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Rice crop loss due to major pathogens and the potential of endophytic microbes for their control and management

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ABSTRACT

Millions of people around the world depend on rice as the staple food which is infested by many pathogens causing a huge loss. Synthetic chemicals, fungicides, and bactericides are being used massively to control these pathogens in many countries. Although these pesticides are being able to control many pathogens, non-judicious applications may lead to many environmental and health concerns. Utilization of endophytic microorganisms may be an eco-friendly and sustainable approach in this direction. Endophytic microorganisms remain asymptomatically inside the plants in a symbiotic manner and impart resistance to plants from many biotic and abiotic stresses. Many endophytes have proved to have antagonistic effects toward many pathogens of plants. Some potential endophytes have consistently been isolated from rice and other plants which could control the growth of many rice pathogens. Considering the importance of rice and its many pathogen enemies, research on the use of endophytes to control these pathogens needs to be intensified to minimize crop loss and to meet future rice demands. The present review accentuated the potential of endophytic microorganisms to control some of the important rice pathogens which cause huge loss in many rice-growing areas of the world. This review may encourage researchers for intensified and integrative research in the mentioned area.

1. INTRODUCTION

Half of the world's population depends on rice (*Oryza sativa* L.) as the fundamental principal food which supplies about 20% of the total calories consumed. Worldwide rice production was 600 million tons in 2000 and with a 1.5-fold increase it may go up to 904 million tons by 2030 [1]. Rice cultivation is carried out on about 161 million ha worldwide, where about 678.7 million tons of paddy are produced annually. About 90% of the world's rice is grown and produced in Asia, i.e., about 143 million ha of land with a production of 612 million tons of paddy [2,3]. With a projection of 34% increase in the world population to 9.3 billion by 2050, the target of more production while losing less seems very compelling because of the recognized threat of increased pathogens and pest introductions due to various reasons like increased human mobility, global trade, and climate change. It is, therefore, very necessary to take seriously the threat possessed by both current and new crop pathogens and pests for any future steps for crop management [4].

Rice plants are infected by many devastating diseases like blast, leaf blights, sheath blight, sheath rot, brown spot, bakane disease, etc., which are caused by a wide range of phytopathogens that include fungi, bacteria, and virus, resulting in crop losses such as lower yield and quality of the crop produced [5]. Yield loss in rice due to pathogens has been estimated to be 15%–30% which costs about 33 billion USD annually. More detailed research reports and better-quality information ares required to firmly establish the manifestation of crop–pathogen interaction and economic loss. Still, these figures could clearly indicate an alarming situation for developing countries where such losses are not only costly in terms of the food security point of view but also regarding the requirements for foreign exchange to import food materials. Furthermore, there is also loss of income of farmers and others who depend on agriculture for their livelihoods [6]. Therefore, implementation of management strategies for rice diseases

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judiciously can result in the improvement of productivity and also enhanced grain harvest [3].

The various methods used for managing rice disease include the use of resistant varieties, cultural practices, chemical control, and biological control. Breeding for disease-resistant varieties has been long used for managing the rice diseases and is one of the most economical methods which has contributed immensely to the world's rice productivity [7,8]. However, most of these varieties possess resistance to some of the major diseases which has been the only concern for plant breeders and where more intensive efforts are required. There is often also a natural tendency among pathogens to evolve into newer and more aggressive biotypes which result in the breakdown of resistance varieties having resistant to restricted pathogens. The scenario is further worsened in case of fungal phytopathogens undergoing sexual reproduction regularly. This creates greater genetic variability the among pathogen population where chances of the development of fungicide-resistant strains are increased to a greater extent resulting in the requirement of a higher dosage of fungicides to sustain crop production [3,6]. Fungicide resistance among foliar pathogens may also arise due to the erratic application of systemic fungicides having narrow spectrum activity coupled with a faster rate of reproduction. Conventional approach of application of chemical pesticides, fungicides, and other microbicides is many a times found to be ineffective, expensive, and usually has serious implications on human and environmental health. Biological control method where antagonistic organisms are utilized to control pests and pathogens has been suggested as an integral part of integrated pest management, which also includes disease management. This has been proved to be the most effective, long-term, eco-friendly, and sustainable solution [9].

In this direction, the use of endophytic fungi to increase plant resistance to pathogens would be a great step toward decreasing the use of fungicides and other synthetic chemicals in rice agriculture and also the probability of development of resistance toward pathogens may be reduced [10,11]. Endophytic microorganisms are a group of intriguing organisms which is associated with various healthy tissues and organs of almost all the terrestrial and some aquatic plants. The infections caused by these microbes remain inconspicuous where the host tissues that have been colonized remain symptomless at least transiently. These extraordinary groups of microbes produce an arsenal of versatile bioactive compounds having antimicrobial properties and many agriculturally important substances [12,13]. The biocontrol activity of endophytes to phytopathogens in the root zone also results in the growth stimulation of host plants by multifaceted way such as production of antibacterial and antifungal agents, production of siderophores, competition for micro and macro nutrients, and induction of immunity or "systematic-acquired host resistance" [14]. With other modes of biological control, such as induced systemic resistance (ISR) and increased growth response, endophytic colonization by the biocontrol organism triggers responses in the plant that reduce or alleviate plant disease [10]. Fungal endophytes have been detected in symbiotic associations with many cultivated rice varieties where they have exhibited plant growth stimulation or promotion and antagonism against many phytopathogens [11].

In spite of the enormous capability to control rice pathogens, endophytes have not been exploited up to the extent of their potential. Some Class-II endophytes have been inoculated in rice to impose habitat-specific abiotic stress tolerance such as high salt concentration. Regarding defense to diseases, very few reports are available where endophytes are inoculated in rice plants. Hence, in the current review, we have brought to light the potential of endophytic microbes to inhibit rice pathogens causing major diseases and also made an attempt to show a future gap regarding its utilization for protection of rice crop.

1.1. Disease Occurrence in Rice: A Major Constraint in Rice Production

Among the biggest problems in rice cultivation is the management and prevention of various devastating diseases caused by pathogens that reduce crop yields. It has been a challenge for the rice researchers to develop strategies for the production of food grains having higher nutritional quality at a lower cost under continual increase in food demand due to population blasts. All these need to be accomplished in the unwanted presence of unrelenting and unforgiving plant pathogens. Yield loss in rice due to pathogens has been estimated to be an average of 10%–15% which might cause absolute destruction in specific cases. Rice plant is the host for 58 fungal (43 of which are seedborne or seed-transmittable), 12 bacterial, 17 viral and mycoplasma-like pathogens [15], and more than 30 species of nematodes. The pathogens cause diseases in every part of the plant like leaves, roots, nodes, and panicles, including seeds and propagules. The infection by the pathogens may be local or systemic, but implications of these diseases may be minimal to severe destructive crop damage. As rice is cultivated in many parts of the world, the distribution of associated pathogens is also worldwide. Some of these kinds of important rice pathogens, like *Helminthosporium oryzae*, *Rhizoctonia solani*, *Gerlachia oryzae*, *Pyricularia oryzae*, *Xanthomonas oryzae*, *Sclerotium oryzae*, etc., have been reported in many rice-growing countries which caused foliar diseases and stem, root, or leaf sheath problems. Agriculture in Asian nations, particularly in the last 15–20 years, has been shifted toward higher productivity with the implementation of high yielding and hybrid varieties replacing traditional landraces with the application of chemical fertilizers and plant growth hormones resulting in crop intensification. Under these changing conditions, many of the rice pathogens (the crafty enemies) have emerged as relatively more important than earlier. Many diseases which have been considered less important in the past gradually had to be added in management strategies. Some of the pathotypes have vanished and many new varieties have appeared in the population [16].

1.2. Endophytes and Their Role as Anti-Plant Pathogen Agents

A widely accepted and inclusive definition of endophytic microorganisms has been given by Bacon and White; "microbes that colonize living, internal tissues of plants without causing any immediate, overt negative effects". Beneficial endophytic microorganisms mainly comprise fungi and bacteria which form symbiotic association with their host plants by colonization of the internal tissues without causing any visible symptoms of damage to the host plant. The intimate association of endophytes with

plants has been an inevitable tool for the improvement of crop performance which has made them an extremely valuable aid for agriculture [14,17]. Endophytic microorganisms are believed to be symbiotically associated with almost all plants in natural ecosystems [17–19]. In this type of symbiotic association, the microbial partner gets nutrition from the plant and in return it may produce chemical factors that can enable the host plant to be protected from the attack of pathogens, insects, and animals [20]. Many plant–microbe interaction studies indicated recently that the adaptation capability of plants to various biotic and abiotic stresses has been attributed to the fitness benefits conferred by mutualistic fungi. It has fascinated many researchers around the globe where in many cases plant–microbe symbiotic associations are required for stress tolerance, even after 400 million years of evolution. Fungal endophytic microorganisms have been proved to be a rich source of a wide range of novel antimicrobial substances. The plants having endophytic association usually produce some metabolites which confer resistance to diseases. The endophytes act as "biological trigger" which activate the defense system of symbiotic plants faster than non-symbiotic plants after a pathogen attack [14,21]. Various types of mechanisms are involved in disease tolerance conferred by symbiosis with endophytes which depend on the biotype of endophytes. Several types of pathosystems have demonstrated the mode of action of endophytes toward plant disease suppression [22]. The various possible mechanisms to control this suppression may include antibiosis which acts directly on the plant pathogen inside the plant tissue. In another way, there might be a competition for nutrients or an indirect way of induction of chemical response for plant resistance [17].

The spectacular improvement in crop production in the past 100 years has been attributed to the heavy use of chemical pesticides, like insecticides, fungicides, herbicides, nematicides, etc., in addition to good cultural practices and fertilizers. The abundance and quality of food, fiber, and feed produced by farmers around the world need to be maintained by controlling the plant diseases [23]. Modern agriculture is depending excessively on synthetic inputs for managing plant diseases and soil fertility. Although agrochemicals are intended and targeted to protect crops from pathogens, they may also harm non-target microorganisms and pollute the soil environment which may result in the alterations of soil equilibrium process for long-term and short-term period and in turn the growth and yield of plants [24]. Endophytic microbes which are potential sources of bioactive agents are thus expected to be an effective, specific, and eco-friendly approach to control rice diseases, especially in the scenario of changing climate.

1.3. Control of Rice Pathogens by Endophytes

Many endophytes have been isolated from rice and other plants which have shown enormous potential to inhibit rice pathogens. Table 1 summarizes some of the major rice diseases and their inhibitions of endophytes. The inhibitory capacity is discussed in further sections.

1.4. Rice Blast Disease Caused by *Magnaporthe grisea*

Rice blast disease, otherwise known in China as rice fever disease since 1,637, has been a model that demonstrated the elusiveness, seriousness, and longevity of some major plant diseases. Rice blast, which is caused by the fungus *Magnaporthe oryzae* B. Couch (synonym *M. grisea* (Hebert) Barr (anamorph *P. oryzae* Cavara) and its different forms, has been a topic of study throughout the world. Many plant pathologists have considered this rice pathogen as a model disease for the study of host–parasite interactions, molecular pathology, genetics, and epidemiology [25]. India, Korea, and China have earlier reported on crop loss of 5%–10%, 8%, and 14%, respectively, due to blast disease. Same was the case of Philippines where 50%–85% yield losses has been reported (Rice Knowledge Bank). In Nepal, the disease caused moderate reduction of crop yield with 10%–20% damage in susceptible varieties, but it could go up to 80% yield reduction in the case of severe infestation [26]. This fungus has been known to occur in almost 85 countries in the world where the amount of crop destroyed yearly could be sufficient to feed 60 million people.

1.5. Control by Endophytes

The blast-causing pathogen has been consistently inhibited by active antifungal metabolites of endophytes isolated from rice and also from many other plants (Table 1). The endophytic Gram-negative bacterial strain *Stenotrophomonas maltophilia* was able to produce a hydrophobic substance 12-methyltetradecanoic acid that inhibits appressorium formation of *M. oryzae*. Appressorium is a specialized infection structure formed by *M. oryzae* and many other plant pathogens to adhere to the leaf surface and then penetrate into the host tissue by high turgor pressure [27]. Antifungal activity against *P. oryzae* was exhibited by endophytic fungus *Cryptosporiopsis quercina* which produced a tetramic acid cryptocin [28]. Endophytic *Penicillium viridicatum* CSE74 and *Chaetomium globosum* have cytotoxicity effects toward *P. oryzae* where *P. viridicatum* could inhibit the mycelia growth of *P. oryzae* up to 63% [29,30]. Even liquid cultures of endophytic fungi isolated by Park et al. [31] from 11 woody plants of Korea showed more than 90% inhibition to *M. grisea* when tested *in vitro*. Endophytic fungi which have been recovered from leaves and seeds of rice plant also inhibited the blast-causing fungi. In a study by Suada et al. [11], three fungal species *Phaeosphaeriopsis musae*, *Phialemonium curvatum*, and *S. oryzae* inhibited the colonial growth of *P. oryzae* by 63.3%, 66.6%, and 61.1%, respectively. Two strains of *Bacillus subtilis*, endophytic in rice plants possessed inhibitory rates of 80%–90% to rice pathogenic fungi *M. grisea* when the bacterial cultures (10^9 CFU/ml) were diluted 10 times, but the two times diluted culture filtrate inhibited up to 50%–70%. However, this culture filtrate could inhibit more than 85% germination of the conidia [32]. Other species like *Bacillus amyloliquefaciens* isolated from soybean also inhibited mycelia growth of *P. oryzae* [33].

1.6. Inhibition of *R. solani*; the Sheath Blight Disease Pathogen

Sheath blight disease of rice caused by a multi-nucleate fungus *R. solani* (Kuhn) (Teleomorph: *Thanatephorus cucumeris*) has been a serious threat in most of the rice-growing areas in the world. Sheath blight disease of rice occurs in all rice-producing ecosystems and on an average worldwide loss was recorded to be 25%. In India alone, crop losses caused by sheath blight

Table 1: Summary of endophytic activity toward controlling of some important diseases of rice crop.

Name of Rice disease	Name of causal Microorganism	Name of antagonistic endophyte	Source of collection	Reported mode ofAntagonism	References
Blast	*M. grisea*	Unidentified fungal strains (F0001 to F0191 series)	*Abies holophylla*; *Pueraria thunbergiana*, *Pinus densiflora*	*In vitro* inhibition	[31]
Blast	*M. oryzae*	*S. maltophilia*	Acacia hybrid	Inhibition of appressorium formation	[27]
Blast	*M. grisea*	*B. subtilis*	Rice plant	Mycelial and conidial inhibition	[32]
Blast	*P. oryzae*	*P. musae, P. curvatum, and S. oryzae*	Rice seeds and leaves	*In vitro* inhibition	[11]
Blast	*P. oryzae*	*B. amyloliquefaciens*	Soybean	Mycelial inhibition	[33]
Blast	*P. oryzae*	*C. quercina*	*Tripterigeum wilfordii*	Production of Cryptocin	[28]
Blast	*P. oryzae*	*Penicillium* spp.	*Cupressaceae* plant	Cytitoxic and antifungal secondary metabolites	[29]
Blast	*P. oryzae*	*C. globosum*	Viguiera robusta (*Asteraceae*)	Cytotoxic chaetoglobosins	[30]
sheath blight	*R. solani*	*Pseudomonas* sp.		ISR	[44]
sheath blight	*R. solani*	*B. subtilis var. Amyloliquefaciens*	Rice leaf sheath	ISR	[34]
sheath blight	*R. solani*	*T. taxi strain ZJUF0986*	*Taxus chinensis* var. *Mairei*	Winding and attachment to pathogen mycelia	[38]
sheath blight	*R. solani*	*A. melinis*	*F. amomi*	*In vitro* inhibition	[41]
sheath blight	*R. solani*	Bacterial endophytes UPS25, UPR36 and UPR40	Rice (*O. sativa*)	*In vitro* inhibition	[40,42]
sheath blight	*R. solani*	Non-sporulating, slow growing endophytic fungus	*T. trilobatum* Schott (Family Araceae)	*In vitro* inhibition	[37]
sheath blight	*R. solani*	*B. cereus, B. pumilus*	*Ageratum conyzoides* L.,*Ficus benyamina* L. and*Camellia sinensis* (L.) Kuntze	*In vitro* inhibition and production of iturin	[43]
BLS	*X. oryzae* pv. *oryzae*	*Streptomyces* spp.	Collections of the Microbiology Laboratory, Bogor Agricultural University	Production of bioactive compounds like antibiotics and cell wall degrading enzymes such as chitinase, phosphatase, and siderophore	[51]
BLS	*X. oryzae* pv. *oryzae*	*B. subtilis* var. *A. strains*	Field crops and medicinal plants	*In vitro* inhibition. Production of defense related enzymes	[53]
BLS	*X. oryzae* pv. *oryzae*	Unidentified	Mangrove plants, *A. alba*, *A. marina*, and *B. gymnorhiza*	*In vitro* and on field	[55]
BLS	*X. oryzae* pv. *oryzae*	*Streptomyces*		In field	[51]
BLS	*X. oryzae pv. oryzicola*	*Aspergillus* sp. *strain IFB-YXS*	*G. biloba* L.	*In vitro*. Production of terphenyl derivatives	[61]
BLS	*X. oryzae pv. oryzicola*	*B. amyloliquefaciens*	*G. biloba* L.	*In vitro*	[62]
Rice bakanae	*F. moniliforme*	*B. amyloliquefaciens* TF28	Soybean root	Antibiosis by lipopeptide compound, mycelial distortion	[75,84]
Mycotoxication	*F. moniliforme/F. verticilloides*	*B. subtilis* RRC101	Maize seedling roots	*In vitro* inhibition. Competitive exclusion principle	[86]
Mycotoxication	*F. verticilloides*	*B. mojavensis*			[87]
Mycotoxication basal node rot and nursery diseases	*F. oxysporum*	*Bacillus* species	Black pepper roots	*In vitro*, secretion of volatile compounds	[85]
		M. variabilis,Cadophora sp.	Barley,Chinese cabbage,Egg plant	*In vitro* inhibition, Reducing ingress of pathogen into plant cell	[88,89]
Rice bakanae, basal node rot	*F. verticilloides, F. oxysporum*	*T. koningii, A. alternate*	Maize root	Reduction *in vitro*	[91]
Seedling disease	*A. klebsiana* and*P. spinosum*	*P. fluorescens* (S3), *P. tolaasii* (S20), *P. veronii* (S21), and *S. trueperi* (S12)	Rice (root and stem)	*In vitro* and pot assays	[92]

disease have been estimated to have gone up to 54.3% [34]. The disease has emerged as important, particularly by the intensification of rice production systems. In Asia, the tropical lowland rice cultivars could face yield losses up to 5%–10%. Around 188 plant genera belonging to more than 32 families have successfully been the host of this aggressive pathogen [35]. The systemic fungicides used to control sheath blight disease are very problematic due to their harmful side effects such as phytotoxicity, carcinogenicity, teratogenicity, residual, and pollution effects [36].

1.7. Antagonistic Property of Endophytes Toward *R. solani*

The potential of both endophytic fungi and bacteria to inhibit *R. solani* is presented in Table 1. Endophytic fungus *Typhomium trilobatum* could control the growth of *R. solani* up to 95% [37]. Similarly, Wang et al. [38] observed strong antifungal activity toward *R. solani* by *Trichoderma taxi* strain ZJUF0986 which degrades *R. solani* hyphae directly when they are contacted through the mode of winding and attachment to pathogen mycelia. Antagonism levels of 72.2% and 62.8% to this pathogen was also exhibited by two spore forming Gram-positive diazotrophic Bacilli designated as BL1 and BR4 obtained from surface-sterilized leaf and root tissues of cultivated rice plants [24]. Inhibition zones of 6.0 mm, 2.0 mm, and 2.1 mm were formed by rice endophytic bacterial isolates UPS25, UPR36, and UPR40, respectively [39]. *Azospirillum melinis* isolated from *Fructus amomi* formed an inhibition zone of 18 mm. In addition to that, the control efficacy in pot or green house experiments and under field trials was 80.7% and 79.4%, respectively [40]. As per the reports of Mew and Rosales [41], the mycelia or vegetative growth of *R. solani* was inhibited by 91% of the endophyte bacterial isolates of rice *in vitro* where the zone of inhibition range was observed to be from 4 to 30 mm. Seed treatment with endophytic bacteria could develop plants with significantly less disease incidence of *Rhizoctonia* sp. than the rice plants grown out of untreated seeds. Another endophytic bacterium *B. subtilis* var. *Amyloliquefaciens* isolated from rice reduced 36% of the colony growth of *R. solani*. A combined treatment method under glasshouse conditions using this bacterium, which included seed treatment, seedling dip, soil application, and foliar application, could result in the lowest severity of sheath blight disease (33%) with around 55% reduction in comparison to the control [34]. Out of 153 endophytic bacterial populations screened by Yuliar et al. [42], two *Bacillus cereus* and one *Bacillus pumilus* strain inhibited the colony growth of *R. solani* by 69%, 78%, and 69%, respectively. One of the *B. cereus* strains produced an antifungal metabolite iturin.

Some endophytic *Pseudomonas* strains reduced sheath blight occurrence in rice up to 18% through ISR [43]. Nagendran et al. [34] also found that the ISR defense mechanism using *B. subtilis* var. *Amyloliquefaciens* resulted in the enhanced production of enzymes related to the plant defense system such as polyphenol oxidase, phenylalanine ammonia lyase, and peroxidase, due to which total phenols were accumulated in higher concentrations. Controls of plant pathogens through ISR hence possess a great potential for future use of endophytes.

1.8. Bacterial Leaf Blight (BLB) Disease of Rice Caused by *X. oryzae pv. oryzae*

BLB disease of rice is among the most common disease which was first observed long ago by farmers in Japan in 1884. The disease is caused by the bacteria *X. oryzae* pv. *oryzae* commonly known as Xoo. The prevalence of BLB is found in both temperate and tropical countries and it has also occurred in Latin America, Australia, and in the Caribbean countries [44]. In India, the destructiveness of the disease is observed mainly in the states of Uttar Pradesh, Bihar, Haryana, and Punjab where it occurs regularly [45]. The disease was endemic in Bihar [46] and Tamil Nadu [47]. Reduction in rice yield as high as 50% could also be recorded when the crop was severely infected [44]. The magnitude of the disease occurrence was further accelerated due to the widespread cultivation of high-yielding dwarf and hybrid varieties of rice which were relatively more responsive for nitrogen absorption. In Japan, BLB could damage 20%–30% and as high as 50% of crop production [48]. The "kresek" syndrome caused by BLB infection mainly affected freshly transplanted seedlings. In tropical countries like India, Indonesia, and Philippines, 60%–70% of crop damage has been recorded due to this manifestation of BLB. The aggravation of the syndrome depended on the type of rice cultivar, location and local weather. In addition to reducing yield, BLB might also affect the maturation process of rice grains, thereby deteriorating the quality of paddy [49].

1.9. Control of BLB Pathogen by Endophytes

This disease has been routinely controlled by the application of chemical bactericides but excessive use frequently lead to the outbreaks of resistant pathotypes and contributed to environmental pollution. Furthermore, grains having bactericide residues might cause health problems to consumers. Utilization of endophytic microbes may be an efficient approach in this regard. In the study by Hastuti et al. [50], some rice endophytic actinomycetes such as *Streptomyces* spp. were capable of suppressing *X. oryzae*. This disease inhibition mechanism is presumably caused by the production of bioactive compounds which can act as antibiotics and/or function as cell wall-degrading enzymes in the decision-nutrient competition [51]. In addition to that, *Streptomyces* spp. isolates were also able to improve the growth of the seedlings and plants. Two *Streptomyces* isolates (AB131-1 and LBR02) were able to produce chitinase, phosphatase, and siderophore which included biocontrol characteristics. Similar antagonists along with plant growth-promoting effect were also observed for endophytic *B. subtilis* var. *Amyloliquefaciens strains* isolated from different plant sources. In addition to that, the *B. subtilis* (strain FZB 24)-treated rice plants registered higher induction of defense-related enzymes, namely peroxidase, polyphenol oxidase, and phenylalanine ammonia lyase, and resulted in higher accumulation of total phenols compared to untreated control plants. The endophytes-treated rice plots registered a significantly lower intensity of bacterial leaf blight (2.80%) compared to untreated control plots (19.82%), which also recorded a higher grain and straw yield [52]. A total of five endophytic bacterial consortiums as biocontrol agents have been developed which exhibited capability in reducing bacterial blight of rice under greenhouse condition.

The bacterial consortium consisting mostly of the *Bacillus* species from rice and sugar cane was applied by the seed dipping method using bacterial suspension prior to transplanting [53]. Antagonistic endophytes have also been isolated from many mangrove plants. Fifty-five bacterial endopytes have been isolated from leaves, stems, stalks, flowers, and fruits of healthy mangrove plants, *Avicenia alba*, *Avicenia marina*, and *Bruguiera gymnorhiza*, of which two bacteria could control leaf blight by 67% under saline condition [54]. These bacteria endophytic actinomycetes provided advantages to the host plant through the enhancement of plant physiological activity or through other modes of action and served as source of agro-active compounds which can be used as biocontrol agent. These types of endophytic microbes hold great potential to be utilized in coastal agricultural ecosystems which were affected by high salt concentration in the soil. Endophytic actinomycetes PS4-16 belonging to *Streptomyces* species, applied by seed coating and soaking techniques, suppressed natural infection of BLB during dry and wet season experiments. Area under disease progress curve values of PS4-16 in dry season and wet season were 1,458 and 1,923, respectively. The application of these endophytic actinomycetes under dry season could increase rice yield by 17% as compared to positive control [50].

1.10. Bacterial Leaf Streak (BLS) Disease of Rice Caused *X. oryzae pv. oryzicola*

BLS is an important disease of rice (*O. sativa*) for which control measures are limited. In particular, no simply inherited gene for resistance to the disease has been reported. The disease is caused by *X. oryzae* pv. *oryzicola*, a member of the gamma subdivision of the class *Proteobacteria*. The pathogen enters through leaf stomata or wounds and colonizes the parenchyma apoplast, causing interveinal lesions that appear water-soaked initially and then develop into translucent, yellow-to-white streaks. Leaf streak is prevalent in Asia and parts of Africa, where it can decrease yield by as much as 30% [55]. The BLS disease is mainly a concern of rice cultivation in tropics and subtropic nations like India, southern China, Malaysia, Thailand, Vietnam, Indonesia, and Philippines. However, it has also damaged crops significantly in northern Australian rice-growing regions [15,56–58] and in some parts of the West African region. Comprehensive documentation is lacking in many areas infested by BLS. Scattered reports could lay out that the disease could hamper crop yield up to 20%. Under favorable climatic conditions and cultivation of susceptible rice cultivars, BLS could be as devastating as BLB and could damage entire crop fields with reduction up to 32% of grain weight [15]. Although BLS is economically less important than BLB and increased cultivation of hybrid rice varieties in many parts of Asia like China, the disease is becoming significant for management aspects [59].

1.11. Efficacy of Endophytic Microorganisms to Control BLS Pathogen

Although few reports are available, *X. oryzae pv. oryzicola* has been found to be inhibited by bacterial and fungal endophytes isolated from some selected plants. Endophyte fungus *Aspergillus* sp. strain "IFB-YXS", isolated from healthy leaves of *Ginkgo biloba* L. could control the growth of *X. oryzae pv. oryzicola*. The terphenyl derivatives present in ethanol extract derived from the solid substrate fermentation was found to have a minimum inhibitory concentration of 10–20 μg/ml [60]. Similarly, in other experiments, 154 endophytic bacterial strains have been isolated from the Ginkgo plant out of which 57 isolates have showed anti phytopathogenic effect including *X. oryzae pv. oryzicola*. Two of those efficient endophytic bacteria were identified as *B. amyloliquefaciens* [61].

1.12. Inhibition to *Fusarium* Pathogens

Different species of *Fusarium* are involved in many drastic diseases of rice. Among them, an emerging disease caused by this fungus is the rice bakanae disease which has been a major threat to cultivated rice. The pathogen responsible for this bakanae disease of rice was recognized as *Fusarium moniliforme* (Sheldon) which was re-identified later as *Fusarium fujikuroi* (Nirenberg) [62], the anamorph of "*Gibberella fujikuroi*" (Sawada). With findings of recent investigations, conflicting results were revealed which suggested the involvement of other *Fusarium* species in the section "*Liseola*" in causing rice bakanae disease. Bakanae disease in Malaysian rice varieties has been found to be caused by five *Fusarium* spp. belonging to species complex of "*G. fujikuroi*" under section *Liseola*, namely *F. fujikuroi*, *Fusarium proliferatum*, *Fusarium sacchari*, *Fusarium subglutinans*, and *Fusarium verticillioides* [63]. The most prominent symptoms of *F. fujikuroi* infection on rice plants can even be observed from a distance which include elongation of seedlings, seedling rot, foot rot, sterility, and discoloration of grains [15,64]. The plants affected by *Fusarium* sp. may be taller than the normal plants probably due to the production of gibberlic acid. Furthermore, the stems are thinner with yellowish green coloration and adventitious roots may be developed at the lower nodes of the culms. Leaves of the rice plants usually dry up earlier than normal. The numbers of tillers are lessened and those also fail to reach maturity, and even the infected plants survive the panicles remain seedless or only chaffs are formed [65–67]. The disease was recorded in almost all countries where rice is grown. Losses due to the bakanae disease were reported as high as 70% in different parts of the world [68]. In India and Thailand, this loss was reported to be 15% and 40%–50% in Japan [69,70]. Bangladesh has a record of 21% yield loss in 2006 [71,72], whereas in Nepal it is up to 40% [73]. Infection of rice by *F. moniliforme* leading to rice bakanae disease has been widely reported in China where 10%–20% yield losses has been reported every year [74].

Sheath rot of rice which is caused by *F. moniliforme* Sheld has been growing alarmingly in India and also in the United States. It also adversely affects seed germination and seedling growth of rice [75,76]. *Fusarium oxysporum* which caused the basal node rot of rice was observed in the experimental fields of the ICAR-National Rice Research Institute, India, and bean research center in Goiania, Brazil [77]. Even in the nursery farms of Bayelsa state of Nigeria, rice plants were infected by *F. moniliforme* and *F. oxysporum* leading to diseased plants [78]. Besides this, *Fusarium* species is mainly concerned for the production of mycotoxins such as fumonisins, zearalenone, trichothecenes, fusaproliferin, beauvericin, enniatins, and moniliformin, etc. [79,80]. *Fusarium* species that produce fumonisins mycotoxins are well-investigated

pathogens infecting a variety of plants. In Asian countries, the most mycotoxin-producing *Fusarium* species isolated from rice has been *Gibberella zeae* (anamorph: *Fusarium graminearum*). In addition to its ability to cause the rice ear scab disease in India, China, and Japan, this pathogen also produces carcinogenic mycotoxins like deoxynivalenol and 8-ketotrichothecene nivalenol. Consumption of food grains contaminated with Trichothecene mycotoxins had led to hemorrhagic syndromes and ailments in animals. Many human disease epidemics also broke out in Japan and Eastern Europe associated with production of *Fusarium* toxins [73].

1.13. Biological Control of *Fusarium* sp. by Endophytic Microorganisms

As evident from many investigations, plant diseases have been controlled by a number of potential bacteria leading endophytic life cycle [81,82]. An endophytic *B. amyloliquefaciens* strain "TF28" showed strong inhibition activity against pathogenic *F. moniliforme* as well as *F. oxysporum*. The crude culture filtrate having antagonistic activity was found to be heat stable, pH insensitive, and lipopeptide in nature which could inhibit both these rice pathogens up to 95% *in vitro*. The lipopeptide distorted the mycelia and converted into granular structure [74]. Under field conditions, the fermented liquid of *B. amyloliquefaciens* strain TF28 was also found to control rice bakanae disease with 87% efficiency [83]. Volatile and diffusible bioactive compounds having antagonistic activity have been reported in some *Bacillus* species isolated from black pepper roots which inhibited mycelia of *F. oxysporum* up to 43% [84].

In an earlier investigation, a biological control system has been developed using an endophytic bacterium *B. subtilis* strain "RRC101". This bacterium exhibited great promise for reduction of mycotoxins by inhibiting growth of *F. moniliforme*, A competitive exclusion principle has worked out in this type of system where the bacterium might be an ecological homologue to *F. moniliforme* as it occupied the identical ecological niche within the plant [85]. Another mycotoxic species Fusarium *verticilloides* which has also been found to be associated with bakanae disease has been controlled by bacterial endophyte *Bacillus mojavensis* [86]. Some subspecies of *F. oxysporum* did not infect rice, but other plants have also been inhibited by fungal endophytes. *Meliniomyces variabilis* isolated from the tomato plant and *Cadophora* sp. isolated from axenically grown seedlings of Chinese cabbage (*Brassica campestris*), barley (*Hordeum vulgare* L. var. *hexastichon* Asch.), and eggplant (*Solanum melongena* L.) had significant suppressing effect on *F. oxysporum* [87,88]. Many endophytic *F. oxysporum* strains have been isolated from asymptomatic parts of plants like rice, maize, tomato, banana, and have shown higher antagonistic activity against pathogenic strain of the same [89]. Other maize root endophytic fungi such as *Trichoderma koningii* and *Alternaria alternate* could reduce the growth of *F. oxysporum* and *F. verticillioides* [90].

1.14. Antagonism of Endophytes to *Achlya* and *Pythium* Causing Root Rot and Water Mold Disease

The "water mold" disease is a major threat to rice cultivation in deep water or water-logging ecosystems which usually lead to re-transplanting also causes loss due to non-uniform stands. The primary pathogens for this disease have been species of *Pythium spinosum* and *Achlya klebsiana*. Rice researchers have isolated some efficient endophytic bacteria from rice roots and stems those could inhibit these pathogens both *in vitro* and in pot assays. These bacterial strains were identified as *Pseudomonas tolaasii* starin-S20, *Pseudomonas fluorescens* strain-S3, *Sphingomonas trueperi* strain-S12, and *Pseudomonas veronii* strain-S21) [91] (Table 1).

1.15. Future Perspectives and Research Opportunities

As discussed earlier, rice is being infested by so many pathogens where synthetic fungicides are being used massively to control them which raise many environmental and health issues. Biological control is the most sustainable way to combat this situation and in this regard use of endophytic microorganisms is a promising ray of hope. This review summarized the potential of endophytes to control some of the rice pathogens. However, still the utilization of endophytic microorganisms against many other rice diseases remains unattended. Integrative and vigorous research is required to study the ecology, interaction, and establishment of these useful endophytes in rice plant. In the future, endophytic microorganisms can be used to increase rice growth through mechanisms such as plant defense against herbivores. Studying these microbes may lead to methods to enhance their ability to improve rice productivity and/or their secondary metabolite production. Furthermore, there is a great opportunity of research on the efficacy of endophytes to control rice pathogens which also infect other crop hosts. For instance, the rice blast pathogen *M. grisea* infects 50 other hosts including weeds and grasses. In such case, endophytic microorganisms from any source can be harnessed for blast management in many crops simultaneously. Even though *in planta* establishment may be a challenge, still the antimicrobial compound can be used to develop formulations for pathogen control.

Most plant species have been found to be colonized by a broad spectrum of bacteria and fungi having endophytic life inside the healthy tissues. These specialized microorganisms have consistently exhibited potential antagonism toward number of plant pathogens. The need of the hour is to explore further the enormous potential of endophytes to be used fruitfully in modern plant disease management strategies. To achieve this goal, a better understanding of the underlying mechanisms of mode of action is very much required. The antagonistic efficiency in response to many environmental factors existing in the agricultural ecosystem also needs to be thoroughly investigated. Furthermore, there is a huge lack of information regarding the population dynamics of endophytes and mechanisms which trigger or accelerate endophytic colonization inside plants. Comprehensive and continuing research in this area may probably lead to new insights and innovative concepts for the biological control and management of plant pathogens.

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