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Stem Rot of Jute: A Serious Threat to Jute Production in North-East India

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ABSTRACT

Stem rot is one of the most devastating diseases of jute caused by M. phaseolina, which is a widespread soil, seed, air borne, and broad host pathogens. The infection may occur at any stage from germination to maturity producing a copious number of sclerotia which blocks the xylem vessels and result in vascular wilting. This research review incorporates comprehensive information such as the biology of pathogen, pathogenicity, epidemiology, and disease management. This information is prerequisite to design and formulate research program to devise an effective strategy to control stem rot. Latest advancement and research in different avenues of management such as; modified cultural practices, fungicide application, biocontrol and genomic improvement have also been well dealt with in this article. The use of pathogen-free seed in combination with plant-to-plant distance and alteration in the date of sowing can minimize the spread of infection. Moreover, recent agricultural practices like crop monitoring with surveillance programs can help early and precise detection, and economic management of this disease. Substitution of traditional fungicides with new molecules and use of potential biological agents can be very decisive controlling stems rot and in addition mitigation of environmental pollution. However, the acclimatizing nature of the pathogen, scarcity of jute varieties resistant to stem rot, non-disclosure of target genes of resistance required in molecular breeding programs and transgenic technology are a few crucial challenges that are detrimental in the exploration of the more effective management system. Holistic and supportive efforts of stakeholders, and research institutions involved in the betterment of jute can be helping hands to deal with challenges as M. phaseolina infects both Indian cultivated species of jute viz., Corchorus olitorius L. and Corchorus capsularis L. which account for a 35-40% reduction in yield. The role of awareness programs and participatory approaches of jute growers will be an added endeavor to root out stem rot disease and cash in on jute cultivation.

Keywords: *Jute, Stem rot, Macrophomina phaseolina, Biology, Diagnosis, Epidemiology, Disease management.*

1. Introduction

Jute (*Corchorus* sp.) known as 'Golden fiber' is the source of ligno-cellulosic bast natural and strong fibre crop. It holds the next position after cotton in fiber crop production [1]. This crop has more than 170 species, which are found in tropical low land areas. *C. olitorius* and *C. capsularis* are the only species of jute that are abundantly grown in South-east-Asian countries including India and Bangladesh, which cover more than 80% of global jute cultivable land. Jute cultivation and jute-based industries are the basis of livelihood of people in North-East Indian States *viz.,* West Bengal and Assam followed by Bihar, Orissa, Andhra Pradesh, Meghalaya, Nagaland and Mizoram. (Fig.1). West Bengal is the leading state in terms of area, production and productivity of jute and 77% producer of jute in India [2]. India is also the prime consumer of jute and derived products as well where about 85% of consumption takes place to meet domestic needs. Therefore, jute cultivation and production is one of the wheels to run the economy of eastern India. According to the Government of India, Ministry of Agriculture & Directorate of Jute Development, production of jute was highest in West Bengal (82.7% from 81.3% acreage), followed by Assam (8.6% from 10.2% acreage) and Bihar (8.5% from 8.3% acreage) in the year 2021-22 [3].

A major portion of the jute growing area shifted in Eastern Pakistan (Bangladesh) after the separation of India in 1947, but jute mills were retained in India. Since then, there has been a considerable rise in the acreage, production, and productivity of jute in the country after the initiative of the Government of India through intensive research work on jute and allied fibers resulting in an increase in the production of jute and allied fibers, improvement in their quality and value-added products. Gunny bags, carpets, hessians, rope, sacks, mats, false ceiling boards and many geo-textile products are divers value-added products of jute in addition to the use of tender green leaves as vegetables. The latest research reveals that jute has many eco-friendly attributes such as dimensional stability, moisture absorption and retention capacity, carbon dioxide absorption and more oxygen production.

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Apart from the use of jute in biodegradable diversified products, it is a potential source of wood fuel in rural areas [4 and 5]. The jute crop holds much scope in the coming future due to the preferential shift of people towards natural fiber rather than synthetic fibers as this is biodegradable and eco-friendly.

Plant diseases and the emergence of undesirable weeds are two major bottle-neck, that jute cultivation faced by farmers. Stem & root rot, anthracnose, leaf blight, seedling blight, leaf mosaic, and charcoal rot are the major diseases responsible for reduction in yield and fiber quality. Out of them, stem rot of jute caused by *Macrophomina phaseolina* (Tassi) Goid is the most devastating one [6]. Loss in yield of jute up to 40% and 30% have been recorded due to stem rot in India and Bangladesh respectively [7, 8, and 9]. Initial 15-45 days after sowing, is very decisive in the case of jute crops which require intensive care for disease and weed control [10]. The hot (25-35°C), humid (70-75%), and intermittent rainfall (50-80 mm) induce huge crop-weed competition besides fungal infection and disease development rendering total fibre yield loss up to 70% [10]. This disease is a major threat in the production of jute particularly in the Mediterranean Basin and India. An effective management approach to stem rot diseases and improvement of jute crops liable to resistance against this dreaded disease are very vital to thrive jute growers and industry in neck-to-neck competitions with synthetic fibers. This article consists of disease distribution, identification criteria, the biology of pathogen, modes of infection, symptomatology, the basis of pathogenicity at the molecular level and recent strategies of management, besides awareness drive.

2. Biology of The Stem Rot Pathogen (*M. phaseolina*)

2.1 Classification and Pathogen Host Range: M. phaseolina is a highly destructive, necrotrophic anamorphic fungus belonging to the family Botryosphaeriaceae under phylum ascomycete [11]. This fungus is cosmopolitan in occurrence and is considered economically more significant, particularly in countries falling under tropical and subtropical zones and semi-arid climatic conditions. It is asexually reproducing and root inhabiting (soil invader) in nature [12]. It can infect the root and basal portion of stem of over 500 plant species including both monocotyledons and dicotyledons, covering more than 100 plant families [13]. Chickpea, cotton, common bean, maize, sorghum, cowpea, and groundnut are the major economically important host crops of *M. phaseolina.* It can remain dormant in soil and crop residue as sclerotia for more than four years without losing its virulence [9]. Sclerotia germinate on the root surface which develop into appressoria with germ tube. Later, it penetrates the epidermal cell layer of the plant either by enzymatic digestion or through natural openings mechanically. Occasionally hyphae come out from the sclerotium directly and penetrate the cell wall for infection under favourable climatic conditions. *M. phaseolina* has enormous potential to grow and give a large number of sclerotia even under severe water stress condition and cause disease.

M. phaseolina is the most common pathogen causing stem rot disease in both cultivated species of jute, *C. olitorius* and *C. capsularis* [14 and 15]. The infection is part and stage independent in the vegetative growth and maturity of the jute plant. The symptoms caused by this pathogen may include seedling blight, collar rot, damping-off, leaf blight, stem & root rot and spot-on pod [8]. The pathogen exists in 3 morphs; sclerotial *(Rhizoctonia bataticola)*, teleomorph (*Orbilia obscura)* (other than jute), and pycnidial (*M. phaseolina)* stage.

However, pycnidial stage appears as the most detrimental phase followed by sclerotial stage in jute making the management of this disease very tedious. Pycnidia, which is 50-100 µm in radius, may appear as singlet or in clusters, dark brown on either leaves or stems, and opens through the apical ostioles. The wall of pycnidia is of multilayers, consisting of deep pigmentation and thick-walled cells in the outer periphery. Conidiophores (phialides) of 5-13X 4-6 µm size which are rod shaped, simple and hyline come from pycnidia. Conidia are of 14-30 X 5 -10 µm size which are hyaline, separated and ellipsoid to obovoid. Hyphal aggregates of 50 to 200 individual cells cemented by melanin material which forms microsclerotia first and micro-sclerotium later. The color of the colony may be either white or brown/gray and darkens with age. Branching are generally found at acute angles and hyphal branches generally lie perpendicular at parent hyphae. *M. phaseolina* exhibits a wide range of host and location specific morphological variations in size of sclerotia and appearance of pycnidia. There are four classes (A, B, C and D) of *M. phaseolina* based on the sclerotial size, out of them class C is very prevalent in India. Further morphology and pathogenicity of sclerotia are the basis of the division of the class into four sub-groups [16]. Virulence is the parameter to analyze the growth rate of each sub-group during the first 5 days of the culture. The 34+1°C temperature and 6.8 pH required for the growth and development of Class C. The virulence of isolate from Assam has exhibited maximum virulence than any isolates in India [16].

3. Stem Rot Infection and Disease Cycle

Stem rot disease of jute spreads generally through soil, seed and air in the field. The fungi lie in dormant stage for many years as sclerotia in soil/ infected plant debris or root stubbles [17], but survival of the pathogen in fallow soils increases after infection of symptomless dicotyledonous weeds. Both pycnidial and sclerotial stages of pathogen are responsible for infection of the jute crop either alone are in combination [18 and 19]. Seed is considered more important source of primary inoculums than that of soil. In field conditions, seed-borne pathogens often cause infection on jute crop. Subsequently, pods or capsules also get affected, and results in production of unhealthy crop and infected seeds [20 and 21]. The cortical tissue of jute plants is invaded by the fungal hyphae which lead to formation of sclerotia and exhibit symptoms of stem rot. At first, hyphae from sclerotia form a network in the soil and penetrates roots of new jute plant through cell wall either by the action of hydrolytic enzymes including carbohydrate-active enzymes or mechanical damage and pass through different phases resulting in necrosis and rot of jute fibers [22 and 23]. Often, the progress of disease takes place from yellowing of the leaf to wilting and ultimately causes death. Jute debris after harvest contaminates the soil to initiate the next cycle (Fig.2). Extensive sporulation is common on infected seed and stem containing pycnidia with an ostiole. Presence of air-borne conidia in favorable seasons also leads to secondary infection or epiphytotic outbreak in susceptible varieties. There is report that pycnidia are formed on the infected roots, stem and other rotting tissues [24]. Cloudy weather, higher temperatures (30-35 °C), high humidity (~80%), low moisture content of soil and high levels of nitrogen favor the infection of *M. phaseolina* [17]. The pathogen can transmit through seed to plant and vice versa through various means [25]. Seeds of infected crops rarely germinate, if germinate, developed disease exacerbate the entire jute plant.

4. Molecular Basis of Pathogenicity

The signals perceived by the cell surface receptors under favorable conditions initiate intracellular signalling pathways leading to pathogenicity. *M. phaseolina* is supposed to have a complex network of pathogen-host-interaction genes due to broad host range. This fungus contains genes to express oxidases, peroxidases, and other hydrolases responsible for the lysis of polysaccharides/ and lignocelluloses of cell wall and penetration into the host. The genome of this fungus comprises a number of genes for the expression of membrane transporters (P450s, MFS type), transposases, glycosidases and other secondary metabolites. Pathogen surpass the plant defences mechanism by reactive oxygen species (ROS) and nitric oxide (NO) with lowering of reactive oxygen species in plant cells. This molecular event renders the yellowing of leaves followed by wilting and ultimately death [26]. 537 putative pathogen host interaction genes have been identified from pathogen-host interaction (PHI) database[9]. These genes are associated with different stages of pathogenesis. These are adhesion, signal transduction, cell wall breakdown, biosynthesis of nitrogenous base of DNA, and the potent mycotoxin (patulin). ATP-binding cassette transporters facilitates defense of pathogen through secondary metabolites produced by the host and also provide essential nutrients [27]. Various detoxification genes encoding covalent organic frameworks protein, cytochrome P450, superoxide dismutase, Cu/Zn protein, etc. are available. In addition, many beta-ketoacyl synthases required in the polyketide antibiotic synthesis, and some tetracycline resistance genes have been recognized in *M. phaseolina* [28]. These findings infer that *M. phaseolina* genome might consist a large repertoire of pathogenicity associated genes involved in the pathogenesis of *M. phaseolina*. However, *M. phaseolina* infecting jute plants possess better fibre retting ability to a few extents, because cellulases and hemicellulases weaken the bonding between fiber tissues in stem [29 and 30]. Several functional genomics approaches, comprising proteomics and transcriptomics, have been utilized to decipher the mechanism of interactions between jute and *M. phaseolina* (Table 1). However, it is yet to be explored to understand the mechanisms of pathogenicity in host plants and to devise an effective control measure.

5. Symptomatology and Disease Identification and Diagnosis

Accurate and early identification and diagnosis is a prerequisite to formulate and apply an effective control measure against stem rot in jute. Symptoms of this disease may be seen during germination to maturity in both fiber and seed crops. The pathogen produces a wide range of symptoms on infected plants including stem rot, root rot, collar rot, seedling blight, damping-off, leaf blight at seedling stage, stem break, at the matured plant stage and brown spot on pods particularly in seed crop. Appearance of stem rot is more prevalent from June to August, in this case leaves turn brown owing to high humidity and rainfall. Sloughing of cortical tissues of the stem is affected by the pathogens and tissue appears grey due to the presence of plenty of sclerotia. It results in the premature death of the host plant, which eventually degrade the quality of fibre (Fig. 3). Symptoms of stem rot are small blackish-brown sunken lesions discernible on green stems. It expands either longitudinally or latitudinally, 11-16 cm or even more, which later coalesces, expands and eventually girdles the stem (Fig. 4*a*). Infected stems may break and droop while exposure to high-speed winds (Fig. 4*b*) and result in shredding of bark fiber (Fig.4*c*). Collar rot appears as brown rot in the collar region (Fig. 4*d*). Roots of affected plants show brown to black discoloration, wilt and defoliation in later stages. Finally, the plant stands as naked stem and eventually dies (Fig. 4*e*). If the affected plants are uprooted, the root remains devoid of rootlets. Leaves fall off the infected plant. Infected plants get dried and become deep brown to black, which can be distinguished in the field very easily. Loss in fibre yield and quality is directly related to the infection intensity of *M. phaseolina* as shown in (Fig. 5) [31]. Late infection may cause deep brown or black colored spots and pycnidia and sclerotia formation on the infected capsule/seed [32]. The infected seeds appear light in color and are small, shrunken, and withered which shows poor germination. The stem and root rot diseases spread rapidly, particularly in susceptible varieties and lead to death of the plant [8 and 18].

6 Epidemiology

Aggressiveness of races, density of pathogen inoculum in soil, on seed, and crop debris, weather conditions (atmospheric temperature, relative humidity, rainfall, soil temperature, soil moisture, soil pH, etc.), cultivar susceptibility and nutrient application are factors, which affects the development of stem rot in jute. A High incidence of stem rot with huge mortality comes during conducive climatic conditions. Susceptibility towards stem rot increases with the age of Jute plants rather than varieties and the disease attains its maxima near harvest stage. Early sown (March) crop is more vulnerable to stem rot than that of late sown crop [18]. Air temperature (28 to 32°C), and soil temperature below 30°C, pH 4 to 6.5 favors pathogen growth/development, and increase disease incidence and severity. High rainfall and cloudy weather condition resulting in high relative humidity is more vulnerable to infection [33 and 19]. L ateritic and alluvial soils with low pH (5.6-6.5), and high level of Nitrogen increase stem rot, while P and K reduce. Higher temperatures (30-32°C), high humidity, high rainfall, low soil moisture, low pH, and high levels of nitrogen favor the growth of pathogen. High temperature (31.95°C), high relative humidity (80%), rainfall and humid thermal ratio (3.4) were significantly correlated with per cent incidence of stem & root rot disease in jute [34]. Rising temperature along with relative humidity (>75%) creates the more congenial condition for development of stem and root rot.

7 Integrated Disease Management Strategies

The versatile nature of pathogens and formation of sclerotia in the soil and plant debris during adverse conditions exacerbate the management of stem rot of jute more difficult. *M. phaseolina* passes through three stages in its life cycle namely, sclerotial stage, *Orbilia obscura* (perfect stage) and pycnidial stage (most common and damaging phase). The pathogen can bear in soil, seed and also in air, therefore, it needs the inclusion of different management strategies for complete control, such as manipulation of soil, seed treatment and need based foliar spray of fungicides, etc. On the other hand, stem rot of jute is a monocyclic disease where the primary inoculum is more dominant for disease initiation. Hence, management of this disease should be oriented towards either exclusion of the pathogen or reduction in the amount and/or efficiency of the initial inoculum. Shifting of sites to avoid high risk soils, reduction or elimination of inoculum in soil, use of pathogen-free seeds and resistant variety, seed treatment and adoption of cropping practices are a few approaches, which can improve the management of stem rot of jute. It can give effective results, if these approaches are capitalized at a single time or in combination under integrated management practices. Recent advancements made for effective management of this disease has been dealt in detail (Fig. 6).

7.1 Exclusion and Eradication of The Pathogen: The use of pathogen-free seed and quarantine is one of the ways for effectively management of stem rot in jute. Seeds are the primary and major source of the infection caused by *M. phaseolina*. Pathogen free areas should be selected for seed production program to avoid soil-borne infection. Low disease-risk soil should be preferred for sowing of seed treated with bio-control in combination with fungicide. Removal of affected jute plant debris, and thermal killing of pathogen would also minimize risk in the next crop. Reduction in the amount of soil-borne inoculum has been observed after burning of affected crop residues [35]. But thermo-sanitation by flaming the crop debris with propane or oil-fueled flamers for more regulated heating is considered an eco-friendly practice [36].

7.2 Modification in The Date of Sowing and Plant Population Density: Raw jute production is greatly affected by the date of sowing and population density of the plant. Jute is conventionally sown during spring in most of the jute cultivating countries and the crop is grown in soil with residual moisture and winter rains. Gradually, the crop faces temperature and soil moisture stress with time that curtail both vegetative and reproductive phases resulting in reduced raw jute yields. Jute crop sown in the month of March are prone to more incidence of stem rot disease, because of warm and dry soil conditions. In the contrary, sowing of jute crop in April month reduces the stem rot incidence [18 and 26]. In one of the reports, lowest incidences of stem rot of jute were recorded in both line sown (5.4%) and broadcast (7.4%) with a very low population density of 3 lakh per ha. However, medium level of incidence was found in both line sown (7-9%) and broadcast crops (10-17%), when optimum jute plant population density were 5-6 lakh per ha (De and Tripathi (2016). Therefore, 25-30 cm row to row and 5-6 cm plant to plant space are advisable to minimize the risk of stem rot incidence [37].

7.3 Biological Control: Bio-control is the use of microorganism/predators to minimise the population of pests or pathogens. This control is not only safe and but also reliable option for the management of plant disease [38]. Bio-control agents, plant metabolites and elicitors of plant defences are being used in the management practice for the last few decades. Few bio-control agents directly act on pathogen by growth inhibition, while others act indirectly by triggering defense pathways (Fig. 7). However, inoculum density of the pathogen, strain or isolate of the pathogen, and existing environmental conditions have been helpful in the suppression of disease [39 and 40]. Microbial biocontrol agents such as *Trichoderma harzianum, T. viride*, *Aspergillus niger* (Strain AN 27), and strains of plant growth-promoting rhizobacteria (PGPR) (*Pseudomonas fluorescens)* exhibited protection of jute crop against stem rot pathogen when applied [41, 42, 43, and 44]. This is due to multiple antagonistic mechanisms such as nutrient competition, antibiotic production, and mycoparasitism. PGPRs are a group of free-living bacteria of rhizosphere, which participate actively in the biosynthesis of phytohormones such as indole acetic acid, gibberellic acid, abscisic acid, etc. in addition to higher uptake which causes solubilisation of phosphates and interference with toxin production of pathogen [45]. Broadcast of treated seed with *T. viride* @ 10 g/kg + soil application by mixing 1 kg formulation of *T. viride* in 100 Kg of FYM in the field condition at the time of final plough has resulted in a low incidence of stem rot [46]. Three-times soil application of *T. viride* @ 2.5kg ha^{-1} at 7, 15, and 30 DAS have been found effective in the management of stem rot, root rot, color rot, and seedling blight diseases of jute [47]. Seed inoculation with PGPR such as *Pseudomonas fluorescence*, *Azotobacter* and *Azospirillum* reduced stem rot incidence without affecting fibre yield [48]. Promising antagonistic features of *Trichoderma*, *Gliocladium*, *Aspergilius*, *Penicillium* and PGPR isolates have been revealed by inhibition of highly aggressive isolates (R9) of *M. phaseolina* causing stem rot in jute [41].

Biocontrol in combination with other disease management practices can improve the effectiveness of biocontrol agents. When *T. viride* is applied as seed treatment with other components, the respective per-cent incidence of stem rot and root rot diseases plummets sharply at 2.40% and 2.70% [7]. This application not only minimized the disease incidence, but also enhances the quality and yield of fiber. The treatment containing 50% N: P: K + seed treatment with *Azotobacter* & Phosphorus solubilizing bacteria (PSB) @ 5g/Kg seed + *T. viride* @ 5g/Kg & @ 2Kg/ha at 21 DAS) as a seed treatment and soil application respectively + *P. fluorescens* spray @ 0.2% at 45 DAS was ecofriendly and decisive with substantial reduced disease incidence (1.43%) in jute [49]. Efforts have also been made to control insects, mite, and diseases in *Olitorius* jute using biocontrol agents as an integrated management [50 and 51].

7.4: Chemical Control: The application of fungicides is the most prevalent method of management of stem rot in jut [52]. Chemical molecules of toxic nature having specific modes of actions are used to kill or inhibit fungal growth. Fungicides cease the development of stem rot acting either on pathogens, *M. phaseolina* and *Rhizoctonia solani* directly or on its sclerotia. It may take place involving various modes such as inhibiting enzymes, disruption of the cell membrane and wall, interference of key metabolism and pathways associated with sterol etc. [53, 54, 55, and 56]. However, the application of fungicides should not be, the only choice to manage the disease, because the consistent use of a similar fungicides enhances the propensity of resistance [57]. The genetic modifications may lead to modified target sites for fungicidal action, higher expression into the target protein, or low uptake or high metabolic inactivation of fungicide leading to quantitative fungicide resistance [58]. Therefore, it is mandatory to change the composition of fungicides for higher specificity, recognition, and action on target fungus. However, the process of development of specific and effective fungicides is very tedious and expensive. Dependence of farmers on the already developed and less effective fungicides is also a problem associated with the application of fungicides. Human health is one of the hazards associated with the use and application of these chemicals in addition to the deleterious effect on the natural ecosystem. Hence, it requires appropriate risk management strategies for its safe use [59 and 60]. Several beneficial soil flora and fauna are also killed by the application of fungicides, slowing down the decomposition of leaves and affecting the nutrient recycling system [61 and 62].

Spray of Dithane M 45 @ 5g/l or carbendazim 50 WP @ 2g/l or copper oxychloride 50 WP @ 5-7 g/l or Tebuconazole 25.9 EC @ 0.1% is recommended for the control of stem rot of jute when the disease incidence is 2% or more [52]. However, 3 to 4 sprays of the above-mentioned fungicides at 15-20 days interval is most effective in case of severe infection[26]. Various fungicides tested under field conditions and found that mancozeb (0.25 %) performed better against stem rot disease of jute [63]. Application of cardendazim @ 0.05% was resulted in maximum (10.76 %) disease control in mung bean blight caused by *M. phaseolina* [64]. Dry root rot of chickpea caused by *M. phaseolina* was found to be effectively controlled by carbendazim [65]. Fungicides treated seeds or foliar spray of fungicides is only feasible strategy now adays to control stem rot disease [66]. Termeric oil (10 g/ml) and curcumin mixture (100 g/ml) shows anti-fungal activity against *M. phaseolina* under *in vitro* condition [52].

8. Genetic Improvement of Jute for Stem Rot Resistance

Most of the strategies of jute improvement research were poised at the varietal improvement through traditional breeding. Therefore, very rare success came out in decoding its genomic information and their application in transgenic technology / marker assisted breeding. The trends of research programs have been changing for a decade, and a great deal of outcomes have been published in the area of genetic improvement of jute encompassing the size of genome, structure of chromosome, sequence of genome, regeneration through in vitro culture, and internal gene transformation system. These findings and technology are being exploited to develop resistant varieties against insect, fungus, bacterial, nematode, herbicide, etc. with low-lignin content in days to come.

8.1 Genetic (Defence related genes) Modification through Biotechnology: Gene modification is one of the most advanced and recent strategy to improve jute varieties against stem rot. The genes involved in the resistance against stem rot of jute are yet to be explored. Most of the researchers have proved that defence-related genes belong to phenyl- propanoid, phytohormone, jasmonic acid, abscisic acid, ethylene and salicylic acid, cell wall synthesis, and proteolytic pathway [29]. The roles of 22-nt miRNA families are evident to express SA/JA/ABA mediated natural systemic acquired resistance as reflected from micro RNA analysis [29]. MicroRNAs initiate a multi-layered defense to develop strong barriers against *M. phaseolina* involving leucine-rich repeat motifs, nucleotide binding site, and regulatory mechanism of reactive oxygen species (ROS) [30]. There is abundance of hydrolytic enzymes which degrade cell wall components and make their way into the host tissue [9]. There is expression of the high amount of the N_2O and ROS in plant cells that help *M. phaseolina* to evade plant defense [26]. The jute genome sequencing data may be helpful to find out genes involved in diseases resistance. These findings may be capitalized in the development of resistance in jute to cope up with stem rot disease [67]. Transgenic jute plant develop resistance (*C. capsularis*, variety JRC-321) through the transfer of the *rice chitinase* (*chi11*) gene [31]. The *rice chitinase* is the most common chitinase gene of plant origin that hydrolyzes β-(1, 4) linkages of chitin, one of the major (60 %) constituent of cell wall in fungi [68]. Therefore, chitinase gene may be exploited for the development of fungal resistant lines of jute [69]. Different explants of CVL-1 and CVE-3 varieties of white jute were transformed with agrobacterium strain LBA4404/pBI121 harboring GUS and nptII genes and this was tested positive [70 and 71]. Therefore, transformation approaches may have scope in the improvement of jute lines with traits of interest.

8.2 RNAi Intervention in the Improvement of Jute: RNAi mediates down regulation of candidates' genes liable for enzymes involved in the synthesis of lignin in both species of *C. capsularis* and *C. olitorius,* which are economically important too. The enzyme 4-coumarate: CoA ligase (4-Cl), which is expressed in initiation of lignin synthesis may be a target to down regulate the synthesis of lignin. It is possible to develop a transgenic jute line with RNAi construct to minimize the quantity of 4-Cl mRNA liable for lignin production based on the sequence profile 4-Cl gene. It is also possible to modulate the lignin synthesis by other promoters and alter the length of RNAi. Hence, RNAi technology may be harnessed as an effective approach to improve jute varieties with low lignin content. The low lignin content of jute is preferred in the processing and production of high-quality paper and cloth [72]. Seed-specific reduction of gossypol has resulted after the transformation of seed-specific promotor with RNAi of the d-cadinene synthase gene [73]. Pathogen and insect resistance similar to that of wild type varieties with high nutritional value has been reported in another fiber crop, cotton [74].

***8.3 Selection of Resistant Line/Varietal Resistance*:** Many varieties of jute endowed with resistance, tolerance or susceptibility against pests and disease are available (Table 2). However, as a part of smart disease management strategies, the evaluation of resistant/ tolerant germplasms against prevailing diseases is a pre-requisite. Jute variety is prone to the stem rot pathogen, weather conditions and pathotypes of specific regions affect the degree of resistance/susceptibility against the pathogen. India and Bangladesh have the largest genotype reservoir of jute and allied fiber crops that can be harnessed to select or develop superior genotypes by inter-varietal hybridization.

In one of the studies, 15 germplasm of both *capsularis* and *olitorius* jute were assessed under field conditions against stem rot disease in the year 2012 and 2013 [75]. *Olitorius* germplasms, OIN-431 were found tolerant during peak incidence in the year 2013. OIJ-63, OIJ-192, OIM-36, OIM-470, OIN-470, OEX- 002 and OIN-250 germplasms exhibited moderate resistance with slight incidence of stem rot in both the years. Location specific resistance was observed in the case of JRC-212 & JRC-321 of *C. capsularis* and JRO-524 & JRO-632 of *C. olitorius* [16]. 196 entries were screened and found that only nine entries such as CIM-036, CIM-064, CIN-109, CIN-358, CIN-360, CIN-362, CIN-371, CIN-386, and CIN-439 were resistant against stem rot disease [76]. A few short-listed tolerant accessions of *olitorius* against *Macrophomina* are 'OIN 107', 'OIN 125', OIN 154, OIN 157, OIN 221, OIN 651, OIN 853, and OIJ 084 [77]. However, some wild accessions of *Corchorus*, like *C. aestuans,* and *C. fascicularis* exhibited intense tolerance against the disease, while trial conducted in Barrackpore [78, 79, and 80]. Therefore, the use of resistant and wild germplasm lines is an excellent approach to develop disease resistant varieties and to investigate their mechanism involving molecular breeding strategies. The resistance specific QTLs in *M. phaseolina* pathogen have explored the role of candidate genes and has facilitated the analysis of functional genomics applicable in both conventional and molecular breeding for the development of resistant varieties [81 and 82].

9 Collective and Complementary Role of Stakeholders and Organization

The passionate involvement of stakeholders such as academician, researcher, extension functionaries, seed multipliers & certifiers, non-governmental organizations, and policy developers are mandatory for extensive management of stem rot disease. The application of advance information and communication tools in agriculture and participatory approaches can benefit in long run as a consequence of retrieval and transmission of pertinent information regarding the management of stem rot disease in time. Various institutes of National importance *viz*., Central Research Institute for Jute & Allied Fiber (CRIJAF), National Institute of Research on Jute & Allied Fiber Technology (NIRJAFT), Indian Jute Industries Research Association (IJIRA), and Institute of Jute Technology (IJT) are working in tune for the improvement of jute and their products. Collaborative work and research of these organization may come up with expected quality improvement in jute, and their product as per demands of National and overseas markets.

10 Conclusion and Future Scope of This Study

Jute has emerged as a “future fiber” crop and the prolific, multifaceted usage and ecofriendly nature of jute have raised the global demand of jute fibers, which are met by few jute-producing countries of Asia only. There are many biotic & abiotic, and financial challenges before farmers of developing countries like India and Bangladesh, which hinders the maintenance of healthy jute crops and production of quality fiber. Higher costs of cultivation or get control over infestation of weeds, pathogens and insects are added adverse factors. Outbreak of stem rot disease for the last decade has been a major obstacle in the economic jute production in North-East India. Therefore, management of this disease is one of the major challenges, which have attracted the attention of researchers to resolve. Modified agricultural practices, non-recalcitrant fungicide, biocontrol and genomic improvement of jute crops holds much potential to get rid of this devastating disease. The adoption of resistant cultivars and improved packages and practice by farmers is another challenge. Awareness and motivation among the jute growers for the adoption of new cultivars may be strengthened by on-farm trail and field level demonstration. Training of farmers on phytosanitary practices and strengthening of jute seed production and distribution system by exploring adequate market, export facility, and promotional activities may also play important role in this regard. Formation of federation of jute growers/farmer producer organizations may result in the cultivation of jute at a large scale and for sound economic return. Consistent strategic research for jute improvement and creation of awareness by policy makers, extension personal, and other agencies will be an added advantage in the holistic management of stem rot disease and dissemination of control measures among the producers.

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12 Author Declarations

Conflict of interest: This is to certify that we all Authors have seen and approved the manuscript which is being submitted. The authors declare that there is no conflict of interest in the publication.

Ethics approval/declarations: Not applicable

Availability of data and material/ Data availability: Not applicable

Code availability (software application or custom code): Not Applicable

Authors' Contributions

Santosh Kumar and Vinod Kumar Singh: Conceptualization the idea, writing & outline of the article.

Shyam Babu Sah and Tamoghna Saha: Composed the manuscript and figure.

Tribhuwan Kumar, Mahendra Singh, and Dhirendra Kumar Singh: Critically review and editing of the manuscript. All the authors read and approved the manuscript for publication

Table 1 Studies of interaction between jute and M. phaseolina

Sl. No.	Name of study	Tools applied in the study	Outcome of the study	References
1	Screening of resistance level in a Recombinant inbred line.	Transcriptomic profile and miRNA analysis	Induction of SA/MeJA1/ABA pathway genes	29
2.	Identification of known and novel microRNAs in resistant RIL lines	*In* silico analysis	Identification of nine novel microRNAs. High expression of known microRNAs and defense by NBS-LRR and ROS.	30

Table 2 Biotic resistant jute varieties released in India during 1977 and 2017 (According to AINP on J & AF, 2018)

Entry No.	Variety	Recommended area	Year of release	Yield in Q/ha	Special characters
JRO 524	Navin	West Bengal	1977	32-40	It shows resistance against root rot diseases under high rainfall condition.
S-19	Subala	West Bengal	2005	30-35	It is tolerant to pest and diseases.
AAUOJ	Tarun	Assam	2007	36	It is resistant against root rot, stem rot, anthracnose diseases and yellow mite.
JBO 2003 H	Ira	West Bengal	2008	38	It is resistant to stem & root rot, anthracnose and yellow mite.
CO 58	Saurav	West Bengal	2010	34	It exhibits resistance to pest and diseases.
JBO 1	Sudhanshu	West Bengal	2010	30-35	It is resistant to pest and diseases.
JROG 1	Rithika	West Bengal	2015	27.93	It shows resistance against stem & root rot diseases.
JRO 2407	Samapati	West Bengal	2016	33.82	It shows pest and diseases resistance.
KRO 4	Gouranga	West Bengal	2017	29.61	It is tolerant to stem rot and insects like BHC, semilooper, apion, and yellow mite.

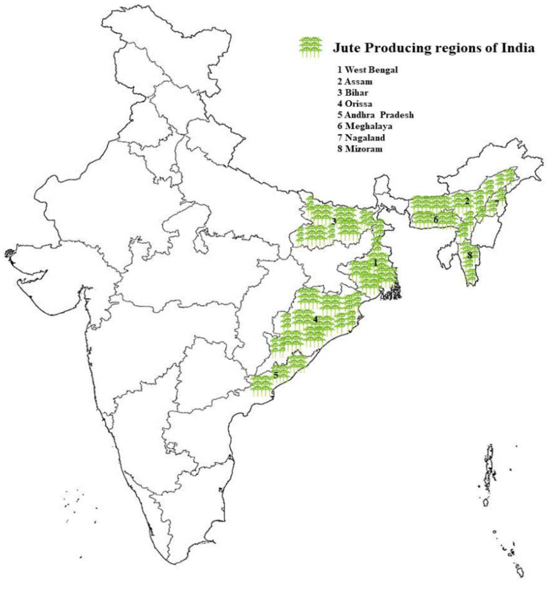

Fig. 1 Jute growing regions in India

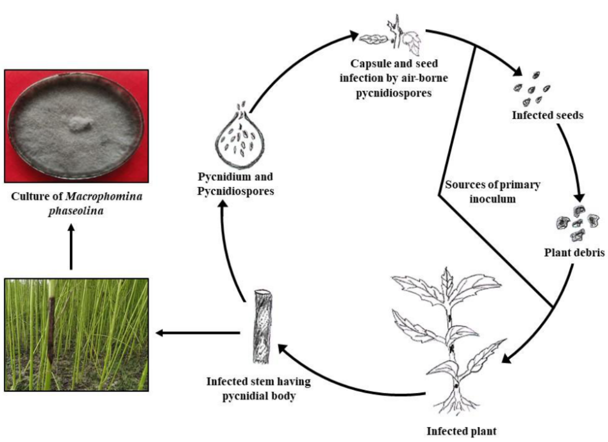

Fig. 2 Disease cycle of M. phaseolina showing different phases of disease development

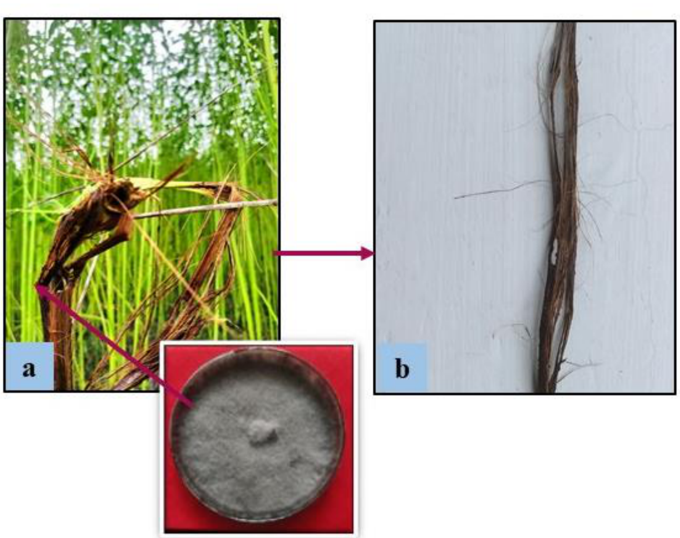

Fig 3. A, Stem rot infection; b, deterioration of fibre

Fig. 4 a, Infected stem showing stem rot symptom; b, Breakdown of infected stem and collapse while strong wind/s; c, Infected plant showing bark rot symptom; d, Color rot symptom; e, Root rot symptom

Fig. 5 Type of plants on the basis of infection intensity in terms of lesion length viz., 0=Immune (No symptom), 1= Highly tolerant (HT), 2= Moderate tolerant (MT), 3= Mild tolerant (MT), 4= very low tolerant (VLT), 5= Highly susceptible

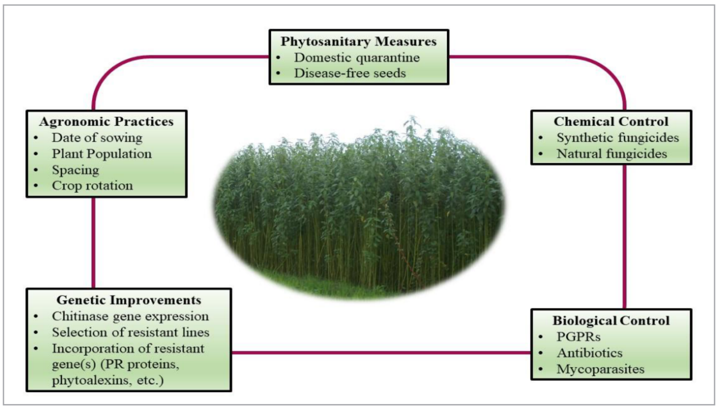

Fig. 6 Integrated Disease management approach to prevent stem rot in jute

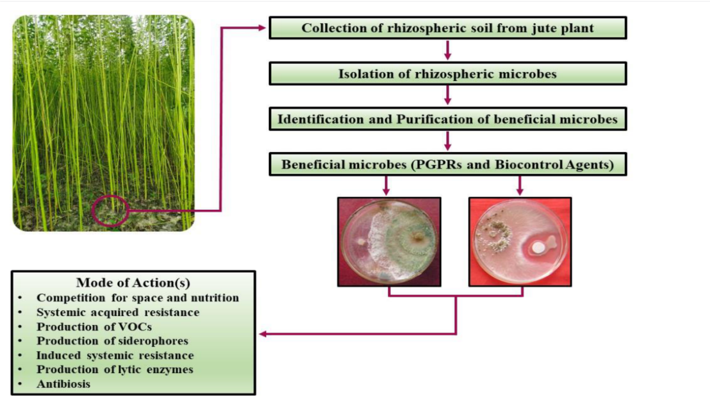

Figure 7. Approach and mechanism of biological control of jute stem rot.

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