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YIELD LOSS CAUSED BY FALSE SMUT DISEASE ON POPULAR RICE CULTIVARS

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ABSTRACT

Rice is one of the major staple food crops of the world. Rice False Smut (RFS) is an emerging disease affecting rice florets and forming smut balls. It is responsible for quantitative and qualitative losses. Accurate data on yield loss due to false smut can guide breeding programs aiming to develop resistant rice varieties and is essential for informed decision-making, effective disease control, resource optimization, and, ultimately, improving sustainability. Understanding the extent of yield loss helps farmers and stakeholders gauge the economic impact and determine the necessary focus on mitigation strategies. Yield loss caused by rice false smut disease in many traditional Indian cultivars is still unknown, especially in the southern state of Karnataka, India, where rice is being grown in six different agroecosystems. Thirty-two popular rice cultivars, including elite genotypes, landraces, farmer-saved seeds, and high-yielding varieties, were selected from all the six paddy growing ecosystems, and yield loss assessment was carried out intensively using randomized block design in two *Kharif* seasons, *i.e.,* 2021 and 2022, at experiment field of ARS, Gangavathi, Karnataka, India by recording various variables for yield loss estimation due to false smut disease, such as percentage infected tillers, percentage infected grains, the difference in the weight of smutted and healthy grains, healthy panicle weight, and reduction in grain weight. The highest yield loss was recorded in elite cultivar GNV-05-01 with 12.62 percent, followed by popular Sanna Batta (12.41%), whereas the lowest was recorded in landrace Burma Black (0.05 %), followed by landrace Gandasale and variety HR-12 recorded at 0.08 percent each. These cultivars include unexplored landraces, which were novel sources of resistance against RFS. Rice breeders can benefit from this less yield loss recorded cultivars as donors in false smut resistance plant breeding programs.

***Keywords*:** Yield loss, False smut, Landraces, *Ustilaginoidea virens,* Disease resistance

Introduction

Rice (*Oryza sativa*) is one of the most widely cultivated cereal crops in the world, followed by wheat in terms of both area and production. More than 50 percent of the world's population depends on paddy for their daily calorie intake. It accounts for about 42 percent of total food grain production and provides a livelihood for about 70 percent of Asian families. About 92 percent of paddy cultivated worldwide is consumed alone in Asia (Fairhurst and Dobermann 2002; Kole 2006; Wilson and Talbot 2009). Paddy grows in all seasons of tropical and subtropical climates in both upland and low land conditions due to its photo-insensitive nature. Rice is largely cultivated after wheat throughout the world. Rice is being cultivated on 167.55 million hectares worldwide, producing 521.52 million metric tons and having an average productivity of 3.13 tons per hectare (Anon. 2024). In India, rice is cultivated in a 47.83-million-hectare area with a production of 13.78 million metric tons and a productivity of 2.87 tons per hectare (Anon. 2023). In Karnataka alone, rice is a major food grain crop being cultivated in an area of 0.93 mha with an annual production of 3.01 mt and productivity of 3.03 t/ha (Anon. 2023).

Rice crop is susceptible to many biotic and abiotic stresses; biotic stresses are the major constraint in production and productivity. Rice crop is attacked by various diseases, including major and minor ones. In India, sheath blight, bacterial leaf blight, blast, and brown spot are major diseases; however, false smut and grain discoloration diseases are emerging in rice, whose severity was increasing year after year (Muniraju *et al.,* 2017a; Pramesh *et al.,* 2020a; Pramesh *et al.,* 2020b; Amoghavarsha *et al.,* 2022a; Amoghavarsha *et al.,* 2022b; Amoghavarsha *et al.,* 2022c; Amoghavarsha *et al.,* 2021; Huded *et al.,* 2022; Raghunandana *et al.,* 2023a; Raghunandana *et al.,* 2023b; Sharanabasav *et al.,* 2021; Sharanabasav *et al.,* 2020). Major reasons for this resurgence were mostly changing climate, monocropping, intensive crop cultivation, excessive use of chemical fertilizers, fungicides, and bactericides, and high-yielding cultivars with lesser genetic diversity, etc. are responsible for high disease severity in re-emerging status (Pramesh *et al.,* 2016a; Pramesh *et al.,* 2016b; Pramesh *et al.,* 2016c; Pramesh *et al.,* 2017a; Pramesh *et al.,* 2017b; Pramesh *et al.,* 2017c; Pramesh *et al.,* 2017d; Pramesh *et al.,* 2017e; Raghu *et al.,* 2020; Sharanabasav *et al.,* 2020; Pramesh *et al.,* 2020; Amoghavarsha *et al.,* 2021; Pramesh *et al.,* 2024b; Alase *et al.,* 2024). Rice False Smut (RFS) disease is a very serious threat to paddy cultivation in terms of production and productivity (Muniraju *et al.,* 2017b; Huded *et al.,* 2022). Due to the characteristics and symptoms produced on grains, the disease has several names, such as green smut, orange smut, and yellow smut. In India, the disease is referred to as "Lakshmi disease" due to its significant correlation between the high yield of rice and existing climatic factors. The disease was first observed in the Tirunelveli district of Tamil Nadu State in the 1870s (Cooke, 1878). Later, the disease appeared sporadically in the majority of rice areas of the world. Later, the disease can be seen in almost all parts of the country wherever paddy is being cultivated, especially in tropical and subtropical conditions (Ladhalakshmi *et al.,* 2012; Pramesh *et al.,* 2020; Huded *et al.,* 2021; Pramesh *et al.,* 2018a; Sharanabasav *et al.,* 2020; Alase *et al.,* 2023). Due to its ability to produce toxin (Ustiloxins), the disease seems to pose a serious threat to humans and animals by contaminating rice grains and fodder. In India, the disease was reported to cause yield losses ranging from 0.2 to 49 percent in different rice cultivars (Baruah *et al.,* 1992; Biswas 2001a). About 44 percent of losses due to rice false smut disease have been reported in Punjab (Pannu *et al.,* 2010). In North India, disease incidence was reported to be varied from 2 to 75 percent (Ladhalakshmi *et al.,* 2012). In Karnataka, the first systematic investigation on false smut disease was initiated in the early 21st century.

In the Indian context, most of the previous investigations focused mainly on disease incidence, symptomatology, pathogen biology, disease epidemiology, morpho, and morphological variability, whereas information on yield losses caused by the disease on popular cultivars of India is limited. In India, few attempts were made to identify the pathogen diversity at the molecular level (Pramesh *et al.,* 2018a; Sharanabasav *et al.,* 2020). The efficient isolation, identification, characterization, and artificial inoculation technique of field isolates were standardized for deciphering the false smut genetic diversity and pathogenic population structure across India previously (Ladhalkshmi *et al.,* 2012; Sharanabasav *et al.,* 2020). However, massive work on host plant resistance is still lacking under natural field conditions due to various constraints in screening varieties under artificial disease conditions due to the laborious, meticulous, and time-consuming process of artificial inoculation to large-scale field screening of the rice varieties for identification of the resistant source against RFSD.

Based on the previous data from four southern states surveys for disease incidence and severity assessment, we determined hot spots and cold spots for false smut disease in the country (Huded *et al.,* 2021). Additionally, comparative genomics, morpho-molecular characterization, and mating type analysis for false smut isolates from the southern part of India were studied (Pramesh *et al.,* 2018a; Sharanabasav *et al.,* 2020). However, data on yield loss assessment due to false smut disease on major cultivars, including landraces, varieties, hybrids, and farmer-owned seeds growing across India, especially under Karnataka state, was not clear.

False smut disease management is quite challenging due to the appearance of RFS symptoms after the panicle emergence. The biocontrol approach was not so effective in disease management due to its perishable effect, location specificity, and stage and niche specificity in disease management. Biological management of false smut was found less popular in RFS management due to its slow-growing nature under in vitro conditions, high multiplication, and spread under field conditions, which made it much more difficult to manage using biocontrol agents. However, some bioagents, *viz*., *Antennariella placitae*, *Bacillus subtilis*, and *Trichoderma harzianum*, were found to be effective in managing RFS to a certain extent (Andargie *et al.,* 2017; Baite *et al.,* 2022). Moreover, the disease symptoms were likely to appear after panicle emergence, especially at the grain setting stage; the fungicide application is not advisable. Since it may pose a serious risk of residue and create a harmful threat to animals by affecting the fodder quality. Although the chemical approach for disease management was successful to a certain extent, fungicides create health risks by creating ecological imbalance and environmental pollution and are hazardous to various living beings, including humans (Sharanabasav *et al.,* 2020). Additionally, fungicide resistance of *Ustilaginoidea virens* to various popular fungicides like Carbendazim, Prochloraz, and Azoxystrobin was found (Song *et al.,* 2022; Fang *et al.,* 2023). Thus, chemicals were less preferred for RFS management. Thus, there is a need for an alternative disease management strategy. Thus, host plant resistance was found to be the cheapest, eco-friendly, and sustainable approach to false smut disease management. Hence, finding resistance sources against RFS is a need of the hour; this study focussed on the identification of resistance sources against RFS along with yield loss assessment in popular cultivars of the Karnataka state of India. However, significant tolerance was observed among the cultivars against RFS. However, no variety has yet been found as immune. Unfortunately, variable reactions were found in tolerant varieties in the following years of cultivation and at multilocation trails. Thus, no variety is found to be 100 percent immune or resistant to disease. Screening for disease resistance is also very difficult in large-scale field conditions.

RFSD can lead to significant crop loss, particularly in high-yielding varieties. Understanding the extent of yield loss helps farmers and stakeholders gauge the economic impact and determine necessary mitigation strategies, such as fungicide application or resistant variety selection. Assessing the impact of false smut on yield allows for better disease management practices. By evaluating the severity of the disease, farmers can tailor interventions, such as adjusting planting dates or using fungicides effectively, to minimize losses. Early detection through yield loss assessment helps in making timely decisions about disease control. Yield loss assessments provide data that can improve crop production forecasting. It helps agricultural agencies, researchers, and extension services predict and manage future outbreaks, which can be critical for food security and ensuring adequate production levels. False smut primarily affects the rice panicles, leading to the formation of smut balls, which are filled with fungal spores instead of grain. This reduces not just the quantity but also the quality of the rice. Yield loss assessment helps evaluate both the quantity and the quality of the harvest, inform harvest decisions, and manage post-harvest. Yield loss specificity caused by the RFS in various cultivars was still unknown. In this regard, an attempt was made to evaluate the yield loss caused by false smut disease and determine resistance sources in thirty-two major and popular cultivars, including elite high-yielding varieties and farmer-saved landraces.

Landraces and farmer-sown rice seeds from tribal and hilly areas of Karnataka state were considered good donor sources for resistance against various diseases and pests. Apart from this, as an added advantage, these varieties and landraces were hardy and able to survive under harsh climatic conditions, which made them suitable for growing in any part of the country. Thus, screening and selecting the less yield loss recording and disease-resistant verities or landraces and donors against false smut disease is essential. Henceforth, we carried out a field experiment in *Kharif* 2021 and 2022 to evaluate the disease incidence, severity, and yield loss caused by RFSD in popular rice cultivars, including elite verities, hybrids, and landraces that are unexplored, being cultivated across hidden hilly and tribal regions of Karnataka state of India which were believed to be novel source of false smut disease resistance in Thunga-Bhadra Command area of Karnataka state.

Materials and Methods

Experimental site and Plant materials

The field experiment was conducted in two seasons, *Kharif*-2021-2022, at the Agriculture Research Station, Gangavathi, to estimate yield loss caused by false smut disease on popular paddy cultivars of Karnataka. A total of 32 popular genotypes, including landraces, varieties, and high-yielding hybrids, were evaluated for yield loss due to RFSD under natural epiphytotic conditions but supplemented with spore inoculum from yellow-colored smut ball during rebooting and booting stages of crop. Cultivars selected for yield loss evaluation were Ajaya, Ambe Mara-105, Bangara Kaddi, BPT-5204, Burma Black, Chityamutyalu-5613, CO-39, CSR-22, Gandasale-253, Gangavathi Emergency, Gangavathi Sanna, Gauri Sanna-2304, GGV-05-01, GNV-10-89, GNV-1109, GNV-1801, HR-12, IABT-17, IR-28, 2322, IR-64, KRH-4 MTU-1010, Navara-254, Ratan Sagara-260, RNR-15048, RP-BIO-226, Sanna Batta-107, Siri-1253, Tatep, GNV-1108, and TN-1 (Table 1).

Experimental design and crop establishment

The experiment was conducted in a randomized block design with three replications with an area of 12 m^2 for each treatment. Before sowing, seeds of all cultivars were soaked in water overnight and were kept in highly humid conditions for 1 day to create humidity. Pre-germinated seeds were raised in small seed beds of $1m^2$ area and later were transplanted, and a standard package of practices was followed to raise the crop. False smut spore balls from the infected field were collected and crushed into fine powder. The spore suspension was prepared and sprayed during the booting and panicle initiation stage of the crop to facilitate the disease onset.

Data recording for disease assessment and yield loss estimation

The observations, such as the number of infected tillers per m^2, the number of smut balls per panicle, and the weight of ten healthy and smutted panicles, were collected randomly from each variety. Yield loss and disease severity were estimated using the following formulae (Upadhyay and Singh, 2013). Disease severity is calculated by multiplying the percentage of infected tillers by the percentage of infected grains (Singh and Dube 1978). Yield loss in percent due to false smut can be calculated according to (Upadhyay and Singh 2013).

* Reduction grain weight = Weight of ten healthy panicles- Weight of ten healthy panicles.

Disease severity (%) = Infected tillers (%) × Smutted grains (%) (Singh and Dube 1978).

$$\text{Yield loss (\%)} = \frac{100 \times \text{Reduction grain weight*}}{\text{Grain weight of unsmutted panicles}} \times \frac{\text{\% Infected tillers}}{100}$$

Statistical analysis

The yield loss data due to false smut disease were subjected to analysis of variance (ANOVA) using SPSS. Significant differences among the means of cultivars were determined using Duncan's Multiple Range Test (DMRT) at a 5% level of significance ($p \leq 0.05$). Yield loss means of cultivars with different letter notations indicate statistically significant differences based on DMRT.

Results

Differential performance of rice cultivars across multiple variables

Paddy is being affected by *U. virens*, a flower-infecting fungus causing false smut balls on panicles, leading to quantitative losses. Karnataka is home to cultivating diverse genotypes and hybrids found to produce higher yields; however, these high-yielding cultivars were susceptible to minor diseases such as false smut and grain discoloration. Thus, it is essential to know the yield loss caused by RFS disease in popular cultivars from the major paddy cultivating ecosystem of Karnataka. Very meager information is available on the yield loss assessment in rice caused by RFS disease under Indian conditions. Keeping this view, a field experiment was conducted in experimental plots of A.R.S, Gangavathi, Karnataka, India. In continuation of our previous efforts, where the potential yield loss caused by false smut disease on 20 popular rice varieties of Karnataka was studied (Muniraju *et al.,* 2017). However, in this study, yield loss assessment due to false smut disease targeted 32 rice cultivars in cultivation in different ecosystems of Karnataka (Table 1). Various yield loss-related observations were taken to study the yield loss assessment, such as percent infected tillers, percent infected grains, average smut balls per panicle, the difference in panicle weight of infected and healthy panicles, and disease severity.

All 32 popular cultivars recorded the disease symptoms with varying severity, with potential yield loss (Figure 1). In this experiment, the percentage of infected tillers ranged from 0.16 to 29.33 percent, while yield loss was reported from 0.08 to 12.62 percent. Disease severity, which was the multiplication of the percent infected tillers and percent infected grains recorded, ranged from 0.12 to 68.15 percent (Table 1 and Figure 2). Smut balls appeared in all the tested varieties, but their severity and incidence varied. Not even a single cultivar is exempt from false smut infection. However, the IR-28 recorded only one smut across the treatment area.

Disease severity

The highest disease severity was observed in RP-Bio-226 (68.15 %), followed by Sanna Batta-107 (50.74%) and also both the cultivars recorded higher yield losses of 11.29 and 12.41 percent, respectively, followed by GNV-05-01 (12.05 %) and with respect to percentage of infected tillers, highest was observed on RP-Bio-226 (27.26 %), followed by Sanna Batta-107 (29.33 %). A minimum percentage of infected tillers was recorded on the HR-12 (0.16 %), with the lowest yield loss (0.08 %) after the IR-28 under field conditions (Table 1). Other cultivars, such as Ratansagar-250 (45.40 %), GNV-1801 (37.11%), Gangavathi-Sanna (36.30%), and CSR-22 (28.31%), recorded higher disease severity; the least disease severity was recorded on HR-12 (0.12%) (Table 17). A direct correlation existed between the disease severity and yield loss (Figure 4). Disease severity was also considered in terms of the percentage of infected grains.

Yield loss

The yield loss percentages observed among different rice cultivars varied significantly, indicating differing levels of susceptibility or resistance to the factors causing yield reduction. Among the cultivars, The highest yield loss was recorded in the cultivar GNV-05-01 (12.62 %) followed by Sanna Batta-107 (12.41%), GNV-1109 (12.23%), RP-Bio-226 (11.29 %), Gangavathi-Sanna (10.94%) and GNV-1801 (9.71%), BPT-5204 (6.07%), IR-64 (4.19%), Siri-1253 (4.32%), GNV-10-89 (3.49%), Ratansagar-250 (3.45%), CSR-22 (3.42%), GNV-1108 (3.02%), and TN-1 (3.04%) (Table 1 and Figure 1).

In several other cultivars demonstrated minimal yield loss was recorded in cultivar IR-28 (0.07%), followed by Burma Black (0.05%), HR-12 (0.08%), Gandasale 103 (0.08%), CO-39 (0.65%), Navara-256 (0.66%), Bangar Kaddi (0.78%), 2322 (0.86%), Tatep (0.33%), Chittmuthyalu (0.32%), KRH-4 (0.26%), and Gangavathi-Emergency (0.22%) recorded very low losses, indicating their potential for better performance under the given environmental conditions and show higher degree of resistance (Table 1 and Figure 1).

Percent infected tillers

Percent infected tillers were also used to represent disease incidence in varietal screening experiments against false smut in rice. In rice, one tiller represents one productive panicle. No significant correlation existed between traits such as the percent infected grains and percent infected tillers (Figure 3). Among the tested cultivars, the percentage of infected tillers recorded ranged from 0.16 to 23.45 percent.

Percent Infected Grains

The cultivar Gouri Sanna-2304 recorded the highest percentage of infected grains, with an average of 3.45 percent infected grains among panicles counted. Cultivars such as IABT-17, CSR-22, Gangavathi Sanna, RNR-15048, and Ambemara-105 recorded 2.69, 5.11, 2.49, 2.35, and 2.30 percent infected grains, respectively (Table 1 and Figure 3).

Smut ball per panicle

Average smut balls per panicle were recorded across all the cultivars and ranged from 1 to 4.5 number. Where maximum smutted balls per panicle were recorded in cultivar CSR-22 (4.50), followed by Gangavathi-Sanna (4.40), RP-Bio-226 (4.30), Ratansagar-250 (3.80), BPT-5204 (3.60), cv. GNV-1108 (3.50) and cv. GNV-10-89 (3.50). The minimum number of smutted balls was recorded on cv. IR-28, cv. HR-12, cv. Gangavathi-Emergency, cv. Burma Black, cv. Bangarkaddi, cv. Navara-256, cv. Gandasale 103 with an average of 1.00 smut ball per panicle (Table 1). Overall, the study highlights significant variation in yield loss among the rice cultivars. The findings suggest that cultivars with minimal yield loss, such as IR-28, Burma Black, HR-12, and Gandasale 103, could be better suited for cultivation in the given environments. In contrast, cultivars with high yield loss, like GNV-05-01, GNV-1109, and Sanna Batta-107, may require further breeding efforts or protective measures to enhance their resilience. These results indicated that rice false smut disease significantly impacts rice yield and related traits among all the tested entries (Figure 5). However, some landraces recorded lower yield loss. All the varieties were recorded as false smut disease with varying extents. The field view of the field experiment is shown in Figure 6.

Discussion

Rice is one of the major staple food crops of the world, and >50 percent of the world's population depends on its calorie intake. This crop has been affected by false smut disease for a long time. India is a land of crop diversification with wide ecological niches and diverse climatic conditions. Karnataka is one of the major contributors to rice production in India, where paddy is being cultivated in six major paddy-growing ecosystems. Among them, the Thunga-Bhadra command area under the Koppal district is the top rice-producing ecosystem in Karnataka (Lamani and Thimmaiah 2022). However, its production is limited for several reasons, including diseases and pests, and the unavailability of resistant cultivars. False smut has recently emerged as a major disease leading to quantitative and qualitative yield loss. In Karnataka, it was reported as 0.09 to 4.25 percent (Muniraju *et al.,* 2017). From 2 to 75 % yield losses caused by RFS in India were reported. In India, it was reported that the disease incidence was up to 23.78 percent (Hegde *et al.,* 2000; Huded *et al.,* 2021) and yield losses were up to 17.12 percent (Muniraju *et al.,* 2017). Various reports are available on the yield loss caused by RFS worldwide (Baruah *et al.,* 1992; Biswas 2001a).

However, information on yield loss caused by this RFS in popular cultivars of Karnataka being grown in major paddy-growing ecosystems, including local cultivars, popular elite genotypes, and genetically diverse landraces, was still scarce and limited. In this background, a field experiment was carried out in two seasons, *Kharif*-2020 and 2021, at experimental fields of A.R.S, Gangavathi, India, to evaluate the yield loss across 32 popular cultivars of Karnataka.

Among all 32 tested cultivars, not even a single variety is devoid of false smut symptoms. However, some level of tolerance was found among a few cultivars. Altogether, yield loss recorded across the cultivars ranged from 0.05 to 12.62 percent (Table 1). The yield loss recorded was moderate compared to previous reports, where they reported up to 49 percent yield loss affected due to false smut in northern states of India (Singh *et al.,* 1992). According to our study, Cultivar IR-28 is considered a resistant cultivar with lesser yield loss (0.07 %). This cultivar is also considered a false smut-resistant cultivar, as shown by previous studies (Han *et al.,* 2015). When they studied the differential expression of defense genes among resistant cultivar IR-28 and Susceptible LYP9, they found that resistance in IR-28 is mainly due to the presence of genes encoding receptor-like kinase (RLKs) and cytoplasmic kinase. Other than 438 opposite-expressed genes, pathogenesis-related (*PR*) and diterpene phytoalexin biosynthetic genes were specifically induced in the IR-28 (resistant variety). More importantly, the cis-regulatory W-boxes were found in excess in the promoter regions of up-regulated genes in cultivar IR28. WRKY, in addition to transcription factors, was also differentially regulated. Finally, they concluded that U. virens genes required for fungal reproduction and pathogenicity were suppressed in the IR-28 (Han *et al.,* 2015). This explains the possible mechanism of resistance in IR-28 to *U. virens* apart from unfavorable climatic conditions with lesser environmental humidity and annual rainfall (Banasode and Hosagoudar 2021; Alase *et al.,* 2021; Masurkar *et al.,* 2023). Some cultivars recorded the lowest yield losses, such as Burma Black, IR-28, Gandasale, HR-12, Chittmuthyalu, KRH-4, Sanna Batta, MTU-1010, Ambemar, Bangar Kaddi, Navara-256, Tatep, Ajaya, Gangavathi Emergency, and CO-39 recorded lower yield loss, i.e., <1%. Most of them are landraces, including one tolerant hybrid. Similar disease reaction was reported in many cultivars from earlier surveys on RFS disease assessment surveys (Muniraju *et al.,* 2017; Huded *et al.,* 2021). The probable reason for lower yield loss among these popular cultivars from surveyed areas was due to commercial and intensive paddy cultivation in the cultivation areas. Timely and scheduled fungicide application in these areas was one of the presumable causes of lower yield loss.

Three of 32 cultivars were highly susceptible to disease and recorded more than 12 percent yield loss, viz., Sanna Batta-107, GNV-1109, and GNV-05-01. These cultivars are high-yielding, more nutrient-responsive, and reported to be susceptible to various diseases, including RFS. A wide variation of response among genotypes was recorded against RFS. Similar studies were also conducted by (Singh and Kang 1987; Sugha *et al.,* 1992, Kurauchi *et al.,* 2006; Kaur *et al.,* 2015; Kumar *et al.,* 2017; Banasode and Hosagoudar 2021; Lore *et al.,* 2022).

Our results for less yield loss and disease severity in hybrids (KRH-4) (0.26 %) were supported by previous studies conducted by Biswas (2001) and Muniraju *et al.,* (2017). Previous efforts reported cultivars Rasi, PA-6444, and Sriram Gold as highly susceptible to false smut disease (Hegde *et al.,* 2000; Ladhalakshmi *et al.,* 2012; Upadhyaya and Singh 2013; Kumari and Kumar 2015; Muniraju 2017; Muniraju *et al.,* 2017a; Ladhalakshmi *et al.,* 2018). This study reported GNV-05-01 and Sanna Batta-107 as highly susceptible to false smut disease. The genetic makeup of the cultivars and environmental factors that might have affected the host-pathogen interactions were the possible reasons for differences in yield loss among screened genotypes. Most of the genotypes with the least yield loss recorded in our study are landraces, which are highly adaptable, genotypically diverse, and less prone to diseases. These genotypes can be used for breeding programs for mapping candidate genes and genome-wide association studies for identification of QTL associated with RFS resistance in the near future (Long *et al.,* 2020; Qui *et al.,* 2020; Hiremath *et al.,* 2021; Neelam *et al.,* 2022). In comparison, the lowest percentage of infected tillers was recorded on hybrid KRH-4 (0.48%) (Table 1 and Figure 3). Surprisingly, landraces such as Bangara Kaddi and Gandasale recorded <1 % infected tillers (Table 1 and Figure 3). This is mainly due to higher genetic diversity and adaptability, which conferred specific resistance-associated alleles or genes against *U. virens*. Anatomically, these landraces do possess thickened epidermal layers of floral structures as barriers with lesser exposed spikelet stigma, which limit *U. viren*s infection and further progression. Apart from this, they may consist of higher antifungal compounds, such as phytoalexins and phenolic compounds, which inhibit further fungal growth and spore germination. These landraces are locally well-adapted to diverse agroecological conditions (Pradhan *et al.,* 2023; Roy *et* *al.,* 2024). These traits make landraces the most valuable genetic resource for breeding programs aimed at developing tolerant cultivars against the RFS. Plant breeders often go for introgression of these landraces with high-yielding cultivars to develop resistant cultivars against RFS.

As the experiment was conducted in two seasons using natural inoculum and epiphytotic conditions, the proportion of yield loss among these cultivars was higher; however, by surprise, it could be more under artificial inoculation conditions or the high epidemic condition. Although artificial inoculation of false smut disease was standardized under greenhouse and polyhouse conditions from ICAR-IIRR, Hyderabad (Unpublished data), it was not completely standardized yet for large-scale field conditions. Thus, the present study relies on natural epiphytotic conditions for yield loss assessment.

The observed disease reaction and yield loss on various cultivars tested may vary between the seasons, locations, and artificial inoculation methods. The varieties tested in this experiment were of different flowering times and intervals. Thus, observed disease reactions may vary under different inoculation conditions, pathogen populations existing in the location, and prevalent climatic conditions. However, the cultivars selected had very diverse genotypic and phenotypic characters. Thus, we presumed that the recorded varied yield loss on different tested cultivars was found to be accountable. Further, these cultivars need to be tested under various artificial inoculation and multi-location conditions in the near future. As expected, the highest yield loss was recorded in popular, elite, high-nutrient-demanding, high-yielding cultivars, especially commercially cultivated under the Tungabhadra command area of Karnataka state. At the same time, less disease severity and yield loss were noticed in traditional cultivated landraces, which farmers maintained for many years. Some of these cultivars were the least explored and underutilized in the breeding program for selecting donor resistance sources. This study provided novel genetic sources that are resistant to RFSD. These cultivars can identify and mine novel QTLs, resistant genes (SNPs), or loci linked with disease resistance. Although the disease was found in all cultivars tested, the extent of severity and yield loss varied. Thus, further advanced genotyping, genome mining, and phenotyping studies were needed to address the resistance stability of these cultivars so a stable disease-resistant population could be developed. This study may help to understand the present status of the RFSD and the varietal susceptibility of popular cultivars in India, especially those cultivated in Karnataka. Also, relative yield loss due to false smut disease on popular cultivars was identified.

False smut is an infectious disease; therefore, its pathogen impact on rice hosts can be directly seen in yield reduction. The possible explanation for yield reduction could be a diversion of grain food material for pathogen growth and smut ball formation (Agarwal and Verma, 1978). After floral organs such as stamens, style, and ovary infection, pathogens start colonizing by utilising simple sugars present in floral organs, thereby damaging the grain-filling process (Zhang *et al.,* 2014). Muniraju *et al* (2017a) reported that a reduction in the test weight of grain is also a reason for yield reduction, and similar results were also published previously (Chib *et al* 1992; Hegde & Anahosur, 2000). In addition to causing direct yield loss, the false smut pathogen produces many antimitotic toxins in grain (Abbas *et al.,* 2014). Consumption of such grains by humans and animals may lead to health hazards (Abbas *et al.,* 2014; Ji 2000; Sinha *et al.,* 2003). The present study has not focused on the differential expression of toxins in cultivars and the toxin profile of *U. virens*; therefore, a detailed study on false smut toxins is warranted.

Conclusion

Rice False Smut disease is a devastating disease occurring in almost all parts of the world, wherever rice is cultivated. Comprehending the magnitude of yield loss caused by RFSD enables farmers and stakeholders to assess the economic ramifications, identify prerequisite mitigation options, such as fungicide uses or the adoption of resistant varieties, and helps to identify the risk areas for resource allocation. Data on yield loss was caused by RFSD, which is still unknown in popular landraces and other elite cultivars of India. This data also enables us to identify the resistant source for an eco-friendly, sustainable approach to RFSD management, *i.e.,* Host plant resistance. In this study, 32 various cultivars popular across Karnataka (India) were assessed for the yield loss caused by RFS. Yield loss recorded among cultivars ranged from 0.05 to 12.62 per cent. The highest yield loss was recorded in GNV-05-01, popularly known as Gangavathi Sona; other cultivars, such as GNV-1109 and RP-Bio-226, also recorded higher yield losses. None of the tested cultivars was immune to disease. However, some promising, tolerant, resistant genotypes, such as Burma Black, HR-12, and Gandasale, were identified. This study identified the yield loss caused by RFSD in different rice cultivars and provided an unexplored resistance source against RFSD. This study provides novel insights into selecting donors for the breeding program against false smut disease. The yield loss assessment from this study also helps policymakers determine the extent of yield loss and resource allocation caused by false smut under natural conditions.

Table 1 : Yield losses due to false smut disease of rice on thirty-two different popular rice cultivars from *Kharif* 2020 and 2021 (Pooled data)

Sl. No.	Cultivar	Infected tillers (%)	Infected grains (%)	Smutted balls/ Panicle (Avg)	Disease severity (%)	Grain weight of 5 panicles (g)		Difference in grain weight (g)	Yield loss (%)	Mean Yield Loss of Varieties
						Wt. of 5 Healthy panicles	Wt. of 5 Smutted panicles			
1	BPT-5204	7.80	2.01	3.60	15.68	1.98	0.44	1.54	6.07	6.10[f]
2	CO-39	1.50	1.94	2.20	2.91	3.60	2.04	1.56	0.65	0.66[no]
3	IR-64	8.34	1.47	3.40	12.26	3.62	1.80	1.82	4.19	4.20[g]
4	IR-28	0.38	0.91	1.00	0.35	2.42	1.96	0.46	0.07	0.07[rs]
5	GNV-05-01	22.80	0.85	2.87	19.38	3.36	1.50	1.86	12.62	12.65
6	Gangavathi-Emergency	0.56	2.17	1.00	1.22	2.18	1.29	0.89	0.22	0.22[qrs]
7	GNV-1108	7.57	1.94	3.50	14.69	3.66	2.20	1.46	3.02	3.05[i]
8	GNV-1109	23.45	1.10	2.50	25.72	2.80	1.34	1.46	12.23	12.28[b]
9	GNV-10-89	6.12	1.32	3.50	8.08	4.66	2.00	2.66	3.49	3.50[h]
10	Gangavathi-Sanna	14.58	2.49	4.40	36.30	3.20	0.80	2.40	10.94	10.98[d]
11	GNV-1801	19.13	1.94	3.10	37.11	3.86	1.90	1.96	9.71	9.71[e]
12	Tatep	0.76	0.84	1.50	0.64	3.60	2.04	1.56	0.33	0.33[q]
13	Ajaya	1.87	1.64	2.70	3.07	4.20	3.00	1.20	0.53	0.53[op]
14	TN-1	9.90	1.50	2.60	14.85	4.33	3.00	1.33	3.04	3.06[i]
15	Burma Black	0.18	1.44	1.00	0.26	2.72	1.96	0.76	0.05	0.05[s]
16	Bangar Kaddi	1.63	0.77	1.00	1.25	3.06	1.60	1.46	0.78	0.78[mn]
17	Navara-256	1.17	1.24	1.00	1.45	1.88	0.82	1.06	0.66	0.66[no]
18	Gandasale 103	0.37	0.93	1.00	0.34	2.04	1.60	0.44	0.08	0.08[rs]
19	Gouri Sanna-2304	3.24	3.45	2.90	11.18	3.50	1.40	2.10	1.94	1.95[k]
20	Ambemar-105	2.00	2.30	3.50	4.60	3.00	2.06	0.94	0.63	0.63[no]
21	Ratansagar-250	22.04	2.06	3.80	45.40	2.30	1.94	0.36	3.45	3.48[h]
22	MTU-1010	3.68	2.00	3.20	7.36	3.69	3.28	0.41	0.41	0.41[pq]
23	Siri-1253	9.86	1.24	2.80	12.23	2.60	1.46	1.14	4.32	4.35[g]
24	HR-12	0.16	0.78	1.00	0.12	3.10	1.58	1.52	0.08	0.08[rs]
25	RNR-15048	5.54	2.35	3.30	13.02	3.30	1.66	1.64	2.75	2.75[j]
26	RP-Bio-226	27.26	2.5	4.30	68.15	2.68	1.57	1.11	11.29	11.31[c]
27	Chittmuthyalu	0.61	1.13	1.60	0.69	1.60	0.76	0.84	0.32	0.33[q]
28	Sanna Batta-107	29.33	1.73	3.20	50.74	3.12	1.80	1.32	12.41	12.46[a]
29	2322	6.69	1.50	2.20	10.04	2.34	2.04	0.30	0.86	0.86[m]
30	IABT-17	10.00	2.69	3.10	26.90	2.36	2.04	0.32	1.36	1.36[l]
31	KRH-4	1.14	0.48	1.67	0.54	5.60	4.33	1.27	0.26	0.26[qr]
32	CSR-22	5.54	5.11	4.50	28.31	3.00	1.15	1.85	3.42	3.43[h]

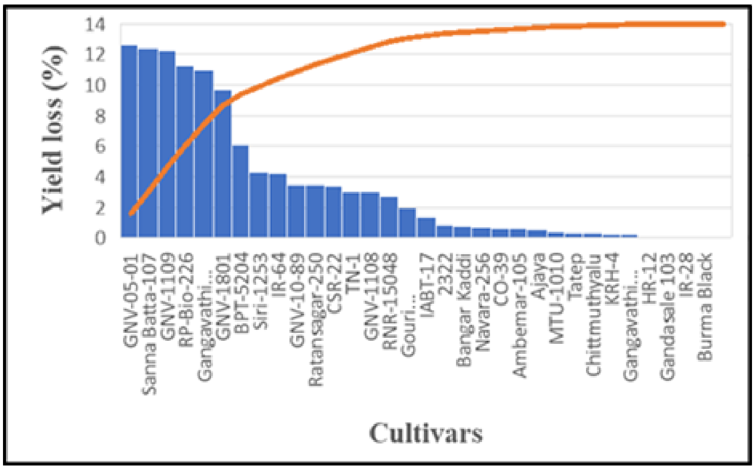

Fig. 1 : Pareto chart plots showing the distribution of the yield loss data in descending order of frequency with cumulative lines of the secondary axis as a percentage of the total.

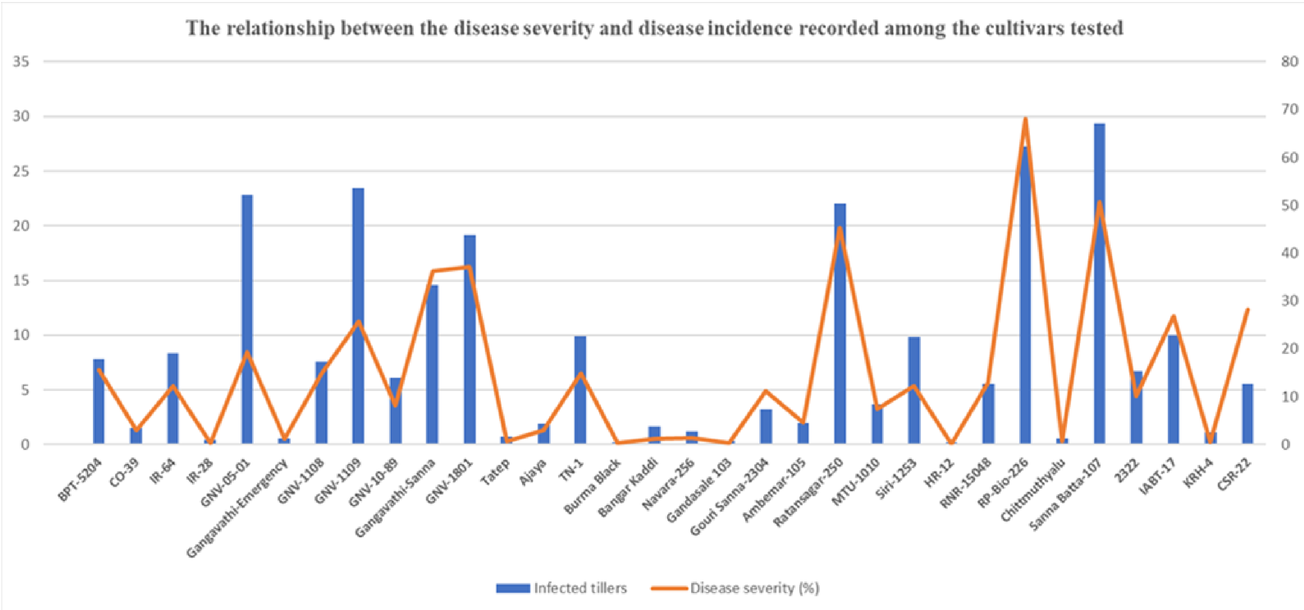

Fig. 2 : Clustered column-line graph showing the relationship between the disease severity and disease incidence (percent infected tillers) among the cultivars tested

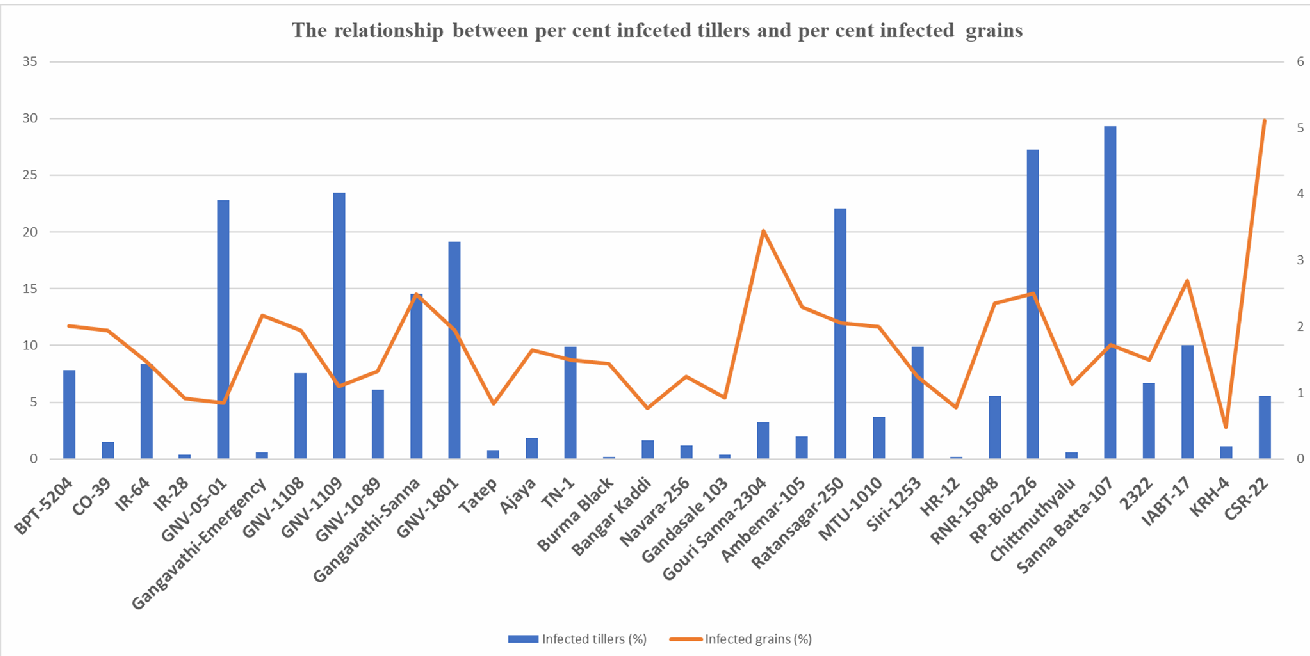

Fig. 3 : Combo plot graph showing the relationship between per cent infected tillers and per cent infected grains

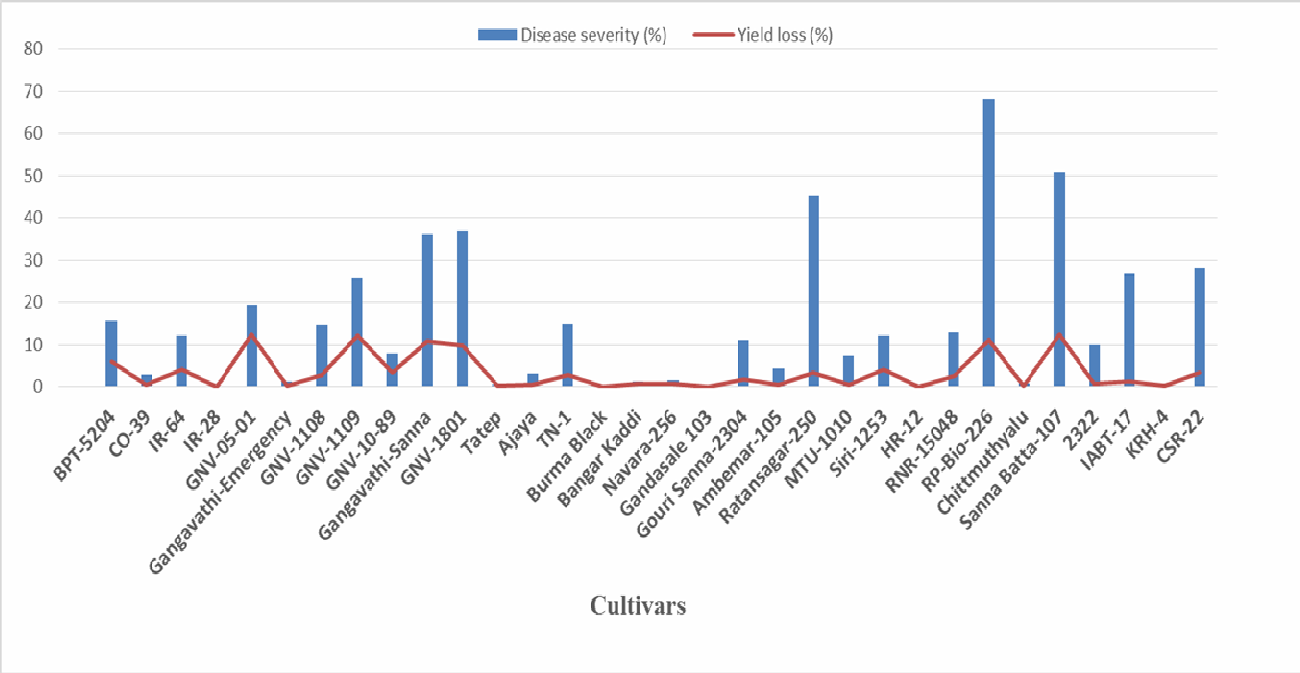

Fig. 4 : Graphical representation of the relationship between the disease severity and yield loss recorded among the cultivars tested

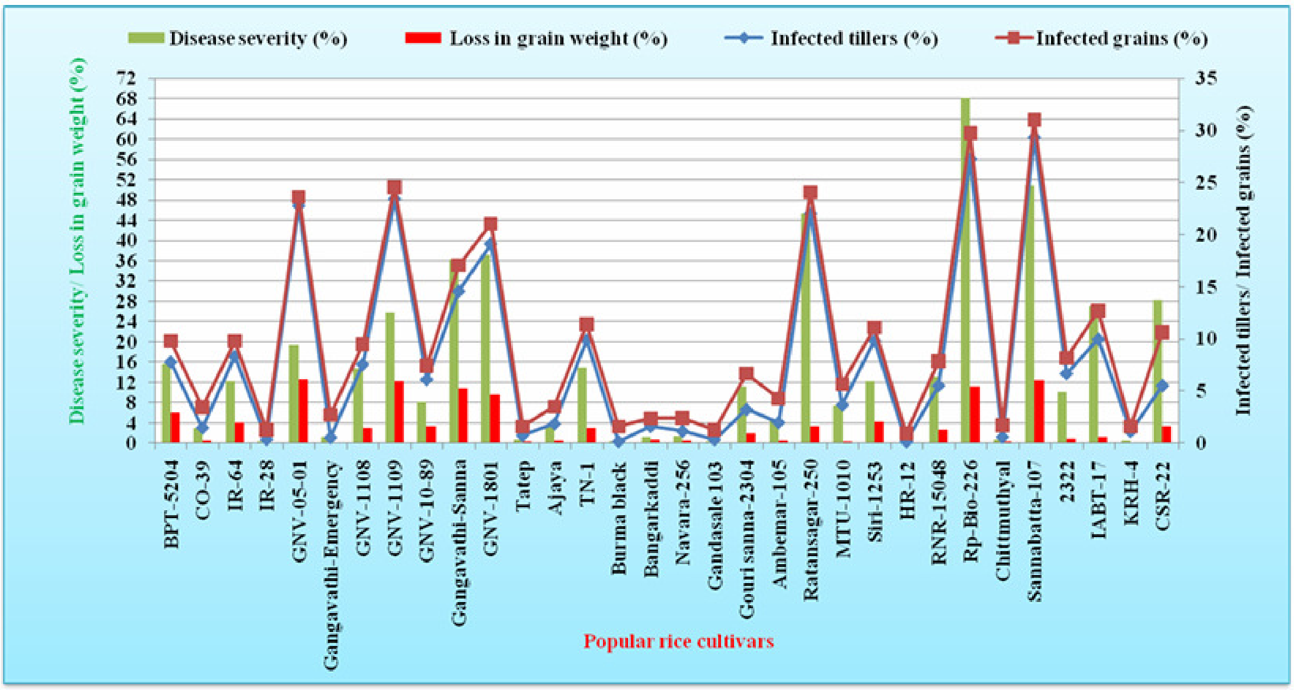

Fig. 5 : Graphical representation of interaction of yield loss related traits such as, Disease severity (%), Loss in the grain weight (%), Infected tillers (%), infected grain (%) due to false smut infection on popular cultivars of Karnataka

Fig. 6 : Field view of experiment on yield loss on different cultivars conducted in ARS, Gangavathi

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