro-climatic conditions significantly affect sugarcane growth and nutrient use efficiency. Sugarcane thrives in temperatures between 28°C to 32°C, with growth arrested above 50°C and slowed below 20°C. Ideal relative humidity is 70% to 85% during growth and 55% to 75% during ripening, with levels below 50% unfavorable for cultivation (4).

Over 100 sugarcane diseases have been reported nationwide, resulting in a sugar reduction of 10-15% (5). More than twenty sugarcane diseases, caused by various pathogens, have been reported in Bihar, significantly impeding production. Fungal diseases collectively result in an estimated crop production loss of 18-31% in India (6), causing significant reductions in yield and quality. Red rot, particularly severe due to favorable conditions for *C. falcatum*, makes Bihar a hotspot for this disease

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(7). The occurrence of red rot in sugarcane was initially reported as a disease in Java in 1893 (8). Its occurrence in India (Andhra Pradesh) was first noted (9), and since then, numerous red rot outbreaks have been recorded across the country, leading to the abandonment of several popular sugarcane varieties (10). An Imperial mycologist at the Imperial Agricultural Research Institute in Pusa, Bihar (India), conducted extensive research on the causal organism and its modes of entry into the sugarcane stalk (11). Observing the characteristic reddish discoloration of internal stalk tissues during rotting, he coined the term "red rot" for the disease.

In India, the initial reported red rot epidemic took place between 1895 and 1901, followed by several significant outbreaks occurring regularly in the sub-tropical and tropical areas of the nation. One of the most extensive epidemics of the disease occurred in eastern Uttar Pradesh (U.P.) and northern Bihar from 1938 to 1940, leading to the collapse of variety Co 213. This outbreak resulted in a decrease of approximately 70,000 tonnes in sugar production across the country in 1939-40, attributed to the red rot epidemic (12). In the 1990s, red rot outbreaks in peninsular India caused significant yield losses, ranging from 30% to 50% in varieties like Co 6304, CoC 671, CoC 85061, CoC 86062, CoC 92061 and CoSi 86071. Ratoon crops in different factory areas experienced complete yield losses of up to 100% (13). Red rot causes a significant decline in cane weight (29% to 83%) and juice extraction (24% to 90%) (14). Since red rot was first identified in sugarcane in India's Godavari and Ganjam Districts, the nation has faced repeated crop failures, especially in Uttar Pradesh and Bihar's sugarcane belts, leading to significant economic losses. This has resulted in the elimination of many popular sugarcane varieties due to their susceptibility to red rot (14,15). In Bihar, survey of different varieties across various months were done and found that red rot occurrence was 0% in May-June, 2-10% in July-August, 5-15% in September-October and 10-20% in November-December. Effective management strategies and a robust seed nursery program are crucial for sustaining and enhancing production for profitable cultivation (16). The failure of the popular variety Co 0238 has led to severe crop losses in Uttar Pradesh (UP) and Bihar. UP alone has seen nearly 0.5 million hectares out of 2.6 million affected during the 2020–2021 season (17). The total loss this season amounts to 1.0 to 1.414 billion US dollars, with previous year losses estimated at 40%–50% of the current figure.

2. Economic Impact

The decline in sugarcane productivity has been approximated at 12 to 44.5% for the initial crop and 35 to 86% for the subsequent ratoon crop, depending on the severity of disease levels (18). Studies indicate that red rot can cause up to a 29% reduction in cane weight and a 31% loss in sugar recovery (19). The highest reduction in sett germinability (41.0%) was seen in variety BO70, followed by 37.0% in BO74, 25.0% in BO141, 18.2% in BO91 and 18.0% in BO142 (20). The adverse effect of red rot disease on sett germinability were also noted by (21). Similarly, it is also reported a reduction in cane juice extraction due to red rot infection (22). The disease not only directly reduces yield and compromises juice quality but also indirectly impacts cultivation by limiting high-sugar, high-yielding genotypes susceptible to red rot (23).

Reductions in yield ranging from 30 to 100 percent, along with decreases in cane juice content ranging from 25 to 75 percent is observed by (24). Farmers suffer from poor sett germination, settling mortality, reduced cane population, low yield, poor ratoon establishment, and crop loss due to disease severity. Industries incur economic losses processing red rot-affected canes, leading to inferior juice quality, reduced sugar recovery, less bagasse and increased molasses production, influenced by the invertase enzyme breaking down sucrose molecules (14, 25). Planting sugarcane setts with varying red rot infection levels resulted in reduced germinability. Naturally infected setts showed the lowest germination (19.5%) and highest red rot incidence (34.5%), followed by artificially inoculated setts with 22.9% germination and 15.5% disease incidence. Simultaneous nodal and internodal infection led to the highest sett mortality (84.7%), followed by setts from six-month-old inoculated cane (39.4%), nodal infection only (35.3%) and setts taken just before planting (32.5%). Damage was more severe when red rot fungus was present with wilt fungi compared to red rot fungus alone (26). Losses attributed to red rot may vary from 10% to 50%, influenced by cultivars, environmental factors, and pathogen strains (27). The CoS 8436 variety in Bihar, known for its high yield, suffered losses of 30,664 q and 147,084 q in cane production due to red rot infection in 2016-17 and 2017-18, respectively. Productivity also declined by 86 q/ha and 456 q/ha in those respective years compared to non-infected years (28). Yield and juice quality were estimated to incur losses ranging from 10% to 20% due to diseases, with specific observations of losses from red rot disease (29). *C. falcatum* pathogen-inoculated plots showed reduced bud germination compared to healthy controls: 43.6% vs. 74.0% in the first year and 46.0% vs. 75.3% in the second year. After 360 days, susceptible varieties CoC 671 and Co 94012 experienced cane population reductions of 80.1% and 86.1%, respectively. Moderately susceptible varieties Co 06030, Co 06022, CoV 09356, and Co 06027 recorded losses ranging from 42.5% to 63.1% (17).

A varying levels of red rot disease incidence in sugarcane, ranging from trace to fifty percent, across different sugar factories in Bihar were observed (30). A survey across five Bihar districts and ten locations assessed red rot disease prevalence, the highest incidence was in Riga (23.32%), followed by Majhaulia (19.90%), Lauriya (18.82%), Sidhwalia (15.83%), Sugauli (15.61%). Gopalganj (12.45%), Narkatiaganj (11.58%), Harinagar (6.30%), Pusa (6.04%) showed varying incidence. Hasanpur had the lowest occurrence at 5.22% during 2019-20 (31).The incidence of red rot disease of sugarcane ranged between trace to 50 per cent in different sugar factory areas of Bihar. Red rot primarily affects cane plants that are upright, often leading to significant losses in varieties susceptible to the disease, sometimes as high as 100 percent (32).

Table 1: Status of sugarcane red rot disease incidence among various varieties at different location of Bihar over past three season (2020-2023)

<table>
<tr><th rowspan="2">S.No</th><th colspan="3">2020-2021</th><th colspan="3">2021-2022</th><th colspan="3">2022-2023</th></tr>
<tr><th>Varieties</th><th>Disease %</th><th>Area</th><th>Varieties</th><th>Disease %</th><th>Area</th><th>Varieties</th><th>Disease%</th><th>Area</th></tr>
<tr><td>1</td><td rowspan="4">Co 0238</td><td>5-10</td><td>Sugauli</td><td rowspan="8">Co 0238</td><td>5-40</td><td>Sidhwalia (Shahpur, Muhammadpur, Manjhaua, Madhopur, Binupur)</td><td rowspan="10">Co 0238</td><td>20</td><td>Riga (Barahi)</td></tr>
<tr><td>2</td><td>30</td><td>Manjhaulia</td><td>20-50</td><td>Riga (Dumariya, Purnahiaya, Rebari, Gopalpur)</td><td>15-20</td><td>Riga (Gopalpur)</td></tr>
<tr><td>3</td><td>30</td><td>Riga</td><td>5-10</td><td>Harinagar (SigriMurila, Chamua, Binvalia)</td><td>5-10</td><td>Narkatiaganj (Katsikri)</td></tr>
<tr><td>4</td><td>15-20</td><td>Sidhwalia</td><td>5-40</td><td>Gopalganj (Sipaya)</td><td>15</td><td>Narkatiaganj (Hardi)</td></tr>
<tr><td>5</td><td>Co 0233</td><td>30</td><td>Riga</td><td>5-40</td><td>Majhaulia (Madhopur, Senwariya, Barwariya)</td><td>10-15</td><td>Sidhwalia (Mirzapur)</td></tr>
<tr><td>6</td><td>CoH 160</td><td>10-30</td><td>Riga</td><td>5-10</td><td>Narkatiaganj</td><td>5-10</td><td>Sidhwalia (Bala)</td></tr>
<tr><td>7</td><td>C0H167</td><td>10-40</td><td>Riga</td><td>5-30</td><td>Sugauli</td><td>10</td><td>Sidhwalia (Bishnupur)</td></tr>
<tr><td>8</td><td>-</td><td>-</td><td>-</td><td>2-10</td><td>Hasanpur</td><td>5-10</td><td>Sidhwalia (Buchia)</td></tr>
<tr><td>9</td><td>-</td><td>-</td><td>-</td><td>CoH 160</td><td>5-40</td><td>Riga (Rebari, Gopalpur)</td><td>2-5</td><td>Hasanpur</td></tr>
<tr><td>10</td><td>-</td><td>-</td><td>-</td><td>CoH 167</td><td>10-60</td><td>Riga (Rebari)</td><td>10-15</td><td>Harinagar</td></tr>
<tr><td>11</td><td>-</td><td>-</td><td>-</td><td>CoJ 85</td><td>5-10</td><td>Riga (Kharsan)</td><td>CoH 160</td><td>5-20</td><td>Riga (Rebari)</td></tr>
<tr><td>12</td><td>-</td><td>-</td><td>-</td><td>Co 98014</td><td>5-10</td><td>Riga (Dumariya)</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>13</td><td>-</td><td>-</td><td>-</td><td>Pv 92</td><td>5-20</td><td>Riga (Purnahiaya, Gopalpur)</td><td>-</td><td>-</td><td>-</td></tr>
</table>

3. Morphological Characteristics and Pathogenic behaviour of Red Rot Isolates

According to (33) isolates showed varying virulence levels, reflecting differences in resistance among sugarcane varieties. Resistance was consistently observed in differentials BO-91 and SES-594 against all isolates, while susceptibility was noted in varieties CO-997, CO-1148, COJ-64, and Khakai. Differentials CO-7717, CO-419, CO-62399, COS-767, and Baragua displayed varied reactions. The conclusion drawn was that at least three pathotypes of the red rot pathogen are prevalent in Bihar. A study in Karnal revealed that Cf8436 was virulent on CoS 8436. Cf64-I in CoJ 64 pathotypes displayed varied reactions on different host differentials, indicating the continuous evolution and adaptation of the red rot pathogen in subtropical India (34). In subtropical India, 12 *C. falcatum* isolates were evaluated across 16 host differentials over eight seasons. CF09 and CF08 from CoS 767 and CoJ 64 showed reduced virulence, while CF02 from Co 7717 exhibited increased virulence over time, notably on susceptible varieties like Co 997 and CoJ 64. CF08 maintained its virulence on CoJ 64 but declined on new cultivars. This investigation employed pathotypes CF08 and CF09 in the North West region, CF07 and CF08 in the North Central area, CF06 along the East Coast and CF06 and CF12 in the Peninsular zone (14, 35). During 2012-2016, resistant reactions were noted in BO 91, Baragua and SES-594, while susceptibility occurred in Co 1148, Co 997, CoJ 64, CoC 671 and Khakai. Differential reactions were observed in Co 419, CoS 767, Co 7717, CoS 8436, Co 62399 and Co 975 against all test isolates. Pathotype CF 07 and isolates RR_1-RR_5 exhibited resistance on Co 419, CoS 767, Co 7717 and Co 975, with intermediate reactions on CoS 8436 and Co 62399. Similarly, pathotype CF 08 and isolates RR_2, RR_6, RR_7, RR_9 and RR_{10} displayed intermediate reactions on Co 419, CoS 767, Co 7717 and Co 975 and susceptibility on CoS 8436 and Co 62399, indicating the presence of two pathotypes of red rot pathogens in Bihar (36). Similar observations of multiple pathotypes were noted in Tamil Nadu by (37). Recent studies revealed the emergence of highly virulent pathotype CF13, breaking resistance in the ruling subtropical variety Co 0238, prompting replacement with a resistant variety (38).

4. Field Evaluation of Sugarcane Genotypes/Varieties for Resistance to Red Rot Disease

Twelve sugarcane genotypes, were tested including three check varieties, for red rot disease resistance at Pusa, Bihar, in 2002-2003 using the plug method. Four varieties (Co 97019, UP 9742, UP 9855, and BO 136) were resistant, while eight (Co 97020, CoP 97181, BO 134, BO 135, CoSe 98335, CoP 97182and BO 137) were moderately resistant (39).

Varieties against red disease were evaluated using CF 07 and CF08 isolates and found that CoSe 95422 and CoSe 92423 were susceptible to both and reported CoP 9301 as resistant to CF 07 (40). Fourty four genotypes were tested in eastern Uttar Pradesh and identified 35 as moderately resistant to *C. falcatum* pathotype CF07 (41). In Shahjahanpur, Uttar Pradesh, 117 genotypes were screened, and found 6 resistant and 12 moderately resistant, with the remainder exhibiting varying susceptibility levels (42).

Fifty-one varieties were evaluated, including one check, for susceptibility to *C. falcatum* pathogen with CF 07 and CF 08 isolates using plug and cotton swab methods. In the plug method, four varieties were susceptible to CF 07, while eight were moderately susceptible and thirty-eight showed moderate resistance. For CF 08, six varieties were resistant, seven were moderately susceptible and five were susceptible. In the cotton swab method, four varieties were susceptible to both isolates, while forty-six were resistant to both. The plug method showed more significant differences in infection severity, indicating its reliability over the cotton swab method for variety screening against red rot under artificial conditions (43).

Fourteen genotypes for red rot resistance were evaluated, among them five demonstrated resistance to *C. falcatum* pathotype CF 06 using the plug inoculation method: 2015A 51, 2015A 59, 2015A 228, 2015A 230 and 2015A 233. Six entries showed moderate resistance, while one displayed moderate susceptibility and two were highly susceptible (44).

5. Degradation of Cane Juice Quality by Red Rot Pathogen Infection

It was found that highly susceptible and susceptible varieties experienced the greatest reductions in Brix (17.6% to 20.0%), Pol (28.26% to 44.59%), sucrose (16.8% to 23.4%), commercial cane sugar (29.06 to 53.57%) and purity (19.0% to 23.1%). Moderately susceptible varieties showed intermediate reductions, while resistant and moderately resistant varieties exhibited minimal depletion in Brix (3.0% to 9.0%), sucrose (3.2% to 9.7%) and purity (3.0% to 13.4%). Reduction extent correlated inversely with resistance levels in sugarcane genotypes (45). Red rot disease caused reductions in quality parameters such as Pol (28.26-44.59%), Brix (20.04-38.79%), Purity (17.68-31.56%), pH (0.57-1.27%), moisture in cane (36.25-54.84%), moisture content in juice (7.27-15.87%), protein content in juice (14.03-21.29%) and commercial cane sugar (29.06-53.57%). However, the content of reducing sugars (19.44-38.70%), titratable acidity (23.52-45.16%), gum content (20.83-34.48%), and soluble salt (27.35-46.67%) increased due to red rot infection (46).

According to an investigation, the various susceptible genotypes like CoSe 95422, CoS 8436 and BO 128 showed significant reductions in Brix (16.60% to 20.80%), Pol (31.60% to 38.26%) and Purity (18.00% to 22.10%). Conversely, resistant and moderately resistant varieties experienced minimal decreases: Brix (2.00% to 8.00%), Pol (6.10% to 19.38%) and Purity (4.20% to 12.40%). This indicates that the red rot pathogen adversely affected cane juice quality (29).

6. *In-vitro* and *In-vivo* efficacy of fungicides, botanicals, biologicals and heat therapy against *Colletotrichum falcatum*

6.1 Chemicals

In an experiment it was found that treating setts with a 0.1% fungicidal solution improved germination, suppressed red rot pathogen growth and sporulation and reduced red rot incidence. Bavistin showed the highest germination (69.6%), followed by Jkstein, Derosal, Topsin-M, Ronilan, Kitazin, Agrozim and Saprol (47).

In experiments by (48), Bavistin exhibited complete inhibition of *C. falcatum* mycelial growth. (49) suggested the use of Azoxystrobin 18.2% + Difenoconazole 11.4% SC at 1.00 ml/l for red rot management, with Azoxystrobin 23% w/w SC also showing a significant reduction in red rot disease according to the same authors. Thiophanate methyl is highly effective under mechanized treatment against red rot among various fungicides (50). Seven fungicides against *C. falcatum* at 10, 15, 20 and 25 ppm were tested in-vitro and seen that higher concentrations resulted in greater pathogen inhibition. Tilt was the most effective, followed by Nativo and Mancozeb, while Metalaxyl was the least effective (51). It was found that sett treatment with Carbendazim 50 WP, Propiconazole 25 EC, *Trichoderma harzianum* and *T. viride* led to increased sett germination compared to the control. Carbendazim 50 WP demonstrated the highest effectiveness, resulting in a maximum increase in germination of 43.2%, followed by 29.5% with Propiconazole 25 EC, 24.0% with *T. harzianum* and 17.2% with *T. viride*. Additionally, Carbendazim 50 WP exhibited the most significant reduction in settling mortality (49.0%), followed by Propiconazole 25 EC (41.0%), *T. harzianum* (38.0%) and *T. viride* (35.0%). Furthermore, the highest reduction in the development of red rot disease was observed with Carbendazim 50 WP (65.3%), followed by Propiconazole 25 EC (55.0%), *T.harzianum* (42.5%) and *T. viride* (37.2%) (43). Seven systemic fungicides as sett treatments against red rot disease were tested among them Tebuconazole + Trifoxystrobin and Thiophanate methyl significantly reduced disease incidence by over 30% for two years and increased yield by more than 40% in the first year and over 27% in the second year (52). In-vitro evaluation of Carbendazim, Propiconazole, and Azoxystrobin at various concentrations (5, 10, 20 and 30 ppm) against three *C. falcatum* isolates (CF 01, CF 07, and CF 08) showed Carbendazim as most effective in inhibiting mycelial growth, followed by Propiconazole, with Azoxystrobin exhibiting the least effectiveness across all isolates (53).

6.2 Botanicals

Botanical extracts such as Ocimum, Ginger, Onion, and Garlic inhibit mycelial growth, while essential oils like Peppermint, Mentha, Geranium, Patchouli and Palmarosa are effective against *C. falcatum* mycelia growth (48). Seaweed extracts from *Sargassum myricocystum* and *Gracilaria edulis* on *C. falcatum* were tested and results showed significant antifungal activity in *S. myricocystum* (ethanol extract), followed by *G. edulis*. The 10% ethanol extract of *S. myricocystum* inhibited mycelial growth the most, at 52 mm compared to the control's 90 mm (54).

It was found that plant extracts from parthenium, essential oils from peppermint, mentha and lemon, and tulsi, along with the strain Th-53 (a strain of *T. harzianum*), were effective against the red rot pathogen (55). It was found that the chloroform and ethanol concentrate of *Vitex negundo* exhibited the highest inhibitory activity (24 mm) against *Colletotrichum sp*. Other notable inhibitory effects were seen with *Calotropis gigantea* and *Centella asiatica* ethanol concentrates (22 mm and 23 mm, respectively). Moderate inhibition was observed with *Ocimum sanctum* and Piper beetle extracts, while *Aloe vera* and *Azadirachta indica* ethanol concentrates displayed the least activity (56). In an experiment both 25% and 50% concentrations of botanical extracts inhibited *C. falcatum* growth significantly. 50% Neem extract showed the highest inhibition (72.79%), followed by 25% Neem (67.93%) and 50% Datura (69.58%). 25% Tobacco and 25% Garlic had the lowest inhibition rates (7.63% and 28.86% respectively) (57). Six plant extracts (Neem, Garlic, Bael, Onion, Tulsi and Aloe Vera) were tested at concentrations of 5%, 10%, 15%, and 20% against three *C. falcatum* isolates (CF 01, CF 07, and CF 08). Neem extract showed the highest efficacy at all concentrations, followed by Tulsi, Garlic, Aloe Vera, Onion and Bael, which exhibited the least inhibition. The highest inhibition (80.19%) was observed with Neem against CF 01 at 20% concentration, while the least inhibition (5.37%) was seen with Bael against CF 08 at 5% concentration (58).

6.3 Biological control

Sett germination increased with treatments of *T. viride*, *T. harzianum*, and Bavistin compared to the control. Bavistin was most effective, surpassing *T. viride* and *T. harzianum* in enhancing germination and reducing sett mortality. The highest germination increase (42.94%) occurred with Bavistin, followed by *T. harzianum* (21.47%) and *T. viride* (16.26%).

Similarly, sett treatments with biomanures and Bavistin reduced sett mortality and disease incidence. The greatest reduction in sett mortality (42.37%) was with *T. harzianum*, followed by bavistin (41.30%) and *T. viride* (30.43%). Bavistin-treated setts also showed the highest decrease in red rot disease development (45.38%), followed by *T. harzianum* (34.61%) and *T. viride* (30.77%) (59). It is elucidate that each42 gene of *Trichoderma spp*. plays a pivotal role in controlling red rot incidence in sugarcane (60). *T. harzianum* and certain *Pseudomonas* species exhibit protective capabilities against soil-borne red rot inoculum, primarily due to the chitinase enzyme they produce (61). It was noted that the decrease in red rot disease could be attributed to the protective effects, possibly resulting from the parasitic activity of *Trichoderma harzianum* on the red rot pathogen, or the induction of systemic resistance in sugarcane (62). Two strains, *Ochrobactrum intermedium* NH-5 and *Stenotrophomonas maltophilia* NH-300, displayed strong bio-control activity, reducing red rot by 44-52% (63). Twenty-six bacterial strains out of 226 collected showed biocontrol activity against *C. falcatum*. Antagonistic activity varied among strains, with inhibition percentages ranging from 28.97% to 61.18% for cfNAV, 34.01% to 69.64% for cfCHA and 28.96% to 53.48% for cf8436. Notably, *Ochrobactrum intermedium* TRD14 and *Escherichia sp.* VRE34 exhibited the highest inhibition against cfNAV and cfCHA, respectively. Twenty-three out of 26 strains demonstrated over 50% inhibition against one or more *C. falcatum* strains (64).

6.4 Heat Therapy

Autoclaved sugarcane leaf pieces were used to test the viability of *C. falcatum* in the buds of sugarcane cultivars Co 290 and CP 65-357. Aerated steam treatment (AST) at 51°C for 4 and 5 hours killed the pathogen in 61% and 75% of infected buds, respectively and at 52°C in 88% and 91%. AST at 52°C also eliminated the pathogen in other infected tissues. After 4 hours at 52°C, no more than one bud per stalk had viable *C. falcatum*. The treatment did not affect CP 65-357 bud germination but reduced Co 290 bud germination (65). Several investigations have shown that moist hot air therapy (MHAT) of seed cane at 54°C for 4 hours (with a relative humidity of 95-100%) was highly effective against red rot (66-69). Additionally, it was found that moist hot air treatment (at 54°C for 2 hours) was more effective than hot water treatment (at 50°C for 2 hours) in reducing red rot (70). Aerated steam treatment at 52°C or soaking setts in cold running water for 48 hours followed by hot-water treatment (at 50°C for 150-180 minutes) have been effective in eliminating the pathogen from infected setts (71).

7. Impact of intercropping on red rot disease and cane parameters

Hailu (2019) found that Intercropping sorghum with common beans and using compost reduced bean anthracnose (*C. lindemuthianum*) severity. Disease severity dropped 21.9-27.0% in the first year and 29-35.7% in the second year in intercropped and compost-amended plots compared to controls (72). A three-year field experiment to explore intercropping sugarcane with mustard, moongbean, lentil, and urdbean were conducted and found that the Sugarcane + Lentil intercropping yielded the highest net income (Rs. 254,250/ha), followed by Sugarcane + Mustard, Sugarcane + Urdbean, and the lowest income (Rs. 184,000/ha) from the Sugarcane + Moongbean system (44).

During the 2019-20 and 2020-21 cropping seasons, nine intercrops were evaluated alongside sugarcane in field conditions. Red rot disease incidence was notably lower in intercropped plots compared to sole sugarcane cultivation. Sugarcane + Garlic (7.19%) exhibited outstanding results in both seasons, followed by Sugarcane + coriander (8.36%), showing lower levels of red rot incidence. Other intercrops, including potato, mangrella, chilli, gram, tomato, rajma, and lentil, also showed relatively lower red rot incidence (ranging from 9.10% to 18.38%) compared to sole sugarcane (26.87%). Sugarcane + garlic intercropping showed the highest germination enhancement (28.24%), followed by sugarcane + coriander (26.27%). Sugarcane + lentil showed lower enhancement (19.29%) but was significantly better than sole sugarcane (15.89%). The maximum increase over the control was in sugarcane + garlic (43.71%), followed by sugarcane + coriander (39.42%). Different intercropping systems significantly influenced the growth and yield parameters of sugarcane. Germination and yield showed a negative correlation with red rot disease incidence. Sugarcane intercropped with garlic exhibited the highest cane girth (2.26 cm), cane length (253.97 cm), cane weight (0.77 kg), number of millable canes per plot (162.49), yield (49.65 t/ha), and percentage increase in yield over control (50.62%). This was followed by sugarcane + coriander and sugarcane + potato, while sugarcane + lentil performed relatively poorly among all intercrops but showed superiority compared to sole crop (31).

8. The impact of fungicides, micronutrients, and botanicals on red rot disease incidence, cane parameters and soil properties

Various treatments, including ST+D+S with Carbendazim + FA of B+Zn, ST+D+S with Propiconazole + FA of B+Zn, ST+D+S with Azoxystrobin + FA of B+Zn, FA of B+Zn, D+S of Neem, D+S of Tulsi, D+S of Neem+Tulsi, along with a control, were evaluated for their impact on red rot disease incidence, as well as quantitative and qualitative parameters of sugarcane and soil properties. ST+D+S with Carbendazim + FA of B+Zn demonstrated the highest effectiveness in reducing red rot disease and enhancing other cane parameters. Following this, ST+D+S with Azoxystrobin + FA of B+Zn, ST+D+S with Propiconazole + FA of B+Zn and D+S of Neem+Tulsi showed effectiveness, while untreated plots were the least effective (31). These findings align with (73), who observed the least disease incidence and maximum germination with Carbendazim (28.8% at 2% concentration), while untreated plots exhibited the maximum disease incidence (90.2%) and least germination (26.4%). Similarly, (49) noted the effectiveness of all doses of Azoxystrobin in managing red rot disease.

It was found that the application of *T. harzianum* Th 37 TMC (Trichoderma multiplied culture) at 20 kg/ha during ratoon initiation increased nitrogen (N) availability by 27%, phosphorus (P) by 65% and potassium (K) by 44%. Micronutrients such as copper (Cu) increased by 6%, iron (Fe) by 100%, manganese (Mn) by 79% and zinc (Zn) by 66%. Organic carbon rose by 55% with a decrease in soil pH to 6. They observed significant differences in nutrient uptake between highly susceptible (CoLk 7710) and moderately resistant (CoS 96268) varieties. Susceptible CoLk 7701 showed a 69% increase in N uptake compared to 45% in CoS 96268. Phosphorus uptake increased by 96% in CoLk 7701 and 69% in CoS 96268, while potassium uptake rose by 128% in CoLk 7701 and 59% in CoS 96268.

Combining TMC with salicylic acid (SA) provided up to 78% protection against red rot and with metabolites, it reached 86%, compared to 60% and 71% with TMC and metabolites alone, respectively. Application of TMC + SA promoted growth, improving ratoon initiation by 15%, number of tillers by 8%, cane height by 5%, girth by 4%, number of internodes by 8%, length of internode by 2%, single cane weight by 5% and number of millable canes by 4%, resulting in a 23% increase in average yield (74).

The impact of different sett treatments on cane attributes were examined and found that three-budded sett treatment with Carbendazim and Gibberellic acid resulted in the highest germination rate (74.4%), while single-budded sett treatment with Carbendazim showed the lowest (58.0%). The highest cane yield (93.7 t/ha) was observed with two-budded sett treatment using Carbendazim and Gibberellic acid, followed by two-budded sett treatment with Carbendazim alone, yielding 87.0 t/ha (75). Thiophanate methyl (0.25%) on five sugarcane cultivars in a field experiment were tested. The treatment significantly reduced disease severity and improved various cane parameters: germination (4.99%-5.91%), cane length (1.11%-5.30%), cane girth (0.85%-1.61%), tillers (2.38%-8.09%), single cane weight (1.25%-6.67%), number of millable canes (4.20%-14.76%) and yield (7.92%-14.24%) (76). The significant impact of Zn and B application on sugarcane growth and yield were observed. In this ST+D+S with Carbendazim + FA of B+Zn demonstrated the highest disease suppression and recorded maximum zinc and boron availability, with boron strengthening cell walls and zinc inhibiting various pathogens in the soil. Boron and Zincapplicationcontrolledpathogens like *Fusarium*, *Plasmodiophora*, *Rhizoctoni,* and *Macrophomina*, as reported in various studies (77).

9. Effect of micronutrients

The impact of red rot infection on nutrient levels in cane juice varied significantly across different cane cultivars, indicating a notable alteration. Studies on wilt infection in sugarcane revealed that wilted canes accumulate nitrogen (62.5-76.2%), magnesium (4.0-15.4%), iron (47.8-62.3%), calcium (31.3-56.6%), and sodium (22.6-25.9%), while phosphorus, potassium (5.2-8.4%), copper (4.6-7.4%), manganese (32.5-39.8%), and zinc (27.3-39.6%) are depleted, varying by variety (78). According to (79) red rot infection led to significant reductions in phosphorus content in cane juice, ranging from 8.4% to 31.4% across varieties, with BO120 experiencing the highest decline (31.4%) and BO130 the lowest (8.4%). This decline may be attributed to nitrogen accumulation and potassium depletion (22). Potassium levels in cane juice also decreased significantly due to red rot infection, ranging from 8.6% to 26.4% across varieties. BO120 exhibited the highest decrease (26.4%), while BO130 showed the lowest (8.6%) (80). Calcium content increased in cane juice upon red rot infection, notably in BO120 (30.2%), followed by BO102 (23.8%) and least in BO130 (7.2%) (22). Conversely, magnesium levels decreased, with BO120 showing the greatest decline (28.4%) and BO130 the least (3.5%), (80). Iron content increased in cane juice due to red rot, with the highest accumulation (20.5%) in BO120 and the lowest (6.4%) in BO130, supported by previous research (81, 82, 22). However, copper content decreased in infected cane juice, likely due to the antagonistic effect of iron, with reductions ranging from 8.5% to 29.0% (22). Similarly, zinc content decreased in cane juice due to red rot infection, ranging from 17.5% to 40.0%, with BO120 showing the highest depletion and BO130 the least, in line with previous observations (83, 22). Micronutrient effects on yield and sucrose content in sugarcane were studied and it was found that application of $ZnSO_4$ at 30 kg/ha alongside recommended NPK doses resulted in a 30% increase in economic returns compared to the control, with yield increases of 19.08% in the first plant and 22.03% in the ratoon crop. Additionally, sucrose content was enhanced by up to 5.91% in the first plant and 8.64% in ratoon crops compared to the control (84).

(85) Reveal the significant effect of nitrogen on cane ripening and juice quality. Red rot pathotypes impact nitrogen accumulation: Pathotype-1 induces the highest accumulation (50.4%), followed by Pathotype-2 (45.5%) and Pathotype-3 (40.5%). Phosphorus content decreases in infected cane juice, most with Pathotype-1 (33.0%), then Pathotype-2 (29.0%) and Pathotype-3 (25.0%). Potassium also decreases, primarily due to Pathotype-1 (22.1%), followed by Pathotype-2 (16.7%) and Pathotype-3 (8.0%). Zinc content reduces significantly, with Pathotype-1 causing the most reduction (30.5%), then Pathotype-2 (21.2%) and Pathotype-3 (9.6%). Copper content decreases in all varieties due to infection, most with Pathotype-1 (30.5%), then Pathotype-2 (21.0%), and Pathotype-3 (11.5%). Magnesium reduction is highest with Pathotype-1 (20.1%), followed by Pathotype-2 (12.3%) and Pathotype-3 (6.4%). Manganese content declines significantly due to infection, particularly with Pathotype-1 (27.0%), then Pathotype-2 (19.5%), and Pathotype-3 (10.6%). Sodium content increases, mainly influenced by Pathotype-1 (38.3%), then Pathotype-2 (29.5%) and Pathotype-3 (19.0%). Boron content rises with infection, most with Pathotype-1 (26.0%), followed by Pathotype-2 (18.4%) and Pathotype-3 (9.3%). Pathotype virulence also affects calcium accumulation. Pathotype-1 induces the highest accumulation (31.5%), followed by Pathotype-2 (18.0%) and Pathotype-3 (7.1%). Iron concentration rises in infected juice, particularly with Pathotype-1 (33.0%), then Pathotype-2 (26.0%), and Pathotype-3 (18.0%).

10. Effect of Different Temperature and pH

According to (86) the maximum growth (396.0 mg) occurred at 30°C, followed by 390.3 mg at 25°C and 370.6 mg at 35°C temperature. Sporulation peaked at 30°C (12.3), followed by 9.0 at 25°C and 8.3 at 35°C. The maximum growth (398.3 mg) and sporulation (12.0) of the red rot pathogen occurred at pH 7. Growth and sporulation increased from pH 4 to 7 but declined beyond pH 7. The fungus failed to grow or sporulate at pH 2, 3 and 10. It was found that disease incidence ranged from 0.8% to 25.5%. The highest incidence (25.5%) occurred in the second fortnight of August, followed by 18.5% and 12.5% in the first fortnight of August and September, respectively. Maximum temperatures ranged from 22.5°C to 36.9°C, minimum temperatures ranged from 7.3°C to 26.6°C, morning relative humidity ranged from 80% to 90%, evening relative humidity ranged from 50% to 76%, rainfall ranged from 6.3 mm to 115.8 mm and sunshine ranged from 2.4 to 8.4 hours during the observation period. The peak disease incidence coincided with weather conditions in the second fortnight of August 2018, with maximum and minimum temperatures of 33.1°C and 26.4°C, morning and evening relative humidity of 88.0% and 74.0%, rainfall of 115.8 mm and sunshine duration of 2.4 hours. Disease incidence was most prevalent during the rainy season (July to the first fortnight of September) (87).

11. Conclusion

Future research and management of red rot disease in sugarcane cultivation are set to focus on several key areas. One primary area is the development of new sugarcane varieties with enhanced resistance to *Colletotrichum falcatum* through breeding programs and genetic modification techniques. Advanced pathogen studies will delve deeper into the molecular and genetic characteristics of the pathogen to better understand its mechanisms and develop rapid diagnostic tools for early detection. Innovative control methods will be explored, including novel chemical treatments, botanical and biological control agents, and optimized heat therapy protocols. Integrated disease management strategies combining multiple control methods will be implemented and the long-term effects of intercropping and crop rotation on disease suppression and soil health will be studied. The influence of environmental factors, such as climate change, on disease incidence and severity, as well as the role of micronutrients and soil health in disease resistance and cane productivity, will be investigated. Data analytics and machine learning will aid in predicting disease outbreaks and optimizing management practices. Sustainable agricultural practices that reduce reliance on chemical inputs and enhance ecosystem health will be promoted, alongside education and training programs for farmers on best practices for disease management and sustainable sugarcane cultivation. Additionally, policies supporting research funding and the adoption of innovative disease management strategies will be developed, and collaboration between researchers, agricultural extension services, and sugarcane growers will be strengthened to ensure the effective transfer of knowledge and technologies. These concerted efforts aim to mitigate the impact of red rot disease, ensuring sustainable sugarcane production and enhancing the resilience of sugarcane varieties against this detrimental pathogen.

Future Scope: Future research can focus on molecular characterization of pathogen strains, development of region-specific integrated disease management modules, and genome-assisted breeding for durable resistance in sugarcane.

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