Indian Phytopathology (2019) 72:587–597
https://doi.org/10.1007/s42360-019-00125-w

REVIEW ARTICLE

Present status of bakanae of rice caused by *Fusarium fujikuroi* Nirenberg

Ram Singh[1] · Pankaj Kumar[2] · G. S. Laha[3]

Received: 18 September 2018 / Revised: 3 January 2019 / Accepted: 5 March 2019 / Published online: 27 March 2019
© Indian Phytopathological Society 2019

Abstract
Bakanae disease of rice caused by *Fusarium fujikuroi* Nirenberg (Syn: *F. moniliforme* (Sheld.) [Teleomorph: *Gibberella fujikuroi* Wineland] is known to occur in almost all the rice growing countries. The disease causes substantial yield losses. In India, it is a major production constraint in north western parts especially in Basmati rice growing belt. The yield loss due to this disease has been reported to range from 3% to almost complete loss depending on extent of infection, variety and weather conditions. This review summarizes the available information on various aspects of the disease viz., history and geographical distribution, symptoms, economic importance pathogen biology, disease epidemiology and different management practices along with future lines of work.

Keywords Foot rot · Bakanae · Rice (*Oryza sativa* L.) · *Fusarium fujikjroi*

History and geographical distribution

The disease is said to have been known in Japan since 1828. It has also been called as Fusarium blight, elongation disease, Fusariosis, white stalk in China, palay lalake (man rice) in British Guiana, foot rot in the Philippines, otoke nae (male seedling) in Japan, bakanae in USA, Africa and Australia, foot rot and bakanae in French Equitorial, Africa and Ceylon and foolish plant or foot rot in India (Singh and Sunder 2012).

The disease has been reported from almost all the rice growing regions of Asia, Africa, north America, south America and central American countries including countries in the carribean region (Anonymous 2018; Gangopadhyay 1983; Ou 1985; Khokhar 1990; Singh and Sunder 2012). The disease has also been reported from most of the European countries though rice is not cultivated in a large area in Europe. However, the disease is widespread in countries like India, Bangladesh, China, Nepal and Laos in Asia, Guyana and Suriname in South America and in Australia (Anonymous 2018).

Though the disease has been detected from most of the rice growing states of India, bakanae was considered as a minor disease in India till 1990. However, during last nearly three decades, it has emerged as one of the most serious diseases of rice in Punjab and Haryana, especially on basmati rice varieties. There are many reports of its occurrence in moderate to severe form in different districts of Haryana and Punjab during 2004–2012, mainly on basmati rice varieties (Laha et al. 2016).

Symptoms

Fusarium fujikuroi causes different types of symptoms starting from pre-emergence seedling death to grain infection at maturity. Bakanae means bad or naughty seedling referring to abnormal elongation or foolish seedling. The disease occurs both in the nursery bed and transplanted crop and also in ratoon crop. The infected seedlings are thinner and elongated than the normal seedlings and have chlorotic stems and bear yellowish leaves. These infected seedlings may die eventually early in the season. However, some plants surviving up to maturity bear only sterile panicles. The bakanae infected field can be easily identified from a

✉ Pankaj Kumar
bodlapankajbodla@gmail.com

[1] CCSHAU Rice Research Station, Kaul 136 021, India

[2] Department of Plant Pathology, CCSHAU, Hisar 125 004, India

[3] Department of Plant Pathology, ICAR-IIRR, Hyderabad 500 030, India

distance as it remains uneven throughout the crop season. White or pink mycelial growth and adventitious roots are also observed on the lower internodes of the infected plants.

Brown discolouration of tissues is also observed at lower nodes of diseased plants facilitating an easy separation of the root system at collar region resulting in foot rot symptoms (Ou 1985; Singh and Sunder 2012). In the end of season, small scattered pycnidia can also be seen in lower sheaths which become blue to black colour. Perithecia are also produced on diseased plants under favourable conditions (Sun and Snyder 1978). The various types of symptoms (such as elongated seedlings, stunted seedlings etc.) produced by the pathogen are determined by the production of relative amount of growth hormones (gibberellic acid and fusaric acid) by the pathogen (Webster and Gunnell 1992; Singh and Sunder 2012).

Economic importance

Disease has been reported to 3% to all most complete loss in grain yield of rice in different countries depending on disease incidence, time of infection and cultivars (Singh and Sunder 2012). The disease is more devastating on specialty basmati rice which earns substantial foreign exchange (Bashyal et al. 2014). It is known to reduce grain yield by 20–50% in Japan, 70% to almost complete loss in Australia, 3.7–14.7% in Thialand, about 25% in Bangladesh, 5–23% in Spain, 3.0–95.4% in India, 40% in Nepal, and 6.7–58.0% in Pakistan (Yasin et al. 2003; Singh and Sunder 2012; Gupta et al. 2015). In addition to direct yield loss, the disease significantly deteriorates the quality of rice (Bashyal and Aggarwal 2013).

Pathogen and its variability

The organism causing bakanae was originally identified as *Fusarium heterosporum* Nees and its ascigerous stage was identified as *Lisea fujikuroi* by Sawada. Ito and Kimura (1931) transferred *L. fujikuroi* to the genus *Gibberella* as *Gibberella fujikuroi* (Sawada) Ito with *Fusarium moniliforme* Sheldon as its anamorph. Later, *F. moniliforme* was re-identified as *Fusarium fujikuroi* Nirenberg (Nirenberg 1976). Initially, *G. fujikuroi* was considered to be a single species; however, phylogenetic studies revealed that the taxon is composed of a several species known as *Gibberella fujikuroi* complex (Kim et al. 2012). This species complex is consisted of at least 11 biological species of *Fusarium* from section *Liseola* (Nirenberg and O'Donnell 1998; Leslie and Summerell 2006; Kovacevic et al. 2013). At least three members of *G. fujikuroi* complex viz., *Fusarium fujikuroi* Nirenberg, *F. proliferatum* (Mats.) Nirenberg and *F. verticillioides* (Sacc.). Nirenberg have been reported to be associated with bakanae symptoms in rice (Jeon et al. 2013). However, there role in causing bakanae disease is not fully understood (Wulff et al. 2010). We have restricted our discussion to *F. fujikuroi* as it has been found to be the most dominant and virulent species causing bakanae disease of rice.

Morphological, physiological and pathogenic variability

Fusarium moniliforme strains have been reported to exhibit significant variation with respect to production of gibberellins, fusaric acid, pectic enzymes and pathogenicity (Candau et al. 1991; Li et al. 1993; Ou 1985; Sidhu 1983; Sunder and Satyavir 1998; Thakur 1974; Wada et al. 1990). In Japan, 56 isolates of *F. moniliforme* collected from different hosts were characterized with respect to mating, production of microconidia, chlamydospores, gibberellins and fusaric acid (Singh and Sunder 2012). Similarly, Thakur (1974) classified 48 isolates Indian isolates of *F. moniliforme* into four groups on the basis of their variable growth rate. Subsequently, Sunder and Satyavir (1998) categorized 28 fungal isolates into five groups based on their virulence and GA_3 production while, Lone et al. (2016) characterized 20 isolates of the pathogen and categorized then into six pathogenic groups based on their reaction pattern on a set of differential rice lines.

In Japan, Wada et al. (1990) reported that the isolates sensitive to ergestrol biosynthesis inhibitors (pefurazoate) and resistant to benomyl did not produce gibberellins but all thoese isolates produced fusaric acid. The less sensitive isolates to triflumizole have been reported to be less pathogenic due to production PF smaller amount of gibberellin like substances (Hamamura et al. 1989). In China, Pan et al. (1997) also reported reduced mycelial growth, sporulation and pathogenicity in carbendazim tolerant isolates.

A wide variation among 66 isolates of *G. fujikuroi* on seedling elongation was reported by Nishikado and Matsumoto (1993). Some of the isolates caused dwarfing of rice seedlings, while the others caused elongation or had no effect on seedlings height. Sharma and Bagga (2007) have also observed variation in symptoms production by four isolates of the pathogen. Puyam et al. (2017) observed that the genetic variability index of 38 isolates of *F. moniliforme*, collected from different Basmati cultivars in Punjab, ranged from 25 to 77% and the isolates were divided into two major clusters. Sunder and Satyavir (1998) and Ma et al. (2008) reported a positive correlation between GA_3 production and bakanae while Thakur (1974) observed a similar relationship between pectic enzymes and foot rot development.

Sensitivity to fungitoxicants

Wide variations in the sensitivity of different strains *of G. fujikuroi* to different fungicides have been reported by several workers. Several strains of *G. fujikuroi* resistant to benzimidazoles (benomyl, carbendazim) and triflumizole have been detected by various workers from Japan (Hamamura et al. 1989; Ishii and Takeda 1989; Ogawa and Takeda 1990; Omatsu et al. 1990) and China (Hollomon et al. 1996). Some of these strains could tolerate as high as 1000 ppm of the benzimidazole fungicides (Yasuda 1986). A considerable amount of variation in sensitivity of the pathogen strains to pefurazoate (Wada et al. 1990), benomyl and hygromycin B (Yan et al. 1993), carbendazim and prochloraz (Chen et al. 2007), methoxy ethyl mercury chloride and carbendazim (Sunder et al. 1998) have been reported. Hamamura et al. (1989) observed that the carbendazim sensitive isolates of the pathogen produced higher quantity of gibberellin like substances and caused high incidence of bakanae while less sensitive isolates produced smaller amount of gibberellin like substances resulting in reduced virulence though both groups produced similar amount of fusaric acid. Chen et al. (2007) reported that resistance in *F. moniliforme* to carbendazim was stable after these strains were transferred 20 times on carbendazim-free potato sucrose agar. However, resistance to prochloraz decreased substantially after passing the strains 5–20 times on fungicide-free medium. Inoculation of plants with a mixture of conidia (1:1) from resistant and sensitive strains revealed that the carbendazim resistant strains had stronger competitive ability than the sensitive ones on rice plants while reverse was observed in prochloraz resistant strains. Iguchi and Takeuchi (1988) reported cross-resistance in benomyl tolerant strains to thiophanate-methyl and thiabendazole.

Heterothallism, genetics, sexuality and heterokaryosis

The members of *G. fujikuroi* species complex are generally heterothallic in which sexual reproduction requires interaction between two mating types having different MAT allele, viz., MAT-1 and MAT-2 allele (Leslie and Summerell 2006). The heterothallic nature of the fungus was confirmed by Snyder and Sun (1973) in the USA and later, Chang and Sun (1975) in Taiwan succeeded in obtaining perithecia by mating two compatible ascospores under artificial condition. Mating information among the isolates of *Fusarium* in section Leiseola provides important information on the genetic diversity and population genetics. *Gibberella fujikuroi* is a species complex comprising of at least 11 different mating populations (MPs) that are denoted by letters A through K. These are MP-A (*F. verticillioides;* Syn: *F. moniliforme*), MP-B (*F. sacchari*), MP-C (*F. fujikuroi*), MP-D (*F. proliferatum*), MP-E (*F. subglutinans*), MP-F (*F. thapsinum*), MP-G (*F. nygamai*), MP-H (*F. circinatum*), MP-I (*F. konzum*), MP-J (*F. gaditjirrii*) and MP-K (*F. xylarioides*) (Kovacevic et al. 2013). Some of these mating populations have been given *Gibberella* species names that parallel the names of their *Fusarium* anamorphs. MP-C (*F. fujikuroi*), first identified from Taiwan (Hsieh et al. 1977), has also been found to cause bakanae in Italy (Amatulli et al. 2010; Dal Pra et al. 2010). The mating populations MP-A and MP-D have been found associated with bakanae disease of rice in Asia; MP-D in Africa, Australia and United states (Gupta et al. 2015) while, other mating populations viz., *F. moniliforme, F. proliferatum, F. verticillioides, F. sacchari* and *F. subglutinans* in Malaysia, Indonesia, Nepal, India, Pakistan, Bangladesh, Iran and Italy (Gupta et al. 2015). Among various mating groups of *F. moniliforme* viz., A, B, C, D, E and F strains of group C are confined to rice (Puhalla and Spieth 1983). In China, out of 37 *Fusarium* isolates of rice, 35 isolates belonged to A, D and F mating populations while two isolates could not be crossed with any of the non-mating populations. In pairing tests of 35 isolates for vegetative compatibility, 25 were heterokaryon and self-compatible and could be classified into 20 vegetative compatibility groups (VCGs). The genetic diversity for the members belonging to D, E and F mating populations were 0.7, 0.8 and 1.0, respectively (Zhang et al. 1998).

Heterokaryosis (vegetative compatibility) has been reported to occur in rice isolates of *F. moniliforme* under laboratory and field conditions (Singh and Sunder 2012) and was studied by using *nit* mutants (Sidhu 1986) and artificially induced auxotrophs (Puhalla and Spieth 1985). Puhalla and Spieth (1983) found that the vegetative compatibility was controlled by nuclear genes (*het* or *vic* genes) and was heterogenic and allelic in all the four mating groups. Group C strains had at least four *vic* loci (Puhalla and Spieth 1985). A total of nine genes were reported for *G. fujikuroi* mating group A. Puhalla and Spieth (1985) identified 12 VCGs among the isolates of group C in China and Taiwan while Sidhu (1986) and Sunder and Satyavir (1998) categorized 38 and 28 isolates of *F. moniliforme* in 13 and 10 VCGs, respectively using *nit* mutants. Isolates from different or same VCGs varied considerably in virulence and GA_3 production. Sunder and Satyavir (1998) did not find any relationship of vegetative compatibility with virulence pattern and GA_3 production. *Nit* mutants, lacking the enzyme nitrate reductase, were recovered on chlorate containing media and their frequency of appearance in culture was strain and environment dependent (Sidhu 1986; Klittich and Leslie 1988). The sectoring frequency on chlorate medium varied between 0.83 and 10/colony in different isolates of *F. moniliforme* from rice (Sunder and Satyavir 1998; Sidhu 1986; Klittich and Leslie 1988) per colony in isolates of mating group A. Klittich et al. (1988) indicated that sectoring is

controlled by many genes. They also reported that *nit* mutations occurred in 7 loci namely, *nit* 1 (a structural gene for nitrate reductase), *nit* 3 (a regulatory gene specific for the nitrate-reduction pathway) and *nit* 2, *nit* 4, *nit* 5, *nit* 6 and *nit* 7 commonly called *Nit* M (genes controlling the production of a molybdenum containing co-factor necessary for nitrate reductase activity). Klittich and Leslie (1988) identified phenotypic classes (*nit* 1, *nit* 3 or Nit M) of *nit* mutants on media containing various nitrogen sources.

Hamamura et al. (1991) observed that triflumizole sensitive isolates representing the same geographical area generally formed a heterokaryon, whereas isolates from different areas were not complementary. Isolates less sensitive to triflumizole were frequently complementary regardless of geographical origin, but these were never complementary with sensitive isolates.

In Spain, Cerda et al. (1994) reviewed the research work done on development of genetic tools for studying *G. fujikuroi* and described the main features of the gibberellin biosynthesis pathway in *Gibberella*. Different workers reported the heterothallic nature of sexual reproduction of *G. fujikuroi* and identified sex factors viz. hermaphrodite, female, male and neuter. Two alleles *A* and *a* controlled the compatibility reactions (Singh and Sunder 2012). Min (1986) confirmed the chromosome number (n = 8) in *F. moniliforme*. Inheritance of mating type, colony colour, morphology and growth rate has been reported to be controlled by single nuclear gene (Sidhu 1983). The gene for colony colour and growth rate were linked whereas, other genes showed independent assortment. Chaisrisook and Leslie (1990) stated that nuclear gene controlling perithecial pigmentation in *G. fujikuroi* was expressed maternally.

Host range

Fusarium fujikuroi has a wide host range. Beside rice, the pathogen is known to attack wheat (Randhawa et al. 1993), mango, pineapple, cotton and pine (Amoah et al. 1995; Singh and Sunder 1997), barley, *Panicum miliaceum* (Rangaswami 1979), sugarcane, maize, sorghum, fig, asparagus (Hsieh et al. 1977). In Taiwan Sun (1975) reported that neither the pathogen strains from rice did infect crops like sugarcane, maize, sorghum and asparagus nor the isolates from these crops infect rice. However, Amoah et al. (1995) reported that maize and rice isolates were cross-pathogenic in Ghana. In China, *F. moniliforme* var. *zhejiangensis* has been found to infect the seedlings of wheat, barley, maize (Luo 1995; Wang et al. 1990), sorghum, sudan grass and soybean (Luo 1995), water melon and pea (Wang et al. 1990). In addition tomato, subabool (*Leucaena leucocephala*), banana, cowpea, barnyard grass and early water grass have also been reported to serve as alternate host of the pathogen (Anderson and Webster 2005; Carter et al. 2008).

Disease cycle

Bakanae is a monocyclic disease. The pathogen is primarily seed borne. Howevere, it can also survive in soil in infected crop residues as thick-walled hyphae or macro-conidia. The soil borne inoculum is of less significance as it is relatively short lived (Watanabe 1974; Singh and Sunder 2012). The fungus is both internally and externally seed-borne and the recovery of the fungus was found to be more in lemma followed by palea (Manandhar 1999; Kumar et al. 2015). The pathogen survived in endosperm and embryo to the extent of 15.00 and 6.25% (Kumar et al. 2015). In India and Pakistan, bakanae incidence and level of highest infestation of *F. moniliforme* in naturally infested samples ranged from 0.5 to 20% (Bashyal et al. 2015) and 21.75% (Raza et al. 1993), respectively. Sowing of 100% infected seeds resulted in production of 30–68.4% diseased seedlings (Yu and Sun 1976; Yasin et al. 2003; Singh et al. 2018). Likewise, the disease spread from infected to healthy seedlings was observed to be 4.4, 5.3 and 6.9% when healthy and infected seedlings were transplanted alternately in a row, in alternate rows and simultaneously in a hill (Singh et al. 2018). In artificially inoculated soil also, the disease development was observed to the extent of 8.5% (Singh et al. 2018).

Seed infection occurs through secondary air-borne conidia and ascospores which are discharged from diseased plants during heading to harvest stage. The fungus grows intercellular in stigma and anthers within 48 h which ultimately reaches and covers the ovary (Kagiwata 1963; Yu and Sun 1976). Fungus remained viable in seeds and infected plants only for 4–10 months (Kanjanasoon 1965). On the other hand, the survival of pathogen in seed has been reported for 10–28 months (Dodan et al. 1994; Misra et al. 1989, Sunder and Satyavir 1997) and for 22–26 months at 10 °C and 40% relative humidity (Manandhar 1999). Seed harvested during wet season had more *G. Fujikuroi* infected seed than those harvested during the dry season regardless of cultivar and number of inoculations with conidial suspension during anthesis (Manandhar 1999).

The fungus infects rice seedlings through roots and the base of the stem and becomes systemic multiplying within the infected tissues. The pathogen was found to be discontinuously distributed in infected seedlings (Nisikado and Kimura 1941; Thomas 1931) with a maximum recovery from the basal 3–4 inches of the stem (Singh and Sunder 2012).

Chan et al. (2004) observed that sprouting period was the most effective period for disease occurrence. They observed positive correlations between disease incidence and soaking

temperature (r = 0.8757) and disease incidence and sprouting temperature (r = 0.9570) in a temperature range of 28–34 °C. The most important sprouting temperature was 34 °C and the most important inoculation time for soaking and sprouting period was 18 and 24 h, respectively. The correlation coefficient between disease incidence and soaking time in these two periods were 0.9620 and 0.8947, respectively. Bud phase was most suitable phase for inoculation of the pathogen.

Sunder and Satyavir (1997) reported that the pathogen also survive in diseased debris for 10–28 months and served as a primary source of inoculum. Though soil inoculum is not very significant in areas where one rice crop is taken in year, the fungus can survive for a limited period in soil through conidia, ascospores, thick-walled hyphae (Sun 1975) and sclerotia (Sharma and Singh 1978). Yu and Sun (1979) reported the survival of *F. moniliforme* up to 280 days in dry soil [10% moisture holding capacity (MHC)], which decreased to 115 days at 45% MHC and only 45–70 days at 100% MHC. Mandal and Chaudhuri 1988) and Sunder and Satyavir (1997) also recorded longer survival of the pathogen in comparatively dry soil (5–10% MHC). On the other hand, Kanjanasoon (1965) observed that survival of pathogen in soil is limited. He reported that freshly inoculated soil resulted in 93% seedling infection while, the percentage of infection drastically reduced to 0.7% and 0.0% after 90 and 180 days of inoculation respectively.

Factors affecting disease development

Intensity of the disease has been aggravated by changes in the climatic parameters. Bakanae incidence was more when rice nursery was raised during summer season and in dry seed beds as high temperature and relatively humidity favoured the disease development. More disease has been reported in upland nurseries than in flooded conditions (Anonymous 1975; Hashioka 1971). In Thialand and Ceylon, disease was found to be more severe in hot season and at low water levels. Mandal and Chaudhuri (1988) reported a reduction in pathogen population in soil due to application of higher dose of nitrogenous fertilizers. Sprouting period has been observed to be the most effective period for disease occurrence (Chan et al. 2004). The most important sprouting temperature was 34° C and the most important inoculation time for soaking and sprouting period was 18 and 24 h, respectively. Bud phase was most suitable phase for inoculation of the pathogen. The grain infection is known to increase at high temperature and poor insolation during flowering (Hino and Furata 1968; Takeuchi 1972).

Rajagopalan and Bhuvaneswari (1964) and Kanjanasoon (1965) found more infection by sowing un-germinated seeds in infested soil in comparison to germinated seeds. The disease incidence has been observed to be more in basmati rice cultivars particularly when the nursery is uprooted under upland/vattar condition (Singh et al. 2018).

Disease management

Host Resistance

Host plant resistance is the most effective and practical approach for disease management. Several rice genotypes have been found resistant to bakanae disease by various researchers under artificial inoculation conditions, which can be utilized as donors for incorporating bakanae resistance in rice cultivars (Table 1).

There is a very limited knowledge on mapped loci governing resistance to bakanae disease. Yang et al. (2006) identified two QTLs viz. QB 1 and QB 10 derived from the chinese japonica cultivar Chunjiang 06 on chromosome 1 and 10 while Naeem et al. (2016) identified qBK1 and qB2 on chromosome 1 and 2 governing resistance to bakanae. Hur et al. (2015) identified a major QTL (qBK1) using NILs derived from a cross between rice varieties Shingwang

Table 1 Rice genotypes showing resistance to foot rot and bakanae

Country	Resistance sources	References
India	CN 1722-4, Haryana Basmati 1, Haryana Mahak, HKR 08-425, HKR 12-406, KMR 1-41, MAUB 2014-1, MAUB 2014-2, NDR 6222, NDR 6345, NP 973-2, Pusa Basmati 1460 (Improved Pusa Basmati 1), Pusa 1557-06-28-188-1-17, RDN 02-01-8-18-11-9, RSK 1045, Shaan, SJR 70-3-2, SJR 129, Super Basmati	Kumar et al. (2016a)
	Co 18, Co 22, Adt 8, PTB 7, GEB 24, GSL-5, GSL-9, GSL-12, GSL-36, GSL-44, GSL-60, GSL-66, GSL-67, GSL-68, IR 20, IR 26, IR 32, IR 38, IR 44, IR 45, Punjab Mehak, Pusa Basmati No.1	Kumar et al. (2014)
	HKR 96-561, HKR 96-565, HKR 07-40, HKR 07-53, HKR 08-13, HKR 08-21, HKR 08-22, MAUB 2009-1, PAU 3456-46-6-1-1, PNR 600, RPDN 01-2-10-9	Sunder et al. (2014)
	Athad, Appunu, BPT 5204, C 101A51, Chandana, Himju, IR 58025B, Panchami, PAU 201, Pusa 1342, Peeli Badam, Suphala, Varun Dhan	Fiyaz et al. (2014)
	GSL-5, GSL-9, GSL-12, GSL-36, GSL-44, GSL-60, GSL-66, GSL-67, GSL-68	Ahangar et al. (2012)
Pakistan	IR 6, KS 133	Ghazanfar et al. (2013)

and Ilpum on long arm of chromosome 1. Subsequently, Fiyaz et al. (2016) detected two novel QTLs viz. qBK1.2 and qBk1.3 on short arm of chromosome 1. The major effect QTL designated as qBK1.2 having 55 annotated genes was mapped on 0.26 Mb region between RM5336 and RM10153. In addition, two novel genomic regions qBk1_628091 and qBK4_317509550 conferring bakanae resistance have also been identified on chromosome 1 and 4 (Volante et al. 2017).

Basmati/scented rice varieties have been found more susceptible to bakanae than the non-scented rice cultivars (Singh et al. 2018). Coarse varieties were more resistant to bakanae disease than the fine ones (Ghazanfar et al. 2013). Rice genotypes carrying dwarf and semi-dwarf genes *d 29, Sd 6* or *Sdq (t)* exhibiting resistance to bakanae disease can be used in developing disease resistant rice cultivars (Ma et al. 2008).

The disease reaction of some genotypes are known to vary with crop stage. In China, Lu (1994) observed that rice genotype Longjiao 86074-6 exhibited resistance at seedling stage and moderate susceptibility at the adult stage. Likewise, genotype Qingxi 96 showed moderately resistant reaction at the seedling stage but resistant at adult stage. However, the rice genotypes namely, Zupei 7, Dongrong 84-21, G-6 and Sui 89-17 were moderately resistant both at seedling and adult stages. Khan et al. (1999) observed that resistance in rice genotype IR 6 was monogenic and recessive while dominant in KS 282.

Agronomic practices

Use of clean non-infected seed, hot water treatment, proper selection of geographical area, time and method of nursery sowing and transplanting, removal and destruction of infected plants from the field and balanced fertilization help in reducing the incidence of bakanae disease by minimizing the inoculum and seed-borne infection of the pathogen (Gupta et al. 2015). Hot water treatment has been found effective in reducing the seed infection and bakanae incidence (Miyasaka et al. 2000; Yamashita et al. 2000). Bagga et al. (2007) recorded minimum disease incidence in July and planted crop owing to the prevalence of lower temperature during infection. Higher levels of nitrogen and potassium and soil amendment with neem cake and press mud have also been found to suppress the bakanae incidence (Kumar et al. 2016a). Seedlings transplanted from nursery box had more bakanae compared to transplanting of rice seedlings from protected nursery (Sung and Yang 1985). Minimizing the root injury by uprooting paddy nursery in standing water has been found helpful in preventing the potential entry of bakanae pathogen and ultimately, in reducing the disease incidence. The disease incidence was significantly low when carbendazim treated and untreated seeds were sown under dry condition compared to conventional method of sowing sprouted seeds in puddled beds (Sunder et al. 2014).

Bio-control and botanical extracts

The work on biological control of bakanae has been reviewd by Kumar et al. (2014) and Gupta et al. (2015). Several fungal and bacterial antagonists and botanical extracts have been reported to suppress the mycelial growth, conidial production & germination of *F. moniliforme* along with a significant reduction in disease incidence (Table 2).

Bhramaramba and Nagamani (2013) and Sharma et al. (2014) reported the antagonistic activity of *Trichoderma*

Table 2 Bio-control agents and botanical extracts found effective against *F. moniliforme*

Bio-control agents/botanicals extracts	Remarks
A. Bio-control agents	
Pseudomonas fluorescens isolates PF-9, PF-13 and *Bacillus thuringiensis* isolate B-44	The antagonists produced lytic enzymes [Chitinase and β-1,3-glucanase {endo-1, 3(4)-β-glucanase}], siderophores, salicylic acid and hydrogen cyanide and suppressed fungal growth & bakanae incidence
*Trichoderma asperellum*SKT-1	-do-
Talaromyces sp. KNB 422	-do-
Bacillus subtilis and *B. megaterium*	-do-
Bacillus subtilis, *Trichoderma harzianum* and *T. virens*	Most effective in reducing bakanae. However, these were inferior to thiophanate methyl thiram 80 WP at 2 g/l
B. Botanicals extracts	
Extract of *Azadirachta indica*, *Decalepis hamiltonii*, *Lawsonia inermis*, *Andrographis paniculata*, *Eucalyptus citriodora*	Inhibited conidial production, germination and mycelial growth of *F. Moniliforme*
Oil of *Hedychium spicatum* and *Acorus calamus*	Completely inhibited the growth at 1.0×10^3 ml/l and 0.5×10^3 ml/l, respectively and exhibited both fungistatic and fungicidal properties depending upon the concentration
Aerated vermicompost tea	Highly effective in controlling the disease in field trials

species to control bakanae disease of rice. Motomura et al. (1997) observed that seed treatment with metabolites produced by five soil-borne bacteria efficiently inhibited bakanae development and were better than benomyl, triflumizole, pefurazoate and prochloraz. Dehkaei et al. (2004) observed that seed treatments with antagonists, such as *Bacillus subtilis, Trichoderma harzianum* and *T. virens*, prior to inoculation was better than their application after seed infection. Dry seed treatment of *T. viride* at 5 g/kg seed before sowing provided about 60% disease control (Kumar et al. 2016b). Lu et al. (1998) reported better efficacy of antagonists applied as seed treatment than spray application. They also observed improved efficacy of bio-control agents when used in combination. Treatment with FYM 10 t/ha + *Trichoderma* + *Pseudomonas* significantly lowered the disease incidence under fields conditions (Wyawahare et al. 2012). Seed treatment with antagonistic yeasts and thermotherapy has given promising results (Matic et al. 2014). Seed treatment and soil incorporation of *Pseudomonas aureofaciens* reduced bakanae incidence by 71.7 to 96.3% (Rosales and Mew 1997). An effective disease control has also been observed by using the bacterial strains B-916 and P-91 in China (Chen et al. 1998). Kazempour et al. (2007) reported that molecular analysis using PCR based RAPD method is useful to differentiate strains of bio-control agents effective against *F. moniforme* at the intraspecific level.

Extracts of *Mimosopus elengi* and *Acacia nilotica* provided more than 85% growth inhibition of *F. moniliforme* (Mohana et al. 2011). Essential oils of *Cymbopogon citratus*, *Ocimum gratissimum* and *Thymus vulgaris* were found highly effective and curtailed the seed-borne infection of bakanae pathogen by 95–100% (Nguefack et al. 2007). In Korea, extract of *Ginkgo biloba* outer seed coat has been reported to provide 80% reduction in bakanae incidence (Oh et al. 2016).

Chemical control

Seed soaking in salt solution has been advocated to reduce the seed-borne inoculum by separating the light-weight, infected seeds from seed lots. Sunder et al. (1998) reported that soaking of seeds in MEMC (0.5 g/l), MEMC 1 g/l) and propiconazole (2 ml/l) solution for 36, 24 and 24 h resulted in complete eradication of the pathogen from grains, respectively. Seed dressing or slurry treatment with benomyl, carbendazim, carbendazim + mancozeb, prochloraz, propiconazole, thiophanate-methyl, benomyl + thiram and thiophanate methyl + thiram, Shibaoke, Jinzhongling, kasugamycin, triforine, prochloraz, prochloraz + carbendazim, mancozeb + benomyl, carboxin + thiram, iprodione, iprodione + triticonazole, ipoconazole, fludioxonil, ferimzone, tebuconazole, trifloxystrobin + tebuconazole and kresoxim methyl have been found effective in reducing bakanae incidence and in enhancing grain yield of rice in different parts of the world. Seed treatment and soil drenching of benzimidazole fungicide Derosal and seed & seedling dip in Bavistin (0.2%) proved highly effective in checking the bakanae disease. Soil drenching with carbendazim and difenoconazole have also been found effective in managing the disease. Seed treatment with Bavistin at 0.05 g + Streptocycline 0.01 g/l water for 12 h and with talc formulation of *T. harzianum* at 15 g/kg of seed and seedling root dip with T. *harzianum* at 15 g/l of water was most effective against bakanae disease (Singh and Sunder 2012; Kumar et al. 2014, 2016b; Gupta et al. 2015; Hossain et al. 2015; Raghu et al. 2018).

The efficacy of fungicides varied with seed treatment method and type of formulations. Wet seed treatment with organo-mercurial fungicides (Takeuchi 1972) and EC formulation of triflumizole (Suzuki et al. 1994) provided better disease control than their dry treatment and WP formulation, respectively. This was due to presence of higher amount of fungicide on the seed and early permeation of EC treatments into seeds through the husk.

Seed dressing with Chitosan S-II, soaking of seeds in 500 ppm of pefurazoate and thermal (72° C for 5 min) and carbendazim treatment provided more than 90% disease control. Fungicides namely, triflumizole, propiconazole, prochloraz, NF 30, pefurazoate, captan + thiabendazole, triflumizole and phenyl pyrrole fungicide CGA 173506 have been reported to be highly effective for controlling benzimidazole (benomyl), thiophanate-methyl and thiobendazole tolerant strains of *F. moniliforme* which are frequently encountered in Japan (Kumar et al. 2014).

Seedling treatment with Bavistin or benomyl at 0.1% for 6 and 8 h has also been found very effective against bakanae (Bagga and Sharma 2006). Propiconazole (Tilt 25 EC) at 0.05% was the most effective treatment in curtailing the disease. However, this fungicide showed phytotoxicity on rice. Foliar application of benzimidazoles (benomyl and carbendazim) at 0.1% significantly reduced the disease incidence, increased the grain yield and reduced the seed-borne infection by *F. moniliforme*. In addition, sand mix application of carbendazim in nursery bed at 1 g/m^2 7 days before uprooting of seedlings and as seedling dip in 0.1% carbendazim solution for 3 h before transplanting has also been reported to impart effective disease control in transplanted crop (Kumar et al. 2014; Sunder et al. 2014).

Conclusion

Foot rot and bakanae of rice is widely distributed throughout the globe. Infected seedlings become lanky, pale yellow and taller than the healthy seedlings which ultimately die and result in substantial reduction in grain yield particularly in

scented rice varieties. The pathogen is primarily seed-borne but also known to survive in soil. Various aspects of the disease have been studied well in different countries. However, further research is necessary on host–pathogen interaction, racial profiling, development and commercialization of highly effective strains of bio-control agents, QTL mapping and virulence pattern, biochemical and molecular aspects of pathogenesis and disease resistance. Besides, characterization of environmental conditions for disease epiphytotics, formation and maturation of perithecia, effect of soil-applied pesticides, soil solarization and flooding on survival of the pathogen, role of internal seed-borne infection and soil-borne inoculum in annual recurrence and epidemiology of the disease need further investigation. An integrated sustainable approach involving development of resistant varieties, use of efficient bio-control agents and effective bio-degradable fungicides along with selection of geographical area for seed production is required for better disease management.

References

Ahangar MA, Najeeb S, Rather AG, Bhat ZA, Parray GA, Sanghara GS, Kashap SC, Ahangar FA, Ahmed H (2012) Evaluation of fungicides and rice genotypes for the management of bakanae. Oryza 49(2):121–126

Amatulli MT, Spadaro D, Gullino ML, Garibaldi A (2010) Molecular identification of *Fusarium* spp. associated with bakanae disease of rice in Italy and assessment of their pathogenicity. Plant Pathol 59:839–844

Amoah BK, Rezanoor HN, Nicholson P, Mac Donald MV (1995) Variation in the *Fusarium* section *Liseola*: pathogenicity and genetic studies of isolates of *Fusarium moniliforme* Sheldon from different hosts in Ghana. Plant Pathol 44:563–572

Anderson LL, Webster RK (2005) A comparison of assays for *Gibberella fujikuroi* and their ability to predict resulting bakanae from seed sources in California. Phytopathology 95(S4):6

Anonymous (1975) Cooperative studies on control of bakanae, brown spot and damping off of rice plant. Rep Chugoku Natl Agric Exp Stn 6:1–77

Anonymous (2018) *Gibberella fujikuroi* (Bakanae disease of rice). https://www.cabi.org/isc/datasheet/25158

Bagga PS, Sharma VK (2006) Evaluation of fungicides as seedling treatment for controlling bakanae/foot rot (*Fusarium moniliforme*) disease in Basmati rice. Indian Phytopathol 59:305–308

Bagga PS, Sharma VK, Pannu PPS (2007) Effect of transplanting dates and chemical seed treatments on foot rot disease of basmati rice caused by *Fusarium moniliforme*. Plant Dis Res 22:60–62

Bashyal BM, Aggarwal R (2013) Molecular identification of *Fusarium* spp. associated with bakanae disease of rice in India. Indian J Agric Sci 83:72–77

Bashyal BM, Aggarwal R, Banerjee S, Gupta S, Sharma S (2014) Pathogenicity, ecology and genetic diversity of the *Fusarium* spp. associated with an emerging bakanae disease of rice (*Oryza sativa* L.) in India. In: Kharwar RN et al (eds) Microbial diversity and biotechnology in food security. Springer, Berlin, pp 307–314

Bashyal BM, Aggarwal R, Sharma S, Gupta S, Rawat K, Singh D, Singh AK, Gopalakrishnan S (2015) Occurrence, identification and pathogenicity of *Fusarium* species associated with bakanae disease of basmati rice in India. J. Plant Pathol Eur. https://doi.org/10.1007/s10658-015-0783-8

Bhramaramba S, Nagamani A (2013) Antagonistic *Trichoderma* isolates to control bakanae pathogen of rice. Agric Sci Digest 33:104–108

Candau R, Avalos J, Cerda-Olmedo E (1991) Gibberellins and carotenoids in the wild type and mutants of *Gibberella fujikuroi*. Appl Environ Microbiol 57:3378–3382

Carter LLA, Leslie FJ, Webster RK (2008) Population structure of *Fusarium fujikuroi* from California rice and water grass. Phytopathology 98:992–998

Cerda OE, Fernandez MR, Avalos J (1994) Genetics and gibberellin production in *Gibberella fujikuroi*. Antonie Van Leeuwenhoek 65(3):217–225

Chaisrisook C, Leslie JF (1990) A maternally expressed nuclear gene controlling perithecial pigmentation in *Gibberella fujikuroi (Fusarium moniliforme)*. J Hered 81:189–192

Chan ZL, Ding KJ, Tan GJ, Zhu SJ, Chen Q, Su XY, Ma K, Wang AE (2004) Epidemic regularity of rice bakanae disease. J. Anhui Agric Univ 31(2):139–142

Chang YC, Sun SK (1975) The perfect stage of *Fusarium moniliforme*. J Agric Res China 24:11–19

Chen ZY, Lu G, Zhao TJ, Yan DF, Wan HZ (1998) Effect of fungicides on antagonistic bacteria from rice seed surface. Chin J Biol Control 14(2):72–74

Chen XJ, Lu GX, Tong YH, Ji Z, Xu JY (2007) Resistance of *Fusarium moniliforme* rice bakanae disease pathogen to three fungicides for seed treatment and competition ability of resistant strains. Acta Phytophylac Sin 34:425–430

Dehkaei FP, Jajaei SM, Rouhani H (2004) Effects of paddy soil antagonistic microorganisms of Guilan on the causal agent of rice bakanae disease. J Sci Technol Agric Nat Res 8(1):213–222

Dodan DS, Singh R, Sunder S (1994) Survival of *Fusarium moniliforme* Sheld. In infected rice grains and its chemical control. Indian J Mycol Plant Pathol 24:135–138

Fiyaz RA, Krishan SG, Rajashekara H, Yadav AK, Bashyal BM, Bhowmick PK, Singh NK, Prabhu KV, Singh AK (2014) Development of high thoroughput screening protocol and identification of novel sources of resistance against bakanae disease in rice (*Oryza sativa*). Indian J Genet 74:414–422

Fiyaz RA, Yadav AK, Gopalakrishnan S, Ellur RK, Bashyal BM, Grover N, Bhowmick PK, Nagarajan M, Vinod KK, Singh NK, Prabhu KV, Singh AK (2016) Mapping quantitative trait loci responsible for resistance to bakanae disease in rice. Rice 9:45. https://doi.org/10.1186/s12284-016-0117-2

Gangopadhyay S (1983) Fusariosis. Current concepts on fungal diseases of rice. Today & Tomorrow's Printers and Publishers, Delhi, pp 193–204

Ghazanfar MU, Javed N, Wakil W, Iqbal M (2013) Screening of some fine and coarse rice varieties against bakanae disease. J Agric Res 51(1):41–49

Gupta AK, Solanki IS, Bashyal BM, Singh Y, Srivastava K (2015) Bakanae of rice-An emerging disease in Asia. J Anim Plant Sci 25:1499–1514

Hamamura H, Kawahara M, Shimoda S (1989) Some characteristics of *Gibberella fujikuroi (Fusarium moniliforme)* isolates less-sensitive to triflumizole. Ann Phytopathol Soc Jpn 55:275–280

Hamamura H, Kawahara M, Shimoda S, Kataoka M (1991) Heterokaryosis of *Gibberella fujikuroi (Fusarium moniliforme)* isolates less sensitive to triflumizole. Ann Phytopathol Soc Jpn 57:387–393

Hashioka Y (1971) Rice diseases in the world. Il Riso 20:235–258

Hino T, Furata T (1968) Studies on the control of bakanae disease of rice plant caused by *Gibberella fujikuroi*. 2. Influence of

flowering season of rice plant on seed transmissibility through flower infection. Bull Chugoku-Shikoku Agric Exp Stn E2:97–102

Hollomon DW, Zhou M, Wang J, Lu Y, Ju L (1996) Selection for carbendazim resistance in *Fusarium* species on wheat and rice in China. In: *Brighton Crop Prot. Conf.: Pests and Diseases-1996, Vol. 2. Proc. Intern. Conf., Brighton, UK,* 18–21 Nov. 1996, Farnham, UK; British Crop Protection Council, p. 707–712

Hossain MS, Ali MA, Mollah M, Khan MAI, Islam AKMS (2015) Evaluation of fungicides for the control of bakanae disease of rice caused by *Fusarium moniliforme* (Sheldon). Bangl Rice J 19:49–55

Hsieh WH, Smith SN, Snyder WC (1977) Mating groups in *Fusarium moniliforme*. Phytopathology 67:1041–1043

Hur YJ, Lee SB, Kim TH, Kwon T, Lee JH, Shin DJ, Park SK, Hwang UH, Cho JH, Yoon YN, Yeo US, Song YC, Kwak DY, Nam MH, Park DS (2015) Mapping of qBK1, a major QTL for bakanae disease resistance in rice. Mol Breed 35:78

Iguchi K, Takeuchi T (1988) Occurrence and control of benomyl resistant strains of *Fusarium moniliforme*, the causal fungus of bakanae disease in Chiba Prefecture. Bull Chiba-Ken Agric Exp Stn 29:115–123

Ishii H, Takeda H (1989) Differential binding of a N-phenyl formamidoxime compound in cell-free extract of benzimidazole-resistant and sensitive isolates of *Venturia nashicole, Botrytis cinerea* and *Gibberella fujikuroi*. Netherland J Plant Pathol 95(suppl. 1):99–108

Ito S, Kimura J (1931) Studies on the bakanae disease of the rice plant. Rep Hokkaido Agric Exp Stn 27:1–95

Jeon YO, Yu SH, Lee YY, Park HJ, Lee S, Sung JS, Kim YG, Lee HS (2013) Incidence, molecular characteristics and pathogenicity of *Gibberella fujikuroi* species complex associated with rice seeds from Asian countries. Microbiology 41(4):225–233

Kagiwata T (1963) Studies on foot rot of the upland rice. Kanagawa Agric Exp Stn Bull 101:1–116

Kanjanasoon P (1965) *Studies on bakanae disease of rice in Thailand. Doc Agric. Thesis,* Tokyo Univ., Japan

Kazempour MN, Tabatabaei SM, Hassanzadeh N (2007) Genetic diversity of antagonistic bacteria against sheath blight and bakanae rice disease by RAPD. Intern J Biol Biotechnol 4:329–333

Khan TZ, Gill MA, Khan MG (1999) Inheritance studies for bakanae disease of rice. Pak J Phytopathol 11:181–182

Khokhar LK (1990) Bakanae and foot rot of rice in Punjab. Pak Intern Rice Res Newsl 15(3):30–31

Kim JH, Kang MR, Kim HK, Lee SH, Lee T, Yun SH (2012) Population structure of the *Gibberella fujikuroi* species complex associated with rice and corn in Korea. Plant Pathol J 28(4):357–363

Klittich CJR, Leslie JF (1988) Nitrate reduction mutants of *Fusarium moniliforme* (*Gibberella fujikuroi*). Genetics 118:417–423

Klittich CJR, Correll JC, Leslie JF (1988) Inheritance of sectoring frequency in *Fusarium moniliforme* (*Gibberella fujikuroi*). Exp Mycol 12:289–294

Kovacevic T, Levic J, Stankovic S, Vukojevic J (2013) Mating populations of *Gibberella fujikuroi* (Sawada) S. Ito species complex isolating from maize, sorghum and wheat in Serbia. Genetika 45(3):749–760

Kumar P, Singh R, Sunder S (2014) Variability and management of *Fusarium fujikuroi* causing foot rot and bakanae disease of rice. J Mycol Plant Pathol 44:227–236

Kumar P, Sunder S, Singh R (2015) Survival of *Fusarium moniliforme* causing foot rot and bakanae disease in different parts of rice grains. Indian Phytopathol. 68:454–455

Kumar P, Sunder S, Singh R, Kumar A (2016a) Management of foot rot and bakanae of rice through non-chemical methods. Indian Phytopathol. 69:16–20

Kumar P, Sunder S, Singh R, Kumar A (2016b) Management of foot rot and bakanae of rice through fungicides. Indian Phytopathol. 69:124–127

Laha GS, Sailaja B, Srinivas Prasad M, Ladhalakshmi D, Krishnaveni D, Singh R, Prakasam V, Yugander A, Kannan C, Valarmathi P, Ravindra Babu V (2016) Changes in rice disease scenario in India: an analysis from production oriented survey. Technical bulletin No. 91. ICAR-Indian Institute of Rice Research, Rajendranagar, p 95

Leslie JF, Summerell BA (2006) The *Fusarium* laboratory manual. Blackwell Publishing, Ames

Li DJ, Luo K, Chen Z (1993) Studies on resistance of rice varieties to bakanae disease and pathogenicity of pathogen (*Fusarium moniliforme*). Acta Phytopath Sin 23(4):315–319

Lone ZA, Bhat ZA, Najeeb S, Ahanger MA, Bhat SJA, Shikari AB, Anwar A, Bhat MA (2016) Pathogenic variability of *Fusarium fujikuroi* causing bakanae disease of rice (*Oryza sativa* L.). Curr Trends Biotechnol Pharm 10:309–315

Lu B (1994) Preliminary report on evaluation of resistance to rice bakanae disease in rice germplasms. Plant Prot. 20(3):20–21

Lu F, Chen ZY, Chen YL, Qin JH, Din Z (1998) Screening of biological control agents against *Fusarium moniliforme* and determination of their biological activity. Jiangsu J Agric Sci 14(3):149–153

Luo JG (1995) Studies on pathogenic *Fusarium* species of rice bakanae disease and strains. Chin J Rice Sci 9(2):119–122

Ma LY, Ji ZJ, Bao JS, Zhu XD, Li XM, Zhuang JY, Yang CD, Xia YW (2008) Responses of rice genotypes carrying different dwarf genes to *Fusarium moniliforme* and gibberellic acid. Plant Prod Sci 11(1):134–138

Manandhar J (1999) *Fusarium moniliforme* in rice seeds: its infection, isolation and longevity. Z Pflkrankh Pflschutz 106:598–607

Mandal DN, Chaudhuri S (1988) Survivality of *Fusarium moniliforme* Sheld. under different moisture regimes and soil conditions. Intern JTrop Plant Dis 6:201–206

Matic S, Spadaro D, Garibaldi A, Gullino ML (2014) Antagonistic yeasts and thermotherapy as seed treatments to control *Fusarium fujikuroi* on rice. Biol Control 73:59–67

Min BR (1986) Chromosomal studies on the genus *Fusarium*. Korean J Mycol 14:253–256

Misra JK, Gergon E, Mew TW (1989) How long do fungal pathogens survive in/on rice seeds? Rice Seed Health Newsl. 1(1):6

Miyasaka A, Ryoichi S, Masataka I (2000) Control of the bakanae disease of rice by soaking seeds in hot water for the hydrophonically raised seedling method in the long mat type rice cultivation. Proc Kanto-Tosan Plant Prot Soc 47:31–33

Mohana DC, Prasad P, Vijaykumar V, Raveesha KA (2011) Plant extracts effect on seed-borne pathogenic fungi from seeds of paddy grown in southern India. J Plant Prot Res 51:101–106. https://doi.org/10.2478/v10045-10-0018-8

Motomura M, Suwa S, Hirooka EY (1997) Biological control: microbial versus chemical fungicides on growth of rice infected with *Fusarium moniliforme*. Rev Microbiol 28(1):11–16

Naeem M, Iqbal M, Parveen N, Ul-Allh S, Abbas Q, Rehman A, Shauket MS (2016) An overview of bakanae disease of rice. Am Eur J Agric Environ Sci 16:270–277

Ngueffack J, Nguikwie SK, Fotio B, Dongmo VL, Nkengfack AE, Zollo PHA (2007) Fungicidal properties of essential oils and fractions from *Cymbopogon citratus*, *Ocimum gratissimmum* and *Thymus vulgaris* to control *Alternaria padwickii* and *Bipolaris oryzae*, two seed-borne fungi of rice (*Oryza sativa* L.). J. Essential Oil Res. 19:581–587

Nirenberg HI (1976) Untersuchungen uber die morphologische und biologische differenzierung in Fusarium-Sektion Liseola, vol 169. Mitt. Biol. Bundesansi. Land-Forstwirtsch, Berlin, pp 1–117

Nirenberg HI, O'Donnell K (1998) New *Fusarium* species and combinations within the *Gibberella fujikuroi* species complex. Mycologia 90:434–458

Nisikado Y, Kimura K (1941) A contribution to the pathological anatomy of rice plants affected by *Gibberella fujikuroi* (Saw.) Wr. I. Ber Ohara Inst Landw Forsch 8:421–426

Nisikado Y, Matsumoto H (1993) Studies on the physiological specialization of *Gibberella fujikuroi* the causal fungus of rice bakanae disease. Trans Tottori Soc Agric Sci 4:200–211

Ogawa K, Takeda S (1990) Population of benomyl-resistant rice bakanae fungus in paddy fields. Ann Phytopathol Soc Jpn 56:247–249

Oh TS, Park YJ, Kim C, Cho YK, Jang MJ (2016) Effect of seed disinfection of bakanae disease in *Ginkgo biloba* outer seed coat extract. Emirates J Food Agric 28:671–675

Omatsu N, Izumi S, Shinyashiki I (1990) Occurrence of benomyl resistant strains of *Gibberella fujikuroi* in Kagoshima Prefecture and control of bakanae disease of rice seed by seed disinfection. Proc Assoc Plant Prot Kyushu 36:5–7

Ou SH (1985) Rice diseases, 2nd edn. CMI, Kew, pp 262–272

Pan Y, Wang ZY, Wu HZ (1997) Mycelial growth, sporulation and pathogenicity of *Fusarium moniliforme* isolates with differential resistance to carbendazim (MBC). Jiangsu J Agric Sci 13(2):90–93

Pra Dal, Tonti MS, Pancaldi D, Nipoti P, Alberti I (2010) First report of *Fusarium andiyazi* associated with rice bakanae in Italy. Plant Dis 94:1070

Puhalla JE, Spieth PT (1983) Heterokaryosis in Fusarium moniliforme. Exp Mycol 7:328–335

Puhalla JE, Spieth PT (1985) A comparison of heterokaryosis and vegetative incompatibility among varieties of *Gibberella fujikuroi (Fusarium moniliforme)*. Exp Mycol 7:39–47

Puyam A, Pannu PPS, Kaur J, Sethi S (2017) Cultural, morphological and molecular variability of *Fusarium moniliforme* Sheld. causing foot rot disease of Basmati rice in Punjab. J Mycol Plant Pathol 47:369–381

Raghu S, Yadav MK, Prabhukarthikeyan SR, Baite MS, Lenka S, Jena M (2018) Occurrence, pathogenicity, characterization of *Fusarium fusikuroi* causing rice bakanae disease from Odisha and in vitro management. Oryza 55:214–223

Rajagopalan K, Bhuvaneswari K (1964) Effect of germination of seeds and host exudations during germination on foot rot disease of rice. Phytopathol Z 50:221–226

Randhawa HS, Sharma HL, Aulakh KS (1993) Incidence of *Fusarium moniliforme* on developing wheat seed. Plant Dis Res 8:59–61

Rangaswami G (1979) Diseases of cereals. Diseases of crop plants in India, 2nd edn. PHI Learning Pvt. Ltd, Delhi, pp 158–160

Raza T, Ahmed MI, Nasir MA (1993) Extent of infection of *Fusarium moniliforme* Sheld. in different rice seed samples and in vitro effect of certain fungicides on the fungus. Sarhad J Agric 9:231–233

Rosales AM, Mew TW (1997) Suppression of *Fusarium moniliforme* in rice by rice-associated antagonistic bacteria. Plant Dis 81:49–52

Sharma VK, Bagga PS (2007) Pathogenic behaviour of *Fusarium* moniliforme isolates causing foot rot disease in Basmati rice. Plant Dis Res 22:165–166

Sharma RD, Singh RS (1978) Survival of *Fusarium moniliforme* in soil. Indian Phytopathol. 31:352–356

Sharma P, Sharma M, Raja M, Shanmugam V (2014) Status of *Trichoderma* research in India: a review. Indian Phytopathol 67:1–19

Sidhu GS (1983) Genetics of *Gibberella fujikuroi*. I. Inheritance of certain cultural traits. Can J Genet Cytol 25:93–96

Sidhu GS (1986) Genetics of *Gibberella fujikuroi*. VIII. Vegetative compatibility groups. Can J Bot 64:117–121

Singh R, Sunder S (1997) Foot rot and bakanae of rice: retrospects and prospects. Intern J Trop Plant Dis 15:153–176

Singh R, Sunder S (2012) Foot rot and bakanae of rice: an overview. Rev Plant Pathol 5:505–604

Singh R, Sunder S, Kumar P, Ram M, Sekhar C (2018) Study of bakanae disease of rice in Haryana. Plant Dis Res 33:15–22

Snyder WC, Sun SK (1973) Heterothallism in *Fusarium moniliforme*. Report. US-ROC cooperative science seminar on plant root diseases. University of California, Berkeley

Sun SK (1975) The disease cycle of rice bakanae disease in Taiwan. Proc Natl Sci Council 8(2):245–256

Sun SK, Snyder WD (1978) The bakanae disease of rice plant. Sci Bull Taiwan 10:7

Sunder S, Satyavir S (1997) Survival of *Fusarium moniliforme* in soil, grains and stubbles of paddy. Indian Phytopathol. 51:47–50

Sunder S, Satyavir S (1998) Vegetative compatability, biosynthesis of GA_3 and virulence of *Fusarium moniliforme* isolates from bakanae disease of rice. Plant Pathol 47:767–772

Sunder S, Satyavir S, Singh A (1998) Evaluation of fungicides for the management of bakanae disease of rice. J Mycol Plant Pathol 28:251–258

Sunder S, Singh R, Dodan DS (2014) Management of bakanae disease of rice caused by *Fusarium moniliforme*. Indian J Agric Sci 84:48–52

Sung JM, Yang SS (1985) Occurrence of bakanae disease by *Fusarium moniliforme* associated with different seedling methods. Kor J Mycol 13:23–26

Suzuki M, Hamamura H, Iwamori M (1994) Relationship between formulations of triflumizole and their efficacy to bakanae disease in rice seed treatmant. J Pestic Sci 19(4):251–256

Takeuchi S (1972) Climatic effect on seed infection of rice plant with bakanae disease and disinfection with organic mercury compounds. Proc Kansai Plant Prot Soc 14:14–19

Thakur KSS (1974) Role of gibberellic acid, fusaric acid and pectic enzymes in the foot-rot disease of rice. Il-Riso 23:191–207

Thomas KM (1931) A new paddy disease in Madras. Madras Agric J 19:34–36

Volante A, Tondelli A, Aragona M, Valente MT, Biselli C, Desiderio F, Bagnaresi P, Matic S, Gullino ML, Infantino A, Spadaro D (2017) Identification of bakanae disease resistance loci in japonica rice through genome wide association study. Rice 10:29. https://doi.org/10.1186/s12284-017-0168-z

Wada T, Kuzuma S, Takenaka M (1990) Sensitivity of *Fusarium moniliforme* isolates to pefurazoate. Ann Phytopathol Soc Jpn 56:449–456

Wang GC, Chen HK, Xu PS, Bao JY (1990) Studies on the pathogens of rice bakanae disease in Zhejiang. Acta Phytopath Sin 20(2):93–97

Watanabe Y (1974) The possibility of soil transmission of bakanae disease and the contamination of seeds with causal fungus during the hastening process of seed germination. Bull Tokai-Kinki Natl Exp Stn 27:35–41

Webster RK, Gunnell PS (1992) Compendium of rice diseases. APS Press-Science, San Antonio, p 62

Wulff EG, Sørensen JL, Lübeck M, Nielsen KF, Thrane U, Torp J (2010) *Fusarium* spp. associated with rice bakanae: ecology, genetic diversity, pathogenicity and toxigenicity. Environ Microbiol 12:649–657

Wyanwahare KK, Sharma OP (2012) Field evaluation of *Trichoderma* and *Pseudomonas* against bakanae disease of rice caused by *Fusarium fujikuroi*. Indian Phytopathol. 65:56

Yamashita T, Eguchi N, Akanuma R, Saito Y (2000) Control of seedborne diseases of rice plants by hot water treatment of rice seeds. Ann Rep Kanto-Tosan Plant Prot Soc 47:7–11

Yan KY, Dickman MB, Yu JR, Leslie JF (1993) Sensitivity of field strains of *Gibberella fujikuroi (Fusarium* section *Liseola)* to benomyl and hygromycin B. Mycologia 85:206–213

Yang CD, Guo LB, Li XM, Ji ZJ, Ma LY, Qian Q (2006) Analysis of QTLs for resistance to rice bakanae disease. Chin J Rice Sci 20(6):657–659

Yasin SI, Khan TZ, Akhtar KM, Muhammad A, Mushtaq A (2003) Economic evaluation of bakanae disease of rice. Mycopath. 1(2):115–117

Yasuda Y (1986) Present situation on benzimidazole resistance of *Gibberella fujikuroi* and *Botrytis cinerea* in Japan. ISPP Chem Control Newsl 7:8–9

Yu KS, Sun SK (1976) Ascospore liberation of *Gibberella fujikuroi* and its contamination of rice grains. Plant Prot Bull Taiwan 18:319–329

Yu SM, Sun SK (1979) Variation of *Fusarium moniliforme*. Plant Prot Bull Taiwan 21:341–350

Zhang CL, Zheng Z, Wang GC (1998) Genetic diversity in *Gibberella fujikuroi* (*Fusarium* section *Liseola*) from rice. J Zhejiang agric Univ 24(6):583–586

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.