REVIEW ARTICLE

CHANGING SCENARIO OF SUGARCANE DISEASES IN INDIA SINCE INTRODUCTION OF HYBRID CANE VARIETIES: PATH TRAVELLED FOR A CENTURY

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Abstract

Sugarcane crop has been traditionally cultivated over centuries in India and other Asian countries for preparation of various sweeteners and to some extent for direct consumption. With the introduction of hybrid varieties, cane cultivation expanded to several regions in the country. During the expansion of the crop area, different disease problems have also been encountered; some were disastrous and decimated the industry very severely. The most important disease, which has hit hard the industry was red rot, caused by *Colletotrichum falcatum* Went and it destroyed cane cultivation by a series of epiphytotics in different decades for more than 100 years. Next to that, two other fungal diseases smut (*Sporisorium scitamineum*) and wilt (*Fusarium sacchari*) have also caused extensive damage to cane cultivation for the last 100 years. Since all the three pathogens damage stalk tissues, the economic losses due to them are always huge. Though these diseases could be managed by deploying resistant varieties now and then, they remain as a threat to the crop in some states. Other than these fungal diseases, foliar diseases such as rust, brown spot, eye spot, brown stripe, pokkah boeng etc were reported during different periods. Unlike the stalk infecting fungal diseases, the foliar diseases were seasonal in occurrence and mostly variety specific. Apart from fungal diseases many diseases caused by viruses, bacteria and phytoplasma were also made huge impact on performance of many sugarcane varieties during the previous decades. Important non-fungal diseases which caused substantial losses were grassy shoot, yellow leaf, mosaic, leaf fleck, ratoon stunting, leaf scald and red stripe. Many of these diseases became prominent after developing specific diagnostic tools in the recent years. Many management practices were developed to tackle the diseases, especially heat treatment of seed canes and virus elimination combined with molecular diagnostics became popular among the sugar industry.

Key words: Sugarcane diseases, epidemics, red rot, smut, wilt, grassy shoot, mosaic, YLD, varietal degeneration, diagnostics

Introduction

Sugarcane diseases are constraints to crop production all over the world, and no country is protected from the destructive influences of plant pathogens and pests. More than 125 diseases of sugarcane caused by fungi, bacteria, viruses, phytoplasma and nematodes have been reported from all over the world (Rott *et al.*, 2000). In India, more than 50 diseases were recorded in sugarcane crop during different occasions (Viswanathan and Rao, 2011). However, only a few diseases such as red rot, wilt, smut, yellow leaf disease (YLD), grassy shoot disease (GSD), leaf scald disease (LSD), ratoon stunting disease (RSD), rust and mosaic threatened sugarcane cultivation during different periods with varying intensities (Viswanathan, 2012a). Among these, researchers focused only on red rot on most of the occasions. The disease was recorded as the first major disease outbreak in Madras Presidency and Bengal, more than a century ago (Barber, 1901, Butler, 1906). Cultivation of imported noble canes in large areas in these regions that time led to spread of red rot with many disease epiphytotics. Hence, there was a need to improve varietal resistance

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to red rot along with other agronomical traits for profitable sugarcane cultivation. Major initiative taken during that time was establishment of ICAR-SBI at Coimbatore in 1912 for developing hybrid varieties to tackle different biotic and abiotic stresses in sugarcane. 'Co 205' the first hybrid variety and subsequent elite varieties released for cultivation made a revolution in sugarcane cultivation and led to sugar revolution in the country. By this, cane cultivation spread to large tracts in different states especially in Indo-Gangetic plains and delta regions during the first few decades. Later, cane cultivation spread to uplands, thanks to lift irrigation opportunities. During the expansion of crop area, problems associated with sugarcane cultivation, especially the diseases emerged as a constraint in different decades in the country. Vegetative propagation through setts was a major contributing factor in disease spread to new areas. Dr. E.J. Butler, the Imperial Mycologist also referred as "Father of Plant Pathology in India" made elaborate studies on sugarcane diseases after severe red rot epiphytotics in Bengal. Subsequently, several researchers have documented different disease problems affecting sugarcane crop in the country for more than 100 years and this review documents important developments in sugarcane pathology since start of scientific sugarcane cultivation in the country.

Red rot

It is the most widespread sugarcane disease in the country and it has been a constraint for the past 100 years in India and other South Asian countries. First large-scale destruction of the cane in India by the disease was noticed in Godavari delta of then Madras Presidency on the cultivar Red Mauritius during 1895 to 1899. Subsequently, many noble cane varieties were severely affected in the tropical and subtropical regions in the country (Barber, 1901, Butler, 1906). To tackle the menace, sugarcane breeding was initiated at Coimbatore by developing hybrid varieties involving *Saccharum officinarum* and *S. spontaneum*. This nobilization process led to development of many outstanding varieties from SBI, Coimbatore. Red rot severity was reduced for a decade in the country since 1918, after introduction of hybrid varieties. However, elite varieties grown in the subtropical region succumbed to the disease one after another that resulted in severe epiphytotics in different decades after 1930s. During the past 100 years the country witnessed series of red rot epidemics and many elite hybrid varieties like Co 312, Co 419, Co 421, Co 453, Co 658, Co 997, Co 1148, Co 6304, Co 7805, Co 89003, CoC 671, CoC 92061, CoJ 64, CoSi 86071, CoS 8436, CoSe 95422, CoSe 92423, CoLk 8102, CoV 09356, BO 11, BO 17, BO 54 etc., succumbed to the disease (Table 1) and new varieties were introduced to combat the disease in different decades and the disease onslaughts were reduced significantly (Viswanathan, 2010, Viswanathan *et al.*, 2018a). The epiphytotic nature of the disease was noticed in the subtropical regions of the country till 1960s and the disease was less severe till the predominant variety Co 1148 succumbed to the pathogen during late 1970s. Subsequently, red rot epidemics resumed on Co 1148, Co 7717 and CoJ 64 after 1980s in the region. After 2000 the popular varieties such as CoLk 8102, CoS 8436, CoSe 92423 and CoSe 95422 were severely damaged in red rot epidemics and the popular variety Co 0238 identified from SBI Research Centre, Karnal has replaced these varieties and contained red rot (Table 2). In the tropical region, after the reports of Dr Barber, the disease was again noticed in Andhra Pradesh during 1960s. Subsequently, it was noticed in Tamil Nadu and Kerala during 1970s and Gujarat and Odisha during 1980s. The popular varieties Co 419 and Co 997 in Andhra Pradesh and Co 658 in Tamil Nadu were affected after the disease epidemics. However, cultivation of the popular

variety CoC 671 over large areas in the tropical region led to severe epiphytotics and ravages to the cane fields (Fig. 1). This has also led to emergence

Fig. 1. Complete destruction of sugarcane crop due to red rot in a field in Odisha.

of virulent pathotype and many varieties fallen prey to the pathogen during 1990s (Viswanathan *et al.*, 1997a). Removal of CoC 671 and adoption of the popular variety of the millennium, Co 86032 over large areas in the region reduced the disease severity. During the same time, in Andhra Pradesh, varieties like CoA 92081, CoV 84101, CoV 09356 etc. reduced red rot severity. Currently the disease occurs in all the sugarcane growing states in India except Karnataka and Maharashtra states in mild to severe intensities. Although Karnataka and Maharashtra states are free from red rot, severe occurrences of red rot was noticed during late 1990s in the cvs CoC 671 and CoC 92061, introduced from Tamil Nadu (Viswanathan and Samiyappan, 1999). However, spread of the disease to large areas was contained by swift action taken by various agencies.

Series of red rot epidemics after the introduction of hybrid varieties led to search for resistant sources among the parents and progenies, hence screening methods were developed for red rot resistance in sugarcane. Dr. B.L. Chona standardized plug method for disease screening (Chona, 1954). Subsequently, Dr. K.V. Srinivasan has developed a 0-9 rating scale and is being followed universally (Srinivasan and Bhat, 1961). Furthermore, to assess red rot resistance based on natural ways of pathogen entry, nodal methods were developed in different occasions (Viswanathan, 2010). However, environmental factors played a crucial role in disease development and inconsistencies were found. The recently developed cotton swab method of ICAR- SBI (Viswanathan, 2013a) has been consistent and adopted at all the AICRP centers in the country. Apart from field inoculation methods, a controlled condition testing which is rapid was developed at ICAR- SBI and is being followed to screen sugarcane progenies every year at SBI (Mohanraj *et al.*, 1997, 2012, Viswanathan *et al.*, 1998). Since 1996, ~51,208 clones / progenies were screened and identified ~16,909 resistant types, thereby facilitated identifying red rot resistance at very early stages in varietal selection (Fig. 2). Without this rapid screening technique, it would not have been possible to screen such a

Fig. 2a. Red rot pathogen inoculated canes under incubation in controlled condition chamber.

large progeny population in sugarcane. Apart from these techniques, a methodology to identify field tolerance to red rot in sugarcane was developed (Mohanraj *et al.*, 2012, Viswanathan, 2010) and recently, it was tested in different AICRP centres.

Fig. 2b. Sugarcane clones exhibiting susceptible (left) modertely susceptible (centre) and resistant (right) reactions in 10 days.

We witnessed failure of many elite varieties from Co 205 in the field in several occasions due to red rot (Agnihotri, 1983, Chona, 1980, Viswanathan, 2010). These varieties were resistant to the pathogen at the time of their release and picked up the disease later. Variety like Co 1148 remained free of red rot for nearly three decades under subtropical conditions. Recently, other major varieties such as CoS 8436, CoSe 92423 and CoS 95422 survived in the region inspite of red rot and finally succumbed to the pathogen after many years of battle. Unlike these varieties, another major variety CoS 767 though succumbed briefly to *C. falcatum* never allowed buildup of disease epidemics during the same period in the subtropical region. Probably except the cv BO 91 almost all the varieties in the red rot prone areas have succumbed to the pathogen. Investigation on frequent breakdown of disease resistance in diverse cane varieties to red rot established emergence of new pathotypes on different occasions (Beniwal *et al.*, 1989, Padmanaban *et al.*, 1996, Viswanathan *et al.*, 2003a). So far about 12 pathotypes have been characterized from tropical and subtropical regions (Viswanathan 2010, 2017a). The new pathotypes were found to be more virulent and the variant population gradually adapted to the varieties in the field that resulted in the buildup of red rot in the varieties hitherto resistant, eventually, the pathogen succeeded by causing a 'varietal breakdown' (Viswanathan, 2017a, Viswanathan *et al.*, 1997a, 2003a).

A set of host differentials were identified to establish pathogenic variation into designated pathotypes for different zones, across the country. The designated pathotypes were recommended for disease screening for the respective zones. Recently studies were conducted to establish molecular variations in *C. falcatum* pathotypes/ isolates (Malathi *et al.*, 2010), however, the genetic variations could not be related to pathogenic variations observed under field conditions. Recently, a large population of *C. falcatum* numbering ~117 isolates from both the tropical and subtropical regions was assessed for pathogenic variation simultaneously at Coimbatore and Karnal on the susceptible cv CoC 671. The results clearly revealed that the isolates exhibited enormous variation and the pathogenic variation was attributable for their innate virulence, host variety for their origin and prevailing environment (Viswanathan *et al.*, 2017a).

Apart from elaborate research works on disease resistance, screening methodologies and pathogen variation, detailed research works on induced resistance (Ashwin *et al.*, 2017a, Ramesh Sundar *et al.*, 2001, 2009, Viswanathan and Samiyappan, 2002, 2008), basis of red rot resistance (Viswanathan *et al.*, 1996a, 2005), molecular basis of host pathogen interaction with different transcriptomic and proteomic tools (Nagarathinam

et al., 2014, Pratima *et al.*, 2013, Sathyabhama *et al.*, 2015, Rahul *et al.*, 2016, Viswanathan *et al.*, 2014a, 2016a), sequencing of complete genome and transcriptome of *C. falcatum* (Prasanth *et al.*, 2017, Viswanathan *et al.*, 2016b), identifying potential pathogen-associated molecular pattern (PAMP) and effectors of *C. falcatum* (Ashwin *et al.*, 2017b, 2018), pathogenicity gene homologues in *C. falcatum* and putative antifungal proteins from antagonistic *Trichoderma* (Elamathi *et al.*, 2017, Kaverinathan *et al.*, 2017, Scindiya *et al.*, 2017, Viswanathan *et al.* 2003b) and other areas were carried out. We could make rapid advances in this area by employing different omic tools and brought out new understanding on the host as well as the pathogen for the first time.

Smut

Smut of sugarcane was reported for the first time during 1906 by Dr. E. J. Butler in the country (Butler, 1906), since then the disease occurs in different states. Mundkur (1939) reported incidence of sugarcane smut, studied the infection and development of the pathogen and reviewed the taxonomic status of the pathogen. After 1940s many smut epidemics were reported from different states and many popular varieties were removed form cultivation (Table 1) (Sinha, 2002). Earlier the disease has been a major constraint in Maharashtra and northern Karnataka when Co 740 was the major variety under cultivation. Large scale replacement of Co 740 with Co 86032 in the region reduced the disease severity significantly during the last two decades (Viswanathan, 2012a). However, with the large-scale adoption of the cv CoA 92081 (87A298) in Andhra Pradesh led to disease epidemics in the region on many varieties. Although the subtropical region has not witnessed severe smut in the recent decades, currently it occurs in many states at moderate or severe levels affecting the crop productivity (Table 2).

Studies of Alexander and Srinivasan (1966) at SBI demonstrated sexuality in the smut pathogen that a combination of two sporidia belonging to opposite sexes was necessary for successful infection and the degree of virulence varied with the combination of haplonts. Subsequently Alexander and Ramakrishnan (1977) found that when cells containing the two mating type alleles are brought together, developmental changes occur, shifting from the saprophytic, budding yeast-like appearance to a mycelial form characteristic of the parasitic phase. Further, the promycelium can also germinate to give hyphae capable of fusion, or the promycelial cells may fuse to form the dikaryon. Viswanathan *et al.* (2000) for the first time

Table 1. Major epidemics of various diseases occurred in sugarcane during different periods in India

Year	Varieties affected	Region/States
Red rot		
1895-1901	Namalu, Keli, Ashy Mauritius, Striped Mauritius	Godavari delta, Andhra Pradesh
1902-1925	Bourbon, Striped Mauritius	Champaran and Muzaffarpur in Bihar Jammu, Punjab
1925-40	Co 205, Co 210, Co 213	Bihar, Uttar Pradesh, Punjab
1940s	Co 290, Co 312, Co 313, Co 357, Co 393, Co 421, Co 453, Co 570, CoS 5, BO 11, BO 17, BO 54	Northern Bihar, Uttar Pradesh
1950-51	Co 301, Co 312, Co 313, Co 385	Punjab

Year	Varieties affected	Region/States
1964-69	BO 10, BO 11, Co 997, CoS 562, BO 3	Bihar, Uttar Pradesh
1960-70	Co 419, Co 421, Co 997, Co 62175	Andhra Pradesh
1970-1974	Co 419, Co 658	Andhra Pradesh, Tamil Nadu and Pondicherry
1981-1982	CoC 671, CoA 7701	Andhra Pradesh
1982-1984	Co 419, Co 785, Co 997	Kerala
1975-1992	BO 54, Co 1148, Co 7717, CoJ 64	Bihar, Punjab, Haryana, Uttar Pradesh
1986-92	Co 6304, CoC 671, CoC 8001, CoC 85061, CoC 86062, Co 6304	Gujarat, Pondicherry and Tamil Nadu
1991-2005	CoJ 64, CoS 767, CoS 8439	Punjab, Haryana, Uttar Pradesh
1992-2000	Co 6304, CoC 671, CoC 90063, CoC 91061, CoC 92061, CoSi 86071, CoSi 96071	Andhra Pradesh, Karnataka, Orissa, Puducherry and Tamil Nadu.
2000-10	CoS 8436, CoSe 95422, CoSe 92423, CoS 98231, CoJ 85, CoH 156, CoJ 64, Co 89003, CoS 91269, BO 128	Uttar Pradesh, Bihar, Uttarakhand, Haryana, Punjab, Madhya Pradesh
	Co 86002, Co 92020, Co 92012, CoSi 6, CoV 09356, Co 62175, 81 A 99, 93 V 297, 81 V 48, CoC 92061	Andhra Pradesh, Odisha, Tamil Nadu, Gujarat, Puducherry
After 2010	CoS 8436, CoLk 8102, CoSe 95422, CoSe 92423, CoS 98231, CoS 07250, CoJ 64, CoJ 85, CoH 156, Co 1148, Co 89003, BO 128,	Uttar Pradesh, Bihar, Uttarakhand, Haryana, Punjab, Madhya Pradesh
	Co 86002, Co 92012, CoSi 6, CoC 24, CoV 09356, 91V83, 87V74, PI 1110, PI 1401	Andhra Pradesh, Odisha, Tamil Nadu, Gujarat, Puducherry
Smut		
1942-43 1950-52	Co 213, Co 453, Co 513, BO 11	Bihar
1947-48	Co 419	Karnataka
1960 onwards	Co 740, Co 7527	Maharashtra and Karnataka for many decades from
After 2000	Co 6907, Co 97009, CoA 92081, CoV 89101, CoV 05356, CoSi 6, CoC 22, CoC 24, CoC 25, PI 96-843 etc	Tropical region
	Co 1158, Co 89003	Subtropical region

Year	Varieties affected	Region/States
Wilt		
1940s	Co 245, Co 321, Co 527, Co 951, Co 1007,Co 1107, Co 1223, CoS 321	Subtropical region
1959-60	Co 419, Co 449, Co 453, Co 527, Co 775, Co 975, Co 997, Co 1122	Andhra Pradesh
After 2000	Co 7717, CoJ 64, CoJ 79, CoS 767, Co 89003, CoS 8436, CoS 88230	Subtropical region
1980-81	CoC 671	Andhra Pradesh
1985 & later	CoC 671	Gujarat
After 2000	Co 86002, Co 86032	Gujarat
1990s & after 2000	Co 740, CoC 671, Co 7527, Co 8011, Co 86032	Maharashtra
YLD		
After 2000	Co 86032, CoV 09356, CoV 92102, CoS 767, Co 0238, 83A10, 87A380	Throughout India
Grassy shoot		
Different decades after 1950s	All the popular varieties like Co 419, Co 453, Co 740, Co 975, Co 1148, Co 62175, Co 6304, CoJ 46, CoJ 64, CoS 510, BO 17, Co 86032, Co, 0238 etc	Throughout India
Rust		
Different decades	Co 475, CoS 510, Co 421, Co 475, Co 603, Co 658, Co 732, CoA 7601, CoVc 03165, CoVSI 9805	Throughout India
Brown spot		
After 2010	CoM 0265	Maharashtra, North Karnataka
Leaf scald		
1970s & later	Co 419, Co 1148, Co 1158, Co 7304, Co 62399, CoS 659, BO 17, BO 70, CoA 92081	Subtropical region and Andhra Pradesh
1990s	CoC 90063, CoSi 86071	Coastal Tamil Nadu, Puducherry

Year	Varieties affected	Region/States
Red stripe		
Different decades	Co 419, Co 312, Co 356, Co 527, Co 443, Co 453, Co 527, Co 617, Co 991, Co 1007, Co 1081, Co 1111, Co 1148, Co 1158, BO 10, BO 17, CoS 510, CoJ 64, CoJ 79, CoJ 82, CoJ 85	Subtropical and tropical states

Table 2. Current scenario of different diseases affecting sugarcane varieties in the country

Disease	Varieties affected*	States
Red rot	CoJ 85, CoJ 88, CoS 8436, CoS 91269, CoS 92423, CoLk 8102, CoSe 95422, UP 9530, Co 1148	Uttar Pradesh
	Co 89003, CoJ 85, CoS 8436,	Haryana
	Co 89003, CoJ 64, CoJ 85, CoPb 91	Punjab
	CoSe 92423, CoSe 95422, CoS 8436, BO 130, Co 0235	Bihar
	Co 740, Co 997, CoBln 09104	Assam
	Co 62175, 81 A 99, 93 V 297, S-12, 81 V 48	Andhra Pradesh
	CoC 24, CoC 23, CoV 09356, TNAU Si8, PI 1110, PI 1401, Co 91017, Co 86027, Co 06022	Tamil Nadu
	Co 6907, Co 86032, Co 86249, CoOr 03151	Odisha
	CoC 671, Co 86002, Co 86032, Co 97009, Co 0323, CoVSI 03102, VSI 0434,	Gujarat
	CoLk 8001, CoS 88230	Madhya Pradesh
Smut	Co 1158, Co 0118, Co 0238, Co 05011, CoLk 94184, CoS 767, CoS 8432, CoS 98231, CoSe 92423, CoSe 01434, CoSe 11453, CoS 08279, UP 05125, CoP 9301	Uttar Pradesh
	Co 89003, Co 0118, Co 0238, Co 05011, CoH 99, CoH 119, CoH 150, CoH 152, CoH 156, CoH 160	Haryana
	Co 89003, Co 0238	Punjab
	BO 141, BO 136	Bihar
	CoA 92081, CoV 09356 (2003V46), 91 V 83, 97 R 83	Andhra Pradesh
	Co 86032, Co 97009, CoC 22, CoSi 6, PI 96-843	Tamil Nadu
	Co 419, Co 7219, Co 86032	Maharashtra
	Co 86002, Co 97009, Co 99004, CoSi 95071	Gujarat
	Co 7219, Co 8014, Co 86032, Co 94012, Co 99004, Co 0238, Co 06027, CoM 0265, CoJ 64, CoS 88230	Madhya Pradesh
	Co 8011, Co 86032, Co 91010, CoC 671	Karnataka

Disease	Varieties affected*	States
Wilt	Co 89003, Co 98014, Co 0238, Co 05011, CoS 08272, CoS 08279, CoS 08276, CoSe 08452	Uttar Pradesh
	Co 1148, Co 89003, Co 05011, CoH 119, CoS 767, CoS 8436,	Haryana
	CoS 767, CoS 88230	Uttarakhand
	Co 89003, CoS 8436	Punjab
	Co 0118, Co 0233, CoLk 94184, CoSe 98231	Bihar
	Co 740, Co 997, CoBln 09104	Assam
	Co 7219, Co 62175, Co 86032, 87 A 380, 91 V 83, CoA 92081, 81 A 99	Andhra Pradesh
	Co 86032	Tamil Nadu
	Co 62175, Co 86032, Co 0323	Karnataka
	CoC 671, Co 86032, Co 86002, CoM 0265, CoSi 95071	Gujarat
	Co 94012	Madhya Pradesh
Pokkah boeng	Co 98014, Co 0118, Co 0238, Co 05011, CoS 08272, CoS 08279, UP 9530, UP 05125, CoS 91269, CoSe 92423, CoSe 96436, CoSe 01434, CoS 06279	Uttar Pradesh
	Co 89003, Co 0238, Co 05011, CoJ 85, CoJ 88, CoH 119, CoH 150, CoH 152, CoH 160, CoS 8436	Haryana
	Co 0238	Uttarakhand
	Co 0238	Punjab
	Co 05011, Co 0238	Bihar
	CoP 13436, CoLk 09204, CoSe 11454, BO 130	Assam
	Co 86032, CoC 671, CoM 0265, CoVSI 9805, CoVSI 8005	Maharashtra
	Co 99004	Gujarat
Red stripe/ top rot	Co 0238, CoJ 85, CoH 119, CoH 150, CoH 152, CoS 8436	Haryana
	Co 0118, CoJ 88, CoS 08272, CoS 08279	Uttar Pradesh
	CoJ 85	Punjab
YLD	Co 89003, Co 0238, Co 05011, CoS 8436, CoH 119, CoH 152, CoH 160	Haryana
	CoPant 84212, CoPant 03220, CoPant 05224, CoPant 90223, CoS 767	Uttarakhand
	Co 0118, Co 0238, Co 05011, CoPant 97222, CoS 8436, CoS 08272, CoS 08279, CoSe 01434, UP 05125,	Uttar Pradesh
	CoS 8436, CoLk 94184, CoSe 95422, Co 0118, Co 0238, BO 130	Bihar
	CoA 92081, 87 A 380, 2001 A 63, CoV 09356 (2003V46), 97 R 83, 81 A 99, CoV 92102, 81 V 48, 91 V 83, 93 V 297, Co 62175, Co 6907, Co 7219, Co 7602, Co 8368, Co 86032, S-12	Andhra Pradesh
	Co 86032, CoA 92081, CoV 09356, CoC 24, CoV 92102, PI 1401	Tamil Nadu
	Co 86032, CoC 671, CoM 0265, Co 419, VSI 434	Maharashtra
	Co 86032, Co 99004	Gujarat
	CoJN 86572, Co 85004, Co 86032, Co 99004, Co 09007, CoVSI 434, CoS 88230	Madhya Pradesh
	Co 740, Co 997, CoBln 09104	Assam

Disease	Varieties affected*	States
GSD	Co 98014, Co 0118, Co 0238, Co 98014, Co 05011, CoS 8436, CoS 88230, CoS 91269, CoS 97261, CoS 08272, CoS 08279, CoS 13231, CoSe 92423, CoSe 01424, UP 5125, CoJ 88	Uttar Pradesh
	Co 0238, Co 89003, CoJ 85, CoH 150, CoJ 88, CoH 119, CoH 152, CoH 160, CoS 8436	Haryana
	Co 0238	Punjab
	Co 0235	Bihar
	Co 419, Co 86032, Co 92005, CoC 671, CoM 0265, CoVSI 9805	Maharashtra
	Co 86032, CoC 671, CoM 0265	Gujarat
	Co 86032, Co J 64	Madhya Pradesh
Foliar diseases	CoPant 99214, CoS 88230, CoS 767, CoS 96268, CoPant 92423, Co 0118 (ring spot and eye spot)	Uttarakhand
	CoBln 09103, BO 130, CoSe 12453 (ring spot)	Assam
	CoM 0265, Co 86032, Co 92005, (rust), CoM 0265 (Brown spot), CoM 0265, Co 86032, Co 92005 (ring spot), CoC 671, Co 92005, Co 86032 (eye spot)	Maharashtra
	Co 0323 (rust)	Karnataka
Banded sclerotial disease	BO 155 and many other varieties	Many states
Pineapple disease	Co 86032 and CoM 0265	Maharashtra

*The varieties listed above vary in their severities to different diseases.

Source: Principal Investigator report, AICRP on Sugarcane (Pathology), 2016-17

reported that inoculation with the teliospores from an ovaricolous smut (*Sphacelotheca sorghi*) from *Ischaemum ciliare* produced culmicolous smut on sugarcane. The study indicated that both the smut fungi have similar mechanism in pathogenicity.

Alexander (1981) conducted studies using 46 teliospore collections from all the sugarcane growing areas, including inoculation tests with nine varieties of known reaction to *S. scitamineum*, and indicated the existence of two races and several biotypes. The recent occurrences of smut in severe form in Andhra Pradesh and in some pockets of Tamil Nadu and Karnataka suggest possible emergence of new biotypes and it needs a detailed study. To screen sugarcane clones for smut resistance, inoculation of smut pathogen by immersing sugarcane setts in a viable teliospore suspension and assessing disease resistance based on cumulative whip production was standardized at SBI (Alexander and Rao, 1981a). Work on sources of resistance identified several clones of *S. officinarum* and *S spontaneum* with high degree of resistance to smut (Srinivasan and Alexander, 1971, Alexander and Rao, 1981b). The inheritance of resistance to smut in sugarcane revealed that the resistance to the disease appeared to be governed by two dominant genes (S1 and S2), whose action was greatly modified by an inhibitor and anti-inhibitor genes (Kandasami *et al*, 1980). Since disease resistance is moderately heritable

and repeatable by adopting a robust screening for smut resistance in the varietal development programme, the disease is managed successfully in the country. Further studies at SBI established that bud morphology is an important factor for smut resistance and buds of resistant cultivars produced extracts capable of inhibiting spore germination (Padmanaban, and Alexander, 1988, Padmanaban and Mohanraj, 1989).

Sinha *et al.* (1982) developed a staining technique for the detection of smut hyphae in nodal buds of sugarcane. This rapid staining technique enabled detection of hyphae of *S. scitamineum* in the growing points of nodal buds of sugarcane. Nallathambi *et al.* (1998) observed that the trypan blue staining also detected smut infection in some clones, which escaped infection in the field. Further this staining technique was found to be very rapid, precise and allows a large number of samples to be tested in a short period. An indirect ELISA technique was also standardized for screening large number of sugarcane clones for smut pathogen detection (Nallathambi *et al.*, 2001). Recent studies using proteomic approaches have revealed new understanding on secretory proteins that are possibly associated with pathogenicity of *S. scitamineum* (Barnabas *et al.*, 2017).

Wilt

The disease was first reported during 1906 by Dr. E. J. Butler in the country (Butler, 1906) and since then its occurrence has been reported throughout the country. Since it was reported that the disease occurs during maturity phase, the researchers and sugar industry personal ignored the disease in spite of severe damages witnessed in different decades. Any field under harvest exhibits 10-15% of dried canes and ~50% of them were affected due to wilt. The author has witnessed wilt from germination phase onwards in sugarcane. Both sett and soil borne pathogen contribute to disease occurrence during germination and in the young crop (Viswanathan, 2012a, 2013b). Many varieties such as Co 245, Co 321, Co 419, Co 449, Co 453, Co 527, Co 951, Co 1107, Co 1122, Co 1223 and Co 89003 etc picked-up severe wilt in the different regions during disease epidemics (Table 1). Further, more damages to cane varieties were recorded during combined infections of red rot and wilt (Agnihotri, 1996, Agnihotri and Rao, 2002). The cv CoC 671 suffered huge losses in Gujarat due to wilt in the 1980s and subsequently to wilt and red rot. Recently also, the author witnessed severe outbreak of wilt on ruling varieties in coastal Andhra Pradesh, causing extensive damages to cane cultivation (Fig. 3). Pathogen characterization has not been done for several decades and many pathogenic organisms were reported (Viswanathan *et al.*, 2006). However, detailed studies conducted at SBI very clearly revealed that only *Fusarium sacchari* is the

Fig. 3. Severe devastation of sugarcane crop due to wilt in coastal Andhra Pradesh.

causative organism based on the studies involving morphological characters, molecular profiles and pathogenicity of the isolates collected from different regions (Viswanathan *et al.*, 2011a).

Under field conditions, managing the disease remains a serious challenge because of root and sett borne nature of the pathogen. Further, the disease

severity in aggravated by many biotic and abiotic factors. Although resistance to wilt in sugarcane varieties is addressed, the emphasis is not given as in the case of red rot and smut. Hence, the disease causes serious losses to cane cultivation and sugar industry also not realized on the problem. Although the disease occurs regularly in the field its reproduction seems to be challenging. Mohanraj and Alexander (1984) developed a methodology with a 0-4 rating scale for the disease screening and is followed in few AICRP centres. However, some centres rely on sick-plots to select wilt resistant varieties. Recent studies at SBI revealed that the disease can be reproduced in sugarcane varieties by employing abiotic stresses. After the pathogen inoculation, drought was found to have major influence on infection and progress of wilt in sugarcane. Further, complete drought favoured more disease development inside the canes than late drought during the incubation period. Overall, it was established that water stress at pre- and post-inoculation period greatly influenced the disease incidence. Across the varieties, variation in symptom development was high under normal conditions followed by late drought and complete drought conditions (Viswanathan *et al.*, 2015).

Since the disease occurs in severe form in many places concerted efforts are needed to manage the disease in the field. Among the management practices, host resistance should be relied upon for sustainable disease management. Sett and soil borne nature of the pathogen along with influence of different abiotic factors make the epidemiological study more challenging. In addition, limited information is available on pathogen variability. Recent studies conducted at SBI provited a clear understanding on variability of the pathogen (Poongothai *et al.*, 2014a,b, 2015). Another challenge is reproduction of the disease in known susceptible varieties like Co 86002, Co 86032, Co 89003, CoC 671 etc. Probably right pathogenic isolate along with conducive environment is the key in artificial reproduction of the discase. More detailed studies are needed in this area to address the disease constraint.

Foliar diseases

Butler (1918) first reported occurrence of rust in India. Presence of downy mildew (*Pseudosclerospora sacchari*) was first reported in the country by Subramaniam (1931) from Pusa on cv Co 316. Subsequently it was reported in few places and almost there is no report of this disease during the last few decades. Eye spot (*Bipolaris* (*Helminthosporium*) *sacchari*) was first identified during 1906 (Butler, 1906) and subsequently it caused severe outbreaks in tropical region especially in Mandya, Karnataka. Currently the disease occurs in mild form in the tropical region. Similarly, ring spot (*Leptosphaeria sacchari*) was also reported during the same time. The disease still continues to cause severe outbreaks during cooler months throughout the country. The disease severity is very high in coastal regions and high rainfall areas where extensive drying of foliage is found due to coalescence of the leaf spots. Occurrence of banded sclerotial disease (*Rhizoctonia solani* syn: *Thanatephorus cucumeris*) was reported during different occasions. The symptoms were conspicuous on leaf sheath and matured leaf lamina. Brown spot (*Cercospora longipes*) has been reported from different states but its severity was noticed in Karnataka and Maharashtra. Due to large-scale cultivation of the cv CoM 0265 in the recent years, the disease attained epiphytotic level in these states impacting crop cultivation significantly. Though the cv CoM 0265 was susceptible at the time of its introduction for cultivation, now other varieties grown in the region like Co 86032 and CoC 671 also picked up the disease and created an alarm in the region (Table 1, 2).

Apart from these diseases severe outbreaks of yellow spot (*Mycovellosiella koepkei*) were reported in India especially from Coastal Andhra Pradesh (Rao *et al.*, 1966). The then popular variety Co 527 was highly susceptible to the disease, whereas other cvs Co 975 and Co 997 were found to be tolerant to the disease at Anakapalle. It was also reported that 24.82% reduction in sucrose in juice due to the disease (Prasada Rao and Rao, 1963). Prakasam and Satyanarayana (1969) reported satisfactory control of the disease with copper oxy chloride. The author has also witnessed severe appearance of yellow spot like symptoms on many varieties in the region; however most of the affected varieties were positive to *Sugarcane bacilliform virus* (SCBV) and it is suspected that the virus may be the real culprit. Possible occurrence of yellow spot in the country needs fresh investigation. In addition, many other foliar diseases such as brown stripe (*Helminthosporium stenospilum*), leaf sheath red rot (*Mycovellosiella vaginae*), leaf spots caused by *Curvularia pallescens, C. clavata* and *Periconia atropurpurea* and *P. sarawatipurensis* were reported to occur under field conditions in different states (Rao, 2002).

After the report of Dr Butler on rust, in 1950's, severe brown rust outbreaks on Co 475, CoS 510 and Co 876 resulted in withdrawal of these varieties from the cultivation in the country (Chona and Munjal., 1950, Tiwari and Singh, 1962). Muthaiyan *et al.* (1966) reported variation in rust pathogen and categorized it into five races in India. Rust has become more severe among the different foliar diseases and currently it occurs in epidemic form in Maharashtra, Andhra Pradesh and Karnataka during post monsoon season. Severe incidences of rust occurred throughout the Maharashtra state in cvs CoM 0265, CoVSI 9805, Co 86032, Co 92005, CoC 671 and Co 94012 and in Andhra Pradesh 50–80% rust was observed in cvs CoV 06356, Co 6907, Co 7219, 97R129 and 85R106 (Viswanathan and Rao, 2011). The author has observed severe epidemic outbreak of brown rust in CoVc 03165 in Mandya District during 2009-10 and recently on Co 0323 in Karnataka. The crop suffered significantly and the variety was withdrawn from cultivation due its high susceptibility to the disease. Similarly, the variety CoVSI 9805 records very severe rust in North Karnataka and Maharashtra in the field and the crop suffers severely. Among the brown (common) and orange rusts, the former is more common and destructive. Apart from the symptoms, the two rusts can be differentiated by the spore characteristics (Viswanathan, 2012a).

Pokkah boeng

Since the pathogen infects foliage pokkah boeng (PB) can also be considered as a foliage disease. Prevalence of the disease was reported for the first time during 1983-84 season in Maharashtra (Patil and Hapase, 1987). Later it was reported from all the states. In some cases, the disease adversely affected crop productivity and withdrawal of varieties from cultivation e.g. Co 99004, an elite variety released for cultivation by CVRC for Peninsular region could not be popularized due to its high susceptibility to PB. Currently the disease is found during monsoon periods at varying severities on varieties in almost all the

Fig. 4. Pokkah boeng

states (Table 2). The disease occurs throughout the crop stages however its severity is felt during hot summer with humid conditions and monsoon period (Fig. 4). Detailed symptoms of the disease with different phases like chronic, acute, knife-cut and top rot were described in detail (Patil *et al.*, 2007, Viswanathan, 2012a). Earlier PB was considered as a minor disease and now its severe occurrences have been recorded in different states and in germplasm (Vishwakarma *et al.*, 2013, Viswanathan *et al.*, 2014b). Further, detailed studies under AICRP on sugarcane generated a wealth of information on its epidemiology, host resistance and management through fungicides. Since the pathogen systemically infects the crop after foliar infection and cause wilt, it assumes significance of a major disease. Currently, evidences have been found on the same pathogen causing wilt in stalk and PB on the leaves in sugarcane. *F. sacchari* initiates infection as PB and later turns systemic and cause wilt in the stalk (Viswanathan *et al.* 2017b). The recent discoveries made at SBI have opened new areas for understanding *Fusarium* diseases of sugarcane.

Sett rot

Sett rot (pineapple disease) is an important fungal disease caused by *Ceratocystis paradoxa* affecting the planted setts in different parts of the country. Occurrence of the disease was first recorded in 1906 by Butler (1906). Even now the disease occurs to varying severities in tropical states. Wherever planting coincides with monsoon season, the disease severity is high. There is a misconception in the country that the disease occurs only during germination phase, however, the author has found in many places that the pathogen attacks standing canes. Such infections are aggravated by lodging of canes and flooding, infection by red rot or wilt pathogens, insect damages, animal bites etc. Detailed works on this disease has been done at VSI, Pune by Patil (2002).

Bacterial diseases

Ratoon stunting (RSD), leaf scald (LSD), red stripe, gummosis and crown rot are the bacterial diseases reported in the country (Agnihotri, 1983). Leaf scald was first identified in 1961 at IARI, New Delhi (Egan, 1962) and its severe occurrence was found in a clone 71A100 at Anakapalle and caused devastating damages to sugarcane varieties in Coastal Andhra Pradesh (Satyanarayana, 1974). In Tamil Nadu, the disease caused huge losses to varieties such as CoC 90063 and CoSi 86071 (Viswanathan *et al.*, 1997b) (Fig. 5). Currently trace incidences of the disease occur in the subtropical region and Coastal AP. Red stripe was

Fig. 5. Leaf scald in CoC 90063

first reported by Desai (1938) and it continues to cause damages in variety like CoJ 85 in the subtropical region. Another bacterial disease, spindle (crown) rot with symptoms similar to top rot has been reported from Maharashtra. *Acidovorax*

avenae subsp. *avenae* was the suspected causative organism (Patil, 2000). RSD was first reported in the cv CoS 510 by Chilton in 1956 when he visited India as a delegate to attend IX ISSCT Congress at Golagokaranath, UP. Although RSD is known for years in the country, its severity is not felt due to ignorance about the symptoms and misconception that it does not affect production. Its severe impact to cane productivity was reported long back (Viswanathan, 2001) and its role in varietal degeneration along with YLD and mosaic has been demonstrated (Viswanathan, 2004, 2016) (Fig. 6). Gummosis was first noticed on the cvs Co 449 and Co 527 at Coimbatore (Rangaswami, 1960) and after that no such report was made (Table 1).

Grassy shoot

Other than the three major fungal diseases, this phytoplasma disease assumed greater significance

Fig. 6. Severe degeneration in sugarcane caused by RSD bacterium

in impacting cane cultivation during the last five decades. Presence of the disease was observed by Barber in 1919, however, Vasudeva (1955) has made detailed observations on GSD and studies during the 1950s in Belapur, Maharashtra. Its spread and damage to sugar industry were realized later (Agnihotri, 1983, 1996, Viswanathan, 2000). Its severity in the field has led to initiation of healthy seed nursery programmes and heat therapy as a strategy to manage this phytoplasma disease in both tropical and subtropical regions. Aerated stream treatment developed by SBI and moist hot air treatment by IISR become popular to manage GSD and RSD (Edison and Ramkrishnan, 1972, Srivastava *et al.*, 1977). This measure reduced the disease severity and sugar industry have given certain importance to nursery programmes. The disease has been associated with varietal degeneration and ratoon failures in many varieties when seed nursery programmes are not in vogue. Recently, the popular variety CoS 767 in Uttar Pradesh suffered seriously due to GSD and has been replaced by Co 0238 to a large extent. Currently GSD is one of the major diseases and causes cent percent losses in susceptible varieties in Uttar Pradesh, Maharashtra, Haryana and Tamil Nadu and hence is of great economic concern to both the farmers and sugar industry (Viswanathan, 2017b) (Table 2) (Fig. 7).

Fig. 7. Grassy shoot disease

The disease exhibits variable phenotypic symptoms of excess tillering with chlorotic, green or partly chlorotic leaves (Nasare *et al.*, 2007, Viswanathan and Padmanaban, 2008, Viswanathan *et al.*, 2011b). Molecular characterization of the phytoplasma associated with GSD has been established (Nasare *et al.*, 2007, Rao *et al.*, 2008). Further studies to characterize the phytoplasmas in the variable phenotypes did not reveal any genotypic variation (Viswanathan *et al.*, 2011b). We need further studies to characterize the phytoplasma genome and also to identify the vector(s) associated with its transmission in the field.

Viral diseases

Many viruses are known to infect sugarcane worldwide. Seriousness of the viral diseases became known after development of molecular diagnostics since that facilitated to discern many

Fig. 8a. Young leaves in the whorl exhibit typical mosaic symptoms.

Fig. 8b. Affected crop with severe symptoms of mosaic blotches.

of the disease symptoms which overlap with nutrient deficiencies. Mosaic of sugarcane was reported way back in 1921 in the country by Dr. C. A. Barber, still, its impact was not realized inspite of its significant role in varietal degeneration. Importance of viral diseases was felt after the report of yellow leaf disease (YLD) by the author in the new millennium (Viswanathan, 2002).

Mosaic disease

Symptoms of mosaic may vary in intensity with cultivar, growing conditions, temperature and strain of the virus. On older leaves, the symptoms tend to recover and appear as healthy. With more virulent strains, stunting, yellowing, chlorosis and sometimes necrosis are also noticed (**Fig. 8**). Hence, it was believed that mosaic does not cause yield reductions in sugarcane. However, systematic studies conducted at SBI, Coimbatore and IISR, Lucknow revealed that the disease affects yield and quality in sugarcane (Singh *et al.*, 2003, Viswanathan and Balamuralikrishnan, 2005). In the absence of precise diagnostic techniques, scientists relied on differential hosts to establish variability in virus strains and serological techniques for the diagnosis. Although serological assays were supportive in diagnosis, large scale cross reactions were ignored especially in members of *Potyviridae* infecting sugarcane

and related hosts. Earlier based on serology and differential host studies presence of strains of several *Sugarcane mosaic virus* (SCMV) and *Sorghum mosaic virus* (SrMV) were reported. However, this has caused much confusion in identifying the virus or virus strains. Meanwhile, Hema *et al.* (1999) reported cause of sugarcane mosaic by a new virus *Sugarcane streak mosaic virus* (SCSMV) not SCMV and SrMV as reported earlier. Hence, detailed studies were conducted to establish mosaic associated viruses in India at SBI and it was clearly established that sugarcane mosaic in India is caused by SCMV and SCSMV in combination or separately (Viswanathan *et al.*, 2007). Later, detailed molecular characterization of several SCMV and SCSMV isolates established variation in coat protein genome of the respective viruses for the first time in India. Occurrence of nine strains of SCMV in India was established (Viswanathan *et al.*, 2009a). Later, SCMV was characterized based on full genome of five isolates from India. SCSMV was characterized as a new genus "Susmovirus" in the family *Potyviridae* based on its distinct coat protein genome (Viswanathan *et al.*, 2008a) and workers from USA also accepted the proposed new genus (Fellers *et al.*, 2009, Xu *et al.*, 2010). Later ICTV, has renamed the genus as *Poacevirus* based on host range of the species in the genus. Recently complete nucleotide sequence of an SCSMV isolate from India, SCSMV-IND was determined. It is a linear single stranded positive sense RNA genome of 9786 nucleotides in length (excluding the Poly A tail) and it comprises a large open-reading frame encoding polyprotein of 3131 amino acid residues (Parameswari *et al.*, 2013).

Yellow leaf disease

The yellow leaf (syndrome) disease (YLD) caused by *Sugarcane yellow leaf virus* (SCYLV), is relatively a new disease in India. From SBI, the disease was reported for the first time during 1999 in the country (Viswanathan *et al.*, 1999). Subsequently, the author has made detailed report on the disease symptoms, spread, impact and diagnosis (Viswanathan, 2002). Unlike mosaic, the symptoms could be very clear after 5 to 6 months of crop growth. The characteristic yellowing symptoms may be confined to midrib region or the yellow discolouration spreads laterally to adjoining laminar region parallel to midrib, giving a sick look to the crop (Fig. 9). The severity of the disease to the crop is mainly due to extensive drying of foliage and premature death of leaves (Viswanathan 2012a). Earlier, the disease symptoms could have been ignored or associated with certain phenotypic characters or nutrient deficiencies. Also onset of the disease in the matured crop with foliage drying was probably attributed to crop ageing. The disease has emerged

Fig. 9. YLD affected crop shows typical symptoms of mid rib yellowing.

as a very serious disease in sugarcane in India and the author found its extensive occurrence across the varieties and regions (Fig. 10).

Fig. 10. Epidemic occurrence of YLD in Gujarat state.

It was found that combined infections of SCYLV and ratoon stunting bacterium in sugarcane cause severe stunting than their infection alone (Viswanathan 2004). The disease occurs in epidemic form on most of the cultivated varieties and it adversely affects cane productivity in the tropical region. The disease infection may result in 25-30 % loss to cane and juice yield in popular varieties (Viswanathan, 2012a,b). Recent assessment on impact of the virus infection on physiological parameters such as photosynthetic rate, stomatal conductance and SPAD meter values revealed significant reduction in these parameters in many sugarcane cultivars. Further, virus-infected crops recorded significant reductions in growth/yield parameters, such as stalk height, stalk thickness and number of internodes. Plant growth reductions were found to be 42.9, 42.3 and 38.9% in YLD-susceptible varieties CoPant 84211, Co 86032 and CoC 671, respectively. In addition to reductions in stalk weight, height and girth, YLD also reduced juice yield in the affected canes up to 34.15% (Viswanathan *et al.*, 2014c). Extensive damage to sugarcane productivity was recorded during the recent years after YLD epiphytotics in several states in the country; probably in the history of sugarcane cultivation no other disease would have caused such severe damage in the country. The popular variety of the millennium Co 86032 grown over one million ha suffered in almost all the states in the tropical region. Such scenario was due to multiplication of single variety in a short time without any care for seed health. Further, before this, no other variety was spread to such an extent in the region. The author has elaborately presented and discussed on the impact of YLD to sugarcane during the last 10 years (Viswanathan, 2008, 2011a,b, 2012b, 2013c,d, 2016). Although Coastal Andhra Pradesh had other varieties like CoA 92081, CoV 94101, CoV 09356 etc under cultivation, YLD severity on them was equally damaging as in the case of Co 86032. Hence cane cultivation has become less profitable for farmers and they shifted to rice, oil palm or other crops. Cane area has dropped significantly in many factory areas in the region mostly due to YLD. Similar damages due to YLD along with RSD and GSD was seen in case of CoS 767, a popular variety in Uttar Pradesh cultivated nearly in one million hectares and this led to its removal. The wonder cane of the subtropics Co 0238 has easily replaced its place and recently crossed one million ha area in the state (Table 1, 2). However, here also, unless healthy seed programme is followed strictly, similar damages to the new variety cannot be prevented.

Association of *Sugarcane yellow virus* (SCYLV) with YLD was conclusively proved after RT-PCR amplification of virus genome target and their sequencing. Detailed molecular characterization established occurrence of three genotypes of the virus including the genotype SCYLV-IND in India (Viswanathan *et al.*, 2008b). Later, complete genome of four isolates of SCYLV (5875 nt) was sequenced from India. Phylogenetic analyses established that all the isolates belong to the genotype SCYLV-IND and the genotype

reported from China CHNI shared a very close relationship with our genotype and they showed a separate lineage, probably of Asian genotypes. Phylogenetic analysis has confirmed the worldwide distribution of at least eight SCYLV genotypes (BRA, CHN1, CHN3, CUB, HAW, IND, PER, and REU). Evidence of recombination has been found in the SCYLV genome, which contains potential recombination signals in ORF1/2 and ORF5 (Chinnaraja *et al.*, 2013).

Apart from healthy seed nursery programme there is a need to exploit host resistance to manage the disease in sugarcane. Since there is lack of information on resistance to the disease in the germplasm and the parents, detailed studies were conducted at SBI to identify disease resistant sources. Initially, YLD screening with 0-5 grading system was developed and surveyed for YLD severity in ~4066 genotypes/ varieties maintained by the Institute at Coimbatore and its research centres, Agali, Kannur and Karnal (Viswanathan *et al.*, 2016c). The study identified 463 resistant sources in the hybrid clones and 773 in *Saccharum* spp in the germplasm. Probably, YLD resistance has been identified in such a large varietal collections and germplasm of sugarcane, for the first time. Further, the outcome of the study will lay foundation for developing YLD resistance in sugarcane progenies in the country.

Leaf fleck

During 1990s suspected occurrence of *Sugarcane bacilliform virus* (SCBV) was reported in *Saccharum officinarum* and other *Saccharum* spp clones in our germplasm. Though foliar symptoms indicated the suspected virus, it was not clear until confirmation by ISEM studies (Viswanathan *et al.*, 1996b). These studies gave authentic confirmation on SCBV infection in sugarcane from India. The virus exhibited enormous variation in symptoms on different genotypes of *Saccharum* spp, *Pennisetum* sp and cultivated varieties (Viswanathan and Premachandran, 1998). Subsequently, characterization of the virus was done based on complete genome at SBI. The virus isolates were demarcated into five different SCBV species and the viral genome ranged from 7553 to 7884 nucleotides in size. The Indian SCBV isolates share identities of 69-85% for the complete genomic sequence, indicating wide genetic diversity among them, and share 70-82% identity with *Sugarcane bacilliform Ireng Maleng virus* (SCBIMV) and *Sugarcane bacilliform Morocco Virus* (SCBMV), as well as 43-46% identity with *Banana streak virus* (BSV) and BSV-related SCBV species and this variation indicates the distinctness of Indian SCBV population. It is concluded that the symptoms associated with badnaviruses in sugarcane in India are caused by at least three new species, SCBBbV, SCBBoV and SCBBruV, besides SCBIMV and SCBMV represented by SCBV-BT and SCBV-Iscam, respectively (Karuppaiah *et al.*, 2013). The virus is closely related to *Banana streak virus* (BSV) and mealy bug *Saccharicoccus sacchari* transmits the virus in the field. The disease caused by SCBV was named recently as leaf fleck (freckle). The virus causes varying symptoms on the leaf lamina, starting from chlorotic specks followed by extended stripes, yellow and red mottles, extensive yellow/ reddish discoloration etc (Fig. 11). Although prevalence of the disease was reported earlier in the germplasm, recent studies convinced that it occurs rampantly in sugarcane fields (Viswanathan *et al.*, 2019). It is going to be an emerging threat to cane cultivation in the country and its impact to sugarcane productivity is to be assessed systematically.

Diagnostics for sugarcane pathogens

Rapid advancements in diagnostics in human and animal medicine led to development of many serological and molecular assay tools in the 1980s and 1990s. Scientists working on plant sciences

Fig. 11. Severe expression of leaf fleck in sugarcane cv CoC 24.

embraced the new tools to precisely detect and identify plant pathogens. In India, these diagnostics were applied at SBI from 1990s and that led to many landmark achievements in identifying new diseases and diagnosing non-fungal pathogens more effectively. Initially, serological assays were used to detect SCMV, SCYLV, GSD-phytoplasma and bacteria causing RSD and LSD (Viswanathan 1997a,b,c, 2001, 2002, Viswanathan and Ramesh Sundar, 2004). Dot-blot and tissue-blot assays were effective in diagnosing RSD bacterial infection in sugarcane (Fig. 12). Later RT-PCR assays were developed and used to detect the viruses associated with mosaic (Viswanathan *et al.*, 2007, Viswanathan and Karuppaiah, 2010). Since association of two viruses either alone or in combination in causing mosaic in sugarcane was established further studies were conducted to

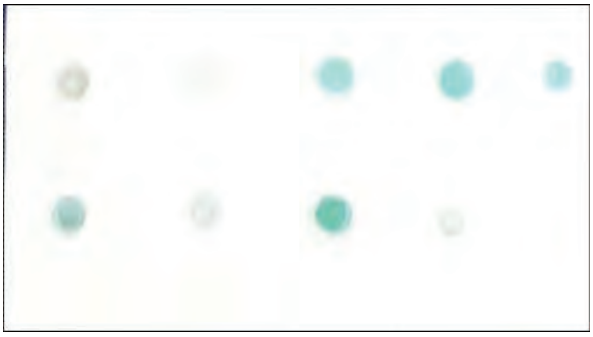

Fig. 12. Dot blot assay: blue dots are RSD positive.

detect the associated viruses in a single reaction. To optimize simultaneous detection of these viruses, a new set of primers were designed from the coat protein region of the viruses to suit duplex reverse transcription polymerase chain reaction (D-RT-PCR) and the conditions were standardized to amplify the target viruses in this assay (Viswanathan *et al.*, 2008c). D-RT-PCR assay was also developed to detect SCSMV and SCYLV in the same reaction (Fig. 13). RT-PCR assay with a target amplicon of 615 bp for SCYLV was developed (Viswanathan *et al.*, 2008b). Subsequently, a multiplex-RT-PCR was developed

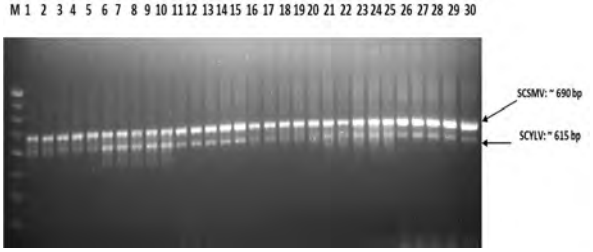

Fig. 13. Duplex-RT-PCR assay for SCYLV and SCSMV diagnosis

for the detection of SCMV, SCSMV and SCYLV, three of the major RNA viruses widely prevailing in the sugarcane growing regions around the world. In this assay, respective fragments of 860, 690 and 615 bp were specifically amplified (Viswanathan *et al.*, 2010).

RT-PCR assay is being routinely used to detect the virus in sugarcane clones or in tissue culture

seedlings. The efficiency of the diagnostic primers *viz*., SCYLV-615F and SCYLV-615R was validated by Viswanathan *et al.* (2009b) with a set of sugarcane samples collected before and after yellow leaf symptom expression. The RT-PCR assays established that almost all the samples were found to be infected with SCYLV and the diagnostic primers efficiently detected all the SCYLV population even in asymptomatic plants.

RT-PCR assays, though highly sensitive, they cannot be applied for diagnosing large-scale samples. Further, the assay costs are very high hence they cannot be applied to test field samples and only suitable for tissue culture plants. In this situation, serological assays are suitable and its assay cost is also moderate. To ease availability of high titre antisera for the viruses for serological assays, detailed studies were carried out to express the SCSMV coat protein (CP) gene in an expression vector along with maltose binding protein (MBP) as a fusion protein (Viswanathan *et al.*, 2011c). Later, polyclonal antisera were produced against recombinant SCSMVcp and the serum detected the recombinant MBP-SCSMV-CP fusion protein upto 1:40,000 dilutions in direct antigen coating (DAC)-ELISA and sensitivity of the antiserum were found to be as low as 2.5 ng in ELISA. The new r-antiserum was validated in DAC-ELISA for its efficacy with 349 leaf samples collected from 332 sugarcane varieties (Viswanathan *et al.*, 2013a). Earlier, Hema *et al.* (2001) reported DAS-ELISA and DAC-ELISA for the diagnosis of SCSMV in leaf extracts, sugarcane juice and partially purified virus. For the conventional RT-PCR, RNA extraction from sugarcane leaves is a cumbersome process. Hence, immunocapture (IC) using r-antiserum developed against SCSMV-CP to trap the virus before reverse transcription (RT) and optimized a duplex immunocapture (IC) –RT-PCR assay. The r-antiserum was found to be sensitive to detect both SCMV and SCSMV. This study established that r-antiserum developed against SCSMV-CP, trapped both SCSMV and SCMV in IC-RT-PCR and it was sensitive enough to detect the two viruses causing mosaic (Viswanathan *et al.*, 2013b). DAC-ELISA is simple and cost effective to diagnose these viruses, whereas in samples with very low virus titre, IC-RT-PCR would be more sensitive.

Usually many of the SCYLV-infected varieties do not exhibit disease symptoms and disease expression is influenced by virus titre and other factors including prevailing climate. Hence qRT-PCR assay by relative standard curve method was standardized to quantify SCYLV in meristem derived tissue culture raised *in vitro* plantlets and asymptomatic sugarcane plants. In this assay, copy number of virus population in *in vitro* plantlets and asymptomatic plants was estimated from 20,314.58 to 4,330.87 and from 8.96 to 0.27 million copy of viruses, respectively. Relative expression level of the virus between *in vitro* plantlets and asymptomatic plants was in the ratio of 38.2:188403.1 based on $2^{\wedge (-(\Delta\Delta Ct))}$ (Chinnaraja *et al.*, 2014). Additionally the assay established that meristem derived tissue culture significantly reduced SCYLV population in sugarcane.

ELISA and ISEM assays were helpful to detect SCBV suspected clones in sugarcane germplasm; however, genomic variation in the causative virus could not be brought out (Viswanathan *et al.*, 1996b, 1999, Viswanathan and Premachandran, 1998). Subsequent studies revealed that PCR was more sensitive than ELISA to detect SCBV in sugarcane (Balamuralikrishnan and Viswanathan, 2005). Recent studies conducted at SBI revealed that many of the cultivated varieties exhibit varying levels of the disease and virus infections are confirmed through PCR assays. Even the newly developed varieties also showed severe leaf fleck under field conditions (Viswanathan *et al.*, 2019).

Varietal degeneration

Systemic infections of non-fungal pathogens like SCMV, SCSMV, SCYLV, SCGS-phytoplasmas and ratoon stunting bacterium in sugarcane cause degeneration in many varieties (Viswanathan, 2012a,b, 2013c, 2016). Decline in varietal performance over the years is mainly due to the accumulated pathogens inside the stalk affecting cane growth and photosynthetic efficiency, which directly results in reduced cane yield and sugar yield (Fig. 14). Although these viral/ bacterial pathogens cause limited symptoms in the field, continuous vegetative propagation results in enhanced pathogen load that would increase the pathogenic potential to cause several disease. Combined infections of two or more viral/bacterial pathogens accelerates the damage to the crop in the field and this is due to infection of one pathogen makes the plant more susceptible to another. In this way, a variety degenerates faster and its yield potential comes down over the years. Author has witnessed such degeneration in a popular cv Co 419 in Karnataka state due its high susceptibility to mosaic, YLD and RSD. Similarly, the cv CoC 671, another popular variety of tropical region degenerated due its high susceptibility to mosaic and YLD in different parts of Karnataka and Maharashtra. Degeneration of the cvs CoC 671 and Co 740 other popular varieties in the region for more than four decades was demonstrated by comparing mosaic free and affected seed canes (Viswanathan and Balamuralikrishnan, 2005). The cv Co 86032 was able to replace in large areas in these states due to degeneration of the cv CoC 671. However, recently the cv 86032 also showed decline in performance due to very poor seed nursery programme in many sugar factories in the tropical region. Similarly degeneration due to mosaic in the subtropical region was reported in three popular varieties (Singh *et al.*, 2003). Varietal degeneration caused by RSD, YLD, GSD and mosaic pathogens in the subtropical region especially in Uttar Pradesh led to withdrawal of the popular variety CoS 767 from cultivation and its replacement by the wonder variety Co 0238. Further, in Andhra Pradesh also varietal degeneration mostly due to YLD, affected cane productivity in many popular varieties in the recent years (Viswanathan, unpublished). Healthy seed nursery programme sustained vigour of the varieties under cultivation in the past decades and ignorance of seed health has led to degeneration of most of the varieties in the country hence many of the promising varieties could not be sustained in the field. Further, least attention given by the scientists and the industry on YLD in sugarcane also led to buildup of disease epiphytotics.

Fig. 14. Degeneration in sugarcane cv Co 86032 due to SCYLV: virus infected canes show poor growth with reduced cane growth and leaves (right) as compared to luxuriant growth of virus-free canes (left).

Disease outbreaks and scenario

In the recent years, apart from red rot, smut and wilt, the country witnessed serious epidemics of YLD, GSD, rust, pokkah boeng (PB) and brown spot in different regions. Among them, epidemics of YLD are very common for the last two decades. The emergence of rust, brown spot and PB is attributed to possible climate change scenarios and deployment of new varieties that are susceptible. Further, promotion of certain varieties favoured buildup of specific diseases e.g. brown rust became a serious disease in Maharashtra and Karnataka due to large-scale cultivation of the cv CoM 0265. Severe devastation to cane cultivation was recorded in the Southern Maharashtra especially in the Kolhapur region due to brown spot. In the history, we never had such a severe outbreak of brown spot and it is because of this variety which is highly susceptible to the disease. This clearly evidences a disease never attains epidemic level till it finds a susceptible host. As explained by Van der Plank (1963), the susceptibility of the host is an important factor in disease spread. Unlike other stalk diseases brown spot being a foliar disease, easily spreads to larger tracts in these states. Similarly rust epidemics were common in different decades and the disease has been managed by withdrawing the susceptible varieties. The author has witnessed serious rust epidemics in Maharashtra, Karnataka, Andhra Pradesh and Tamil Nadu. Recently, brown rust devastated the cv CoVc 03165 in Southern Karnataka and the variety was withdrawn from cultivation. Similarly another variety Co 0323 also suffered severely due to rust during 2015-16 in the region. The variety Co 0218 released for cultivation by CVRC could not be popularized due to its susceptibility to rust. Still, Karnataka, Maharashtra and Andhra Pradesh states remain endemic to rust and severe disease outbreaks are noticed during monsoon and post-monsoon months.

During the last 10 years pokkah boeng has become a serious disease in different parts of the country and many varieties succumbed to the disease in different years. Though it was considered as a minor disease, the recent incidences portray its negative impact to cane productivity. Many varieties like Co 99004, Co 0238, CoVSI 9805 etc suffered in the field due to their susceptibility to PB. Many elite varieties were withdrawn in specific regions due to their susceptibility to this foliar disease. Recently, severe outbreak of PB was found in National Hybridization Garden (NHG) of the Institute which houses more than 600 sugarcane parental clones of diverse origin for the national sugarcane varietal development programme. In the milieu, it was found that apart from independent occurrences of PB and wilt in different parental clones, some genotypes were affected by both the diseases (Viswanathan *et al.*, 2014b). Earlier, Viswanathan (2013b) recorded wilt in sugarcane after PB occurrences and he opined that the same pathogen might cause both the diseases in sugarcane. Later, detailed studies were conducted to characterize Fusariums associated with wilt and PB in sugarcane to establish whether the same *Fusarium* causes both the diseases or not using conventional and molecular tools. The study established that under Indian scenario, *F. sacchari* is the major causative agent of both wilt and PB and the same pathogen causes the two diseases in a sugarcane plant for the first time. Perhaps *F. proliferatum* also causes these diseases to a limited extent however it's role like *F. sacchari* in pathogenicity of wilt and PB is to be established (Viswanathan *et al.*, is 2017b). Further, occurrence of stalk rot caused by *Phaeocytostroma sacchari* in sugarcane germplasm and in cultivated varieties was reported for the first time from SBI (Viswanathan *et al.*, 2003c). This disease is a stress associated one affecting matured stalks and probably many other pathogens may also be involved in death of stalks

in stressed environment. To address these disease constraints, efforts were made to screen sugarcane varieties for YLD, rust and PB under AICRP on sugarcane. A 0-5 rating has been included in the programme to identify YLD resistance in the varieties and a whorl method of inoculation has been standardized for rust screening.

Recent developments in disease management

Adoption of disease resistant varieties is still considered as the best option to manage the diseases in sugarcane in the past. This is considered as environmentally safe and economically feasible. However, the major challenge is that an elite variety does not possess resistance to all the designated diseases. Hence, alternate disease management strategies were developed and being implemented successfully in the country. Seed nursery programme combined with heat treatment has been successful to manage GSD and RSD. However, the present recommendation of seed nursery programme has tissue culture-combined with molecular diagnosis for viruses/ phytoplasma and it is highly beneficial to address all the non-fungal diseases in sugarcane including the dreaded YLD. By following this approach an yield of 250 tonnes/ha is recently achieved in the popular cv Co 86032 in Erode district in Tamil Nadu. Earlier fungicides were not recommended in sugarcane due to lack of efficient delivery methods. Recently, SBI has developed an efficient fungicide delivery through sett treatment device (Fig. 15) in colloboration with ICAR-CIAE. Such improved fungicide delivery through planting materials has prevented disease development from primary sources of red rot and smut inocula (Malathi *et al.*, 2017, Viswanathan *et al.*, 2016d, 2017c). Biocontrol approaches were also effective in managing red rot, wilt and other fungal diseases (Malathi *et al.*, 2008, Viswanathan and Samiyappan, 2002, 2008, Viswanathan *et al.*, 2012).

In the recent years, molecular tools have been applied in sugarcane pathology to characterize the pathogen and to understand host-pathogen interactions. Complete genomes of important viruses such as SCYLV, SCMV, SCSMV, and SCBV were characterized from India (Viswanathan *et al.* 2018b). Prevalence of new variants, genotypes, species and genera in sugarcane viruses in India was reported. A new understanding has been established on host resistance in sugarcane to red rot and smut by using genomic, proteomic and transcriptomic tools. Complete genome and transcriptome of red rot pathogen were sequenced and studies are in progress to identify key pathogenicity genes.

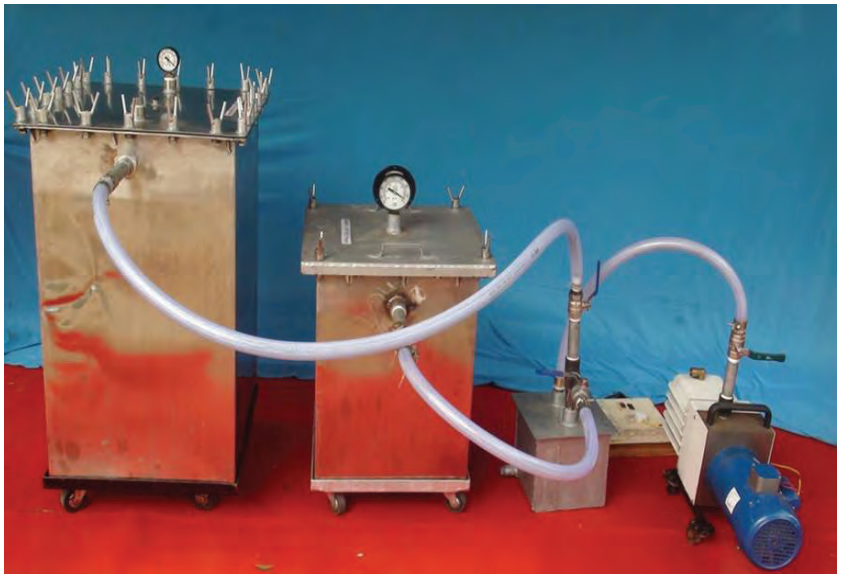

Fig. 15. Sett treatment device.

Epilogue

If we look back the 100 years of research in sugarcane pathology, concerted efforts were made to identify resistance in germplasm and varieties to important diseases and to develop

appropriate screening methodologies. This has benefited in sustainable sugarcane cultivation in the country. Diseases outbreaks were investigated in detail and new disease threats were tackled in time. The scientific community has been benefited by the new understanding on host resistance, pathogen variation, and diagnostics. The sugar industry is benefited from the heat therapy and virus-indexing service of the Institute to produce healthy planting material and sustain cane yield potential in commercial varieties. Adoption of the healthy nursery programme resulted in huge benefits in the field, especially in the peninsular region. Further, mechanized delivery of fungicides through sett treatment device is a new development to address fungal disease problems in sugarcane. In the recent years, various omic tools are applied in sugarcane pathology and it would immensely benefit sugarcane disease management through genetic engineering approaches.

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