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REVIEW ARTICLE

Past, present and future of rice blast management

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Abstract

Blast disease caused by fungal pathogen *Magnaporthe oryzae* is the most severe disease of rice (*Oryza sativa* L). On an estimate it annually destroys rice, which can feed around 60 million people. Keeping in view the importance of the disease, various management strategies like controlled use of nitrogen fertilizers, application of silica and flooding of paddy fields are the practices in use to reduce the rice blast since long time. Improved chemical methods include utilization of copper fungicides, organomercuric and organophosphorus compounds. Some antibiotics *e.g.*, Blasticidin S and Kasugamycin and many systemic and site specific fungicides including melanin biosynthesis inhibitors and plant activators were also utilized effectively for blast management. In the recent years leaf extracts of tulsi and bael have been found effective. Due to the highly variable nature of *M. oryzae*, exploitation of durable host resistance has remained a challenging job for plant pathologists and breeders. Lots of efforts have been made worldwide to study the variability in the pathogen and to find out the resistance sources. To date approximately 100 R genes for blast resistance have been mapped and 20 of these genes have been cloned in rice. Now, scientists are looking forward to develop durable resistant varieties through pyramiding of quantitative trait loci and major genes. Among the biocontrol agents, different strains of *Bacillus* spp. and *Streptomyces sindeneusis* are in use. The availability of rice and *M. oryzae* genome sequence data are facilitating blast resistance management program to new paradigms which includes isolation and characterization of R and Avr genes, development of noble fungicides, transformed bioagents, transgenic rice and durable resistance.

Keywords: rice; blast; resistance management

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Introduction

Rice (*Oryza sativa* L.) is the world's most important crop and a primary source of food for more than half of the world's population. More than 90% of the world's rice is grown and consumed in Asia where 60% of the earth's people live (Kole, 2006). Globally rice occupies an area of 163 m ha with a production of 719 m t of paddy (FAO, 2012). Rice is known to be attacked by many pests and diseases which cause huge losses annually worldwide. Among fungal diseases of rice, rice blast caused by *Magnaporthe oryzae* is of significant economic importance.

Outbreaks of rice blast are a serious and recurrent problem in all rice growing regions of the world. It is estimated that each year enough of rice is destroyed by rice blast alone to feed 60 million people (Zeigler, Leong, & Teng, 1994). Rice blast probably the disease known as rice fever disease in China as early as 1637 and then reported in Japan in 1704, Italy 1828, USA 1876 and in India in 1913 (Ou, Nuque, Ebron, & Awoderu, 1971). It is a disease of immense importance in temperate, tropical, subtropical Asia, Latin America and Africa and found in approximately 85 countries throughout the world.

Blast is known to attack nearly all above ground parts as well as during all growth stages of plant. Recent reports have shown that the fungus has the capacity to infect plant roots also (Sesma & Osbourn, 2004). The disease is weather driven and the pathogen is highly variable. The infection of rice blast occur when fungal spores land and attach themselves to leaves using a special adhesive released from the tip of each spore (Hamer, Howard, Chumley, & Valent, 1988). The germinating spore develops an appressorium, a specialized infection cell which generates enormous turgor pressure (up to 8MPa) that ruptures the leaf cuticle, allowing invasion of the underlying leaf tissue (Dean, 1997; Hamer *et al*., 1988). Subsequent colonization of the leaf produces disease lesions from which the fungus sporulates and spreads to new plants. When rice blast infects young rice seedlings, whole plants often die, whereas spread of the disease to the stems, nodes or panicle of older plants results in nearly total loss of the rice grain (Talbot, 2003). Different host-limited forms of *M. oryzae* also infect a broad range of grass species including wheat, barley and millet.

Life cycle of *Magnaporthe oryzae*

Asexual spores called conidia germinate and develop a specialized infection structure, the appressorium. Invasive growth within and between cells culminates with sporulation and lesion formation. Sexual reproduction occurs when two strains of opposite mating type meet and form a perithecium in which ascospores develop. Once released, ascospores can develop appressoria and infect host cells.

Rice Blast Management

Many of the control practices useful in reducing plant diseases are of limited use to control rice blast. Since blast is present in most rice growing areas, and it has such a wide host range, eradication and crop rotation are of little value. Although exclusion may appear to be a useless concern, one should keep in mind that pathogen is quite variable and that virulence factors present in one population may not be present in another geographically isolated one. It is probably worth to make sure that rice material moved from one area to another is healthy. Lots of work on developing effective rice blast management strategies has been done over a century. The control measures found effective and utilized in the fields are described below. They can be broadly classified as:

1. Cultural Control
2. Chemical Control
3. Host Resistance
4. Biological Control

Cultural Control

When there were no methods of disease management in the past, cultivation practices were the only mean to control the diseases. These include nutrient management, water management, time of planting, spacing etc.

Nutrient Management

In case of rice blast, two nutrients *viz*. Nitrogen and Silicon have been found to affect the disease occurrence and development significantly. Since long time back, studies have shown that high N supply always induces heavy incidence of rice blast (Hori, 1898). Delayed or large top dressings are often responsible for severe disease. (Murata, Kuribayashi, & Kawai, 1933; Ikeda, 1933). A limit of 15 kg N/ha is recommended for upland rice in Brazil, specifically to reduce vulnerability to blast (Prabhu & Morais, 1986). Plant receiving large amount of N are found to have fewer silicated epidermal cells and thus have lower resistance (Miyake & Ikeda, 1932) The correlation between silica content and disease incidence was also studied on different cultivars of rice and it was observed that plants with high silica content or large number of silicated epidermal cells had slight damage from blast disease (Onodera, 1917). So it is suggested that resistance of rice to blast can be increased by applying silica slag in the field (Kawashima, 1927). Studies conducted at University of Florida USA, showed that reduction in the rice blast with the application of silica (calcium silicate slag) was comparable to that of fungicide (Benomyl) and now silicon fertilization has become a routine practice in Florida rice production (Datnoff, Deren, & Snyder, 1997). In 1980, Singh & Singh reported that application of water hyacinth compost to soil reduces the rice blast disease.

Water Management

The availability of water also affects the susceptibility of host plant to *P. oryzae*. Rice grown under upland conditions is more susceptible than rice grown in flooded soil (Kahn & Libby, 1958). Under upland conditions, susceptibility is increased further with increasing drought stress. Hence flooding the field in upland rice can reduce the severity of blast.

Time of Planting

Planting time also has a marked effect on the development of blast within a rice crop. For rice blast control early planting is recommended. In tropical upland rice, crops sown early during the rainy season generally have a higher probability of escaping blast infection than late-sown crops, which are often blasted severely. In upland areas of Brazil, farmers are advised to sow early to escape inoculum produced on neighbouring farms (Prabhu & Morais, 1986).

Chemical Control

Chemicals, mainly fungicides are the most frequently and widely used method of plant disease management worldwide. For rice blast most aggressive and successful chemical control program in world has been shown by Japan. The copper fungicides were first effectively used in Japan shortly after the turn of the century and continued to be used until the Second World War (Thurston, 1998) but as they are highly phytotoxic, a more attractive alternative was sought. Subsequently, copper fungicides were used in mixture with phenylemercuric acetate (PMA) which was more effective than copper alone in rice blast control and were less toxic to the rice plant. Later, discovery was made by Ogawa (1953) that a mixture of PMA and slaked lime provides much more effective control of rice blast and was less toxic and cheap, hence used extensively. However these fungicides are toxic to mammals and are severe environmental pollutants, so banned by Japanese Government in mid 1968 (Ou, 1985).

Then the Organophosphorus fungicides were introduced to control blast in Japan but in the late 1970's the reports of resistance in *P. oryzae* to these compounds started emerging. Further studies revealed that resistance to one organophosphorus fungicide did not necessarily confer resistance to other specific fungicides. So it was suggested that rotating the use of fungicides or mixing them, rather than continuously relying on single compound, greatly reduces the risk of developing highly resistant populations (Uesugi, 1978). At the same time development and implication of new systemic fungicides was also on progress. The phosphorothiolate fungicides, including iprobenfos and edifenphos, were introduced in Japan as rice blast fungicides in 1963. Iprobenfos and isoprothiolane have systemic action and are used mainly as granules for application on the surface of paddy water (soil application).

Copper fungicides were found effective for rice blast control in India as well, but it was seen that high yielding varieties (HYVs) were copper-shy, hence the emphasis was shifted to another group of fungicides *viz*., Dithiocarbamate and Edifenphose but they were having shorter residual activity. So in 1974-75, the first generation systemic fungicides Benomyl, Carbendazim and others were evaluated and found effective. Following these, many systemic fungicides with different mode of action, like anti-mitotic compounds, melanin inhibitors, ergosterol biosynthesis inhibitor (EBI) and other organic compounds were discovered for rice blast control (Siddiq, 1996). In a chemical scheduling trial Bavistin 1g/L spray at tillering + Hinosan 1g/L at heading and after flowering provided the best yield increase. Tricyclazole and Pyroquilon fungicides as seed dressers have been found effective to provide protection to seed upto 8 weeks after sowing.

Some of the recently developed chemicals for blast control are:

1. Carpropamid (1999, melanin biosynthesis inhibitor)
2. Fenoxanil (2002, melanin biosynthesis inhibitor)
3. Tiadinil (2004, plant activator)

In the most recent field evaluation of commercial fungicidal formulations Rabicide (tetrachlorophthalide), Nativo (tebuconazole + trifloxystobin) and Score (difenoconazole) are found most effective (Usman, Wakil, Sahi, & Saleem, 2009). The site specific fungicides are recommended to be used in mixture or in rotation due to the development of resistance in the pathogen. The non fungicidal agents are supposedly specific to the target organism and are less likely to lead to resistance problems (Yamaguchi, 2004).

Antibiotics

The first antibiotic which was found to inhibit the growth of rice blast fungus on rice leaves was 'cephalothecin', produced by a species of *Cephalothecium* (Yoshii, 1949). Following this, 'antiblastin' (Suzuki, 1954), 'antimycin-A' (Harada, 1955), 'blastmycin' (Watanabe *et al*., 1957) and 'blasticidin-A' (Fukunaga, Misato, Ishii, Asakawa, & Katagiri, 1968) were found and tested but due to their chemical instability and toxicity to fish none of them was put to practical use. Then in 1955 a new systemic antibiotic, Blasticidin S was developed by Fukunaga which is produced by *Streptomyces griseochromogenes*. It was found to be superior for blast control and effective mainly in post-infectional control. But it was an inferior protectant and highly toxic to plants and mammals (Ou, 1985). Shortly after the discovery of blasticidin S a new antibiotic Kasugamycin, produced by *Streptomyces kasugaensis* was discovered. It gave excellent control of rice blast and had very less toxicity to mammals and rice plant (Okamoto, 1972). In around 1970, in the areas where the antibiotics have been used extensively and exclusively for blast control, population of *P. oryzae* began to show resistance to antibiotic compounds (Uesugi, 1978). However after halting the use of antibiotics in the areas with resistant populations of *P. oryzae*, the population of resistant types reduced to nearly zero and later the use of antibiotics in some areas successfully resumed (Uesugi, 1978). Katagiri & Uesugi (1978) reported the frequency of emergence of resistant mutants of *P. oryzae* against different chemicals. It was highest in kasugamycin, followed by IBP, edifenphose and isoprothiolane, and was lowest in benomyl.

Forecasting

Van Der Plank (1963) quoted that "Chemical industries and plant breeders forge fine tactical weapons but only epidemiology sets the strategy". So the good knowledge of epidemiology of a disease can help to utilize the available disease management strategies in a better way. For the economic and most effective use of fungicides it is best to follow the forecast. In the early works many studies on methods of forecasting have been made, based upon the information on fungus, host plant and environment (Ou, Nuque, Ebron, & Awoderu, 1971). Using 13 year data, Padmanabhan (1963) concluded that whenever the minimum temperature of 24°C or below was associated with RH of 90% or above, the conditions were favourable to blast infection. Attempts to correlate spore content and blast incidence was also done India. Later on EI Refaei (1977) found that number of lesions was more closely correlated with the dew point than the number of air born spores. Today number of computer simulation based forecast models are available such as:

1. LEAFBLAST (Choi, Park, & Lee, 1988)
2. EPIBLAST (Kim & Kim, 1993)
3. EPIBLA (Manibhushanrao & Krishnan, 1991)

The recent work on forecasting, through machine learning technique based on support vector machines

(SVM) method have been found better than existing machine learning technique and conventional multiple regression (REG) approaches in forecasting plant diseases. An online SVM based web-server for rice blast prediction was the first of its kind worldwide and helping the plant science community and farmers in their decision making process (Kaundal, Kapoor, & Raghava, 2006).

Botanicals

In the recent years, some botanicals were evaluated for their antifungal activity against *P. oryzae* and few of them were found very effective. The leaf extract of *Atalantia monophylla* was found to control disease up to 82.22% followed by *Plumbago rosea*, 70.57%. The biochemical studies showed that *A. monophylla* have higher content of phenols (4.8 mg/g) and flavinoids (24.5 mg/g) compared to others (Parimelazhagan, 2001). In India, in the same year *i.e.* in 2001 experiments conducted at UAS Dharwad, to find out best bioagents, fungicides and neem based formulations showed the neem based formulations such as Nimbicidine and Neem gold were most effective among the tested ones. At CRRI Cuttak, *Ocimum sanctum* (Tulasi) and *Aegle marmelos* (Bael) were found very effective in blast control. When tried on field the plots treated with leaf extracts of bael and tulsi had only 2% disease intensity as compared to Henosan treated (25% DI) and control (85%DI) (CRRI 2007-08).

Host Resistance

Exploitation of host resistance is the most cost-effective and reliable method of disease management. In some instances, resistant varieties have provided effective and durable disease control. But in the case of rice blast, success is short-lived or not easily achieved. It is because of the presence of lineages (that may consist of different physiologic races) overcoming host resistance (IRRI, 2010).

Early studies on host resistance were more concentrated on nature of resistance. Miyake and Ikeda (1932) reported that the cultivar Bozu, resistant to rice blast contains a large amount of silicon than the susceptible cultivar. Further studies showed that degree of resistance increases in proportion to the amount of silica applied and also to the amount of silicon accumulated in the plant. Ito & Sakamoto (1939) found that resistance to mechanical puncture of the leaf epidermis was positively related with resistance to blast. They found that puncture resistance was reduced by application of nitrogen fertilizer and by low soil moisture, but was increased as the plant become older. Hori, Arata, & Inoue (1960) reported that distribution of starch in the leaf sheath is related to resistance *i.e.* longer accumulation indicates more resistance. It is known that resistance to penetration of fungus is obviously less important than resistance to its spread within the host plant after penetration. A hypersensitive reaction is common in resistant cultivars. Kawamura and Ono (1948) were able to isolate *P. oryzae* from hypersensitive lesion 2 days after inoculation but not after 4 days.

Low toxins pyricularin and α-picolinic acid produced by *P. oryzae* are toxic to rice plant and cause stunting of seedlings, leaf spotting and other injurious effects. Earlier, Tamari & Kaji (1955) found that when combined with chlorogenic acid or ferulic acid, both present in the rice plant, they (pyricularin & α-picolinic acid) become nontoxic to rice plant. So they believed that ability of rice plant to biosynthesize chlorogenic acid is related to resistance. All these findings not only generated the knowledge of host pathogen interaction but also contributed in searching resistance sources and setting the strategies of breeding for blast resistance.

First most important step in resistance breeding is the evaluation of germplasm for disease resistance sources. In 1969, Link and Ou proposed a system of standardization of race numbers of *P. oryzae*. IRRI also stepped forward and planted uniform blast nurseries in 50 testing stations in 22 different countries for pathogen race evaluation and till 1975 more than 260 physiologic races of *P. oryzae* were reported from the different parts of world. Resistance to *P. oryzae* in rice is usually dominant and controlled by one or few pairs of genes (Thurston, 1998). At IRRI in 1979 almost 1,00,000 lines and accessions were tested and no single one was found to be completely resistant to all races. Host plant resistance can be broadly categorized as:

1. Vertical Resistance
2. Horizontal Resistance

Vertical Resistance: Vertical Resistance (also known as Complete resistance, specific resistance or true resistance), in which the pathogen fails to produce sporulating lesions, can be manipulated easily by breeders. But it also has been known to break down, sometimes with serious economic consequences. In Korea, the resistance of the Tongil varieties was effective for 5 years before a virulent race appeared in 1976 (Lee, Kim, & Ryn, 1976). The variety Reiho had complete resistance to Japanese races upon its release in Japan in 1969. Its area of cultivation increased until 1973, when it was damaged severely by blast (Matsumoto, 1974). In Japan, the longevity of complete resistance seems to be about 3 years. Similarly, when var. Reiho was later released in Egypt as a blast resistant variety in 1984, it occupied about 25% of the rice crop area within a year But resistance was overcome in the first year, resulting in a blast epidemic of some consequence (Bonman & Rush, 1985). In Colombia, a series of resistant varieties was released from 1969 to 1986, but their resistance lasted only a year or two before being overcome by previously unidentified virulent races (Ahn & Mukelar, 1986).

Horizontal resistance: Assuming the gene-for-gene relationship (Flor, 1956) and given the variability of the pathogen, it is not difficult to understand why the effectiveness of complete blast resistance is short-lived. It has been observed that when complete resistance was overcome by the pathogen, usually some level of residual resistance remains. This residual resistance has been referred to variously as, horizontal resistance (HR), general resistance, field resistance, slow-blasting, and partial resistance, among others. The general, HR to *P. oryzae* was reported in 1971 (Ou *et al*., 1971). Efforts to identify, characterize and exploit this type of resistance which is effective against all races of pathogen were undertaken by IRRI. But the 1978 epidemic of *P. oryzae* in Korea altered the attitude of IRRI breeders and pathologists towards HR. The improved indica-japonica hybrid rice cultivars grown in Korea were possessing vertical (monogenic) as well as horizontal (polygenic) resistance suddenly became susceptible to *P. oryzae* in 1978 (Crill, Ham, & Beachell, 1982). Korean pathologists had defined the HR as varieties with disease ratings 4-5. Since HR studies in Korea (Crill *et al*., 1982) may have been defined qualitatively and not quantitatively, the Korean experience should not be used as a reason to discontinue the search for rice cultivars with HR (Thurston, 1998).

There are many examples of partial resistance that appear to be effective and durable under field conditions. The varieties IR36 and IR50 are susceptible to the same races of *P. oryzae* (Bonman, De Dios, & Khin, 1986), but when inoculated with the same isolates, IR36 produces fewer and smaller lesions than does IR50 (Yeh & Bonman, 1986). These differences in partial resistance were evident both in blast nursery miniplot tests and under field conditions.

Philippines and in other Asian countries in blast nursery miniplot tests and under field conditions in the Philippines and in other Asian countries. Frequently, the main strategy of breeder and pathologist, given the choice, is to save only the most resistant-appearing lines in a screening nursery, and usually these are lines with complete resistance to the races present in the nursery. Because complete resistance masks partial resistance, there is no way to evaluate such lines without either challenging them with isolates of *P. oryzae* that are virulent (*i.e.*, the complete resistance is overcome), or by progeny-testing of a cross with a highly susceptible variety. Using the IRRI 1975 blast rating scale, lines with ratings of 3-6 probably represent those with usable levels of partial resistance that are not masked by complete resistance. So by introducing such lines into a breeding program and avoiding lines with little partial resistance, a strong pool of genes that contribute to race-nonspecific partial resistance could be gradually accumulated in the breeding population. Effective resistance can be achieved by combining into the same cultivar, different race-specific genes and genes conferring quantitative resistance.

Another method is by deploying resistance genes in mixed plant populations. Recent studies indicated that use of cultivar mixture is an effective tool in blast management. IRRI scientists introduced the practice of interplanting glutinous rice varieties with blast-resistant hybrid varieties in Yunnan province, China. Blast caused great yield loss on traditional glutinous rice varieties in China and farmers were spraying fungicides for up to seven times. Interplanting has prevented the fungus from continuous build-up of inoculum that had previously occurred in the monoculture fields of the glutinous varieties.

Biotechnological approaches

From the end of 1980s, the scenario of rice blast research has totally changed because of the use of biotechnological tools for studies. Initially biotechnology was applied in rice blast research for detection purpose using RFLP (Hamer, Farrall, Orbach, Valent, & Chumley, 1989). Then the studies on genome organization and molecular analysis of blast fungus taken step forward (Valent & Chumley, 1991). The further research explored the mechanism of host pathogen interaction at molecular level involving MAP kinase and cAMP signaling pathways (Xu & Hamer, 1996). Then the studies extended towards the identification, isolation, cloning and characterization of R and Avr genes. Biotechnological tools have also been exploited for gene pyramiding through marker assisted selection (MAS) and for the identification and mapping of QTLs for partial resistance to blast. Today, a total of 73 R genes, conferring blast resistance in rice have been identified. Many of them have been mapped but only 5 *viz.* Pi-b, Pi-ta, Pi-25, Pi-5 & Pi-9 have been isolated and characterized using molecular techniques (Tacconi *et al*., 2010).

(i) Molecular diagnosis of plant pathogen

Several techniques have been developed which have found application in plant pathogen diagnosis; these include the use of monoclonal antibodies and enzyme linked immunosorbant assay (ELISA) and DNA based technologies, such as the polymerase chain reaction which enables region of pathogens' genome to be amplified by several million fold, thus increasing the sensitivity of pathogen detection. Furthermore, diagnostic PCR has been significantly improved by the introduction of second generation PCR, known as the real time PCR. It is now possible not only to detect the presence or absence of the target pathogen, but also to quantify the amount present in the sample. Enumerating the pathogen upon detection is crucial to estimate the potential risks with respect to disease development and provides a useful basis for disease management decisions. The DNA microarray technology, originally designed to study gene expression and generate single nucleotide polymorphism (SNP) profiles is currently a new and emerging pathogen diagnostic technology and offers a platform for unlimited multiplexing capability. The fast growing databases generated by genomics and biosystematics research provide unique opportunities for the design of more versatile, high throughput, sensitive and specific molecular assays that will address the major limitation of the current technologies and benefit plant pathology. Finally, the so far restricted use of robotics to DNA technology will become economically feasible and will offer the possibility of using single DNA chip as practical tool for the diagnosis of hundreds of plant pathogens (Kumar, 2013).

(ii) Analysis of molecular variability in plant pathogens

Different molecular markers have been used in characterization of genetic diversity of plant pathogens. In most of the cases, these are Random amplified polymorphhic DNA (RAPD), restricted fragment length polymorphism (RFLP), amplified fragment length polymorphism (AFLP), simple sequence repeat (SSR)/inter simple sequence repeat (ISSR), internal transcribed spacer (ITS). The RAPD markers have been mostly used for characterization of fungal pathogens, followed by AFLP and ITS markers.

(iii) Mapping of disease resistance genes using DNA markers

Molecular mapping can be used for direct selection of disease resistance genes for the use in plant breeding programmes. Commonly used markers are RFLPs, AFLPs, SSRs, and SNP with predilection of PCR based markers.

(iv) Marker assisted pyramiding of disease resistance genes

Marker assisted pyramiding of disease resistance genes termed as “Breeding by design” can help to control the pathogen which recurrently and rapidly develop their new virulence. Efforts are made in India under Asian Rice Biotechnology Network (ARBN) to pyramid resistance gene against bacterial blight of rice. Rice varieties developed by using MAS have now been released for commercial cultivation for the first time in India. The variety amend as Improved Pusa Basmati-1 was developed by using conventional plant breeding approach integrated with MAS and two bacterial blight resistance genes Xa13 and Xa21 incorporated in Pusa Basmati-1 (Gopalakrishnan *et al*., 2008). Another variety of rice resistant to bacterial blight was developed in non basmati type rice in India by using MAS. PCR based molecular markers were used in a backcross breeding program to introgress three major bacterial blight resistance genes (Xa21, Xa13 and Xa5) into Samba Mashuri from a donor line (SS1113) in which all the three genes are present in a homozygous condition (Sundaram *et al*., 2008). These two reports successfully demonstrate the application of MAS to control the pathogens.

(v) Transgenics

Disease resistant transgenics have been developed in banana and tobacco by transferring a synthetic substitution analogue of a short peptide, Maganin (Chakarbarti, Ganapathi, Mukherjee, & Bapat, 2003). Magainin is one of the earliest reported antimicrobial peptides from skin secretions of the African clawed frog. The peptide is not stable in its native form and, therefore, researchers modified it to express in foreign plant systems. Tobacco plants transformed with the peptide showed enhanced resistance against *Sclerotinia sclerotium*, *Alternaria alternata* and *Botrytis cinerea*. Transgenic banana plants showed resistance to *Fusarium oxysporum* f. sp. *cubense* and *Mycosphaerella musicola* (Kumar & Gupta, 2012).

(vi) Application of genomics

Genomics has emerged as one of the frontier technologies during this century. Using high throughput genome sequencing technologies many plant pathogens are being sequenced world over. A list of pathogens which are at different stages of the genomic sequencing has been given by Jalali (2008). The massive genome sequence data being generated on different microorganisms can be used for simultaneous detection of multiple plant pathogens. The unique sequence from a wide range of pathogens could be used to develop microarrays for the simultaneous detection of large number of different strains. The probes and primers could be designed for differential detection of pathogens and their characterization at molecular level.

(vii) Application of RNA interference

RNA interference (RNAi) has emerged as a powerful tool for battling some of the most notoriously challenging diseases caused by viruses, bacteria and fungi (Wani, Sanghera, & Singh, 2013). The application of tissue specific inducible gene silencing in combination with the use of appropriate promoters to silence several genes simultaneously will result in protection of crops against destructive pathogens. RNAi application has resulted in successful control of many economically important diseases and pests in plants. RNAi approaches have also been used effectively to knockout the expressions of genes and to understand their biological functions (Anandalakshmi, 2013).

(viii) Post transcriptional gene silencing

The expression of virus derived sense or antisense RNA in transgenic plants conferring RNA mediated virus resistance appears to induce a form of post transcriptional gene silencing (PGTS). It’s a nucleotide sequence specific process that includes mRNA degradation, RNA silencing, an evolutionary mechanism protecting cells from pathogenic RNA and DNA, is viewed as an adaptive immune system of plants against viruses (Krishnaraj, 2013).

Biological Control

The search for the biological agents which can control the rice blast started in end of 1980's. The first report of a biological agent found effective in control of *P. oryzae* was of *Chaetomium cochliodes*. When the rice seeds were coated with spore suspension of *C. cochlioides* the early infection by blast was controlled and seedlings were healthy and taller than the control. It has been found that rice blast incidence can be reduced by mass vaccination method with avirulent isolates of *P. oryzae*. In India the studies on bacterial agents for the control of rice blast were conducted at "Center for Advanced Studies in Botany, University of Madras", and it was found that among the 400 bacterial isolates collected from rice fields of IRRI, 3 strains of *Pseudomonas fluorescens*, 5 of *Bacillus* spp., and one of *Enterobacter* spp., were inhibitory under *in vitro* conditions. Microbes have also been engineered to control rice blast. An epiphytic bacterium *Erwinia ananas* transformed with the chitinolytic enzyme gene (Chi A) from an antagonistic bacterium *Serratia marcescens* strain B2, a tomato epiphytic bacterium, was found inhibitory against *P. oryzae*. (Someya, Numata, Nakajima, Hasebe, & Akutsu, 2004). Recent studies on biocontrol of rice blast showed that *Bacillus subtillis* strain B-332 (Mu, Liu, Lu, Jiang, & Zhu, 2007), 1Pe2, 2R37 and 1Re14 (Yang *et al*., 2008) and *Streptomyces sindenius* isolate 263 have good antagonistic activity against *P. oryzae*.

Future of rice blast management

Molecular biology and biotechnological tools have totally changed the research on rice blast management. The availability of genome sequences of both, the host rice (Dean *et al*., 2005) and the pathogen has opened many doors for further research. Introduction of new sciences like nanotechnology in agricultural research and management could be proved very beneficial in future as a nanotech based company *viz*., NANO GREEN has reported the control of rice blast using nanomolecules. Cloning of R and Avr genes and study of their gene products will add to the knowledge of host pathogen interaction. The development of genetically engineered bioagents will supplement the environment friendly ways of management of rice blast. There is still a need for the further development of noble fungicides and fungistats with longer residual effect which can be better assisted by biotechnology in future. For resistance management, strategies like gene rotation, gene pyramiding, spatial and temporal gene deployment and use of varietal mixtures will be the best mean to reduce the epidemics. The development and use of transgenic rice would be the best way of rice blast management in the future.

Conclusion

The highly destructive and variable nature of rice blast has made it a disease of immense importance for the whole of the world. Yet the lots of management tools and practices are available for the disease but the effectiveness is dependent on their integrated use. Sanitation measures, fertilizer practices, and other aspects of rice culture, as they relate to the onset and development of blast needs further research. Durable resistance is influenced by environmental factors, so other means of disease management must be applied to assist host-plant resistance. The breeding strategies such as pyramiding of genes, gene rotation, and multiline varieties have been found effective in resistance management. Biotechnological tools and techniques, assisting the development of control measures have very bright future. Due to the highly variable nature of pathogen, need for the continuous research on development of durably resistant cultivars, will always be there. Finally, the knowledge gained through research must be communicated and demonstrated to the farmers so that they can use it.

References

Ahn, S., & Mukelar, A. (1986). Rice blast management under upland conditions. *Progress in Upland Rice Research.* Manila: International Rice Research Institute, 363-374.

Anandalakshmi, R. (2013). Application of RNAi for engineering disease tolerance in crops with special reference to horticultural crops. *Journal of Mycology and Plant Pathology, 43*(1), 111.

Bonman, J., & Rush, M. (1985). *Report on rice blast in Egypt.* National Rice Institute, Egypt.

Bonman, J., De Dios, T. V., & Khin, M. (1986). Physiologic specialization of *Pyricularia oryzae* in the Philippines. *Plant disease (USA).* http://dx.doi.org/10.1094/PD-70-767

Central Rice Research Institute (CRRI). (2007-08). Annual Report, CRRI Cuttack, (India).

Chakarbarti, A., Ganapathi, T. R., Mukherjee, P. K., & Bapat, V. A. (2003). MSI-99, a magainin analogue, imparts enhanced disease resistance in transgenic tobacco and banana. *Planta, 216*, 587-596. PMID: 12569400. http://dx.doi.org/10.1007/s00425-002-0918-y

Choi, W., Park, E., & Lee, E. (1988). LEAFBLAST: A computer simulation model for leaf blast development on rice. *Korean Journal of Plant Pathology (Korea R.), 4,* 25–32.

Crill, P., Ham, Y., & Beachell, H. (1982). The rice blast disease in Korea and its control with race prediction and gene rotation. In *Evolution of the gene rotation concept for rice blast control,* p123-130. Int. Rice Res. Inst., Los Baños, Philippines.

Datnoff, L., Deren, C., & Snyder, G. (1997). Silicon fertilization for disease management of rice in Florida. *Crop protection, 16*(6), 525-531. http://dx.doi.org/10.1016/j.bbr.2011.03.031

Dean, R. A. (1997). Signal pathways and appressorium morphogenesis. *Annual review of phytopathology, 35*(1), 211-234. PMid:15012522 http://dx.doi.org/10.1146/annurev.phyto.35.1.211

Dean, R. A., Talbot, N. J., Ebbole, D. J., Farman, M. L., Mitchell, T. K., Orbach, M. J., ... Pan, H. (2005). The genome sequence of the rice blast fungus *Magnaporthe grisea*. *Nature, 434*(7036), 980-986. PMID: 24145399 http://dx.doi.org/10.1073/pnas.1318211110

EI Refaei, M. I. (1977). *Epidemiology of rice blast disease in the tropics with special reference to the leaf wetness in relation to disease development*. Ph.D. thesis, Indian Agricultural research Institute, New Delhi, (India).

Flor, H. (1956). The complementary genic systems in flax and flax rust. *Advances in genetics, 8,* 29-54. http://dx.doi.org/10.1016/S0065-2660(08)60498-8

Food and Agriculture Organization (FAO). (2012). Food and Agricultural organization of United Nations. Website: http://FAOSTAT.fao.org [8th May 2014]

Fukunaga, K, Misato, T., Ishii, I., Asakawa, M. & Katagiri, M. (1968). Research and development of antibiotics for rice blast control. *Bulletin of the National Institute of Agricultural Sciences Tokyo 22*, 1-94.

Gopalakrishnan, S., Sharma, R. K., Rajkumar, K. A., Joseph, M., Singh, M. P., Singh, A. K., ... & Mohapatra, T. (2008). Integrating marker assisted background analysis with foreground selection for identification of superior bacterial blight resistant recombinants in Basmati rice. *Plant Breeding, 127,* 131-139. http://dx.doi.org/10.1111/j.1439-0523.2007.01458.x

Hamer, J. E., Farrall, L., Orbach, M. J., Valent, B., & Chumley, F. G. (1989). Host species-specific conservation of a family of repeated DNA sequences in the genome of a fungal plant pathogen. *Proceedings of the National Academy of Sciences, 86*(24), 9981-9985. PMid:2602385 http://dx.doi.org/10.1073/pnas.86.24.9981

Hamer, J. E., Howard, R. J., Chumley, F. G., & Valent, B. (1988). A mechanism for surface attachment in spores of a plant pathogenic fungus. *Science, 239*(4837), 288-290. PMid: 17769992 http://dx.doi.org/10.1126/science.239.4837.288

Harada, Y. (1955). Studies on a new antibiotic for rice blast control. Lecture given at the annual meeting of the Agricultural Chemical Society of Japan (Cited by Okamoto 1965).

Hori, M., Arata, T. & Inoue, Y. (1960). Studies on the forecasting method of blast disease. VI. Forecasting by the degree of accumulated starch in the sheath of rice plant. *Annals of Phytopathological Society of Japan, 25*(1), 2.

Hori, S. (1898). Blast Disease of rice plants. *Special Report, Imperial Agricultural Experimental Station, Tokyo. 1*, 1-36.

Ikeda, M. (1933). Influence of application of various nitrogenous fertilizers on silica content of rice plants. *Tottori Society of Agricultural sciences 4,* 23-33.

International Rice Research Institute (IRRI). 2010. International Rice Research Institute. http://irri.org/component/itpgooglesearch/search?q=annual+reports [10th Nov 2013].

Ito, S., & Sakamoto, M. (1939). Studies on rice blast. Res. Hokkaido Univ. Bot. Lab. Fac. Agric. Rep, 1943.

Jalali, B. L. (2008). Molecular plant pathology: Where do we stand. *Journal of Mycology and Plant Pathology, 38*(3), 419-429.

Kahn, R. P., & Libby, J. L. (1958). The effect of environmental factors and plant age on the infection of rice by the blast fungus, *Pyricularia oryzae*. *Phytopathology, 48*, 25-30.

Katagiri, M., & Uesugi, Y. (1978). *In vitro* selection of mutants of *Pyricularia oryzae* resistant to fungicides [rice]. *Annals of the Phytopathological Society of Japan, 44*. http://dx.doi.org/10.3186/jjphytopath.44.218

Kaundal, R., Kapoor, A. S., & Raghava, G. P. (2006). Machine learning techniques in disease forecasting: a case study on rice blast prediction. *BMC bioinformatics, 7*(1), 485. PMid: 17083731 http://dx.doi.org/10.1186/1471-2105-7-485

Kawamura, E., & Ono, K. (1948). Study on the relation between the pre–infection behavior of rice blast fungus, *Pyricularia oryzae*, and water droplets on rice plant leaves. *Bulletin of the National Agricultural Experiment Station, 4*, 1-12.

Kawashima, R. (1927). Influence of silica on rice blast disease. *Japanese Journal of Soil Science and Plant Nutrition, 1,* 86-91.

Kim, C. K., & Kim, C. H. (1993). The rice leaf blast simulation model EPIBLAST Systems approaches for agricultural development (pp. 309-321): Springer.

Kole, C. (2006). Cereals and millets (Vol. 1): Springer. http://dx.doi.org/10.1007/978-3-540-34389-9

Krishnaraj, P. U. (2013). Post transcriptional gene silencing: A tool to develop virus disease resistance. *Journal of Mycology and Plant Pathology, 43*(1), 133.

Kumar, S. (2013). Selection of suitable medium and organic substrate for maximum growth and sporulation of *Trichoderma viride*. *Proceedings of IX World Soybean Research Conference*, Durban South Africa, pp. 2-3.

Kumar, S., & Gupta, O. (2012). Expanding dimensions of plant pathology. *JNKVV research journal 46*(3), 286-293.

Lee, E. J., Kim, H. K., & Ryn, J. D. (1976). Studies on the resistance of rice varieties to the blast fungus, *Pyricularia oryzae* Cav. [in Korean]. Research report for 1976. Institute of Agricultural Sciences, Office of Rural Development, (Korea).

Link, K. C., & Ou, S. H. (1969). Standardization of the international race numbers of *Pyricularia oryzae*. *Phytopathology 59*,339-342.

Manibhushanrao, K., & Krishnan, P. (1991). Epidemiology of blast (EPIBLA): a simulation model and forecasting system for tropical rice in India. *Rice blast modeling and forecasting* IRRI, Manila, Philippines, 31-38.

Matsumoto, S. (1974). Pathogenic race occurred on a blast resistant variety Reiho [in Japanese, English summary]. *Proceedings of Association of Plant Protection*, Kyushu 20, 72-74. http://dx.doi.org/10.4241/kyubyochu.20.72

Miyake, K., & Ikeda, M. (1932). Influence of silica application on rice blast. *Japanese Journal of Soil Science and Plant Nutrition, 6*, 53-76.

Mu, C., Liu, X., Lu, Q., Jiang, X., & Zhu, C. (2007). Biological control of rice blast by *Bacillus subtilis* B-332 strain. Acta *Phytophylacica Sinica, 34*(2): 123-128.

Murata, J., Kuribayashi, K. & Kawai, I. (1933). Studies on the control of rice blast III. Influence of homemade manure on blast disease. *Nogi Kairyo Shiryo 64*, 1-138.

Ogawa, M. (1953). Studies on blast control of Ceresan lime. *Ohugoku-Shikoku Agricultural Resesearch 3*, 1-5.

Okamoto, M. (1972). On the characteristics of Kasumin, antibiotic fungicide. *Japan Pesticide Information 10*, 66-69.

Onodera, I. (1917). Chemical studies on rice blast (*Dactylaria parasitance* Cavara*). Journal of Scientific Agricultural Society 180*, 606-617.

Ou, S. H. (1985). Rice diseases: International Rice Research Institute, Manila, Philippines

Ou, S., Nuque, F., Ebron, T., & Awoderu, V. (1971). A type of stable resistance to blast disease of rice. *Phytopathology, 61*(6). http://dx.doi.org/10.1094/Phyto-61-703

Padmanabhan, S. (1963). The role of therapeutic treatments in plant disease control with special reference to rice diseases. *Indian Phytopathology Society Bulletin, 1,* 79-84.

Parimelazhagan, T. (2001). Botanical fungicide for the control of rice blast disease. *Bioved, 12*(1/2), 11-15.

Prabhu, A., & Morais, O. (1986). Blast disease management in upland rice in Brazil. In *Proceedings of Symposium on Progress in Upland Rice Research*, International Rice Research Institute, Manila, Philippines.

Sesma, A., & Osbourn, A. E. (2004). The rice leaf blast pathogen undergoes developmental processes typical of root-infecting fungi. *Nature, 431*(7008), 582-586. PMID:15457264 http://dx.doi.org/10.1038/nature02880

Siddiq, E. A. (1996). Rice. In: *50 Years of Crop Science Research in India* (R. S. Paroda and K. L. Chadha, eds.). ICAR (Indian Council of Agricultural Research),(India).

Singh, N. & Singh, R. S. (1980). Lysis of *Fusarium oxysporium* f. udum caused by soil amended with organic matter. *Journal of Mycology and Plant Pathology, 10*, 146-150.

Someya, N., Numata, S., Nakajima, M., Hasebe, A., & Akutsu, K. (2004). Influence of rice-isolated bacteria on chitinase production by the biocontrol bacterium *Serratia marcescens* strain B2 and the genetically modified rice epiphytic bacterium. *Journal of General Plant Pathology, 70*(6), 371-375. http://dx.doi.org/10.1007/s10327-004-0141-8

Sundaram, R. M., Manne, R., Vishnupriya, R., Biradar, S. K., Laha, G. S., Reddy, G. A., ... & Sonti, R. V. (2008). Marker assisted introgression of bacterial blight resistance in Samba Mahsuri, and elite indica rice variety. *Euphytica, 160*, 411-422. http://dx.doi.org/10.1007/s10681-007-9564-6

Suzuki, H. (1954). Studies on antiblastin (I-IV). *Annals of Phytopathological Society of Japan 18*, p138.

Tacconi, G., Baldassarre, V., Lanzanova, C., Faivre-Rampant, O., Cavigiolo, S., Urso, S., ... Valè, G. (2010). Polymorphism analysis of genomic regions associated with broad-spectrum effective blast resistance genes for marker development in rice. *Molecular breeding, 26*(4), 595-617. http://dx.doi.org/10.1007/s11032-010-9394-4

Talbot, N. J. (2003). On the trail of a cereal killer: exploring the biology of *Magnaporthe grisea. Annual Reviews in Microbiology, 57*(1), 177-202. PMid:14527276 http://dx.doi.org/10.1146/annurev.micro.57.030502.090957

Tamari, K. & Kaji, J. (1955). Biochemical studies of the blast fungus (*Pyricularia oryzae* Cavara) . Part 2. Studies on the physiological action of pyricularin, a toxin produced by the blast fungus on rice plants. *Ibid 29,* 185-190.

Thurston, H. D. (1998). *Tropical plant diseases*: American Phytopathological Society (APS Press).

Uesugi, Y. (1978). Resistance of phytopathogenic fungi to fungicides. Japan Pesticide Information (Japan).

Usman, G. M, Wakil, W, Sahi, S. T. & Saleem, il. Y. (2009). Influence of various fungicides on the management of rice blast disease. *Mycopathology 7*(1), 29-34.

Valent, B., & Chumley, F. G. (1991). Molecular genetic analysis of the rice blast fungus, *Magnaporthe grisea*. *Annual review of phytopathology, 29*(1), 443-467. PMid: 18479196 http://dx.doi.org/10.1146/annurev.py.29.090191.002303

Van Der Plank, J. E. (1963). Plant diseases: epidemics and control. Plant diseases: epidemics and control. New York and London: Academic Press.

Wani, S. H., Sanghera, G. S., & Singh, N. B. (2013). Biotechnology and plant disease control-Role of RNA interference. *American Journal of Plant Science, 1*, 55-68. http://dx.doi.org/10.4236/ajps.2010.12008

Watanabe, K., Tanaka, T., Fukuhara, K., Miyairi, N., yonehara, H., & Umezawa, H. (1957). Blastmycin, a new antibiotic from *Streptomyces* sp. *The Journal of Antibiotics, Series A, 10*(1), 39-45.

Xu, J.-R., & Hamer, J. E. (1996). MAP kinase and cAMP signaling regulate infection structure formation and pathogenic growth in the rice blast fungus *Magnaporthe grisea. Genes & development, 10*(21), 2696-2706. PMID:8946911 http://dx.doi.org/10.1101/gad.10.21.2696

Yamaguchi, I. (2004). Overview on the chemical control of rice blast disease. In: *Rice Blast: Interaction with rice and control*; Proceedings of the 3rd International Rice Blast Conference, Tsukuba Science City, Ibaraki, (Japan).

Yang, J. H., Liu, H. X., Zhu, G. M., Pan, Y. L., Xu, L. P., & Guo, J. H. (2008). Diversity analysis of antagonists from rice-associated bacteria and their application in biocontrol of rice diseases. *Journal of applied microbiology, 104*(1), 91-104. PMid: 17850318 http://dx.doi.org/10.1111/j.1365-2672.2007.03534.x

Yeh, W., & Bonman, J. (1986). Assessment of partial resistance to *Pyricularia oryzae* in six rice cultivars. *Plant pathology, 35*(3), 319-323. http://dx.doi.org/10.1111/j.1365-3059.1986.tb02021.x

Yoshii, K. (1949). Studies on Cephalothecium as a means of artificial immunization of agricultural crops. *Ibid 13,* 37-40.

Zeigler, R. S., Leong, S. A., & Teng, P. (1994). Rice blast disease: International Rice Research Institute, Manila, Philippines.