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Red rot disease in sugarcane: Challenges and prospects

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Abstract : Red rot disease of sugarcane caused by *Colletotrichum falcatum* Went is the major constraint for sugarcane production in different regions in India and other countries. The pathogen affects the economically valuable stalk tissues leading to crop loss and impaired juice quality. Several epidemics of the disease have resulted in the failure of important commercial varieties in the past. The epiphytotic nature of the disease was noticed in the subtropical regions of the country till 1970s and later such epidemics occur in the tropical region also. Primary infection occurs through dormant infections in infected seed canes and secondary infections occur through water/air borne pathogen inoculum. Disease resistant varieties are being recommended to manage the disease under field conditions. However, development of new pathogen variants causes breakdown of resistant varieties in the field. Selection of red rot resistance in sugarcane progenies became a difficult task due to the existence of higher levels of pathogenic variability. Although breeding programmes yield many resistant clones inheritance of red rot resistance is not known due to genetic complexities in the host. Similarly resistant mechanisms governing disease resistance in sugarcane is not clearly elucidated. Recent studies have indicated possible involvement of certain pathogenesis-related proteins, oxidative enzymes and anthocyanin compounds in red rot resistance. Fungicides are not effective in eliminating disease infections in the setts. An integrated approach for the management of the disease under field condition has been envisaged time to time. Among the different approaches, going for disease resistant varieties and healthy seed for planting give success in the field. ***(Key words : Sugarcane; Red rot disease; Integrated management)***

The red rot disease was first reported to the scientific community from Java (now Indonesia) in 1893 by Went (Went, 1893) and later from India by Barber (1901). However, earlier Buddhist literatures have the mention about the presence of the disease in that time itself (Deerr, 1949; Daniels and Daniels, 1976). First large scale destruction of the cane by the disease was noticed in Godavari delta of then Madras Presidency on the cultivar Red Mauritius during 1895 to 1899 (Barber, 1901). Butler (1906) studied in detail of the pathogen and its portals of entry into cane stalks. The disease caused severe losses to the farmers but resulted in the initiation of search for disease resistant varieties and ultimately led to the establishment of the Sugarcane Breeding Institute (SBI) at Coimbatore in 1912 presently under ICAR control. Later many interspecific hybrids were developed at SBI and it became a success stroy for the management of red rot disease in the field. In 1957, Sugarcane Research Station at Cuddalore was established for evolving red rot resistant cane varieties which is under the control of TNAU since 1971.

Epidemics of the disease have been very common ever since its occurrence in India. It was involved in the failure of important commercial varieties like Co 312 (1939-40, Terai region); Co 312, Co 453, BO 11, BO 17 and BO 54 (1946-47, Punjab and Terai region); BO 10 and BO 11 (1964-65, Uttar Pradesh); Co 997, CoS 562 and BO 3 (1968-69, Uttar Pradesh); Co 419 and Co 658 (1970-72, Andhra Pradesh, Pondicherry and Tamil Nadu); CoC 671 (1981-82, Andhra Pradesh); Co 997, Co 785 and Co 419 (1982-84, Kerala); CoC 671 (1986-92, Tamil Nadu and Gujarat) and CoC 92061 (1992-98, Tamil Nadu and Pondicherry). The epiphytotic nature of the disease was noticed in the subtropical regions of the country till 1970s and later the pathogen got a foothold in the tropical regions and is presently in a devastating form in many parts of the Peninsular India particularly in South Gujarat and Tamil Nadu. Though Maharastra and Karnataka states were reported to be free from the disease (Alexander and Viswanathan, 1996), recent reports say extensive damage is being noticed in Northern Karnataka (Yadahalli and Kumbar, 1998) and Kolhapur regions of Maharastra (Viswanathan, Personal Communication). Several important varieties like Co 312, Co 419, Co 453, Co 658, Co 997, Co 1148, Co 6304, CoS 562, CoS 687, CoC 671, CoC 85061, CoC 86062, CoC 92061, CoC 98061, CoC 99061, BO 11, BO 17 and BO 54 have been removed from the field due to their high susceptibility to the disease. At present severe outbreaks of the disease is noticed in entire state of Tamil Nadu and detailed studies showed that the pathogen has acquired greater virulence in the state (Viswanathan *et al.* 1997a). Such outbreaks have also been noticed in Coastal

Andhra Pradesh, Pondicherry and Orrisa. As of now the disease has distribution throughout the country with varying intensities.

Red rot menace in Tamil Nadu

The disease was first reported from the state on the cultivar Co 658 during 1972 at Nellikuppam areas. Later it was also noticed on Co 419, Co 527 and Co 6304 in a limited scale of which Co 658 was finally wiped out of cultivation due to red rot. The disease epiphytotic situation prevailed till the end of 1976 and disease had a recurrence in 1986 (Alexander and Viswanathan, 1994). The epidemics in late 1980s occurred on the cultivars like CoC 671, CoC 8001, CoC 85061 and CoC 86062 in South Arcot district. Later, the disease had spread to different sugar factories in Tamil Nadu. Epidemics in the 1990s showed severe disease incidence on the new cultivars like CoC 90063, CoC 91061 and CoC 92061 and CoSi 86071 (Viswanathan *et al.* 1997a). At present Tamil Nadu state and adjoining Pondicherry areas are witnessing a critical state of epidemics in the history of red rot in India. In many fields in sugar factory areas 100% crop loss and abandoning of sugarcane cultivation were noticed. The recent red rot epidemic in Dharapuram, Palani and Udumalpet areas in the western parts of the state shows the disease can cause severe loss to the crop even in the isolated pockets and upland crop.

Pathogen and its variation

The fungus *Colletotrichum falcatum* Went (Perfect state; *Glomerella tucumanensis* (Speg) Arx & Muller) is the causative organism. In general only imperfect state of the pathogen is being found associated with the disease. Occurrence of perfect stage is rare in nature. Carvajal and Edgerton (1944) first reported sexual stage of the fungus in USA. In India, the occurrence of the sexual stage was demonstrated in culture medium (Chona and Srivastava, 1952). It was also observed on leaf lamina, midribs and leaf sheaths of dry foliage in nature (Chona and Bajaj, 1953; Misra, 1957). So far, occurrence of perfect stage was not recorded from tropical parts of the country.

Since *C. falcatum* is a facultative parasite, which keeps on mutating in nature new races of the pathogen are evolved frequently. Edgerton and Moreland (1920) in USA first demonstrated physiologic specialization in this fungus. Under field conditions occurrence of new pathogenic strains of the fungus has been reported from time to time. Development of new pathogen variants is the major reason for the breakdown of resistant varieties under field conditions. So far, researchers are not able to identify the exact mechanism by which new variation occurs in the pathogen. But they were able to create variation in the pathogen by mutation (Bajaj and Chatrath, 1960; Bajaj and Dhanraj, 1960) and heterokaryosis (Singh and Payak, 1968; Carvalho, 1968). These mutants were not stable and did not have any impact on pathogenicity. Adaptation of the pathogen to the newer sugarcane varieties is considered as a major cause for the development of newer pathotypes / races. Srinivasan (1965) observed that isolates of the red rot pathogen are often unstable in their pathogenicity and have a tendency to pass irreversibly into an avirulent phase, which may be cause for the elimination of many existing pathotypes. When a particular variety is withdrawn the pathotypes adapt to newer varieties which are being introduced to the field to replace the susceptible varieties. Here the pathogen slowly adapts to new cytoplasm of the host or becomes tolerant to host resistance. So, the new pathotype becomes compatible with the host.

Differential interaction of the pathotypes collected from different cultivated varieties exhibited clear variation in their virulence on different host cultivars. Variation in virulence of the pathotypes was reported after the red rot epidemic in the subtropical India (Rafay, 1950; Singh 1957; Chona and Srivastava, 1960). Srinivasan (1962) reported that light coloured isolates of the pathogen were highly virulent and were generally prevalent in the red rot epiphytotic areas of subtropical India. Dark coloured poorly sporulating and less virulent isolates were in tropical India, which are relatively free of red rot epidemics. However, since 1970s frequent and severe epiphytotic of red rot in peninsular India showed prevalence of highly virulent pathotypes (Padmanaban *et al.* 1996; Viswanathan *et al.* 1997a). Existence of pathogen variability in the subtropical region in 1980s was reported by Beniwal *et al.* (1989).

Recently detailed studies on the differential interaction of sugarcane genotypes to different pathotypes of the pathogen collected from all over India was done at SBI. The studies showed existence of clear cut variation among the pathotypes. In general pathotypes from tropical regions were more virulent than the subtropical ones. The pathotype isolated from the variety CoC 671 was found to be most virulent among all the pathotypes (Padmanabhan *et al.* 1996; Viswanathan *et al.* 1997a). The acquisition of higher virulence and dominance of the pathotype may be due to the extensive cultivation of the highly susceptible variety over large areas. Moreover, since its second appearance in 1986 no systematic integrated approach for control of red rot had ever been launched in Tamil Nadu. This situation depicts the adaptation of the pathogen to the host genotypes. In the past few years CoC 671 was replaced with another variety CoC 92061 in different parts of Tamil Nadu state which was also susceptible and resulted in higher virulence of the pathogen being maintained throughout the state.

Biochemical changes in the red rot infected canes

The pathogen affects the economically valuable stalk tissues, even a limited infection can bring about drastic changes in the juice quality. The disease affected cane gives poor sugar recovery because impaired sucrose metabolism. The red rot infection reduced total carbohydrates in the diseased canes and the reduction is more in highly susceptible varieties (Agnihotri *et al.* 1989). Moreover, the pathogen produces abundant quantities of acid invertases, which break the sucrose into glucose and fructose which are consumed by the pathogen. Higher production of acid invertases was noticed upon pathogen infection in the highly susceptible varieties as compared to resistant varieties (De Silva *et al.* 1977). Pathogen infection also results in increased levels of total soluble salts, acidity, reducing sugars and gum and simultaneously decrease in pH, sucrose and purity of cane juice (Singh and Waraitch, 1977). Increased activity of the enzyme invertase or inhibition of normal synthesis of carbohydrates and / or the inhibition to the utilization of these as a substrate by the pathogen is indicated by degradation of sucrose and increase in the levels of reducing sugars. Similarly, our studies have revealed that pathogen infection has drastically reduced Brix, sucrose percentage, purity and CCS per cent in the diseased canes. The affected canes recorded 25 to 75 % reduced sucrose content than the healthy canes (Viswanathan and Samiyappan, 1999a).

Nature of resistance in sugarcane to red rot

Exact mechanism governing the resistance has not been understood clearly. But two kinds of resistance have been recorded, one morphological, which prevents and/or retards the infection and development of the pathogen in the host and biochemical and physiological where, the living cells of the host plant suppress or prevent development of the pathogen. Morphological resistance refers to the thickness of the cuticle, epidermis, rind, bud scales, relative abundance of vascular bundles under the rind and the presence of septa in the vascular bundles thus preventing the rapid migration of conidia (Edgerton, 1959). In general, it was observed that large number of continuous vessels throughout the nodes was prone for more pathogen development than in a clone with many discontinuous vessels. But features governing the morphological resistance in many of the disease resistance varieties have not been brought out.

Biochemical resistance

Different biochemical features that impart resistance in a particular genotype have been reported. In resistant varieties, a brown gummy substance is formed in response to infection. This process takes place in advance of infection and seals off further spread of the pathogen in adjoining tissues (Edgerton, 1950 ; Srinivasan and Bhat, 1961). Gum formation may also takes place in susceptible varieties, but to a lesser extent and usually after the tissue has been invaded. Srinivasan and Bhat (1961) termed this as hypersensitive gummy reaction.

Earlier studies have reported about the role of phenolic compounds in red rot resistance. Higher quantities of phenols in resistant and moderately resistant varieties were reported by some workers (Rao *et al.* 1968; Wilson and Srivastava, 1970). However, later studies revealed that there was no correlation between total phenolic content and degree of resistance to red rot (Singh *et al.* 1976 ; Godshall and Lonergan, 1987). These workers have found that in resistant varieties the level of total phenols increased after infection and it was maintained, while in susceptible varieties, the level of phenolic content dropped after an initial increase.

Number of host enzyme like peroxidase (PO), polyphenol oxidase (PPO), phenylalanine ammonia lyase (PAL) and tyrosine ammonia lyase (TAL) were reported to be associated with resistance in many sugarcane varieties. Srivastava and Soloman (1990) found higher levels of peroxidase and PPO in disease resistant mutants. Earlier, Srinivasan (1969) found a correlation between oxidative enzymes and disease resistance in sugarcane. Detailed studies on PO levels in sugarcane varieties varying in red rot resistance revealed that resistant varieties like BO 91 and CoS 767 have multifolds of this enzyme as compared to the susceptible varieties like CoC 671 and CoC 86062 (Viswanathan *et al.* 1996a). High activity of PAL and TAL was invariably found associated with the varieties resistant to red rot (Madan *et al.* 1991). All these studies have been done with tissues from intact cane tissues. Recently studies have been conducted to assess the role of these defence enzyme at cellular levels. Results of the study showed that calli from a resistant variety BO 91 recorded very high levels of PO, PAL and TAL than the calli cells of CoC 671. The pathogen toxin treatment elicited significantly higher levels of peroxidase in the callus tissue of BO 91 than in CoC 671. Induction of the defence enzymes was rapid in resistant cells. Among the enzymes induction of PAL, TAL and PPO was not rapid as that of PO upon pathogen toxin treatment. Further studies on electrolyte leakage revealed that a more pronounced loss of electrolytes in the callus cells of CoC 671 than in BO 91 (Ramesh Sundar *et al,* 1997; 1998; 1999; Ramesh Sunder and Viswanathan, 1997).

In disease infected cane stalks, a red substance is released in cells and intercellular spaces near invading hyphae. The resistance of the genotype is correlated with the intensity of pigment production (Edgerton and Carvajal, 1944). Fractionation of red rot pigment (RRP) showed several compounds (Godshall and Lonergan, 1987; Viswanathan *et al,* 1996b). The RRPs from resistant cane tissues showed seven compounds, of them three were missing in the susceptible variety (Viswanathan *et al.* 1996b). Further fractionation of the pigments by HPLC revealed the presence of 3-deoxyanthocyanidin compounds. These compounds were identified as luteolinidin, apigeninidin and coffeic acid ester of 5-o-apigeninidin (Viswanathan *et al.* 1996c; d). These three compounds were identified as phytoelexins in sorghum and *C. graminicola* interaction (Snyder *et al.* 1991). Work done on 3-deoxyanthocyanidin reveals such phytoalexins in sugarcane and red rot interaction. These findings clearly demonstrated that the phytoalexins were accumulated only in incompatible host pathogen interactions and compatible interactions had no such phytoalexins or with trace quantities. Partially purified pathogen toxin induced very high levels of phytoalexins in resistant variety than in a susceptible variety (Viswanathan *et al.* 1996d 2000).

Earlier studies of Brinkler and Siegler (1993) reported a piceatannol compound as sugarcane phytoalexins and may govern red rot resistance in sugarcane. Though previous studies have been unsucessful in pinpointing biochemical basis of disease resistance, recent studies have shown the role of some oxidative enzymes and phytoalexins in red rot resistance (Ramesh Sundar and Viswanathan, 1997). Recent studies by the authors revealed that chitinase and β-1, 3-glucanase, the pathogenesis related protiens have definite role in red rot resistance. Here also resistant varieties accumulate higher quantities of the enzymes than the susceptible varieties (Viswanathan and Samiyappan, 1999a & b). Studies of Ramesh Sunder (Unpublished) conducted at cellular level also revealsed similar findings. This area work is highly rewarding one, since isolation of chitinase / β-1, 3-glucanase gene(s) from the sugarcane would lead to development of transgenic sugarcane against the dreaded pathogen in due course.

Evaluation of resistance

Since resistance screening for red rot forms an integral part of sugarcane varietal development, several resistance evaluation methods to red rot were developed from time to time. Among the different methods, plug method was first standardized by Chona (1954) based on the average linear spread of the pathogen symptom in the stalk. Later Srinivasan and Bhat (1961) modified the earlier method by increasing four characters, *viz.,* nodal transgression, lesion width, occurrence and nature of white spot and drying of tops for assessing the resistance. This method of evaluation is now uniformly used in India and varieties are rated on a 0-9 ISSCT grading system. Prasada Rao *et al.* (1978) developed a mathematical model of discriminate function for grading varieties for resistance. Since inoculum is introduced into the stalk through a borehole in the plug method scientists felt that natural barriers of the host being by-passed here. To test the real resistance potential of the host another method referred as nodal method was developed. Here the inoculum is applied into the gap between leafsheath and the stalk of the third to fourth leaf position from the top and the pathogen is allowed to enter into the stalk on its own. Thus this method of resistance evaluation can be called as natural way of testing (Singh and Budhraja, 1964; Rana and Gupta, 1968). But here large amount of disease escape was noticed which is mostly attributed to the environmental conditions. Recently Mohanraj *et al.* (1997) have developed a new system of evaluating red rot resistance based on a 0-9 scale under controlled conditions. This method was developed to rectify the shortfalls in the previous systems of evaluations. Viswanathan *et al.* (1998a) compared all the three different systems of evaluations and they found nodal system allows large number of disease escapes. Resistance evaluated by the of other two methods showed good correlation. They concluded that for initial screening of large number of breeding stocks and germplasm the new method is most suitable and plug method can be used later to evaluate the varieties under field conditions.

Epidemiology

The pathogen inoculum survives in the soil in the form of thick-walled mycelium, appressoria, setae, chlamydospores and conidia in the soil. But opinion about the survival period in soil varies among the scientists. Occurrence of red rot from the soil is generally associated with the persistence of inoculum through these resting structures in the debris in the soil. These resting structures of *C. falcatum* like appressoria, chlamydospores and thick walled mycelium are tolerant to adverse soil conditions and can survive for longer periods.

Survival of the pathogen in the absence of the host is influenced by various environmental conditions which may affect the saprophytic ability as also formation of resting structures by *C. falcatum.* Experiences of various workers reveal that cane varieties easily succumb to the pathogen under water logged conditions and even a resistant variety can not stand well against the onslaught of the pathogen. Different hypotheses were put forwarded to explain the varietal breakdown of resistant variety under waterlogged condition. Predisposition of the host to the infection under water logged condition was considered as a major reason for the disease build up in the canes (Singh and Lal, 1987). Maximum viability of the inoculum under damp soil was observed when infected debris was used as compared to conidia. Duttamajumder *et al.* (1990) found that water logged conditions favour fusion of conidia in *C. falcatum,* and this may be one of the major factors responsible for the quick development of virulence of the pathogen and thereby high susceptibility of sugarcane varieties under waterlogged situations. The fungal conidia, acervuli or other structures float on the water and come in contact with the nodal region. This situation is highly favourable for initiating conidial germination and infection.

Infective propagules like conidia, appressoria, chlamydospores, setae or thick-walled hyphae produced on stubble or decaying canes in soil cause infection after planting. Infected planting materials serve as major source of inoculum for the annual recurrence of red rot disease in endemic areas. Planting of infected setts has completely affected germination in the cultivar CoC 671 (Viswanathan, Unpublished). The setts may carry internal or external or both types of the pathogen propagules. Often the thick-walled swollen and short celled hyphae and appressoria act as dormant infective structures. The fungus can grow into the nodal and adjoining internodal tissues of the stalk and dormant infections are produced. These dormant infections are mainly responsible for spreading the disease because such infections are difficult to be detected by naked eyes.

Conidia produced on the infected plant or dried clumps due to the pathogen attack in early stages of growth cause secondary infection. Here the inoculum is disseminated by irrigation or rainwater and comes in contact with the lower nodal portion of the standing canes. Conidia carried by the wind also responsible for secondary spread of the pathogen. The conidial deposition on the spindle or leaves, cause aerial infection. In this situation the pathogen moves to bottom internodes from the top. Typical top drying with prominent midrib lesions and lower normal canes are the characteristic symptoms of such air-borne infection. The senior author has noticed these aerial infections on CoC 671, CoC 90063, Co 6304 and CoC 92061 in many sugar factory areas of Tamil Nadu.

Management of the disease

An integrated approach for the management of the disease under field conditions has been envisaged time to time. Among the different approaches, going for disease resistant varieties and healthy seed for planting gave success in the field (Viswanathan and Alexander, 1997 ; Viswanathan and Samiyappan, 1999a)

Breeding for disease resistance

In the early decades of this century breeding programmes in India were aimed at identifying varieties for subtropical India, to replace poor yielding Indian sugarcane *Saccharum barberi.* The breeding and selection process gave emphasis to adaptability, yield and quality improvement and resistance to red rot disease utilizing *S. officinarum*, *S. bareri* and the wild species *S. spontaneum.* The result was the release of outstanding varieties from SBI which were high yielding and tolerant to the major disease, *viz.,* red rot. But recurrent outbreaks of red rot in epidemic forms resulted in the replacement of varieties which succumbed to this disease. The evolution of new races of the pathogen is the major factor for the breakdown of resistance to the changing fungal race flora and which is considered as another major factor for the breakdown of the new varieties in shorter life span.

Extensive studies on sources of resistance have been carried out at SBI (Srinivasan and Alexander, 1971; Alexander and Rao, 1976; Alexander *et al.* 1983; 1985). These studies indicated that *S. spontaneun* has a large number of clones with red rot resistance. In *S. officinarum,* resistance sources were found to be low. Resistance in *S. barberi, S. sinense* and *S. robustum* to red rot is low although resistance in *S. barberi* is better than the other two species. Sugarcane is highly heterozygous and complex polyploid with meiotic irregularities. Thus information on inheritance of red rot resistance is practically lacking. Studies on the inheritance of red rot resistance have shown indiscriminate distribution of resistance or susceptibility among the progenies (Chona, 1980). Even a cross be between two susceptible varieties has given some resistant seedlings and vice-versa. Thus, it is essential to know mycelium are tolerant to adverse soil conditions and can survive for longer periods.

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Breeding for red rot resistance has been carried out at Coimbatore, Pusa and Shajahanpur. Recently other stations in North Indian sugarcane belt have also taken up work on breeding for red rot resistance. Biparental crossing involving a resistant parent is used for obtaining desired resistance in the progeny. A directed breeding programme to evolve varieties with broad spectrum of resistance against two or more major pathotypes of the pathogen was initiated by Alexander *et al.* (1979) at SBI and the programme yielded many resistant progenies to multiple pathotypes. Resistance to the pathogen was identified in the commercial and near commercial clones, interspecific hybrids and basic species in the sugarcane germplasm collection (Sreenivasan, 1995). Utilizing the resistant colones, many resistant varieties have been developed (Alexander and Viswanathan, 1994; Viswanathan and Rao 1996).

Healthy planting materials

Infected planting materials are responsible for the primary spread of the disease in the field. Hence, going for the disease-free setts would reduce the risk of disease introduction to disease free areas. As already reported the dormant infections of the pathogen are very difficult to identify under field conditions, therefore, disease escape can occur. So, improved techniques are essential to diagnose such dormant infections. Viswanathan *et al.* (1997b), reported use of an indirect-ELISA technique for the detection of the pathogen utilizing the serum produced against the mycelial protein of the fungus. Later the technique was improved by producing polyclonal antiserum against 101kDa polypeptide of the fungal mycelium witch is common to all the 13 pathotypes of *C. falcatum* and absent in *C. lindemuthianum* isolate. This has resulted in more specific detection of the red rot pathogen in the host irrespective of the pathogen strain infected. These studies also found the suitability of dot-blot and Western blot in the detection, in addition to ELISA (Viswanathan and Samiyappan, 1997a; Viswanathan *et al.* 1998b). All these studies proved that the host tissues like buds, root eyes, growth ring and white spot regions had more fungal loads. This findings also corroborate with the earlier report of dormant infection in the host tissues (Srinivasan and Alexander, 1965). These improved techniques would help to monitor the supply of disease-free seed materials to sugar factories in the coming years.

Other management practices

Different agronomical approaches like burning of infected trashes, crop rotation and drainage in the field and avoiding ratoons if the plant crop had red rot infection are recommended to farmers. These practices if followed in the epidemic locations it would help in reducing the pathogen survival in the field. But most of the practices are in paper and implementation is needed to benefit the farming community.

By and large, fungitoxicants are not effective in eliminating infections of the red rot pathogen in setts when dipped for a definite period. Studies of Rao and Satyanarayana (1995) revealed that none of the systemic fungicides like benomyl, carbendazim, triforine, chlobenthiozone, triadimefon, carboxin and thiophanate methyl offer complete control of the disease, when naturally infected two or three budded setts were treated. But reduction in disease incidence was observed with carbendazim and triadimefon when single bud setts were soaked for 24hours. Hot water treatment alone or in combination with carbendazim (0.1%) completely eliminated infection of red rot in single budded setts. Single budded setts are not recommended for large scale field planting hence, this finding will have only limited field application. Three possible reasons were considered for the failure of fungicides to give satisfactory control of the disease in seed pieces *viz.*, 1. Impervious nature of the rind, 2. The presence of fibrous nodes at the cut ends inhibiting movement of chemicals and 3. Lack of effective water soluble systemic fungicides.

Thermotherapy as a measure to eliminate other sugarcane pathogens was successful in different countries. Scientists have made attempts to sandardize thermotherapy treatments for the management of red rot disease. Though there were few reports of elimination of pathogen infection by thermotherapy, most of the studies indicated that such treatments were ineffective in eliminating the red rot infection in the setts (Edgerton *et al.* 1942; Srinivasan, 1971). There is also a report on combination of fungicide bavistin (0.1%) and hot water treatment to give complete control of the disease, when single budded setts were used (Rao and Satyanarayana, 1995). The divergent results obtained by various workers working on thermotherapy may be due to the type and depth of pathogen infection in the setts, varietal characters and state of cane maturity. Like chemical control methods, use of thermotherapy practices have not been successful under field conditions.

It is well known that the pathogen is carried to different places through the infected seed materials. In India, quarantine measures are not followed effectively to prevent largescale movement of infected seed materials. Also there is a craze for the newly released varieties for their better qualities. When such varieties are infected it favours introduction of the disease to newer areas. Unrestricted movement of cane materials of CoC 671 with in Tamil Nadu and to other states resulted in the introduction of the disease in many sugarcane tracts in the past 12 years (Viswanathan *et al.* 1997a). Hence there is an urgent need to establish inter-state quarantines so as to restrict the movement of infected materials from one location to another. Such measures are also essential when the seed canes are transported within a state. These quarantine measures greatly benefit sugar mills/ farmers in avoiding introduction of the disease.

Biological control

Since most of the management practices failed under field conditions, efforts were made to find out suitable biological control agents to reduce the pathogen survival in the system. Studies of Singh (1994) indicated that sett treatment of *Trichoderma harzianum* and *Chaetomium* sp. significantly improved germination in the infected setts. Disease build up in the field was also reduced significantly by the biocontrol fungi. Similar to this finding efficacy of other *Trichoderma* spp on reduction of red rot disease under controlled conditions were reported. However, so far success of the introduced *Trichoderma* spp or other biocontrol fungi under field conditions was not reported. Authors are aware that many sugar factories in Tamil Nadu have recommended *T. viride* formulations with peat, press mud, talc and bagasse to manage the serious disease. But recommendations have not yielded any desired results under field conditions. Possible reason for the failure to *Trichoderma* spp. under field could be due to low survival of the pathogen in the soil, infection by air-borne inoculum or deep seated infection in the standing stalks. Recent studies of the authors (Viswanthan and Samiyappan, 2000) indicated that sett treatment followed by soil application of *Pseudomonas* formulations has protected the crop in a pathogen-sick soil. Here the mode of antagonistic bacteria against the pathogen is not clearly established. It could be due to the direct antagonism of the bacteria against the surviving pathogen or induced state of host would have restricted the pathogen entry.

Induced resistance

In many other crops like cucumber, radish and rice, strains of fluorescent pseudomonads were effective in inducing systemic resistance against fungal pathogens causing foliar diseases (Wei *et al.* 1996; Hoffland *et al.* 1996; Nandakumar, 1998). Studies were conducted by the authors to find out the utility of fluorescent pseudomonads in inducing systemic resistance against red rot pathogen. The results showed that these strains were effective in reducing the pathogen development in the susceptible variety CoC 671. ELISA studies indicated that pathogen colonization at different nodal positions in the *Pseudomonas* treated stalks were significantly lower than the control (Viswanathan *et al.* 1998b). Further studies also indicated that sett treatment followed by soil application of talc formulation of the strains two times in the field was better in improving plant growth and reducing disease development. In addition to the significant reduction in the disease development in the cane stalks it was also found that *Pseudomonas* strain treatments recorded higher cane juice characters and less invertase enzymes. Systemic accumulation of chitinases and peroxidases was found associated with the induced systemic resistance by fluorescent pseudomonads against red rot pathogen in sugarcane (Viswanathan and Samiyappan, 1999a;b;c). However, detailed studies on the efficacy of selected strains in inducing systemic resistance under different endemic locations is required before recommendations are made for large scale use of fluorescent pseudomonads.

Conclusions

The disease was recorded about 100 years ago in India and it is one of the few diseases, that caused panic in the agricultural scenario in the country. Still this disease is posing serious challenges to the researchers, farmers and millers. Though vegetative propagation of the cane is considered as a major constraint in the disease management, lack of suitable legislative measures also caused introduction of the disease to newer areas in the country. Absence of clear race picture of the pathogen also added confusion in rating varieties for disease resistance. Sudden breakdown of resistance in released varieties is assumed to be the cause of emergence of new races of the pathogen and molecular mechanism behind the origin of new variant of the pathogen is not known. Conventional approaches other than healthy seed programme and resistant varieties have not yielded fruitful results under field conditions. Cultivation of resistant varieties in endemic locations saved the crop on many occasions. Healthy seed programmes may not work in endemic situations since secondary inoculum coming from other sources may cause severe infection.

Need of the hour is critically assessing the resistance before releasing cane varieties and proper monitoring the breakdown of the released varieties in the field. Also seed materials supplied to the mill/farmers should be precisely screened for the latent infection of the pathogen. In addition stronger legislative measures must be enacted to prevent movement of diseased cane materials from place to place to place. Certain unresolved areas like, molecular biology of disease resistance, variation in the pathogen races, break down of disease resistance and inheritance of red rot resistance have not been properly understood. Application of molecular biological approaches may answer these unresolved puzzles. Recent studies of the authors have revealed the involvement of pathogenesis related proteins like chitinase, β-1,3-glucanase and thaumatin like proteins in induced systemic resistance against red rot in sugarcane. This finding gives a new dimension on the understanding of red rot resistance in sugarcane.

Work on introducing disease resistance genes into sugarcane through genetic transformation is in its incipient stage. Attempts on this line of work may enhance the possibility of getting durable resistance to the disease.

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