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Rice Blast, A Major Threat to the Rice Production and its Various Management Techniques

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ABSTRACT

Rice (*Oryza sativa L.*) is the most important staple cereal crop which is consumed by more than 50% of world population. It contributes 23% and 50% of total calories consumed by world and Nepalese population respectively. Among various abiotic factors affecting rice, rice blast is the most disastrous, causing 70-80% yield loss. This disease was originated in China around 7000 years ago. In Nepal, it was first reported in Thimi, Bhaktapur in 1966. It is caused by a filamentous ascomycete fungus *Magnaporthe oryzae* (Anaemorphic form- *Pyricularia oryzae*). It infects all the developmental stage of plant and produce symptoms on the leaf, collar, neck, panicle and even in the glumes. It decreases the rice production by an amount, enough to feed 60 million people every year. Cloudy weather, high relative humidity (93-99%), low night temperature (15- 20°C), longer duration of dew is the most favorable condition for the outbreak of disease. The most usual approaches for the management of rice blast diseases are management in nutrient fertilizer and irrigation, application of fungicides and plantation of resistant cultivars. Besides, the use of extracts of *C. arabica* are reported to have an inhibitory effect on the disease. Seed treatment with *Trichoderma viridae* @ 5ml/lit of water have also been found effective. The chemical means of controlling blast disease shall be reduced, instead eco-friendly measures like biocontrol agents, resistant varieties, plant extracts can be practiced for disease control. Different forecasting model can be used in order to predict the disease prevalence.

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Introduction

Rice (*Oryza sativa L.*) is a major cereal crop belonging to the family *Poaceae*. It is the most important staple cereal crop of the world and is consumed by more than 50% of world population, mostly in Asia (Yan & Bao, 2014; Thapa & Bhusal, 2020). On an average 755,473,800 tonnes of rice is produced worldwide from 162,055,938 ha of land with an average yield of 4661.8 kg/ha (FAO, 2019). China is the world's largest producer of rice followed by India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, Philippines, Japan and rest of the world (FAO, 2019). Its importance to food security is spotlighted by the fact that it contributes 23% of the calories consumed by the global human population and is the most important food produced in Asia, where 55% of the world's population lives and 92% of rice is grown and consumed (Wilson & Talbot, 2009) and that is why it is said "Rice brings the Asians together" (Basnet, 2008). In Nepal, rice is one of the most important staples crop whose production amounts to about half of the total cereal grains produced in the country and contributes more than 50% of the total calories required to the Nepalese people (Basnet, 2008; Ghimire et al., 2013). Rice ranks the first among cereal crops in terms of area, production and livelihood of people in Nepal as 1,458,915 ha of cultivable land is being used for rice production and 5,550,878 metric tonnes of rice is obtained after harvesting of the rice with a productivity of 3,804 kg/ha (AITC, 2021). Rice contributes nearly 20% to the agricultural gross domestic product (AGDP) and almost 7% to GDP (DoA/CDD, 2015). Prior to the Nepal, Population is increasing at an alarming rate and to feed these population, production in rice has also to be increase in similar fashion but studies show that in the last 39 years, the rice area and yield grew annually by only 0.59 and 1.75 percent, respectively (DoA/CDD, 2015).

Rice is the main source of nutrition for 2.5 to 3.5 billion people, the majority of whom live in rapidly developing low-income countries, especially in South Asia (Muthayya et al., 2014). Rice production has increased substantially over time; however, it is inadequate to subsist with the increasing global demand (Sasaki & Burr, 2000; Thapa &

Bhusal, 2020). Since 2000, global rice production has been less than rice consumption (Nguyen, 2002) and the annual shortage of rice is estimated to increase from 400,000 tons in 2016 to 800,000 tons by 2030 (Thirze, 2016). A recent analysis by the International Food Policy Research Institutes indicates that rice production will need to be increase by 38% by 2030 to feed the expanding human population and will need to be cultivated on less land as more arable land is lost to housing and industry (Wilson & Talbot, 2009).

Furthermore, rice production is affected by biotic and abiotic factors (Acharya et al., 2019). Drought, cold, acidity, salinity are abiotic factors while pests, weeds and diseases are biotic factors (Onyango, 2014). Among the biotic factors, fungal diseases alone are estimated to reduce annual rice production by 14% globally (Agrios, 2005) and among the fungal diseases of rice, rice blast caused by *Magnaporthe oryzae* is of significant economic importance that can cause 70% to 80% yield loss of rice (Nasruddin & Amin, 2012; Miah et al., 2013). Under the favorable conditions, this disease can damage entire rice plants within 15 to 20 days and cause yield losses of up to 100% (Musiime et al., 2005). Therefore, it is considered as one of the largest obstructions to increased rice production, which directly decreases rice yields and indirectly increases production costs (Nasruddin & Amin, 2012). Reduced rice yield due to rice blast is a significant threat to global food security because rice is an important source of calories for most of the world's population (Asibi et al., 2019). Therefore, emphasis must be taken to minimize, mitigate and control the infestation of blast disease worldwide so that global food security can be ensured. For this, different available management techniques should be followed and also many strategies should be developed in accordance with the time as the pathogen shows variable behavior according to the environmental conditions (Khemmuk, 2017). In this limelight, a brief information about the blast disease is presented along with its various management practices to minimize its infestation so that global rice production can be increased and the global food security can be ensured.

Materials and Methods

This review has been made consulting relevant articles and various reports. Collected information was arranged and findings from them are summarized and presented in texts, tables and figures under different headings with conclusions.

History and Occurrence of Blast Disease

Rice blast is one of the most widely distributed plant diseases of a major food crop with a high destructive potential in most rice-growing countries. It is believed to have originated from Yangtze middle valley of China around 7000 years ago (Couch et al., 2005; Mew, 2018). Soong Ying-shin described a rice problem similar to what we know today as blast in his book 'Utilization of Natural Resources' published in 1637 and he described the disease as a "fever" of rice seedlings due to heat absorbed into the grains during drying in hot sunshine and thereafter being stored it before cooled off (Ou, 1985). However, the Chinese literature did not provide any information of the occurrence or the cause of this "fever" but attributed it to seed drying (Mew, 2018). Rice blast was first known as rice fever disease in China (Yan & Bao, 2014). In Japan, this disease was reported as Imochi-byo by Tsuchiya in 1704 and in Italy, it was reported in the year of 1828 (Ou, 1985). In India, it was first reported in Tamil Nadu in 1913 (Padmanabhan, 1965). After the green revolution of 1960s, introduction of first high-yielding varieties, semi-dwarf rice cultivars and their good response to nitrogen fertilizer lead to increased use of inputs which increases the susceptibility of rice to blast and set the stage for the invasion of novel blast pathogen into modern rice (Waller, 1987; Khush, 2001).

In Nepal, blast disease was first reported in Thimi, Bhaktapur in 1966 (Bhatt, 1966). Blast can be found in all rice-growing regions, from the lowlands (60masl) to the high hills (3050masl) (Bhandari et al., 2017). Its incidence and severity used to be very high until a few years back especially in inner terai and foot hills where one of the most popular varieties Mansuli was cultivated and in valleys of mid hills growing Taichung-176 and Chainan-242 (Bhandari et al., 2017). In Nepal, it is locally known as "Maruwa rog" (Acharya et al., 2019).

Severity and Economic Significance of Rice Blast

Outbreaks of rice blast are considered as a serious and recurrent problem in over 85 countries where rice is gown in both lowland and upland conditions, with annual rice harvest losses ranging from 10 to 30% (Skamnioti & Gurr, 2009; Pooja & Katoch, 2014). Yield loss from this disease may reach 80 % under ideal conditions of heavy dew, high mean temperatures, high humidity, drought and excessive nitrogen fertilizer (Piotti et al., 2005). Different studies revealed that on an average, a total of US$203.49 million is lost annually with addition of both mitigation cost and yield loss (Nalley et al., 2016). According to the Zeigler et al. (1994), it is estimated that each year enough of rice is destroyed by rice blast alone which alone could feed 60 million people of the world. In Japan, the disease affects approximately 865,000 hectares of rice fields each year and more than 50% yield losses each year is caused by rice blast in the Philippines (IRRI, 2003). Moreover, from 2000 to 2004 in southeastern and central China along the Yangzi River Delta, 3.3 to 5.7 million ha of rice fields was affected by Blast epidemics (Mew, 2018). In Sichuan, the most important rice-producing province in China, leaf and panicle blast infected 0.5 and 0.3 million ha of rice, respectively, resulting in 400 thousand tons of yield loss in the year 2005 alone (Mew, 2018). Moreover, in the year 2004, in upland rice production in West Java, Indonesia, total yield was reduced by 70 % by rice blast (Ballini et al., 2008).

In the context of Nepal, Chaudhary (1999) reported that with 1% increase in neck blast, the yield losses in 'Mansuli' and 'Radha-17' cultivars was 38.5 and 76.0 kg/ha respectively. According to Mathur et al. (1992) the disease causes 10-20% yield reduction in Nepal in susceptible varieties, but in severe case it went up to 80%. Jumli Marshi, the most traditional variety of Jumla is also highly susceptible to blast and in the year 2011, blast destroyed 80% Jumli Marshi in the Tila valley of Jumla, Karnali (Bhandari et al., 2017).

Rice blast is a disease of immense importance and it is increasingly worrisome to rice farmers around the world and threatening the global food security (Deng et al., 2017). Therefore, controlling rice blast should be the main strategy to restore economy and sustain the food security of any country particularly Asian countries.

Causative Agent

Rice blast disease is caused by the filamentous ascomycete fungus *Magnaporthe oryzae* (Synonyms- *Pyricularia oryzae*), which was recently defined as a new species, separate from *Magnaporthe grisea*, based on multilocus genealogy and mating experiments (Couch & Kohn, 2002). Phylogenetic analysis divides *Magnaporthe* isolates into two clades which are morphologically indistinguishable; one that infects *Digitaria* (Crab grass) was named as *Magnaporthe grisea* and another that infects rice, millets and other grasses (Species of *oryza*, *setaria*, *lolium*, *Eragrostis and Eleusine*) which was named as *Magnaporthe oryzae* (Couch & Kohn, 2002). This fungus is part of a species complex that can cause blast diseases on about 50 grass (*Poaceae*) and sedge (*Cyperaceae*) species, including rice *(Oryza sativa*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), maize (*Zea mays*), oats (*Avena sativa*), rye (*Secale cereale*), finger millet (*Eleusine corocana*) and perennial ryegrass (*Lolium perenne*) (Skamnioti & Gurr, 2009).

The genus *Pyricularia* is classified in the family *Pyriculariaceae*, order *Magnaporthales*, subclass *Diaportheomycetidae*, class *Sordariomycetes*, subphylum *Pezizomycotina*, phylum *Ascomycota* (Klaubauf et al., 2014; Maharachchikumbura et al., 2015). The *Pyriculariaceae* currently contains about 70 species distributed in the following nine genera, namely, *Bambusicularia*, *Barretomyces*, *Deightoniella*, *Macgarvieomyces*, *Neopyricularia*, *Proxipyricularia*, *Pseudopyricularia*, *Pyricularia* and *Xenopyricularia* (Klaubauf et al., 2014). The most widely studied species in the *Magnaporthales* is *Pyricularia oryzae* (synonym- *Magnaporthe oryzae*), which was ranked first in a list of the top 10 fungal plant pathogens in the world based on scientific and economic importance of the disease caused by it on rice as one-half of the world population is relying on rice as main source of calories (Dean et al., 2012).

Pathogen Biology and Disease Cycle

M.grisea, teleomorphic (Sexual) stage of *Pyricularia oryzae*, is a pyrenomycete that produces fusiform, curved ascospores in perithecia in an unorganized manner (Lundqvist et al., 1994). *M.oryzae* follows a series of developmental and metabolic pathways from the time the spores land on the waxy leaf surface until the production of sporulating lesions (Richard J. Howard & Valent, 1996). Theoretically, infested seed could initially lead to disease development through root colonization with subsequent lesion formation and aerial dispersal of conidia (Ebbole, 2007). During one growing season, a single lesion can produce 2000-6000 conidia per day for up to 14 days, with multiple cycles of infection and reproduction, serving as a source for secondary dispersal, however, the number of cycles and the number of spores that are produced on each individual lesion can be influenced by many factors, including the temperature, rainfall, the depth of the water in the paddy, the amount of nitrogen used to fertilize the rice and the level of genetic resistance in the cultivar that is infected (Couch et al., 2005). Experiment conducted by Lee et al. (2006) suggested that the constant blue light (but not red light) inhibits conidiophore development and also the conidiation period requires a period of dark (Atkins, 1974). Mature conidia are three- celled, pyriform or pear-shaped septate structures that bear a basal appendage at the point of attachment to the conidiophore called as hilum as shown in Figure 1 (Howard and Valent, 1996).

Blast lesions that develop on an infected plant produces numerous conidia that are released in moist air and inoculate neighboring plants which indicates the beginning of infection cycle (Hamer et al., 1988). In the presence of high humidity, contact between the spore and the leaf cuticle induces release of mucilage from the spore apex, enabling the conidia to attach to the leaf surface (Hamer et al., 1988). Once the conidia get attached, it germinates by rapid growth of a germ tube that later forms a dome-shaped, melanin pigmented infections structures called appressorium within 4-6 hours (Veneault-Fourrey & Talbot, 2005). The *Magnaporthe grisea* appressorium generates up to 8MPa of turgor to provide the motive force necessary to break the tough cuticle of the rice plant through a narrow penetration peg (Howard et al., 1991; De Jong et al., 1997). The infection cycle is shown in the Fig. 2 below.

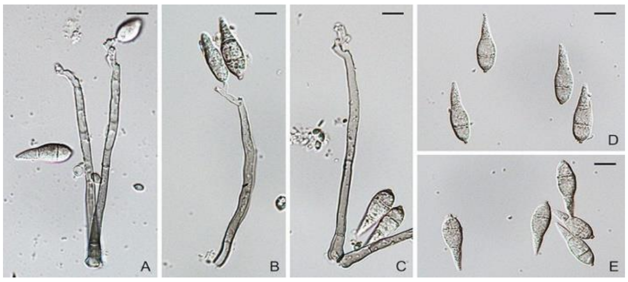

Fig. 1: *Pyricularia oryzae*; Conidiophores and conidia (Source: (Luo J, Zhang, 2019))

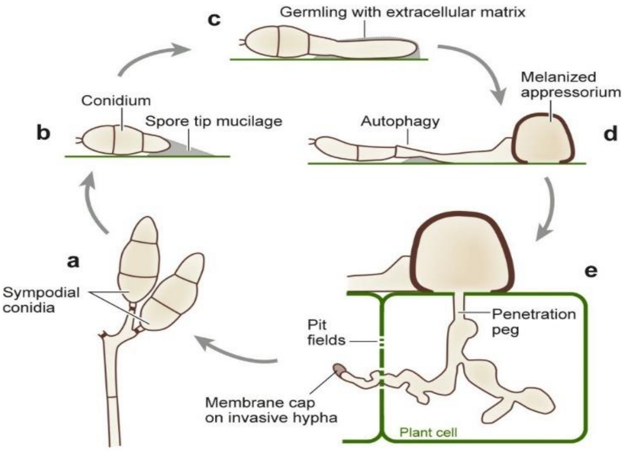

Fig. 2: Infection process of rice blast pathogen (The conidia of *M. grisea* first adhere to the plant surface, germinate and develop a specialized infection structure termed as appressorium. A huge turgor pressure is developed within the appressoria and a penetration peg emerges in order to allow the fungus to penetrate into the first epidermal cell). (Adopted from: Magnaporthe grisea as a model for understanding host-pathogen interactions (Ebbole, 2007).

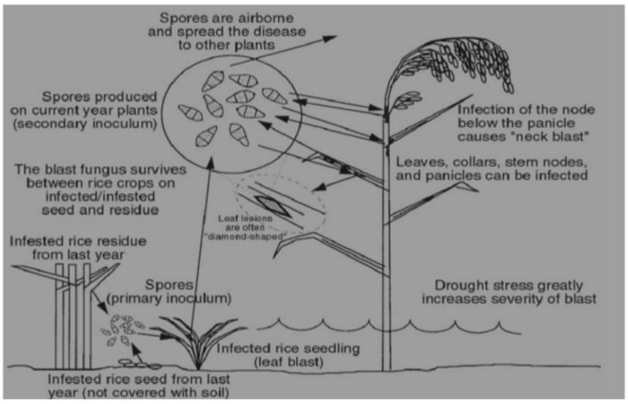

Figure 3. Disease cycle of *Magnaporthe oryzae* (Adopted from (Wamishe et al., 2013))

Figure 4. Typical diamond shaped blast symptoms in rice leaves. Adopted from: (Blast (Leaf and Collar) - IRRI Rice Knowledge Bank.)

Figure 5. Nodal symptoms due to rice blast disease. Adopted from: (Blast (Node and Neck) - IRRI Rice Knowledge Bank)

Figure 6. Typical symptoms on collar regions of rice leaf. Adopted from: (Blast (Leaf and Collar) - IRRI Rice Knowledge Bank)

Mycelium and conidia over-wintered on straw and seeds as well as on the collateral hosts like *Eleusine coracana*, *E. indica*, *Panicum sp.*, *Setaria sp*. etc. which serves as the primary source of inoculums (Bhandari et al., 2017). The disease cycle can be summarized in Figure 3 below.

Symptoms of Rice Blast

M. oryzae infects all the developmental stages of the rice plant including roots and disease symptoms can be observed on the leaf, collar, neck, panicle and even in the glumes (Sesma & Osbourn, 2004; Yasuda et al., 2014). The major symptoms are briefly discussed below:

Symptoms on Rice Leaf

Symptoms of leaf blast typically consist of elongated diamond-shaped lesions with grey or whitish centers and brown or reddish-brown margin (Acharya et al., 2019). Later, the small spots collapse together, becomes eye-shaped in mature stage and give blistering appearance (Neupane & Bhusal, 2021). Lesion reduces the net photosynthetic rate and impaired the transport of water or nutrients or both and consequently affect the leaf tissues situated near the lesions (Bastiaans, 1991). The pathogen can account for up to 10% of the biomass of infected leaf tips by three days after inoculation (Talbot et al., 1993). Typical leaf symptoms can be seen in Figure 4 below.

Node/Culm Blast Symptoms

When the node of plant is affected, node portion of the culms turn brown, grayish brown or black and the portion above the infected node may die and breakdown as the xylem and phloem vessel of plant blocked which affects the nutrient and water supply to the portion above the infection point (Neupane & Bhusal, 2021) as shown the Figure 5 below.

Collar Blast Symptoms

The spores undergoing overwintering when infects the collar of the flag leaf, produce symptoms which are collar rot (TeBeest et al., 2007). At initial stage infection starts at the base of the flag leaf near the leaf sheath (Neupane & Bhusal, 2021). At later stage, infection proceeds upward to the leaf that girdles the flag leaf which turned brown, dry and fall off (TeBeest et al., 2007). Collar blast (rot) is shown in the Figure 6 below.

Neck/Panicle Blast Symptoms

It is the most devastating blast disease infection on the panicle which results in chalky kernels, sterile grain or losses at harvest (Candole et al., 1999). The node immediately below the ear forms grayish brown lesions, as a result, the whole inflorescence may break off at the rotten neck (Neupane & Bhusal, 2021). No grain is formed if infection of the neck occurs before milky stage whereas poor quality grains are formed if the infection occurs later. It also results in discoloration of grains (Candole et al., 1999). It is shown in Figure 7 below.

Epidemiology

The ultimate goal of epidemiology research is to precisely forecast prevalence of the disease and as a result, aids in reducing disease related yield damage.

Fig. 7: Infected panicle of rice due to blast infection. Adopted from: (Blast (Node and Neck) - IRRI Rice Knowledge Bank)

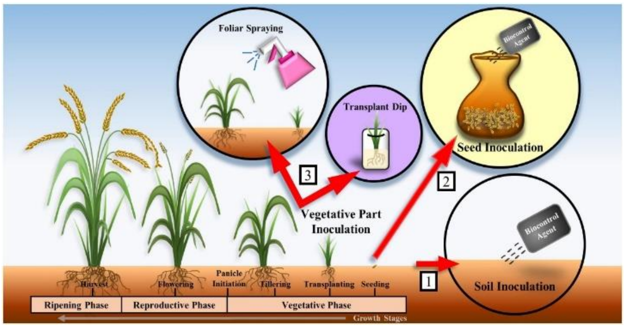

Figure 8. Method of application of biocontrol agents. Source: (Law et al., 2017)

According to Neupane & Bhusal (2021), the most suitable conditions for the outbreak of blast fungus are cloudy weather, high relative humidity (93-99 percent), low night temperatures between 15-20°C and longer dew duration. In Taichung-176 and Radha-17, blast lesions were detected within a week of transplantation of three weeks old seedling raised at 15- 20°C to higher temperature of 25-30°C (Manandhar et al., 1998). Host nutrition also affects the pathogen infection as susceptibility increases with higher doses of nitrogen because it encourages more vegetative growth during early stage and hence increase the blast severity (Johnston et al., 1970; Sobrizal & Anggiani, 2007). Experiments conducted in California suggested that typical leaf wetness periods of 14h in California rice fields are more than sufficient for conidia production, however, peak conidia release is typically at 6:00 A.M. (Greer & Webster, 2001). Closer planting of rice also favors the microclimate for disease development (Chaudhary et al., 1994). Ou & Britain (1985) found out that longer dew periods and regular moisture stress in upland rice also leads to increase disease incidence.

Management and Control

The effectiveness and efficiency of each control or management strategy depend largely on rice ecosystems and production environments and also on understanding the biology of its causal pathogen and the disease it causes (Mew, 2018). Management of pathogen is difficult because it is seed borne fungal diseases (Ou, 1985). However, there are various practices to mitigate the infestation of *Magnaporthe* fungus. Some of the significant management practices are broadly discussed below.

Cultural Management

In the absence of immediate control measures, such as a highly resistant variety or chemical control, cultural practices have been one of the oldest and reliable methods to minimize blast damage in the rice field (Kozaka, 1963). Blast fungus also survive in unfavorable conditions so proper field sanitation by removal or burning of plant stubbles, long term crop rotation, summer ploughing and removal of collateral hosts is necessary (TeBeest et al., 2007). Burning residues prevents pathogen from overwintering, but it does not inhibit the spread of inoculums (Oerke, 1996). High plant density and a high level of nitrogen result in vigorous vegetative growth and a dense leaf canopy which leads to a favorable microclimate for blast disease development, therefore, higher plant density should be controlled (Kim & Kim, 1993).

Irrigation Management

The availability of moisture content in the soil also affects the susceptibility of host plant to *P. oryzae* (Pooja & Katoch, 2014). Rice grown under upland conditions is more susceptible than rice grown in flooded soil (Kahn & Libby, 1958). Flooding a rice field creates an anaerobic environment which kills disease causing pathogen as water creates unhealthy environment for them (Kim, 1986). Moreover, plants grown under consistent, deeper irrigation floods (≥4 inches) are much less prone to blast than plants that are grown under more shallow floods, moist soil or drought-stressed condition (Wamishe et al., 2013).

Time of Planting

Early planting is also recommended for blast pathogen control. In tropical upland rice, crops sown early during the rainy season generally have a higher probability of escaping blast infection than late-sown crops (Pooja & Katoch, 2014).

Nutrient Management

Nutrient management plays a significant role in pathogen infestation control. Osuna-Canizalez et al. (1991) mentioned that Nitrogen (N) and silicon (Si) elements greatly affects disease incidence and development. Application of Nitrogen in Split doses reduces excessive vegetative growth during early season and reduces severity of blast diseases (Johnston et al., 1970). A limit of 15kgN/ha is recommended for upland rice in Brazil particularly to reduce the vulnerability of blast diseases (Prabhu & Morais, 1986). Experiments conducted at University of Floride, USA showed that reduction in the rice blast with the application of calcium silicate slag was comparable to that of fungicide (Benomyl) and therefore, farmers of that region prefer a silicon fertilization (Datnoff et al., 1997). Presence of large amount of silica in rice leaves makes the plant resistant against the infection as silica get localized in leaf surface which acts as a physical barrier against blast fungus penetration (Ishiguro, 2001). Moreover, the experiment conducted in a green house, at the Universidadae Federal de Uberlandia, MG was observed that greatest reduction of blast incidence at 4 g Si/L, regardless of solution pH (Buck et al., 2008). Cheap sources of silicon, such as locally available straws of rice genotypes with high silicon content, can also be used as an alternative (Marxen et al., 2016).

Table 1. Inhibitory effect of aqueous plant extracts of different plants species against *P. Oyzae*

Plant extracts	Plant extracts concentration (%)	Inhibitory effects (%)
C. arabica	25	89.40
C. arabica	10	81.12
N. tabacum	10	80.35
A. vera	25	76.15
C. Coccineum flower	25	78.83
Z. officinalis	25	75.60
A. indica	5	69.38
A. sativum	25	68.75

Source: (Hubert et al., 2015)

Table 2. List of different forecasting models.

Forecasting Models	First Developed	References
BLASTCAST	Japan	(Ohta et al., 1982)
BILASTL	Japan	(Hashimoto et al., 1982)
PYTRICULARIA	Netherland	(Gunther, 1986)
Leaf blast simulation model	Philippines	(Torres, 1986)
PYRNEW	Indonesia	(Tastra et al., 1987)
LEAFBLAST	Korea	(Choi et al., 1988)
EPIBLA	India	(Manibhushanrao & Krishnan, 1991)
EPIBLAST	Korea	(Kim & Kim, 1993)
DYMEX and CLIMEX	Australia	(Lanoiselet et al., 2002)
BLASTMUL	Japan	(Ashizawa et al., 2005)
Machine learning technique	India	(Kaundal et al., 2006)
EPIRICE	Korea	(Savary et al., 2012)

Chemical Control

To control blast pathogen infestations, farmers depend heavily on chemical fungicides because it is readily available and quick responsive. Research conducted in Chitwan, Nepal found out that applying Tricyclazole 22 % + Hexaconazole 3 % SC three times at weekly intervals from the booting stage resulted in the best disease control (87.03 % and 79.62 % in leaf and neck blast, respectively), the highest grain yield (4.23t/ha), and a 56.09 %) improvement in yield over the control one (Magar et al., 2015). Experiments performed in Pakistan by Hajano et al. (2012) discovered that using the fungicide mancozeb at 1000 and 10,000 ppm fully inhibits the mycelial growth of Magnaporthe grisea, making it the most effective fungicide. Similarly, experiments conducted in Thailand by Kongcharoen et al. (2020) found that mancozeb exhibited the highest level of fungicidal activity against the blast pathogen *Pyricularia oryzae* with an EC50 value of 0.25 parts per million (ppm). Furthermore, experiments conducted in Nigeria concluded that two systemic fungicides benomyl and tricyclazole were found to be effective and significantly increased grain yield over the control one by 18.14% and 42.17% respectively (Enyinnia, 1996). In an experiment conducted by Padmanabhan et al. (1971) found out that spraying copper and organic mercury-based fungicides in a schedule covering 5-6 sprays; one spray at seed bed (on 21 days old seedlings), two to three sprays at post-tillering phase at an interval of 10-15 days and two sprays at ear emergence; one spray before emergence and other 5 days later were also effective in controlling neck blast infections on local indica varieties.

Use of chemicals are non-environmental friendly (Thapa et al., 2019) and overuse of chemicals for a successive year develops a resistance in the fungus and has serious threats in the future. Moreover, pesticide exposure leads to acute pesticide poisoning that has adverse health effects on vital body systems such as the digestive, respiratory, and nervous system and farmers are the most at risk of pesticide poisoning because of their prolonged exposure during the production season (Pingali & Roger, 2012; Qiao et al., 2012). The residue of chemicals persists in the grain, straw and soil which may cause adverse effect for the farm labor (Pingali & Roger, 2012), therefore, use of chemical fungicides should be minimize.

Botanical Control

The indiscriminate use of various plant protection chemicals has resulted in environmental hazards, hence finding alternative sources is of immense importance and also preferable (Thapa et al., 2019; Ahamad et al., 2020). Many farmers in India and other developing countries use leaf, seed kernel or cake extracts and oils for crop pest control, but the preparation of these materials takes time and moreover, oils cannot be stored for long periods of time due to the risk of rancidity, which reduces their effectiveness (Rajappan et al., 2001).

Garlic juice and the compound obtained from it (Allicin) were found to be highly effective against the rice blast fungus *M. oryzae* (Slusarenko et al., 2008). Experiments conducted by Hubert et al. (2015) confirmed that plant extracts were not phytotoxic to rice seedlings, therefore can be successively used to control rice blast disease. According to Hubert et al. (2015), various plant extracts are used in controlling rice blast, among them *C.arabica* at 25% plant extracts concentration was found to be more effective and various plant extracts are shown in the Table 1.

Biological Control

Biological control of plant diseases is typically inexpensive, long lasting and safe towards the environment and living organisms, however, biological control can be a slow process and the search for suitable biocontrol agents requires considerable time and effort (Law et al., 2017). The first report of a biological agent found effective against *Pyricularia oryzae* was *Chaetomium cochliodes* (Pooja & Katoch, 2014). 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 (Pooja & Katoch, 2014). Experiments conducted by Bhusal et al. (2018) showed that seed treatment by *Trichoderma virdi* @5ml/lt of water was found to be effective against leaf blast. Moreover, experiments conducted by Hajano et al. (2012) found out that among the six bio-control agents tested against the M. oryzae, the maximum inhibition was obtained from *P. lilacinus* followed by *T. pseudokoningii*, *T. polysporum* and *T. harzianum*. According to greenhouse studies conducted by Law et al. (2017), infected rice seedlings treated with Streptomyces resulted in up to 88.3% disease reduction of rice blast. Furthermore, recent studies on biocontrol of rice blast showed that *Bacillus subtillis* strain B-332, 1Pe2, 2R37 and 1Re14 was found more effective (Changqing et al., 2007; Jh et al., 2008). Rice blast biocontrol experiments revealed that a powder formulation of *Pseudomonas fluorescens* strain Pf1 at 10g/kg inhibits rice blast growth (Vidhyasekaran et al., 1997).

In order to achieve successful biological control, the biocontrol agents should be isolated from and applied to locations with similar environmental conditions (Suprapta, 2012). The proper way of applying biocontrol agents is shown in the Figure 8.

Use of Resistant Cultivars

Cultivation of the host resistant plants are the most efficient way to manage the disease because it is a convenient, cost-effective, environment friendly, long-term, reliable and realistic approach of plant protection for resource constrained farmers (Ou, 1985; Bonman et al., 1992; Sharma, 1997). Studies shows that degree of resistance increases with increase in the proportion of silica applied and also to the amount of silicon accumulated in the plant (Pooja & Katoch, 2014). Generally, horizontal and vertical resistance is used in developing disease resistant cultivars (Rijal & Devkota, 2020). Due to the high genetic variability of the fungus, resistance to infection by *Pyricularia oryzae* can be short-lived (Khemmuk, 2017). The breakdown of resistance to *Pyricularia oryzae* results from evolution of genetic variants (races) in the pathogen populations (Liu et al., 2011).

In Nepal, planting blast resistant varieties like Khumal-1, Khumal-2, Khumal-3, Radha-12, Chandannath-1, Chandannath-3, Sabitri and Palung-2 is perhaps the most cost-effective method of blast control, but research revealed that these varieties also start to show susceptibility after two to three years of repeated planting (Bhandari et al., 2017). In case of Jumli Marshi, Chandanath-1 and chandanath-3 were developed by NARC which were more resistant than Jumli Marshi however after two to three years, they also become susceptible as the pathogens develop resistance against the new germplasm (Basnet, 2008; Bhandari et al., 2017).

Use of Biotechnological Approaches

From the end of 1980s, the scenario of rice blast research has totally changed because of the use of biotechnological approaches such as 1) Molecular diagnosis of plant pathogen which includes monoclonal antibodies, enzyme linked immunosorbent assay (ELISA) and PCR, 2) Analysis of molecular variability in plant pathogens, 3) Mapping of disease resistant genes using DNA makers, 4) Marker assisted pyramiding of disease resistant genes, 5) Use of transgenic variety, 6) Application of genomics, 7) Application of RNA interference and viii) Post transcriptional gene silencing (Pooja & Katoch, 2014), which are used in detecting, mitigating and controlling pathogen and its infestation.

Biotechnological methods have also been used to identify and map QTLs for partial blast resistance, as well as for gene pyramiding by marker assisted selection (MAS) (Pooja & Katoch, 2014). 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).

Disease Forecasting

Plank & E (1963) quoted that “Chemical industries and plant breeders forge fine tactical weapons but only epidemiology sets the strategy”. Therefore, the good knowledge of epidemiology of a disease can help to utilize the available disease management strategies in a more effective way. Moreover, Farmers can prevent overuse application of agrochemicals by using an effective disease forecasting system and suitable disease management technologies, as a result, a better harvest and profit can be achieved by making efficient use of labor, resources, and capital (Kim & Kim, 1993). The findings from the experiments of 13 years by Padmanabhan (1965) shows that forecasting a blast outbreak in India can be done on the basis of a minimum night temperature range of 20-26 ° C in combination with a high relative humidity range of 90% and above lasting for a week or more during any of the susceptible stages of crop development, such as seedling stage, post-transplanting, tillering stage, and at neck-emergence.

Several modelling approaches have been followed in recent times for the disease forecasting. Support Vector Machine model is a first web server for rice blast prediction, which is found better than existing machine learning technique and conventional multiple regression (REG) approaches and it is helping the plant science community and farmers in their decision-making process (Kaundal et al., 2006). Today number of computer simulation based forecast models are available which are given in the table 2

Conclusion

Use of chemical means to minimize the pathogen attack should be reduced in near future and eco-friendly and sustainable means such as use of bio-control agents, use of resistant variety, botanical means of controlling pathogen and different biotechnological approaches should be followed. Importantly, more research should be done in disease forecasting so that we can forecast disease prevalence and plan accordingly. In the context of Nepal where more than 60% of population are engaged in agriculture, forecasting models could be a good option. Overall, the rice production should be increased regardless of any cause because no other sector of the economy is likely to bring a sustainable level of food security for the rapidly growing population.

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