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Impact of Fungicides on Rice Production in India

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Additional information is available at the end of the chapter

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1. Introduction

Rice is the most economically important staple food crop in India, China, East-Asia, South East Asia, Africa and Latin America catering to nutritional needs of 70% of the population in these countries (FAO, 1995). In several developed countries such as North America and European Union (EU) also, rice consumption has increased due to food diversification and immigration (Faure and Mazaud, 1996). Worldwide, rice is grown on 161 million hectares, with an annual production of about 678.7 million tons of paddy (FAO, 2009). About 90% of the world's rice is grown and produced (143 million ha of area with a production of 612 million tons of paddy) in Asia (FAO, 2009). Rice provides 30–75% of the total calories to more than 3 billion Asians (Khush, 2004; von Braun and Bos, 2004). To meet the global rice demand, it is estimated that about 114 million tons of additional milled rice needs to be produced by 2035, which is equivalent to an overall increase of 26% in the next 25 years. The possibility of expanding the area under rice in the near future is limited. Therefore, this extra rice production needed has to come from a productivity gain (Kumar and Ladha, 2011). Maximum yields per unit area of land can be achieved and sustained only if along with high yielding crop varieties there is also a provision for protection of the crop against its enemies (Srivastava *et al.*, 2010). Amongst the various biotic factors affecting rice production and productivity, rice diseases are one of the most important ones. The annual losses due to rice diseases are estimated to be 10-15% on an average basis worldwide. Therefore, judicious management of rice diseases can result in improved productivity and additional grain harvested. Rice diseases are caused by wide variety of pathogen including fungus, bacteria, virus and nematodes (Ling, 1980). In the pre-war period, diseases of rice were practically unimportant in Tropical Asia where ancient varieties were traditionally grown on soils of low fertility (Areygunawardena, 1968). However, with the increasing demand for world rice supplies and advent of green revolution resulting in use of improved varieties, high fertilization, irrigation and intensive cultural practices have resulted in great increase in the occurrence and severity of diseases infesting rice in several countries (Teng,

1990). The major rice diseases that often cause great economic losses are rice blast (*Magnaporthe grisea*), sheath blight (*Rhizoctonia solani*), Bacterial blight (*Xanthomonas oryzae*) and Tungro virus disease especially in South and South East Asia (Ling, 1980).

The various methods used for managing rice disease includes, use of resistant varieties, cultural practices, biological and chemical control. All these methods have varied degrees of success in managing rice diseases. The most important control tactics used worldwide includes use of resistant varieties and chemical control. Breeding for disease resistant varieties has been long used for managing the rice diseases and is one of the most economical methods which contributed immensely to world's rice productivity (Mew, 1991; Bonman, *et al.* 1992). But, most varieties are resistant only to a few major diseases that are the subjects of intensive breeding efforts. The rice production environments, particularly in the tropics, are habitats of many rice pathogens causing varying degrees of damage. Even the "minor" diseases collectively could pose a significant threat to production (Mew, 1992). Moreover, the pathogen often develops new biotypes resulting in breaking down of resistance in the resistant varieties. Therefore, chemical control provides great opportunity for controlling rice diseases and over last two decades a lot of focus has been shifted towards developing new molecules that can be used for controlling rice diseases. As the most destructive rice diseases prevalent across the globe are caused by fungus (Ling, 1980), fungicides are an important tool to control them. This chapter discusses about importance of different fungicides for the control of major rice diseases.

2. Rice diseases dynamics and fungicide market in India

Rice blast and brown spot were the major diseases noticed during pre independent India and before introduction of high yielding varieties. After introduction of HYV, along with them, BLB, tungro and sheath blight have become major diseases. Recently diseases like sheath rot, false smut, stem rot and grain discolouration which were minor and occurring sporadically are emerging and causing considerable yield loss. This is primarily due to climate change, crop intensification and changes in practice. Out of the total yield loss due to diseases in rice, 35% is by blast, 25% by sheath blight, 20% by BLB, 10% by tungro and remaining 10% by other diseases.

The market share of fungicide used on rice in India during 2010-11 is Rs 380 crores, of which blast and sheath blight fungicides alone constitute 280 crores and the share of fungicides used against brown spot, BLB, grain discoloration, stem rot and false smut is 100 crores.

3. Rice fungicides

Fungicides prevent rice diseases which can result in severe damage to the crop in terms of both quality and quantity. Globally 8.4 % of fungicides market share is for rice (Collins, 2007). Synthesizing and characterizing a new molecule to be used as fungicide involves several steps. Initially the new lead molecule is tested in-vitro for its efficacy against the target pathogen and then it is characterized under field condition to ascertain its efficacy against the target disease and to finalize the most effective dose/rate that can be used for the control of the target disease. Several fungicides belonging to different groups have been

synthesized and evaluated for use in rice ecosystem. More than 30 fungicides have been registered for use in rice (Table 1) and several new molecules are under testing. The rice fungicides can be broadly classified in two categories.

Technical Name	Trade Name	Chemical group	Mode of Action	Target pest	Formulation Dosage/ha	g.a.i/ha
Azoxystrobin23%SC	Amistar 25EC	Strobilurin	protectant, curative, eradicant, translaminar and systemic properties	Sheath blight	500	125
Carbendazim 50 WP	Bavistin	Benzimadozole	Preventive & Curative	Brown spots, Blast, Sheath blight	500	250
Carpropamide 27.8%SC	Protega	Carbamate	Preventive	Blast	500	139
Chlorothalonil 75%WP	Kavoch, Bravo	Aromatic fungicide	Preventive & Curative	Sigatoka, Rusts	1000	750
Copper oxychloride 50 WP	Blitox	Copper fungicides	Protective and Eradicants	BLB,	1250	625
Copper Hydroxide 77% WP	Kocide	Copper fungicides	Protective and Eradicants	False smut	2000 gm	1000 gm
Difenconazole25%EC	Score 25EC	Triazole	Preventive & Curative	Sheath blight	250-500	62.5-125
Ediphenphos50%EC	Hinosan	Organophosphatic	Preventive & Curative	Blast and Brown leaf spots	500-600	250-300
Epoxiconazole 7.5%EC	Opus 7.5EC	Triazole	Preventive & Curative	Sheath blight	1.5ml/lit	
Eprobenfos 48%EC	Kitazin48%EC	Organophosphatic	Protective & Curative	Blast, Sheath blight	500	240
Fenbuconazole 24 SC		Triazole	Preventive & Curative	False smut & grain discoloraion	520	125
Flusilazole 12.5 +Carbendazim25%	Lustre 37.5%SE	Triazole +Benzimidazole	Preventive & Curative	Sheath blight	2ml/lit	
Flusilazole40%EC	Cursor 40EC	Triazole	Preventive & Curative	Sheath blight	300	120
Hexaconazole 5 EC	Contaf	Triazole	Preventive & Curative	Sheath blight	1000	50
Hexaconazole 5 SC	Contaf plus	Triazole	Preventive & Curative	Sheath blight	1000	50
Iprodione 50%WP			Proventiv & Curative	Sheath blight	1125	2250
Iprodione25%+Carbendazim 25%WP	Quintal 50%WP	Dicarboximide	Preventive&Curative	Sheath blight, Blast	500	250
Isoprothiolane 40%EC	Fuji-one	Triazole	Preventive & Curative	Blast	750	300
Kasugamycin 3%SL	Kasu-B	Aminoglycoside Antibiotic		Blast	1000-1500	30-50

Table 1. Rice fungicides registered in India (Source: Central Insecticide Board, Govt. of India)

Technical Name	Trade Name	Chemical group	Mode of Action	Target pest	Formulation Dosage/ha	g.a.i/ha
Kresoxim methyl 44.3%SC	Ergon	Strobilarin	Preventive & Curative	Sheath blight,Blast	500	250
Mancozeb 35 SC	Eurofil-NT 35% SC	Mn Eth-Bishithiocarbamate	Protective &Eradicants	Brown spots, Blast, Sheath blight	2500	875
Mancozeb 63 + Carbendazim 12 WP	Companion-75%WP	Dithiocarbamate+Benzimidazole	Preventive & Curative	Blast ,Sheath blight	750	375
Mancozeb 75 WP	Dithane M 45	Dithiocarbamate	Protective	Broad spectrum	1000	750
Mancozeb 75WG	Manfil 75%WG	Dithiocarbamate	Protective	Broad spectrum	1000	750
Metominostrobin 20SC		Strobularin	Preventive &Curative	Blast and sheath blight	500	100
Pencycuron 22.9%SC	Monceren 25 SC	Urea fungicides	Preventive & Curative	Sheath blight	750	187.5
Propiconazole 25 EC	Tilt 25% EC	Triazole	Preventive & Curative	Sheath blights	500	125
Pyroclostrobin20%WG	Headline	Strobularin	Preventive & Curative	ELB	375-500	75-100
Propineb 70% WP		polymeric ainc propylenebis(dithiocarbamate)	protective	Brown leaf spot	2000	1400
Tebuconazole 25.9%EC	Folicure 25EC	Triazole	Preventive & Curative	Balst, Sheath blight, false smut	750	187.5
Thifluzamide 24% SC	Spencer	Carboximide	Preventive & Curative	Sheath blight	90	375
Thiram 75%WS				Seed borne diseases	25-30	18.8 - 22.5
Tricyclozole 76 WP	Beam 75%WP	triazolobenzothiazole	Preventive	Blast and Brown leaf spots	300-400	225-300
Trifloxystrobin25%+Tebuconazole 50%	Nativo 75%WG	Strobilurin+Triazole	Preventive & Curative	Sheath blight	350	262.5
Validamycin 3%L	Sheathmar 3L	Antibiotics	Preventive & Curative	Sheath blight	2000	60
Zineb 75%WP	Phytox	Zinc ethylenebis-(dithiocarbamate)	protective and curative	Blast	2000	1500

3.1. Seed treatment fungicides

These fungicides have narrow to moderate spectrum of control and are highly specific. These are applied on the seed surface before sowing. The seed is dressed with either a dry formulation or wet treated with a slurry or liquid formulation. Low cost earthen pots can be used for mixing pesticides with seed or seed can be spread on a polythene sheet and required quantity of chemical can be sprinkled on seed lot and mixed mechanically by the farmers (http://agritech.tnau.ac.in/seed_certification/seed_treatment_Insecticides%20&%20Fungicides.html). The major advantage is that it provides high level of control at low dose and with low residue. In the greenhouse study, tricyclazole at 0.2g/kg of seed effectively controlled leaf blast upto 21 days after planting and resulted in 8.2 µg/g tricyclazole in the leaves at that time according to GLC assay (Froyd *et al.*, 1976). Anwar and Bhat (2005) evaluated few fungicides *viz.*, Isoprothiolene, Tricyclazole, Edifenphos, Hexaconazole and Mancozeb as seed treatment at two varying doses. Isoprothiolene and Tricyclazole 75WP were most effective in controlling the nursery blast disease, exhibiting no incidence and severity at both the doses tested at 35 DAS. The list of fungicides for use as seed treatment from the IRRI website is shown in table 2.

% Active Ingredient(s)	Rate	Additional Information
Metalaxyl 28.35%	0.75 - 1.5 fl. oz. per 100 lbs. of seed.	For <i>Pythium</i> caused seed rot and damping-off control. For use as a commercial seed treatment.
Trifloxystrobin 22%	0.32 - 0.64 fl. oz./cwt	For <i>Rhizoctonia solani</i> control
Mefenoxam 33.3%	Apply 0.0425 to 0.085 oz. per 100 lbs. of seed for <i>Pythium</i> seed rot and damping-off control in rice when applied in combination with Vitavax-200, 42-S Thiram, or RTU-Vitavax-Thiram at labeled rates.	For <i>Pythium</i> seed rot and damping-off control. For use as a commercial seed treatment.
Thiram 42%	1.5 fl oz/bu	For seed decay, damping off, and seedling blights caused by <i>Pythium</i> and <i>Rhizoctonia</i>
Mancozeb 50%	4 oz. per 100 lbs. of seed.	For control of damping-off, seed rots, and seedling blights caused by <i>Drechslera</i> and <i>Pythium</i> . Drill box treatment.
Mancozeb 37%	3.4 to 6.7 oz. per 100 lbs. of seed.	For control of soil borne and seed borne fungi causing seed rot and reduced seedling vigor. Apply before, during, or after soaking in water.

% Active Ingredient(s)	Rate	Additional Information
Carboxin 10% + Thiram 10%	5 to 6.8 fl. oz. per 100 lbs. of seed.	For control of various seed and seedling diseases. The higher rate is recommended for control of <i>Helminthosporium oryzae</i> . Ready to use seed treatment which may be applied as a commercial seed treatment or as a pour-on hopper box application.
Carboxin 5.7% + Thiram 5.7%	9 to 12 fl. oz. per 100 lbs. of seed.	To control various seed and seedling diseases, especially effective against <i>Rhizoctonia solani</i> and <i>Helminthosporium oryzae</i> . The higher rate is recommended for control of <i>Helminthosporium oryzae</i> . Apply as a pour-on treatment or by machine.
Carbendazim 50 WP	4 g/kg of seeds	To control blast, brown spot and udbatta disease of rice
Tricyclazole 75 WP	3 g/kg of seeds	To control rice blast disease

Note: 1 oz.= 29.57 ml; 1 lb = 0.45 kgs

(Source: <http://www.knowledgebank.irri.org/qualityseedcourse/index.php/module-2-production-of-rice-seed-in-irrigated-mainmenu-103/2-seed-cleaning-and-treatment-before-planting-mainmenu-47/162-table-rice-seed-treatment-fungicides>)

Table 2. Rice Seed treatment fungicides:

3.2. Foliar fungicides

These fungicides are applied as spray using power or back pack sprayers directed towards the plant foliage. These fungicides may be contact (surface acting) or systemic (translocated inside plant) in action. They are highly effective in controlling foliar rice diseases with good residuality. Based on their chemical class and mode of action, rice fungicides can be further grouped into following categories;

- a. *Melanin biosynthesis inhibitors (MBI) [FRAC CODE – 16]*: This group of fungicides are only effective against rice blast disease. They prevent melanin biosynthesis in appressoria of *Pyricularia oryzae* and penetration of rice plants via appressoria by inhibiting either polyhydroxynaphthaline reductase (eg Tricyclazole, Pyroquilon, Chlobenthiazone etc) or scytalone Dehydratase enzymes (Carpropamid, Dichlocymet etc) (Kurahashi, 2001). Tricyclazole inhibits the NADPH-dependent reduction of 1,3,6,8-tetrahydroxynaphthaline to scytalone and 1,3,8-trihydroxynaphthaline to vermeline (Wheeler, 1982). While, carpropamid inhibits the enzyme scytalone dehydratase essential for the synthesis of the melanin precursors 1,3,8-trihydroxynaphthaline and 1,8-dihydroxynaphthaline (Kurahashi et al., 1998).
- b. *Benzimidazole [FRAC CODE – 1]*: This group fungicide was introduced for plant disease control in the 1960s and early 1970s as foliar fungicides, seed treatments and for use in post harvest applications. They possess unique properties not seen before in the

- protectants. These included low use rates, broad spectrum and systemicity with post-infection action that allowed for extended spray interval. All these qualities made them very popular with growers but also subject to misuse, such as poor spray coverage and curative spraying. These fungicides are single site inhibitors of fungal microtubule assembly during mitosis, via tubulin-benzimidazole-interactions (Smith, 1988). The current ranking of global sales is: carbendazim, thiophanate, thiabendazole.
- c. *Strobilurins* [FRAC CODE – 11]: The first fungicides in this family were isolated from wood-rotting mushroom fungi, including one called *Strobilurus tenacellus*. The name strobilurin was coined for this chemical family of fungicides in recognition of the source of the first compounds of this type. These fungicides are now more properly referred to as QoI fungicides (Vincelli, 2002). They were first launched in 1996 and now include the world's biggest selling fungicide, azoxystrobin (Bartlett *et al.*, 2004). Some of the other commonly used strobilurins against rice diseases are fenamidone, kresoxim methyl, pyraclostrobin and trifloxystrobin either as stand alone or mixed with other multi-site inhibitor fungicides or triazoles like propiconazole. They have broad spectrum activity and are effective against most of the pathogens with few exceptions (Vincelli, 2002). In rice they are used against blast, sheath blight and other foliar diseases.
 - d. *Triazole fungicides* [FRAC CODE – 3]: This is the largest class of fungicides. They are highly systemic with mobility through xylem. They are known to have low resistance development risk and broad spectrum activity against major diseases except oomycetes. In rice they are used for the control of sheath blight, grain discoloration and other foliar diseases. Some of the commonly used triazoles in rice are propiconazole, tebuconazole, hexaconazole, difenconazole etc. They are good mixture partners with other fungicides and are used in combination with other single site/specific fungicides for increased disease control and resistance management.
 - e. *MET II inhibitors* [FRAC CODE – 7]: Inhibit succinate dehydrogenase in fungi (examples are thifluzamide and flutalonil). Very low resistance risk and highly effective towards sheath blight. These fungicides are systemic (Xylem mobile) and have good residue.
 - f. *Antibiotics*: Antibiotics are compounds produced by one micro organisms and toxic to other micro organisms. Chemical formulae of antibiotics are complex and are not related to one another. Antibiotics used for plant disease control are generally absorbed and translocated systemically by plants to a limited extent. They may control plant disease by acting on the pathogen or the host (George, 2005). Kasugamycin [FRAC CODE – 24], blastocidin [FRAC CODE – 23] and validamycin [FRAC CODE – 26] are some of the common antibiotics which are used for the control fungal diseases in rice. Kasugamycin and blastocidin have been used for blast control while validamycin provides effective control of sheath blight. Kannaiyan and Prasad (1979) carried out a field study to evaluate several antibiotics for the control of sheath blight disease of rice and found that all the antibiotics were effective in controlling the disease and achieving higher yields as compared to control.

Some of the new fungicides as per the AgroProjects and Agranova database are mentioned below:

Prothioconazole: Prothioconazole is considered particularly effective for the control of stem rot and sheath rot diseases of rice with C-14 demethylation inhibitor (DMI) mode of action

Dimoxystrobin: This fungicide is the second analogue developed which is structurally similar to the first, metominostrobin. Dimoxystrobin is known to control *Pyricularia oryzae*, *Rhizoctonia solani*. QoI (MET III, Strobilurin).

Pyraclostrobin: belongs to QoI (MET III, Strobilurin). Pyraclostrobin provides a broader spectrum of disease control against many diseases including important diseases of rice *Pyricularia grisea* and *Rhizoctonia solani*. Pyraclostrobin provides excellent curative activity, whereas the existing strobilurins are primarily protectant.

Oryastrobin: Provides systemic and protectant activity with a long residual effect against rice blast (*Pyricularia oryzae*) and sheath blight (*Rhizoctonia solani*). This acts as QoI (MET III, Strobilurin).

Isotianil: In 2010, Bayer CropScience introduced the rice fungicide isotianil (Routine®) in Japan and Korea to control the plant disease rice blast. This new fungicide is known to stimulate the natural defense mechanisms of rice plants, thus boosting their resistance. This is the first time that a substance which combines low application rates with what is termed a resistance-inducing effect. This fungicide can also play an important role in future seed treatment portfolio in rice.

4. Timing of fungicide application

Fungicide timing is a very critical component in disease control and management. The disease needs to be present in order to justify any fungicide application and its effectiveness. This is not the case in every field and the variety grown greatly influences the disease impact, even if present. The geographical and sometimes micro-climatic conditions of the cropping area also greatly influence the incidence and intensity of any plant disease. Thus scouting and sound decision-making are worthwhile, compared to “blanket” preventative fungicide applications (Cartwright *et al.*, 2004). Application of right chemical (Hexaconazole 5SC) at a right time (maximum tillering stage) was very important in control of sheath blight (Swamy *et al.*, 2009). While, Pencycuron 250 EC was very effective under Punjab and West Bengal rice growing conditions against sheath blight when sprayed at maximum tillering stage (Lore *et al.*, 2005; Biswas, 2002).

Several studies have revealed that many new fungicides have been identified for managing sheath blight in rice which differs in their efficacy from place to place and time of application. Dithane M-45 (Das and Mishra, 1990), Carbendazim and Mancozeb (Thangaswamy and Ranagswamy, 1989; Roy and Saikia, 1976) Iprodione (Izadyar and Baradaram, 1989) Triazole (Suryadi *et al.*, 1989) and Carbandazim + Mancozeb (Prasad *et al.*, 2006) were found effective when applied at maximum tillering stage. Groth and Bond (2006) showed that application of azoxystrobin between panicle differentiation and 50% heading stage reduced sheath blight severity and incidence, resulting in higher yield and high head rice milling yield compared with inoculated but nonsprayed plots. Similarly, previous

studies as reported by Groth (2005), demonstrated that fungicides can be applied over a range of growth stages and obtain satisfactory control of sheath blight. Therefore, in designing an effective disease management program it is essential to understand the most vulnerable stage of the crop for disease incidence, level of disease incidence/severity, pathogenicity, crop micro-climatic condition and suitable fungicide molecule.

5. Fungicide resistance

The major consideration for the design of fungicide use strategies is the threat of fungicide resistance. Fungicide resistance can occur when a *selection pressure* is placed on the fungal pathogen population. Characteristics of both the fungicide and the pathogen play a role in the magnitude of the selection pressure and the risk of resistance occurring. Fungicides that have a single site of action tend to be more at risk for resistance developing compared to those that have multi-site activity. Fungal pathogens that regularly undergo sexual reproduction are more likely to have greater *variability* in the population, which increases the chances of developing a strain that is less sensitive to a fungicide. When diseases have a repeating stage (polycyclic disease), such as blast, the fungal pathogen may also be more likely to develop resistance to a fungicide partially due to the high number of spores that are produced within a season.

Considerable efforts have been made by industry to conduct research in the areas of mode of action, resistance risk, field monitoring for baseline sensitivity and sensitivity variations in treated fields. Numerous pathogens that attack the highly maintained grasses, such as those found on golf courses, frequently require weekly spray applications through out the summer. This has led to resistance development in *Magnaporthe grisea* (gray leaf spot) to strobilurins. Some of the fungicides used to control rice blast disease (e.g. probenazole, isoprothiolane and tricyclazole) have retained effectiveness over many years of widespread use (Brent and Hollomon, 2007).

The first report of practical resistance to fungicides in rice crop was recorded in 1971 on blast pathogen (*Magnaporthe grisea*) against Kasugamycin due to altered target site (ribosomes) and in 1979 for Phosphorothiolates by metabolic detoxification (Kato, 1988). Kaku *et al.* (2003), reported resistance to carpropamid (Melanin Biosynthesis Inhibitors (Dehydratase) (MBI-D)) with altered target site (scytalone dehydratase) as possible mechanism of resistance. Resistance to carpropamid was confirmed in the strains of *Magnaporthe grisea* due to V75M mutation that causes low sensitivities of SDHs of the carpropamid –resistant strains, and strongly suggests that the V75M mutation confers resistance of these strains to carpropamid (Takagaki *et al.*, 2004).

Bennett (2012), reported a suspected mutation of the *Rhizoctonia solani* fungus that has been found to be resistant to azoxystrobin (strobilurin fungicide). Following a series of major tests, the pathologists from Louisiana came up with (fungicide) tolerance levels for *Rhizoctonia solani*. Brent and Hollomon (2007) reported the mechanism of resistance of QoIs (strobilurins) which is due to altered target site (ubiquinol-cytochrome c reductase). This decrease in sensitivity to a fungicide was certainly not unprecedented.

Kim *et al.*, 2010, reported on Bakanae disease pathogen *Fusarium fujikuroi* strain CF245 which completely degraded 1.0 mg/L of prochloraz in 5 days after incubation, whereas no degradation of prochloraz was observed by the strain CF106 at the same treatment level under in-vitro conditions. Liquid chromatography Q-TOF MS detected N-(2-(2,4,6-trichlorophenoxy)ethyl)propan-1-amine as a major degradation product of prochloraz by the strain CF245. These results indicated that the degradation of prochloraz may account for the reduced sensitivity of the strain CF245 to prochloraz. All living organisms are constantly mutating and evolving, and changes in sensitivity to pesticides are common not only in fungicides but also in insecticides and herbicides.

Studying the case histories of resistance development by considering the genetic, biochemical and epidemiological process which explains the complex interaction and changing factors determining the rate and severity of development of fungicide resistance

6. Fungicide resistant management

Acquired fungicide resistance is a major threat to plant disease control by chemicals. Pathogens respond to fungicides by evolving resistance against them. Fungicides which provide maximum control also create maximum selection pressure on the pathogen to acquire resistance. Resistance results from one or more changes at genetic level of pathogen population due to mutations occurring in nature. Fungicide itself does not induce resistance. It selects resistant propagules already present at low frequency in natural population of pathogen.

Fungicides may be categorised based on resistance development by the pathogen as low resistant risk fungicides –dithiocarbamate which are protectant fungicides and have multisite action, medium risk fungicides- SBI's where mutation of several genes is required and high risk fungicides – benzimidazole and strobilins where resistance is controlled by single gene. Thus, a major consideration for the design of fungicide use strategies is the threat of fungicide resistance. There have been considerable efforts by industry to conduct research in the areas of mode of action, resistance risk and field monitoring.

7. Efficacy of fungicides against important rice diseases

7.1. Blast

Blast is the most important fungal disease of rice and occurs in all the rice growing regions of the world. Fungicidal control is largely practised for blast disease in temperate or subtropical rice cultivation, mainly in Japan, China, South Korea, Taiwan and, increasingly, Vietnam. The majority of the fungicides used in blast control are protectants. In early years, copper and mercury compounds were recommended against blast but were found not suitable because of phytotoxicity and mammalian toxicity. Current major products are mainly systemics with a residual activity of at least 15 days, although older organophosphorous products such as edifenphos are still widely used. The modern rice fungicides include isoprothiolane, probenazole, pyroquilon and tricyclazole (Anon., 1992; Filippi and Prabhu, 1997), and are applied as foliar sprays, as granules into water or seed-box treatments (irrigated lowland rice),

or as seed dressings for upland rice. In recent years, newer melanin biosynthesis inhibitors such as carpropamid (Motoyama *et al.*, 1999; Thieron *et al.*, 1999) or broad-spectrum fungicides like azoxystrobin (strobilurin)(Lee and Beaty, 1999) have gained favour.

According to Kapoor and Singh (1982) benomyl seed treatment (1:400 w/w) gives protection to seedlings in nursery for 24-25 days. It inhibits spore germination and appressorium formation. Venkata Rao and Muralidharan (1983) found benomyl, carbendazim, MBC, edifenphos (all 0.1%) and 0.25% mancozeb effective against the blast in the order listed, and significantly better than other fungicides. Tewari and Kameshwar Rao (1983) applied carbendazim through mud balls, soil drench and foliar spray at the rate of 0.5 kg a i/ha and found effective control of the disease. Three sprays were given at the tillering stage at 10 day interval and two sprays at the neck emergence stage at 5 days interval. Saikia (1991) has confirmed the same number and timing of sprays of edifenphos, thiophanate methyl and carbendazim at 0.1% effectively reducing the leaf blast by 71.3-81% and neck blast by 60-65% with corresponding increase in yield. Studies on efficacy of fungicides indicated that tricyclazole and isoprothiolane are highly effective resulting in 87.9 and 83.8% reduction in neck blast and 33.8 and 29.9% increase in grain yield over check, respectively (Sachin and Rana, 2011). Sood and Kapoor (1997) evaluated seven fungicides and found that tricyclozole 75 WP was most effective and reduced the leaf and neck blast by 89.2% and 94.5% respectively. Muhammad Saifulla *et. al.* (1998) confirmed that chlorothalonil and hexaconazole were comparatively more effective in controlling the disease. Tsuda *et. al.* (1998) and Thiron (1999) reported that root application systemic fungicides pyroquilon and carpropamid respectively were effective against rice blast.

Prasanna Kumar *et. al.* (2011c) evaluated three new QoI fungicides (Kresoxim methyl, Metaminostrobin and Trifloxystrobin) in combinations with other groups for two seasons against against blast and sheath blight of rice. All the QoI group fungicides were very effective in controlling leaf and neck blast and also improved the growth of the plant in terms of height, test weight and yield. Kresoxim methyl 40% + Hexaconazole 8% SC @ 200+40 g ai/ha was effective against leaf blast (5.18% and 11.11%) and neck blast (11.11% and 11.85%) with highest yield of 45.75 and 53.42 q/ha respectively during Kharif 2010 and summer 2011. Similar effectiveness was recorded in Kresoxim methyl 50% @ 200 g ai/ha against leaf blast (5.18% and 11.11%) and neck blast (11.85% and 11.11%) which was found on par with tricyclozole @ 225 g ai/ha. Application of Metaminostrobin 20% SC + hexaconazole 5% SC and Metaminostrobin alone gave higher grain yield 41.26 and 41.23 q/ha respectively and was on par with tricyclozole 75%WP. The combination was effective against leaf blast (21.11 and 18.89%) and neck blast (25.56 and 33.89%) during Kharif 2009 and summer 2010.

Nine combinations of fungicides and insecticides were tested for their efficacy and compatibility on major pests and disease of rice (Prasanna Kumar *et. al.*, 2011a). The combination treatments involving the insecticides and fungicide treatment recorded moderate severity ranged from 12.1 to 18.5%. Combination of tricyclazole 75% WP + Fipronil 5% SC recorded least disease severity and insect infestation (17% neck blast) and highest yield of 5190 kg/ha, followed by isoprothiolane 40% EC + fipronil 5% SC compared to untreated check which recorded highest neck blast incidence(34%).

Similar results regarding the efficacy of various fungicides have been reported by different researchers globally. Varier *et al.*, (1993) used eight fungicides for management of rice blast and observed that seed treatment with tricyclazole @ 4kg/kg seed proved effective after 40 days of sowing. Dubey (1995) conducted field trials of eight fungicides for control of *Pyricularia oryzae*, Topsin M + Indofil M-45 was proved to be most effective against leaf blast disease of rice. Minami and Ando (1994) reported that probenazole induce a resistant reaction in rice plants against infection by rice blast fungus. Probenazole pre-treatment increased accumulation of salicylic acid and pathogenesis related (PR) proteins in the eighth leaves of adult rice plants at the 8-leaf stage, resulting in the formation of hypersensitive reaction (HR) lesions (HRLs). Enyinnia (1996) evaluated two systemic fungicides Benomyl and Tricyclazole on Faro / 29, a rice cultivar, at full booting stage and reported good control of natural infection of rice leaf blast. Filippi and Prabhu (1997) reported that propagation fungicide (40 g a.i. per Kg of seed) was effective in controlling leaf and panicle blast. Moletti *et al.*, (1998) conducted field trial against *Pyricularia oryzae*, and found that pyroquilon granules or wettable powder 2 kg / ha once or twice gave good results against leaf blast. Tirmali and Patil, (2000) conducted field experiment on susceptible rice cultivar E. K. 70 with 5 new fungicide formulations *viz.* Antaco 170, Carpropamid 30 SC, Fliqiconazate 25 WP, Ocatve 50 WP and Opus 15.5 SC. These fungicides were sprayed at tillering, booting and heading stages of crop. The new formulation reduce neck blast incidence by 16.27% to 29.23%, Opus 15.5 SC was highly effective in controlling neck blast (29.23%) and increasing grain yield. Tirmali *et al.* (2001) reported the efficacy of new fungicides in controlling rice neck blast caused by *Pyricularia oryzae* on rice cultivar Ek- 70 (blast susceptible) treated with Capropamid 30 SC, Folicur 250, WE Swing 250 EC and Beam 75 WP at maximum tillering, panicle initiation and at heading stage of the crop and found that all these new fungicides have significantly reduced neck blast. Ghazanfar *et al.*, 2009 evaluated several fungicides on a highly susceptible rice variety Basmati C-622 and observed that Tetrachlorophthalide 30 WP @ 3g/litre, Tebuconazole + Trifloxystobin @ 0.8 g/litre of water and Difenoconazole 250 EC @ 1.25 ml/litre proved effective in reducing the disease percentage. The control of disease in case of neck blast was shown by Tetrachlorophthalide 30 WP @ 3g/litre, Difenoconazole 250 EC and Tebuconazole + Trifloxystobin @ 0.8 g/litre of water to the tune of 12.81%, 14.24% and 17.01%, respectively.

7.2. Sheath blight

Sheath blight is one of the most important rice diseases worldwide and ranks number two position after blast disease. Common fungicides used earlier against sheath blight were copper, organomercury and organo-arsenic compounds (Ou 1985). Carbendazim, benomyl, ediphenfos and kitazin have been reported to be the most effective chemicals recorded by various Indian workers (Premalatha Dath 1990). The fungicidal control of sheath blight in India was attempted by Kannaiyan and Prasad (1976) and Bhaktavatsalam *et. al.* (1977). The rhizosphere population of the pathogen of rice seedlings was drastically reduced through foliar sprays of the fungicides such as kitazin, edifenphos, benomyl, carboxin and carbendazim. The efficacy of benomyl (Das and Panda, 1984) and carbendazim (Bhaktavatsalam *et. al.*, 1977; Rajan and Alexander, 1988) in the management of sheath blight

was studied. Benomyl and captan at 0.2% were highly effective in reducing the seedling infection while soil drenching with edifenphos, kitazin and benomyl during tillering stage was also effective in controlling the disease. Seed treatment with carbendazim, chloroneb, chlorothalonil, carboxin, benomyl and phenyl mercury acetate (PMA) reduced the seed borne infection of the pathogen and improved the seed germination, shoots and root growth, seedling vigour and prolonged the viability of the seeds. Again, 0.2% sprays of benomyl, kitazin, edifenphos and chlorothalonil were highly effective in controlling sheath blight and increased the grain yield in field trials. Roy and Saikia (1976) obtained the best control of sheath blight with carbendazim or by benomyl sprays (0.05%) both in green house and field tests. In field trials with six fungicides, kitazin granule was the most effective in reducing the disease severity, followed by edifenphos (Verma and Menon, 1977) but Mathai and Nair (1977) showed that edifenphos was the best as it increased the yield.

Flutolanil, a new systemic fungicide developed with both protective and curative properties is very effective to control various Rhizoctonia groups of fungi including rice sheath blight (Araki, 1985; Hirooka *et al.*, 1989). However, sheath blight disease was effectively controlled by 80% at low concentration of 1.6 to 3.2 µg/g of plant. Foliar spray, soil drenching and seed treatment have been tried effectively under green house and field studies. Sundravadana *et al.*, 2007, reported that for controlling sheath blight disease, the optimum rate of azoxystrobin was 125 g/ha. Field trials in 2008 and 2009 conducted by Parsons *et al.*, (2009) showed that a newly formulated mixture of azoxystrobin and propiconazole called Quilt Xcel™ was highly effective in controlling sheath blight and protecting rice yield and milling quality.

PrasannaKumar *et al.* (2011c) evaluated three new QoI fungicides (Kresoxim methyl, Metaminostrobin and Trifloxystrobin) and combinations with other groups were evaluated for two seasons against blast and sheath blight of rice. All the QoI group fungicides were very effective in controlling sheath blight and also improved the growth of the plant in terms of height, test weight and yield. Kresoxim methyl 40% + Hexaconazole 8% SC @ 200+40 g ai/ha was effective against sheath blight (12.59% and 20.74%) with highest yield of 45.75 and 53.42 q/ha respectively during Kharif 2010 and summer 2011. During summer 2010, application of Metaminostrobin 20% SC+hexaconazole 5% SC and Metaminostrobin alone gave higher grain yield 41.26 and 41.23 q/ha respectively. The combination was effective against sheath blight (25 and 16.11%) during Kharif 2009 and summer 2010. They also found that Trifloxystrobin 50% WG @ 200 g ai/ha recorded higher yield (47.66 q/ha and 50.17 q/ha) in both the seasons (Kharif 2010 and summer 2011). The stand alone formulation of trifloxystrobin 50% WG @ 200 g ai/ha was effective against sheath blight with PDI of 15 and 11.11% during Kharif 2010 and summer 2011 respectively.

PrasannaKumar *et al.* (2011b) also reported that application of hexaconazole 75% WG @ 50g ai/ha, tetraconazole 11.6% w/w ME @ 1.0 L/ha and thifluzamide 24% SC @ 110 ai/ha were found highly effective in controlling sheath blight with increased yield when compared to untreated check. Thifluzamide a new fungicide group of carboxynilide was tested for its efficacy against sheath blight in three seasons (PrasannaKumar *et al.*, 2012). They found that among different concentrations, thifluzamide 24% SC at 110 g ai/ha was effective in reducing the disease severity [12 % (2005), 19.33% (2006) and 21.33 (2009)] when compared

to uncontrolled check [47% (2005), 62.33 (2006) and 59.67 (2009)]. Carboxynilide group fungicide was both preventive and curative in effect without phytotoxicity.

A combination of fungicide and insecticide were evaluated against important diseases and insects in rice during kharif 2007, 2008, 2009 and 2010 (PrasannaKumar *et. al.*, 2011a). They found that during 2009, the ready mix formulation of flubendiamide 3.5% + hexaconazole 5% WG @ 85 g/ha were effective in controlling rice pests to maximum extent. The combination treatment recorded least sheath blight severity of 13.9% with the yield of 4190 kg/ha when compared to the standard check (40.6% and 2409 kg/ha).

Swamy *et. al.* (2009) reported that new fungicide formulations tricyclozole 400g + propiconazole 125g @ 0.25% and trifloxystrobin 25g + tebuconazole 50g @ 0.04% was on par with the standard checks hexaconazole 5% EC @ 0.2% and validamycin 3L @ 0.25%. Similarly, a new formulation Captan 70% + Hexaconazole 5% WP @ 0.2% was significantly effective in reducing the sheath blight of rice (Kiran Kumar and PrasannaKumar, 2011).

Foliar sprays of fungicides such as validamycin A in Vietnam, Thailand, Korea, Malaysia and Japan and pencycuron in Malaysia have been widely used (IRRI, 1993). First spray is applied between the stage of early internode elongation and the development of 2.5- to 5-cm panicle in the boot, and the second on 80-90% of emerging panicles from 10-14 days later. The best time to apply chemicals was at the jointing stage, during which time the percentage tiller infected was highly correlated with sheath blight at wax ripeness stage: percentage yield loss depended on disease index at wax ripeness (CPC, 2005).

7.3. Brown spot

Brown spot is one of the most important rice diseases in India. The disease affects the yield and milling quality of the grain. Sulpha drugs like sulphanilamide and antibiotics like nyastatin and griseofulvin have been used for seed treatment to control brown spot in rice. Spraying with captafol, edifenphos and zineb was also found to be effective (Chakrabarthi *et. al.* (1975). A new formulation Captan 70% + Hexaconazole 5% WP @ 0.2% was significantly effective in reducing the brown spot of rice (Kiran Kumar and PrasannaKumar, 2011). According to Sunder *et. al.* (2010), among six fungicides evaluated, propiconazole (2ml/l) proved most effective and reduced the brown leaf spot with significant increase in yield.

7.4. Sheath rot

Sheath rot of rice occurs in most rice-growing regions of the country. Chemical control of sheath rot has been intensively studied in India. Murty (1986) found that carbendazim, edifenphos and mancozeb (seed treatment and two foliar sprays around the booting stage) reduced sheath rot incidence significantly. Benomyl and copper oxychloride have also been reported to be effective in the field. However, studies by Lewin and Vidhyasekaran (1987) indicated that all fungicides they tested (captafol, carbendazim, carboxin, copper oxychloride, edifenphos, iprobenfos, iprodione, mancozeb, tridemorph, thiophanate-methyl and validamycin) were ineffective. Seed treatment with benlate and panoptine improves germination of sheath rot infected seeds (Alagarsamy and Bhaskaran, 1987). For field control of the disease, hinosan, bavistin, and

dithane M-45 proved to be effective. Fungicides like kitazin, benlate, difolatan, miltox, NF-48 and deconil were sprayed @ 0.2% separately on plants twice at 10 days interval during the flowering stage, could control the disease effectively. According to Raina and Singh (1980) and Chinnaswamy *et. al.* (1981), the most effective fungicide for the control of sheath rot was carbendazim followed by MBC, aureofungin and difolatan.

Effective combinations of fungicides (carbendazim) and insecticides (monocrotophos) to control sheath rot and leaf-folder, *Cnaphalocrocis medinalis* (Raju *et al.*, 1988) resulted in lower incidence of sheath rot. Combined spraying of monocrotophos with any of the fungicides edifenphos, mancozeb and carbendazim resulted in reduced sheath rot and highest yields. Tridemorph + phosphamidon followed by carbendazim + phosphamidon and tridemorph + neem oil provided the best control and increased yield against sheath rot and rice mealybug, *Brevennia rehi*, (Lakshmanan, 1992). Two sprays of either thiophanate-methyl (Das *et al.*, 1997), carbendazim (Das *et al.*, 1997; Dodan *et al.*, 1996) or propiconazole (Dodan *et al.*, 1996) were highly effective in controlling rice sheath rot and significantly increased grain yield.

7.5. False smut

False smut has recently become an important disease of rice in India. Hybrids are more prone for this disease and fungicides have been extensively tested to manage the disease. Singh (1984) identified aureofungin, captan, captafol, fentin hydroxide, furcarbanil, mancozeb, and thiocyanomethylthiobenzothiazole to be effective in inhibiting conidial germination. Seed treatment with fungicides did not check the disease, but spraying the rice crop with carbendazim and copper fungicides at the time of tillering and pre-flowering effectively controlled the disease and yields increased (Anon., 1990). Copper oxychloride was most effective in decreasing disease incidence by 95.5 and 96.1% on the basis of infected tillers and grains, respectively, with a corresponding increase of 7.2% in grain yield (Dodan *et al.*, 1997). Propiconazole or azoxystrobin applied during the boot stage of rice reduced the number of false smut balls in harvested rice grain by 50-75% but yield was not affected. Copper hydroxide fungicides reduced false smut balls in harvested rice by 80% but yield was also often reduced significantly. Barnwal (2011) observed that two sprays of propiconazole (0.1%) was found effective which recorded least false smut disease with number of affected florets panicle (1 of 4.13) with disease severity of 22.2 per cent and disease control over check of 77.6 per cent.

Singh and Singh (1985) have reported that 0.4% Bordeaux mixture or 0.25% COC sprayed thrice at 10 days interval starting when the crop is 60-65 days old gave about 90% reduction in disease incidence.

7.6. Stem rot

Stem rot disease is becoming more serious mainly in rain-fed crop. In India under field conditions, foliar application of mercurial fungicides like mercurin and agrosan GN were found to be better than non mercurial like captan and thiram (Kang *et. al.*, 1970). Hinosan, kitazin and brassicol were also found effective in reducing the disease with corresponding increase in yield (Jain, 1975).

7.7. Foot rot

Bakanae or foot rot disease is not widely distributed in all rice-growing areas of the country. However, the disease more serious in some endemic areas. Seed treatment with organo-mercury compounds is highly effective in controlling *G. fujikuroi* infection, but the use of these chemicals is no longer advisable due to ban on these groups. Benomyl, thiram and thiophanate-methyl have replaced organo-mercury seed disinfectants; these chemicals are now used extensively in Japan, Taiwan and Korea. These chemicals are highly effective against bakanae, rice blast and brown spot; with the exception that benomyl is not effective against brown spot (Okata, 1981).

Seed treatment with wettable powder containing ipconazole offered protection against seedborne diseases including bakanae (Tateishi *et al.*, 1998). Seed treatments with benomyl + thiram and thiophanate methyl + thiram were more effective than carboxin + thiram. A drench treatment on seedlings did not provide significant control of the disease (Padasht *et al.*, 1996). Seed soaking for 8 h in a suspension of emisan alone or emisan + streptocycline gave effective control of soil microflora including *G. fujikuroi*, followed by carbendazim + thiram (Sharma and Chahal, 1996).

7.8. Narrow brown spot

Narrow brown spot is generally not considered economically important, and no crop loss information is available on the disease. The commonly used fungicides *viz.*, Benomyl and propiconazole controlled narrow leaf blight (*C. oryzae*) when applied as foliar sprays (Groth *et al.*, 1990). In pot trials, fungicides that are effective against this disease include carbendazim (Singh, 1988).

From past three decades several fungicides have been tested at All India Co-ordinated Research Centres in India for their efficacy against important diseases of rice (Table 3).

8. Future of fungicides

The ability of the pathogens to adopt to intensive cultivation of cereals and need to feed the increasing population will lead to increase in area of intensive cropping along with increase in consumption of fungicides. The key change in fungicide use have usually been associated with changes in the spectra of pathogens as well as in crop intensities, practices or prices. Shift in pathogen spectra could not be predicted and will continue to occur in the future due to increase in free trade. The R&D expenditures of major Agro companies on fungicides is > 60 % as against 40% for seed and traits. This ensures that new fungicides will continue to be developed to protect the cultivars species with no genetic disease resistance. Efforts are made develop a new strategy for environmentally friendly control of fungal plant diseases with the development of proteomics-based fungicides.

The trend towards a more judicious use of fungicides in combination with disease forecasting done would be continued which will help reduce the risk of adaptation by the target pathogen and at the same time will reduce residues in the environment and on the produce. The efforts

of breeding for disease resistance will increase along with tools of genetic engineering. Both genetic resistance and selective fungicides are prone to adaptation by the pathogen. Another new area of research is the use of antimicrobial peptides (AMP) for improving resistance to pathogens using transgenic plants as bio-factories for fungicides or bactericides. The balance between genetic and chemical control will continue and research on both areas will complement each other to assure the availability of effective combinations of host resistance and fungicides for crops to produce higher and quality produce.

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