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Management of red rot of sugarcane caused by *colletotrichum falcatum* went: A review

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Abstract
The red rot disease of sugarcane is so devastating in nature that's why considered as cancer of sugarcane. The disease occurs in all the growing states of our country and even several epiphytotic have been in credit in past from Uttar Pradesh, Bihar, Haryana, Punjab, Andre Pradesh, Kerala etc. A virulent strain of red rot was appeared in India between 1932 and 1942 which results withdrawal of many susceptible varieties and finally thereby threatening the sugar industry. A similar outbreak was also reported from Nigeria in 1951. The disease cause severe losses and has been recognized as of international importance. The red rot pathogen effect the economically valuable stalk lead to reduction in cane yield and degradation in juice quality. The source of primary inoculum of *Colletotrichum falcate* Went, a test pathogen is infected seed cane while the secondary spread of the disease occurs through irrigation water/rain water. Temperature ranged from 25^0 to 30^0 C and high humidity favors the development of disease finally affect the juice quality and cane yield. The pathogen is highly variable in nature which results break down of red rot resistant varieties with in short duration. So breeding for red rot resistance is major challenge for sugarcane breeder. Once the disease appear in field, it will be difficult to manage so need to follow the integrated approach of disease management. An integrated approach for management against red rot disease under field condition has been envisaged time to time. Integration of cultural control, breeding for resistance, physical control, biological control, chemical control and biotechnological approaches will be helpful for management of red rot disease of sugarcane.

Keywords: Sugarcane, red rot, management, cultivars, chemicals, *Colletotrichum falcatum*, *Glomerella tucumenansis*

1. Introduction
Red rotis one of the most dreaded disease of sugarcane and losses due to red rot may range from 10-50 % depending upon the cultivars, environment and pathogen strain (Ghazanfar and Kamran, 2016). The perfect stage of the fungus was identified as *Physalosporat cumanesis* Speg. (Carbajal and Edgerton, 1944) [20]. and finally known as *Glomerular ucumanensis* Speg. (Arx and Muller, 1954) [8]. Red rot pathogen hydrolyze the stored sucrose by producing the enzyme invertage which break the sucrose molecule into glucose and fructose. As a result the quantity of molasses increases (Sehtiya *et al*., 1993) [79]. It is aptly called the cancer of sugarcane (Khan *et al*., 2011) [49]. As this disease has become major constraint in the profitable cultivation of sugarcane (Mohan and Sangeeta, 2009) [68]. It causes reduction in cane weight, yield and quality of sugarcane cultivars in Indian sub-continent (Satyavir, 2003; Duttama jumder, 2008; Singh *et al*., 2008) [89-103].
Red rot is a widely distributed and has been reported in 68 sugarcane growing countries of the world (Bharti *et al*., 2012) [17]. This disease was first reported from Java/ Indonesia by Went in 1893 (Went, 1893). He called the fungus *Colletotrichum falcatum* Went and disease named as het root snot meaning red smut disease. Red rot disease from India was first recorded by Barber (Barber, 1901) [12]. Barber noticed the first large scale destruction by red rot disease from Godavari delta of Madras presidency during 1895 to 1899 in Red Mauritius cultivar. Thereafter it was observed in almost all the states of our country (Yadav, 2006) [124]. Kalaimani *et al*., (2012) [46-47]. Also reported that in India, the first documented epidemic occurred in 1895–1901 and in subsequent years a number of major outbreaks have been recorded as a regular event in the sub-tropical and tropical regions of the country.
This disease has several epidemics to its credit and virtually during 1938-1940, it wiped out sugarcane cultivation in Northern Uttar Pradesh and Bihar (Duttamajumder and Mishra, 2004). Red rot epidemic have been very common ever since its presence in India. These epidemic are resulted from failure of important commercial varieties like Co 312 (1939-40, *Tarai* region),

Co 312, Co 453, BO 11, BO 17, and BO 54 (1946-47, Punjab and *Tarai* 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, Andra Pradesh, Pondicherry and Tamil Nadu), CoC 671 (1981-82, Andra Pradesh), Co 997, Co 785, Co 419 (1982-84, Kerala), CoC 671 (1986-92,Tamil Nadu, Gujrat), CoC 92061(1992-98, Tamil Nadu and Pondicherry) (Viswanathan and Samiyappan, 2000; Singh, 2008; Babu *et al*., 2009; Babu, 2010) [10]. There have been several reports of red rot epidemics in many other countries i.e. U.S.A. Mauritius, Australia, Hawaiiand Myanmar etc. The disease also causes appreciable damage to canes in Bangladesh, Taiwan and Pakistan (Singh, 2008) [98-90-94].

Causal organism

The pathogen belongs toKingdom: Fungi, Divison: Eumycota, Subdivision: Deuteromycotina, Class: Coelomycetes, Order: Melanconiales, Family: Melanconiaceae, Genus: *Colletotrichum*, Species: *falcatum*. *Glomerella tucumanensis* (Speg) Arx & Muller is the teleomorph (perfect stage) of *Colletotrichum falcatum* Went, the causal agent of sugarcane red rot. This perfect stage was earlier named as *Physalospora tucumenensis* (speg) by Spegazzini in 1896. The taxonomic status was re-examined by Arx and Muller who referred it to the genus *Glomerella* as *Glomerella tucumanensis* (Speg) Arx and Muller. The teleomorph belongs to Kingdom: Fungi, Phylum: Ascomycotina, Sub-phylum: Pezizomycotina, Class: Sordariomycetes, Subclass: Sordariomycetidae, Order: Glomerellales, Family: Glomerellaceae, Genus *Glomerella* and Species *tucumanensis*.

The typical morphological and cultural features of *Colletotrichum falcatum* include acervuli with setae, presence or absence of teleomorph, colony colour, sporulation and growth rate (Viswanathan *et al*., 2003a) [115]. Other special features include intercellular as well as intracellular mycelium, linear or club shaped conidiophores producing elongated, single celled, thin walled, greenish black chlamydospores and the presence of appressoria (Duttamajumder, 2008).

Conidial Stage of pathogen

Conidial stage of red rot fungus as *Colletotrichum falcatum* was firstly described by Went in 1893. Conidia are produced by the pathogen in the conidial stage. Conidia are minute, black, dot like bodies present on the surface of host under favourable environmental conditions. They are falcate (sickle shaped), hyaline, aseptate, 20-38 µ m long and 5-7 µ m wide and have a large oil globule in the centre. These are produced from conidiophores arranged in acervuli. Acervuli are rounded or elongated and 70-300 µ m across. Another structure termed as setae which are brown in colour, about 150 µ m long, 4-6 µ m wide, swollen at the base with a tapered to rounded tip, 1-4 septate, are interspersed between conidiophores.

Perfect stage of pathogen

The pathogen *Colletotrichum falcatum* also possesses perfect stage firstly reported in India (Carvajal and Edgerton, 1944; Chona and Bajaj, 1952) [22]. Perithecia are produced on various parts of the sugarcane plant but found abundantly on leaf sheaths and blades. These are globose in shape and 150-300µ m in diameter. Asci are hyaline, bear eight spore, clavate, thickened at the apex and having 50-60 µ m x 7-10.5 µ msize. Ascospores are straight or slightly fusiod, ellipsoid or ovoid when mature, aseptate, hyaline and 12-30 x 5-11µ m. Paraphyses are many in number, septate, unbranched and with granular contents extending along the ostiole.

Physiological specialization

Colletotrichum falcatum shows a great diversity in virulence and new physiological races have been frequently reported from different parts of the world. Red rot pathotypes are distinguished on the basis of various parameters i.e. morphology, physiology and host reaction etc. Some strains have also been characterized by studying the hydrolytic and polyphenol oxidase enzymes in sugarcane red rot just to know the relationship of hydrolytic enzymes to hydrolysis. A considerable difference in the hydrolytic enzymes production by different strains of pathogen has been observed *in vitro* and *in vivo* (Srinavasan, 1969). Virulent pathotypes of *Colletotrichum falcatum* responsible for severe disease outbreak are also being differentiated genetically by using molecular techniques like RAPD, PCR based diagonistic kit etc. (Suman *et al.*, 2005).

Pathgenic variability

The perfect stage of red rot fungus, *Glomerella tucumanensis* (Speg) Arx & Muller is rare in nature. The fungus keeps on mutating in nature which results evolution of new races of pathogen. Edgerton and Moreland (1920) in USA first studied the pathogenic variability in *Colletotrichum falcatum*. Variation in virulence of the pathotypes was reported after red rot epidemic in the sub-tropical India (Chona and Srivastava, 1960). Srinivasan (1962) reported that light coloured isolates of pathogen were highly virulent and mostly prevalent in red rot epidemic areas of sub-tropical India. Dark coloured isolates are less sporulating and less virulent were occurred in tropical India. Pathogenic variability in subtropical regions in 1980s was also reported (Beniwal *et al*., 1989) [13]. Since 1970s frequent and severe epiphytotic of red rot in Peninsular India showed presence of highly virulent pathogen (Padmanaban *et al*., 1996; Viswanathan *et al*., 1997a) [113].

By using nodal as well as plug method of inoculation, virulent pattern was studied in fungus. Varibility in red rot fungus depends on virulent pattern was reported by several workers (Khirbat *et al*., 1980; Beniwal *et al*., 1989) [13]. From North West zone, pathotype Cf01, Cf02, C f 03 in sugarcane cultivars Co 1148, Co 7717 and Co J 64 respectively whereas C f 04, C f 05 and C f 06 in sugarcane cultivars Co 449, Co 997 and Co C 671 respectively from East Coast zone were reported through host differentials (Satyavir, 2003) [77]. Nageswararao and Achutaramarao, (2004) and Nageswararao and Patro, (2005) also reported the presence of different pathotypes of fungus by using host differentials.

Various DNA based molecular characterization methods for identification of different *Colletotrichum* spp attacking the different hosts were also studied (Latha *et al*., 2003; Kumar *et al*., 2010). Different time periodand different locations of fungus showed the pathogenic variability and the isolates obtain from different location and time were distinguished at morphological, cultural, pathogenicity and serological level (Viswanathan *et al*., 2003a) [115]. and at molecular level by Random Amplified Polymorphic DNA (Suman *et al*., 2005). Dattama jumdar (2008) reported that difference in virulence pattern of the fungus is also due to host varieties cultivated. RAPD, Universal Rice Primar (URP) and Inter Simple Sequence Repeat (ISSR) markers were used for high molecular diversity of red rot isolates taken from different commercial varieties grown in North India (Kumar *et al*.,

2010). Malathi and Viswanathan (2012) [119]. reported that there is positive correlation with quantity and quality of toxin and symptoms produced by them. It was also inferred that morphological similar isolates possess positive correlation with pathogen variability whereas molecular diversity did not show such co-relation (Kumar *et al*., 2014). The higher virulence was noticed in the tropical isolates as compared to subtropical isolates. *Colletotrichum falcatum* isolates are culturally, morphologically and pathologically dissimilar (Bharti *et al*., 2014) [15-16].

Diagnostic measures of *Colletotrichum falcatum*

For identification of *Colletotrichum falcatum*, different serologicals techniques were developed. ELISA technique was found very effective in assessing the pathogen load at different nodal positions in sugarcane when crop was treated with plant growth promoting rhizobacteria (Viswanathan and Samiyappan, 1999a) [113-114]. Further refinement in ELISA with polyclonal antiserum raised against test pathogen also helped in detection of pathogen colonization before expression of symptoms (Viswanathan *et al*., 2000) [112-119]. For accurate, exact and sensitive detection of *Colletotrichum falcatum* in planting material, polymerase chain reaction (PCR) assay was developed (Nithya *et al*., 2012). Identification of red rot fungus was first started at Sugarcane Breeding Institute, Coimbatore and valuable information was generated on serological variations among isolates of *Colletotrichum falcatum*. Viswanathan *et al*., (2000) [112-119]. reported that polyclonal antiserum was developed against four different pathotypes i.e Cf687, Cf997, Cf1148 and Cf86062 of *Colletotrichum falcatum*. Different serological assays i.e. Enzyme Linked Immune Sorbent Assay (ELISA), Dot Immune Binding Assay (DIBA) and Western Blotting were further tried for detection of red rot fungus in plant tissues (Viswanathan *et al*., 1998; Hiermath and Naik, 2004). Red rot infection was also confirmed by PCR analysis (Sharma *et al*., 2017) [84-86].

Symptomatology

Duringinitial stage of crop in field, it is very difficult to recognize the disease. Disease symptoms are visible after mansoon season. The pathogen attacks entire plant which includes stalk, leaf, buds or roots however the most interesting phase is its attack on the stalk. Therefore it is considered a stalk and seed plant disease (Suman *et al*., 2005). In field, disease is noticed by withering of 3rd and 4th leaf of the crown either at the top or along the margin or both. In severe conditions, the whole crown dries up. Initially affected sugarcane stalk shows purple discoloration of rind.

The distinguishable feature of red rot can be observed only by splitting the stalk of standing cane. Longitudinal reddening of the normally white or yellowish white internodes, especially when this red colour is interrupted by occasional white spots extending cross wise of the stalk (Sharma *et al*., 2017) [84-86]. The typical stalk symptoms include presence of white spots in otherwise rotten intermodal tissues with alcoholic sour smell and nodal rotting appear when the crop is at the flag end of grand growth phase during August-September in Sub-tropical India (Srivastava and Rai, 2012). Brown or reddish brown stripes appear externally in the nodal region. Acervuli, the fruiting bodies of fungus develop on the outer surface of shrinkened internodes.

Dark reddish areas with straw colour center are also common on the leaf midrib which elongate rapidly and extends the entire length of the inner midrib. When fructification starts, the lesion covers with black powdery masses of conidia and acervuli with dark reddish brown margins. The lesion from single point of infection is usually continuous along the midrib but it may breakup into succession of red blotches alternating with apparently healthy tissue (Sharma, *et al*., 2017) [84-86]. Lesion with 2 to 3 mm in length and approximately 0.5 mm width are common. Sometime minute spots with red in colour are common in upper surface of midribs.

Epidemiology

Sugarcane is also one of the crops which consume large quantity of water and moisture plays a major role in the development of diseasein the crop plants (Kalaimani and Jeyaraj, 2012) [46-47]. Rainy season and 25^0 to 30^0 C temperature favors the development of disease (Khan *et al*., 2011) [49]. Mean temperature range from 29.4^0 to 31^0 C, pH 5-6, drought conditions during the initial growth phase, high atmospheric humidity i.e. 90 %, water logged conditions of the soil etc are the favourable conditions for disease development (Sharma and Tamta, 2015) [85].

The red rot fungus is set borne in nature. The fungus perpetuates in infected canes/ infected sugarcane setts, crop debries, disease stubble and in soil in the form of thick walled mycelium, appressoria, setae, chlamydospores, conidia. Occurrence of disease from the soil is generally depends on the persistence of inoculum through these resting structures in the debries in the soil. These resting structure are tolerant to adverse soil condition and can survive for longer period of time. Infected planting materials serve as major source of inoculum for the annual recurrence of red rot disease. Infected propagules like conidia, appressoria, chlamydospores, setae, or thick walled hyphae produced on stubble or decaying canes in soil cause infection after planting (Viswanathan and Samiyyapan, 2000) [112-119]. Tiwari *et al*., (2010) reported the favourable environmental conditions i.e high humidity and ideal temperature during crop season is responsible for havoc condition in North Western part of the country. The disease also covered the peninsular parts of the country. It appears in low as well as severe condition in some important sugarcane growing states i.e. Uttar Pradesh, Northern Bihar and some pockets of Punjab (Babu, 2010) [10].

In general, dormant mycelia present in the bud scales are responsible for post germination infection of young emerging shoots (Viswanthan *et al*., 2011). With the advent of pre-mansoon showers, symptoms of the disease start appearing and with the onset of the mansoon when the weather is most suitable, full manifestation of the disease take place (Duttamajumder, 2008). The secondry transmission of the fungus during mansoon is mediated through irrigation, rain, water, rain splash and results in the infection of mid rib, lamina, leaf sheath and stalk while in winter air currents help in the spread of pathogen (Sharma and Tamta, 2015) [85]. The disease is mostly caused by the imperfect stage, though the perfect stage of the fungus has been observed in nature, the role of ascospores in the disease cycle is not understood.

Possible factors for red rot epidemic

Significance of incipient infection in disease spread

The main reason of epiphytotic conditions of red rot is because of use of infected seed setts which contain incipient infections in the nodal region which is difficult to recognize unless otherwise inspected by trained eyes. The symptoms in nodal regions appears as brown lesion in the place of root primordial, leaf scar and growing ring upon scrapping this

region. The incipient/dormant infections appear in the form of disease in the month of July. With more favourable environmental conditions during July and thereafter, disease burst out and creates havoc conditions in field.

Abiotic stress

Moisture stress conditions during pre-monsoon and monsoon period predispose the plants to red rot attack. This condition also leads to formation of resting structure of pathogen. These resting/dormant structure present on the crop debries, sporulate and produce number of acervuli loaded with condiain favourable conditions due to recurrent rains during monsoon season. Hollow pith in some sugarcane cultivars also seems under water stress condition. Moisture stress is one of the potent factor for red rot epidemic.

Water logging situation

Water logged situation during monsoon period i.e. July to September predispose the sugarcane plant to red rot attack. This condition results more infection in the nodal regions especially at the air water interface. The fungal spores, acervuli etc float on water very easily come in contact with root primordia, leaf scars, buds and growth rings for germination and enter in the host tissues. Under water logged condition, condia present in acervuli start germination and fuse with other conidia and forms aggregates of fuse conidia which shows higher virulence finally responsible for breakdown of resistanceand cause epidemic condition.

Variability

Colletotrichum falcatum is facultative saprophyte and keep on changing because of mutation, hetero karyosis and adaptation which results development of new pathogenic race in nature and it became very challenging task for sugarcane breeder to develop a resistant variety against red rot pathogen.

Economic importance

Red rot of sugarcane is widely distributed disease throughout the tropics and consider as major threat in India, Louisiana and Australia. It has been attributed with losses from 25 to 50 percent of the crop (Viswana than and Samiy appan, 2000). It is a disease of economic importance not only in India but also in other South Asian countries which is responsible for 5 to 10 percent loss in cane yield. Hussnain and Afghan, (2006) reported that red root causes approximately 29.07 % losses in cane yield and 30.8 % in sugar recovery. Viswanathan, (2010) reported that 100 percent losses due to occurrence of epidemic conditions in our country which resulted removal of some sugarcane cultivars i.e. Co 419, Co997, Co1148, Co6304,CoS 767, CoS 87231, Co Se 92423, Co C 671, Co C 85061, Co C 92061 and Co J 64 from cultivation.

Jayashree *et al*., (2010) [44]. reported that in our country the estimated average loss in sugarcane production due to red rot is about 18- 31 %. Minnatullah *et al*., (2012) [67]. observed that there was substantial reduction in juice quality due to red rot infection. Minnatullah and Kamat, (2018) [66]. reported that there was reduction ranging from 16.60 % to 20.80 % in brix % , 31.60 to 38.26 % in pol % and 18 to 22.10 % in purity in susceptible cultivars while in resistant cultivar reduction ranged from 2 to 8 % in brix, 6.10 to 19.38 % in pol % and 4.20 to 12.40 % in purity. The reduction may be due to utilization of some solid materials of cane juice by red rot pathogen as a substrate.

Host Resistance

Thickness of epidermis, cuticle, bud scales, rind, relative abundance of vascular bundles under the rind, presence of septa in vascular bundles etc. are modifications in the sugarcane plant tissues which prevent or resist the entry and spread of red rot pathogen in the sugarcane plant.

- The nodal tissue consisting of a thick walled sclerenchymatous tissue which operates against the transnodal growth of the pathogen.
- Presence of the septa in the tracheal tubes at the nodes which generally block the free upwards movement of conidia in the vascular stream and consequently the development of lesions
- Continuity of vessels in internodes of the sugarcane clones effect the red rot resistance Further the formation of brown gummy substance in infection process in resistant cultivars resulting seal off further spread of red rot fungus in adjoining areas (Edgerton, 1959). Srinivasan and Bhatt, (1961) reported the hypersensitive gumming reaction in sugarcane. After infection, level of total phenolics increased in resistant cultivars of sugarcane while drop down with initial increase in case of susceptible cultivars (Jaglan, 1990) [42]. Higher activity of poly phenol oxidase as well as flavone glycosides is associated with red rot resistance (Srivastava and Solomon, 1990) [101]. Phenylalanine ammonia lyase, tyrosine ammonia lyase and phytoalexin 3-deoxyanthocyanin have also an important role in red rot resistance reaction (Madan *et al*, 1991; Viswanathan *et al*., 1996) [111-118]. Newly released sugarcane cultivars get prone to red rot with in the short period of time due to highly variable nature of pathogen so much more details study is needed to understand the true basis of disease resistance at molecular level (Satyavir, 2003). So that it can play important role in management of red rot of sugarcane (Sharma and Tamta, 2015) [85]. Ashwin *et al*., (2018) [9]. reported that the novel protein CfPDIP1 of *Colletotrichum falcatum* has the potential to trigger a multitude of defence response in sugarcane.

Host range

Besides sugarcane, isolation of *Colletotrichum falcatum* from sorghum and johnson grass has alsobeen reported. *Sorghumvulgare*, *Sorghum halepense* and *Saccharum spontaneum* works as collateral host for red rot pathogen. Perithecial stage has been found on common grass *(Liptochloa flliformis)* and *Miscanthus* in Louisiana and Taiwan respectively. However the role of alternate hostseems to be negligible (Satyavir *et al.,* 2002) [78].

Disease Management

Management of red rot disease is based on cultural control, use of disease free material, resistant varieties, physical control, biological control, fungicidal control etc. Because of fibrous nodes, impervious nature of rind etc. disease cannot be managed through only one method of control. An integrated approach for the management of the disease under field conditions has been envisaged time to time. So integration of all management practices is considered as best option for red rot management.

Cultural control

Healthy cultural practices as preventive measure is always consider as a better option. Disease can be minimize by use of healthy as well as certified seeds, field sanitation, crop rotation, proper drainage facility etc. These cultural practices have been recommended not only to reduce the inoculum

from the field but also to minimize crop losses. Red rot disease is a seed borne in nature so disease free nursery should maintain in farm and farmers field (Satyavir, 2003). In field sanitation, removal and burry of crop debries, trash, stubble etc. is helpful and must be adopted in field prior to planting (Agnihotri, 1996) [2]. Strict enforcement of a nursery programme is essential. Seed material free from diseases, pests and mixtures of other varieties must be ensured. The nurseries with less than one percent of red rot infection, must be deleted from the seed programme. Sugarcane setts exhibiting reddened cut ends, shrunken nodes, stalk borer holes and damaged buds should be avoided. This alone will improve the ten per cent germination and reduce the red rot incidence.

In case of disease prone areas and heavily infected plant crops, ratooning should not be done. By adopting other crops in same piece of land as crop rotation practices will help to minimize the soil borne inoculum. The sugarcane crop should be rotated after every two to three years. Generally red rot disease is spread through irrigation water so proper drainage facilities must be adopted and always avoids the flow of water from diseased field to healthy field. Field should be properly leveled with hygienic cultivation conditions. Anwar *et al*., (2010) reported that three or four budded sugarcane setts play important role in management of soil borne inoculum. Gupta *et al*., (2018) [35]. reported that there was accumulation of nitrogen and iron content while depletion of phosphorus, potash, copper and zinc content due to red rot attack. So fertilizer management is very important.

Breeding for resistance

Earlier the breeding programmes in India were focused to develop new sugarcane varieties for subtropical India, just to replace Indian sugarcane (*Saccharum barberi*) which waspoor yielding in nature. But recurrent outbreak of red rot in epiphytotic condition changed the scenario and breeder tried to develop red rot resistance varieties. The evolution of new races of pathogen considered as major factor for breakdown of new varieties in shorter life span. Alexander and Rao, (1972) reported that red rot resistance in sugarcane species is being transferred through interspecific, intraspecific or intergeneric crosses. Among the various species of sugarcane, *Saccharum spontanium* consider as major source of resistance while the cultivated species of sugarcane, *Saccharum officinarum* has low level of resistance.

A breeding programme to evolve varieties with broad spectrum of resistance against two or more than two pathotypes of *Colletotrichum falcatum* was initiated at Sugarcane Breeding Institute, Coimbatore and yielded many resistant progenies to multiple pathotypes (Alexander *et al*., 1979). Resistance to the pathogen was identified in the commercial clones, interspecific hybrids and basic species in the sugarcane germplasm collection (Sreenivasan, 1995). Many resistant varieties have been developed utilizing the resistant clones (Viswana thanand Rao, 1996).

Breeding of resistant cultivar is an important task. Many sugarcane varieties have gone out of cultivation due to red rot disease. The use of resistant varieties is the cheapest practical method of disease control commonly applied as major component of integrated disease management strategy. Breeding for resistance is inevitable to suitably manage the disease and avoid epiphytotics of red rot. Kalaimani *et al*., (2012) [46-47]. Reported the some sugarcane cultivars which break down due to red rot infection.

Table 1: Reported the some sugarcane cultivars which break down due to red rot infection.

S. No	Varieties	Year of release	Year of break down to red rot infection	Total survival period
1	Co 6304	1970	1985	15
2	Co C 671	1975	1986	11
3	Co C 771	1977	-	-
4	Co C 772	1977	-	-
5	Co Si 776	1977	-	-
6	Co C 8001	1980	1986	6
7	Co C 8201	1982	-	-
8	Co C 85061	1985	1990	5
9	Co C 86062	1986	1989	3
10	Co Si 86071	1986	1995	9
11	Co 8021	1986	1997	11
12	Co C 90063	1990	1994	4
13	Co C 91061	1991	1993	2
14	Co C 92061	1992	1993	1
15	Co G 93076	1993	-	-
16	Co Si 95071	1995	-	-
17	Co Si 96071	1996	-	-
18	Co Si 98071	1998	1998	-
19	Co 86032	1999	2003	4

Malathi *et al*., (2012) [58]. also observed that source of resistance is high in *Saccharum barberi* followed by *Saccharum sinense* and *Saccharum robustumm*. Sugarcane breeding work is mainly focused on developing red rot resistance cultivars (Agnihotri, 1996) [2]. There is no resistant variety in sugarcane because of highly variable nature of *Colletotrichum falcatum*. Moderately resistant varieties become susceptible within 8-10 years with the development of new virulent races of the pathogen (Yadav, 2006).Singh *et al*., (2017) reported that six accessions found resistant while twelve clones showed moderately resistant reaction against red rot which can be further utilized during breeding programme to produce new resistant varieties of sugarcane against *Colletotrichum falcatum*.

Physical control

Management of sett borne infection of red rot pathogen through heat therapy has been reported from earlier days but there are only few reports available in literature regarding physical control of red rot of sugarcane. Joshi, (1954) and

Singh, (1973) observed that complete elimination of sett borne infection in sugarcane through hot air treatment at 54^0 C for 8 hours. Various workers also reported that heat therapy at 54^0 C for 4 hours was found effective against red rot disease (Srivastava *et al*., 1977., Singh *et al*., 1980., Dhillon *et al*., 1983., Agnihotri, 1984). Hot water treatment at 54^0 C for 8 hrs against red rot of sugarcane was also reported (Singh and Pandey, 2012).

Biological control

Red rot disease of sugarcane was observed to be biologically controlled through rhizobacteria and their metabolic products (Vanitha *et al*., 2009; de Vasconcellos and Cardoso, 2009; Loper and Gross, 2007). Rhizobacteria inhibit the plant pathogens through secretion of metabolites like siderophores (Matthijs *et al*., 2007), hydrolytic enzymes which degrade the cell wall of pathogen (El-Tarabily *et al*., 2006) and antibiotics which induce systemic resistance in plants. Bacillus strain also showed a good ability to colonize the sugarcane roots and protect the crop from the red rot disease under greenhouse condition (Hasssan *et al*., 2010a). Hassan *et al*., (2012) also reported that *Bacillus*strain proved its potential and can be used to develop different formulations.

An ecologically friendly alternative approach to manage the disease is biological control by using *Trichoderma harzianum* and *Trichoderma viride* (Singh *et al*., 2008) [90-94]. Malathi and Viswanathan, (2013) [57]. observed that *Trichoderma harzianum* and *Pseudomonas* spp possess the ability to protect the crop due to chitinase enzyme produce by them. Singh *et al*., (2013) clearly supported that ech42 gene of *Trichoderma* spp is responsible for controllingthe red rot incidence. Shailbala *et al*., (2013) reported that reduction in red rot disease because of protection offered might be due to parasitic action of *Trichoderma harzianum* on red rot pathogen or systemic resistance induced in sugarcane. Shailbala and Kashyap, (2014) also concluded that the treatment metabolites were found to be more efficient and significantly better which lowered down the red rot intensity in sugarcane. Hassan *et al*., (2014) reported that two strains *Ochrobactrum intermedium* NH-5 and *Stenotro phomonas maltophilia* NH-300 exhibited good bio-control activity suppressing red rot by 44-52 %.

The applicability of plant based extracts for the suppression of sugarcane red rot disease is an environment friendly tool in combination with antagonists (Jayakumar *et al*., 2007). It was also concluded that essential oils i.e. peppermint oil, mentha oil, geranium oil, patchouli oil and palmroza oil were effective in inhibiting the growth of mycelia of *Colletotrichum falcatum*. Leaf extract of *Curcuma domestica* and *Datura metel* inhibited the conidial and mycelial growth of fungus (Imtiaj *et al*., 2007) [41]. Patel *et al*., (2015) [75]. reported that the use of cow urine and dung can be the cost effective and eco-friendly approach for controlling sugarcane red rot disease. Rautella (2017) [76]. reported that plant extract of parthenium, essential oil from pepper mint, mentha and lemon tulsi as well as strain Th-53 (strain of *Trichoderma harzianum*) were found effective against red rot pathogen.

Bio agents with fungicides

Studies were conducted on compatibility of biological agents with fungicides against red rot pathogen. Antagonistic activity of *Trichoderma* strains was influenced by addition of 1 ppm thiophanate methyl which resulted in enhanced suppression of fungal growth. Fungicide at lower concentration improved the antagonistic potential of *Trichoderma* spp which may be due to weakening of pathogen by fungicide (Malathi *et al*., 2002). Singh *et al*., (2008) reported that *Trichoderma viride* along with MHAT and fungicide Carbendazim treated plot showed the low incidence of red rot disease.

Induced resistance

Induced resistance is a "state of enhanced defensive capacity" which a plant builds up physiologically upon exposure to specific stimuli i.e microorganisms or environmental stress (Van Loon *et al*., 1998; Vallad and Goodman, 2004). This enhanced state of defensive capacity has a proven efficacy against multiple pests like fungi, viruses, bacteria, nematodes etc. (Van Loon *et al*., 1998; McDowell and Dangl, 2000; Walling, 2000; Kessler and Baldwin, 2002; Vallad and Goodman, 2004). Induced resistance particularly involves two form of resistance i.e. Systemic acquired resistance (SAR) and induced systemic resistance (ISR).Activity of SAR is usually considered to prevail for the life time of the plant while the ISR becomes diluted with the passage of time especially in new developing foliage. ISR and SAR mechanisms differ in signal transduction pathway as well as the nature of elicitors has been broadly integrated into the biological strategies of plant diseases management (Chin-A-Woeng *et al*., 2003; Vallad and Goodman, 2004).

Viswanathan and Samiyappan, (1999) [113-114]. established plant growth promoting rhizobacteria mediated induced systemic resistance against red rot pathogen. Viswanathan *et al*., (2005) also indicated a possible role of pathogenesis related proteins in conferring red rot resistance in sugarcane crop. The peptides MUC1 60 mer and purothionins mixture significantly inhibited the mycelial as well as spore germination of *Colletotrichum falcatum* (Edward *et al*. 2013).Singh *et al*., (2018) [91]. reported that *Trichoderma* elicitor, a chemical barrier against *Colletotrichum falcatum* enhanced accumulation of phenols, poly phenol oxidase, per oxidase, superoxidase dismutase, tyrosine ammonia lyase, phenylalanie ammonia lyase etc. This chemical barrier orchestrated the diverse biochemical pathway for induced systemic resistance.

Chemical control

The endless struggle between varieties and the complexity of disease have led to the development of correspondingly a variety of approaches for control. Fungicides are often a vital part of disease management as they control disease satisfactorily.Malathi *et al*. (2004) [59]. reported that soaking of sugarcane setts in a 0.25% suspension of Thiophanate Methyl found effective against red rot disease. The role of fungicides in modernizing and changing the condition of agriculture is quite significant (Subhani *et al*., 2008). Subhani *et al*. (2008) reported that fungicides Benomyl, Folicur, Ridomil gave the best results against red rot of sugarcane. Khan *et al*., (2009) [50]. also studied the control of red rot disease through fungicides. Bharadwaj and Sahu (2014) evaluated fungicides, botanicals and essential oils against red rot fungus. Bharti *et al*., (2014) [15-16]. observed that the maximum inhibition in fungal growth (i.e. 98 % inhibition) was found by Bavistin followed by fungicide Vitavax (i.e. 91.00% inhibition).

Role of sett treatment for the management of primary source of red rot from setts have been established earlier (Malathi *et al*., 2016) [60]. and use of fungicides to control the red rot is normally restricted to the sett treatment. Shailbala and Kumar, (2016) reported that a new generation fungicide i.e. Azoxystrobin 18.2 % + Difenoconazole 11.4 % SC @ 1.00 ml/l could be used for management of red rot disease. Shailbala and Kumar, (2016) also reported that fungicide

Azoxystrobin 23 % w/w SC reduced the red rot disease significantly. Malathi *et al*., (2016) [60]. observed that among the various fungicides, thiophanate methyl was found to be highly suitable under mechanized treatment against red rot.

Biotechnological approaches

Now a day's biotechnology plays a pivotal role for the improvement of sugarcane varieties. Biotechnological approaches include cell and tissue culture, introduction of red rot resistance gene into commercial cultivars, molecular tools for detection of red rot fungus, development of genetic maps using molecular marker and molecular characterization etc for sugarcane improvement (Tiwari *et al*., 2010).Now a days molecular marker become an effective tool which aid the plant breeder in improving the genetic makeup of sugarcane varieties (Bundock *et al*., 2009; Parida *et al*., 2009). Pathogen diversity has been studied using ribosomal DNA (Glaszmann *et al*., 1990), simple sequence repeats (Cordeiro *et al*., 2000), AFLP (Butterfield *et al*., 2001), RFLP (Coto *et al*., 2000), TRAP (Alwala *et al*., 2006) and random amplified polymorphic DNA (Alvi *et al*., 2008).

Collective efforts for identification of red rot resistance gene and markers associated with resistance gene will help the breeder to develop the resistant variety. The research is being conducted into developing molecular markers for disease resistance traits. The genetically modified sugarcane would really be the answer to cope with the challenge of red rot resistance. Nayyar, (2017) reported that red rot resistant transgenic sugarcane was developed through expression of β 1-3 glucanase gene from *Trichoderma* spp. The transgenic plants with high transgene expression were resistant to two virulent patho types of *Colletotrichum falcatum*. Tariq *et al*., (2018) reported that transgenic lines of sugarcane were modified with barley chitinase class II gene to create resistance against red rot. Development of new varieties with the help of biotechnology may open up new avenues for sugarcane growers.

Conclusion

Among fungal diseases of sugarcane, red rot is the most devastating and threatening disease mostly prevailing in India. The pathogen attacks sucrose accumulating parenchyma cells of cane stalk leading to severe losses in cane yield and sugar recovery. Incipient dormantin fection of pathogen, abiotic stress, waterlogged situation and variability are the important factors for red rot epidemic.As the fungus is highly variable in nature hence it causes frequent outbreak of red rot resistant varieties. There is different management approaches i.e. cultural control, use of resistant varieties, physical control, biological control, chemical control, biotechnological approaches etc. for management of red rot disease but every approach has its limitation. For management of red rot disease, seed treatment is the good option but the pathogen can also spread through irrigation water in the field. Due to variable nature of pathogen, the resistant varieties become susceptible to new race of pathogen. Now a day's molecular diagnostic tool are available for precise as well rapid detection of pathogen. But these molecular tools are not easily accessible to the farmers. Due to health hazardous, few effective fungicides were banned. Rather than relying upon the single method, integration of all the controlling method is the best option.

No doubt, impressive research work has been carried out over the years on many dimensions of red rot, still in-depth studies on the epidemiology with special reference to role of theincipient infection, sexual stage and environmental factors is needed. The spectrum of prevailing races in *Colletotrichum falcatum* needs to be catalogued by using molecular markers. Concerted efforts needs to be launched on molecular biology of host-parasite interactions to understand the operational mechanism involved in pathogenesis. Definitely there is need to identify newer fungicides and induced resistance to red rot by exploiting chemicals and micro-organisms for tailoring pragmatic strategy for integrated disease management. Integrated disease management practices will not only help to reduce the disease incidence but also improve qualitative as well as quantitative parameters of sugarcane. In addition to available management strategies, some novel strategies including possibility of induce systemic resistance against *Colletotrichum falcatum*, quarantine regulations, clean cultural practices, bio-agents etc. is need to explore. Further the identification of defence gene, development of transgenic sugarcane with inbuilt red rot resistance may be the good option for future and there is need to focus in this direction too.

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