BADEGGI JOURNAL OF AGRICULTURAL RESEARCH AND ENVIRONMENT, 2024, 06(03), 24-37

NCRI Press

Available online: www.ncribjare.org
ISSN: 2695-2122, e-ISSN: 2695-2114
DOI: https://doi.org/10.35849/BJARE202403/197/03
Journal homepage: www.ncribjare.org

Research Article

A Review of Two Emerging Rice Diseases, in the Major Rice Growing Areas of the World

Maji, E. A[1]., Ocean, H. O[1]., Olopade, R. T[1] and Gbadeyan, S. T[2].
[1]Department of Bioscience, College of Natural and Applied Sciences, Salem University Lokoja, Kogi State, Nigeria
[2]National Cereals Research Institute, Badeggi. Niger state
Correspondence e-mail: adejoh_ojone@yahoo.com

Abstract
The disease known as kernel smut, which is brought on by *Tilletia horrida*, is typified by the sooty black masses of teliospores or chlamydospores that replace rice grains. The color of the chlamydospores in kernel smut is different from that of rice fake smut, which is generated by *Ustilaginoidea virens*. Spore balls that are globose and velvety, with colors ranging from orangish yellow to greenish black, are the hallmark of false smut. Due to their irregular breakouts and little economic impact, kernel smut and fake smut which were first identified in the late 1870s and continued to persist are regarded as minor illnesses in many nations. However, in many nations, particularly the US, kernel smut and fake smut have become two of the most commercially significant disease affecting rice, including organic rice, in recent years. Grain production and quality have significantly decreased as a result of the growing use of sensitive rice cultivars particularly hybrids, excessive nitrogen fertilizer use, and short crop rotations. These factors have also led to a rise in kernel smut and fake smut. The distribution and economic significance of kernel smut are reviewed in this article, along with our current knowledge of the taxonomy, biology, and epidemiology of kernel smut and the genomics of the kernel smut fungus in comparison to fake smut and its causative agent. We also provide an update on the current management strategies of pathogen exclusion, cultivar resistance, fungicides, biological control, and cultural practices for kernel smut and false smut of rice.

Keywords: *Kernel smut, False smut, Epidemiology, Spores and Fungicides.*

Introduction

With an annual production of 503 million metric tons, rice (*Oryza sativa L.*) is the third most important cereal crop in the world, behind corn and wheat (*Triticum aestivum*) (FAOSTAT 2021; Statista 2023). It is also one of the most significant food crops, providing food for over half of the global population. It is grown in over 100 nations, with Asia accounting for the majority of its output. With an expected 10 million metric tons of rice produced in 2019 (USDA 2020a), the US is a major producer of rice as well. With more than 1.3 million hectares of rice, the Sacramento Valley of California and the Southern states of Arkansas, Louisiana, Mississippi, Missouri, and Texas are the main rice-growing regions in the United States. Whereas the majority of rice grown in California is short or medium grain, the majority of rice grown in the South is long grain. Mexico, Central America, Northeast Asia, and the Middle East are the top export destinations for around half of the rice produced in the United States (Singh *et al*. 2017 and Khanal *et al*., 2023). In the United States, direct-seeding techniques are used to grow all of the rice on irrigated land. Whereas practically all rice farmed in California is water-seeded, the majority of rice grown in the South is dry-seeded.

Received on XXXX, 2024; Revised XXXX, 2024; Accepted 18th December, 2024 and Published on 30th December 2024

Rice grain yield and quality are decreased by kernel smut, which can result in partial or whole bunts of rice grains. The first reports of rice kernel smut date back to 1896 in Japan (Takahashi, 1896) and 1897 in the United States. Because the disease only occasionally breaks out on small areas of land, it has long been regarded as a minor illness. In recent years, kernel smut has become a significant disease due to the extensive use of sensitive hybrids, overuse of nitrogen fertilizers, and short crop rotations. As of right now, kernel smut is present in practically every nation that grows rice (Whitney and Cartwright 2018; Khanal *et al*. 2023). There have been reports of kernel smut in 29 countries and on six continents. Grain quality losses are the main cause of the disease's losses. In the United States, milled rice is limited to 3% smutted rice (USDA 2020a). Despite estimates that rice kernel smut disease incidence is 15% on average the illness incidence has been reported to be as high as 87 and 100% in Pakistan and China, respectively (Biswas 2003).

Rice smut management comes with a number of difficulties. Even with the use of fungicides, kernel smut is hard to manage (Whitney and Cartwright 2018). Research on the control of fake smut has been more extensive than that on kernel smut. There are cultivars that are quantitatively resistant to false smut. Given the recent rise in the frequency, severity, and economic significance of rice smuts, it's critical to assess the state of our current comprehension of rice smuts' occurrence, biology, epidemiology, and management. Enhanced comprehension of these fields, particularly biology and epidemiology, will facilitate the creation of efficient management plans for these newly emerging diseases. The economic significance of kernel smut, our present understanding of its biology and epidemiology, the genetics of the kernel smut fungus, and current management approaches in comparison to fake smut in some of the most pertinent domains are the main points of emphasis in this review study. Prior reviews of rice kernel smut's biology, history, taxonomy, and management techniques have been conducted (Biswas 2003; Carris *et al*., 2006; Singh *et al*.,1998). A number of review studies have also been published recently that address different facets of fake smut (Dangi *et al.*, 2020; Fan *et al*., 2016; Kumar *et al*., 2018; Sun *et al*., 2020; Wang *et al*., 2019b).

Kernel Smut and False Smut as Emerging Diseases

Kernel smut

Since its discovery, kernel smut has continued to be an ongoing disease in numerous nations. A portion of the global rise in kernel smut has been attributed to the growing use of susceptible hybrid cultivars for rice production since 2006 in the United States and since 1976 in China and other nations (El-kazzat *et., al.* 2014; Shi *et al*., 2021; Wang *et al*. 2015). China, Egypt, and many other nations are experiencing rice production problems due to the newly discovered disease known as kernel smut (Allen *et al*. 2020; Elshafey, 2018; El-kazzaz *et al.*, 2014; Wang *et al*., 2015; Zhou *et al*., 2020). The majority of rice-growing regions in China are affected by kernel smut, which can result in yield decreases of 5 to 20% and grain infections of up to 60% (Wang *et al*. 2015).

According to Espino (2020), there has been a rise in the incidence of kernel smut in Californian rice production in recent years, due to the fact that farmers have been reporting decreases in yield and quality—particularly in milling quality. Since the middle of the 1980s, the disease has been present in the Sacramento Valley of California (Espino 2019). Likewise, the Mississippi Delta rice-growing region, Texas, and Louisiana have all reported an increase in the occurrence of kernel smut disease in recent years. The high levels of kernel smut in Louisiana have resulted in rice rejections. In recent times, it has emerged as a significant rice disease in Texas as well (Uppala *et al*., 2016; Zhou *et al*., 2020, 2021b).

Between 2015 and 2019, outbreaks of kernel smut affected sensitive rice cultivars such as CL153, Cheniere, Dixiebelle, Presidio, XL723 (hybrid), and XL753 (hybrid) in Texas's western and eastern rice-producing regions of Houston (Wang *et al*. 2021). Severe outbreaks of kernel smut spread over the Texas Rice Belt and southwest Louisiana in 2021; up to 50% of panicles were impacted, and up to 20% of panicles contained contaminated kernels (Zhou *et al*., 2021b). Furthermore, as more vulnerable cultivars are used for organic production, a new disease known as kernel smut is posing a danger to organic rice production in Texas and California, the two states that produce the most organic rice in the United States (Zhou *et al*., 2021a, b).

False smut

False smut epidemics happen all across the world during epidemic years, much like kernel smut (Ladhalakshmi*et al*. 2012; Rush *et al*. 2000; Snehlata and Kumar 2015). False smut has been linked to an increase in yield losses and incidence in recent years. According to Lu *et al*. (2018), China had output losses of 158.6 million kilos annually between 2008 and 2016. According to Harrell (2020), there has been a rise in fake smut levels in a number of Louisiana rice cultivars. In addition to being vulnerable to kernel smut, the rice cultivar Presidio was also vulnerable to fake smut. Additional cultivars that were vulnerable to both smuts were CL172, Gemini 241 CL, CLXL745, and PLV01 (Harrell 2020). While there isn't a stated maximum permitted for the frequency of fake smut in the selling of kernel smut, false smut, however, mycotoxins (ustiloxins and ustilaginoidins) produced by false smut have the potential to negatively impact both human and livestock health (Fan *et al.* 2016; Nakamura *et al*. 1994; Sun *et al*. 2020; Wang *et al*. 2019b). Incidence and severity of false smut caused by Ustilaginoidea virens (Cook) Tak. on upland rice in eight rice producing locations in Edo State of Nigeria were assessed in 1992 through survey where is was recommended that planting an early maturing variety at the start of rains may be a good method of escaping the disease(Monday and Adepoju 2002).

Economic Importance and Economic Losses

Kernel smut

According to USDA 2020b, the rice market in the US is worth about $2.46 billion. The two states that produce the most rice are Arkansas and California (USDA 2020a). Kernel smut causes financial losses by lowering grain production and milling quality. But the losses resulting from worse milling quality outweigh the costs resulting from lower output. Even at low disease levels, kernel smut can have a major negative economic impact and result in a considerable loss in rice grain quality, with milling yield decreases ranging from 0.05 to 0.25% (Espino 2019).There is a 3% smutted rice limit in the US; rice beyond this limit cannot be parboiled. According to Harrell (2020), rice crops are being turned down at Louisiana delivery locations.

According to USDA 2020b, the average yield and price per kilogram in Louisiana for 2019 were roughly 7,150 kg/ha and $0.224 per kilogram, respectively. This meant that Louisiana farmers lost about 1,600 kg/ha due to rice rejection. With an average price of $0.223 per kilogram of rice, Texas rice farmers earned more than $135 million in 2018–2019 (USDA 2020a, b). Texas farmers face millions of dollars in losses due to the growing threat of kernel smut. Grains having a high degree of kernel smut have resulted in price docking or outright rejection for some Texas farmers. Grains contaminated with 0.1 to 1%, 1.1 to 2%, and 2.1 to 3% each had their prices lowered by $0.05, $0.10, and $0.15 each. Millers reject rice grains with more than 3% kernel smut, which often leads to the total loss of rice crops during epidemic years. In Texas alone, the anticipated yearly economic loss is expected to exceed $18 million. In areas like California and Arkansas that produce a lot of rice where the crop is worth billions of dollars the stakes are even higher (USDA 2020a, b).

False smut

Depending on the weather and rice cultivar, false smut of rice can result in yield losses of 3 to 70% (Baite*et al*. 2021). There is no cap on the proportion of rice contaminated by fake smut, in contrast to kernel smut. But according to Wang *et al*. (2019b), the false smut fungus produces two different kinds of mycotoxins: ustiloxins and ustilaginoidins. When rice grains and straw are contaminated with mycotoxins, it can be harmful to both human and animal health and cause cancer.

Taxonomy of Kernel smut and false smut

The rice kernel smut was initially identified as *Tilletiahorrida* Tak by Takahashi in 1896 (Takahashi 1896). Based on their spore germination research, Padwick and Khan (1944) regrouped the names to become *Neovossiahorrida* (Tak.) Padwick& Khan and placed the fungus in *Neovossia*. Tullis and Johnson (1952) carried out the methodical inoculation of the fungus into multiple *Pennisetum* species. Based on the findings, they accepted Padwick and Khan's categorization of fungi and classified the kernel smut fungus under *Neovossia*, giving it the name *N. barclayana* because of its physical similarities to *N. barclayana*. Nonetheless, Durán and Fisher (1961) discovered that while the fungus likewise harmed grasses, its spores were more typical of *Tilletia* than *Neovossia*.

The fungus was later determined to belong to the genus *Neovossia* by Singh and Pavgi (1973) based on the findings of a study on spore germination and development. The reason Whitney (1989) classified the fungus in *Neovossia* instead of *Tilletia* was explained. This is due to the fact that *Tilletia* only produces one type of secondary sporidia, while *Neovossia* produces two. Whitney (1989) disagreed with Tullis and Johnson (1952) regarding the fungus's placement in *N. barclayana*, though, because the authors described the fungus as systemic. They supported Padwick and Khan's fungal placement and proposed calling the fungus *N. horrida*. However, the preferred scientific name for rice kernel smut is now *Tilletiahorrida* (Khanal*et al*. 2022, 2023; Wang *et al*. 2015, 2018a, 2019a, 2020). The ascomycetes fungus *Ustilaginoidea virens* (Cooke) Takahashi is the source of false smut in rice. *Villosiclavavirens* (Nakata) E. Tanaka & C. Tanaka is the name of its teleomorph. In the literature, both phrases are used synonymously (Fan *et al*. 2016; Sun *et al*. 2020). For false smut of rice, however, *Ustilaginoideavirens* (Cooke) Takahashi is the preferred scientific name.

Disease Symptoms and Epidemiology

Kernel smut

The black, sooty masses of spores known as teliospores or chlamydospores replace the rice grains in cases of kernel smut disease. Typically, a panicle containing one or a small number of diseased grain kernels will have kernel smut. However, in Louisiana and Texas, it has been reported that up to 50% of the kernels in as many as 20% of the panicles in the fields are damaged (Zhou *et al*. 2021b). A powdery mass may replace grains that have been partially or totally affected by the kernel smut fungus. Early in the morning, when dew or moisture causes smutted kernels to swell and burst in preparation for the release of teliospores, symptoms are easier to observe (Whitney and Cartwright 2018).

Due to their strong wall construction, teliospores of the kernel smut fungus have been shown to survive in soil for two to three years in field settings (Chahal 2001; Singh et al. 1998). In the presence of irrigation water, teliospores have been found to germinate, and primary sporidia are typically formed above the waterline. According to a study by Goates (2010), *Tilletia* spp. secondary sporidia viability was more resilient than previously believed. The main causes of the severe incidence of kernel smut include temperatures between 25 and 33°C during the flowering stage, lengthy periods of rain, or high relative humidity (>85%) (Chahal 2001; Whitney and Cartwright 2018).

False smut

The hue of the smut balls distinguishes false smut symptoms from actual smut symptoms. Unlike kernel smut, which often only exhibits symptoms at harvest or late maturity stages, fake smut symptoms are easily noticeable outside of rice kernels in addition to their color. The hallmark of false smut is the substitution of powdery chlamydospores for globose, velvety spore balls that resemble rice kernels (Schneider and Groth 2018; Sun *et al.* 2020). Mature smut balls turn greenish black, while immature smut balls are orangish yellow. According to Tang *et al*. (2013), the false smut fungus attacks rice lossoms, replacing the internal organs with fungal mycelia. The asexual stage of the false smut fungus produces chlamydospores, whereas the sexual stage produces sclerotia.Upon germination, sclerotia and chlamydospores can both produce conidia, which can serve as the main source of inoculum.

Biology and Disease Cycle

Kernel smut

T. horrida produces teliospores, also known as chlamydospores, which are light to dark brown and act as overwintering structures. Before or during harvest, smutted grains release teliospores that contaminate soil, plant detritus, and rice seed (Whitney and Cartwright 2018). Hyaline are the sterile teliospore cells. There have been disagreements over the use of varying teliospore sizes to identify certain isolates, despite the fact that varying sizes have been observed (Elshafey 2018). The teliospores of rice kernel smut are known to display postharvest dormancy.

Teliospores may go latent for four to five months, according to studies (Chahal 2001; Chahal*et al*. 1993). It has been documented that the teliospore germination rate ranges from 15 to 30%, and it has infrequently been recorded to surpass 50% in the following the year. Primary sporidia that are uninucleate and non-conjugating are produced from teliospores (Castlebury et al. 2005; Carris*et al*. 2006). The primary sporidia, or basidiospores, of *T. horrida* are often filiform and aseptate in morphology. Studies have shown that isolates produce different numbers of basidiospores. Mycelia, which are produced when primary sporidia germinate, give rise to both allantoid and filiform secondary sporidia (Carris*et al*. 2006; Whitney 1989). The disease's severity was reduced when the rice plant's flag leaves were removed prior to heading, demonstrating the significance of the flag leaves in kernel smut infection. *T. horrida* can form two different kinds of colonies: one that produces just white sporidia and one that has purple coloring when basidiospores start to create secondary sporidia.

False smut

When rice reaches maturity, fake smut-infected plants produce greenish-black smut balls. False rice smut, in contrast to kernel smut, generates sclerotia and fungus chlamydospores, which hibernate in soil and rice seeds (Fan *et al*. 2016; Sun *et al*. 2020). *Panicumtenellum*, *Digitariamarginate*, *Panicumtrypheron*, *Imperatacylindrica, and Echinochloacrusgalli* are among the grass and weed species that the fungus can infect in addition to rice (Schneider and Groth 2018; Shetty and Shetty 1985; Sun *et al*. 2020). These substitute hosts might serve as possible inoculum reservoirs in between crops or in the off-seasons. Additionally, the fungus forms horseshoe-shaped sclerotia, which are sexual structures that are known to hibernate for a few months (Wang *et al*. 2019b).). Nevertheless, there are still unanswered questions about how chlamydospores germinate and how an infection starts in rice in false smut disease cycle. During the booting stage, rice can become infected by both sclerotiaascospores and chlamydospores that are still germinating. The fake smut fungus produces conidia, which, given the right circumstances, develop into chlamydospores with noticeable spines on the surface. According to a preliminary investigation, the fungus invades the ovary during the flowering stage and only colonizes the fertilized spikelets. However, a recent study (Qin *et al*. 2013) discovered that the fungus can also colonize male sterile rice. The inner organ of the rice floret is surrounded by the fungus. Small pigmented colonies are also produced by the false smut fungus on the potato sucrose agar medium. Potato sucrose is a rich source of conidia produced by the fungus.

Genomics of Rice Smuts

Kernel smut

Compared to the genomics of *U. virens*, relatively little is known about the genomics of *T. horrida*. The *T. horrida* QB-1 strain's first draft genome is accessible to the general public (Wang *et al*. 2015). The genetic diversity of *T. horrida* populations in the United States was recently described for the first time by Khanal*et al*. (2022), where 63 isolates from six different states that grow rice were grouped into five distinct clades. Similarly, single-nucleotide polymorphisms, tiny indels, and structural differences between the *T. horrida* strains were found by genome re-sequencing of six strains of the fungus in China, indicating polymorphisms in the kernel smut (Wang *et al*. 2018a).The genes for *T. horrida's*carbohydrate-active enzyme (CAZyme) were comparable to those predicted by Wang *et al*. (2018a, 2019a).It has been discovered that *T. horrida* has fewer genes than *M. grisea* and *Rhizoctoniasolani* AG-1A that are predicted to encode the enzymes cellulose, hemi-cellulose, and pectin (Wang *et al*. 2018a, b). This could be because rice stamen filaments lack pectin and cellulose (Kemen*et al*. 2011; Tang *et al*. 2013; Wang *et al*. 2018b). Apart from CAZyme genes, transcriptome analysis indicated additional putative virulence-associated genes encoding G protein-couple receptor genes, ATP-binding cassette (ABC) transporter genes, cytochrome P450 genes, and secondary metabolites (host-selective poisons) (Wang *et al*. 2019a). According to Que*et al.* (2014), these genes are recognized to be crucial in the interactions between pathogens and hosts. Comparative transcriptome analysis of Wang *et al*. (2020).

To comprehend the regulatory mechanisms of disease resistance, lines Jiangchen 3A (J3A) (3% infection by *T. horrida*) and a susceptible line 9311A (17% infection) were used. According to the study, line J3A (4,415) has more uniquely differentially expressed genes (DEGs) than line 9311A (1,732). These DEGs were analyzed using Kyoto Encyclopedia of Genes and Genomes (KEGG) and Gene Ontology (GO), which identified various pathways including cutin, suberine and wax biosynthesis, oxidoreductase activity, and flavonoid biosynthesis. Additionally, this study showed that line J3A had higher salicylic acid (SA) content than line 9311A did, suggesting that SA may be important in rice kernel smut resistance (Wang *et al*. 2020).

False smut

Unlike *T. horrida*, the genomes of several *U. virens* species have been sequenced and added to the NCBI database. *U. virens* has a genome that ranges in size from 26.97 to 39.40 megabytes. Repetitive elements are said to be the cause of these size variations (Sun *et al*. 2020). Unlike rice cultivars, genetic changes in *U. virens* have been connected to geographic distribution (Jia*et al*. 2015; Sun *et al*. 2013; Wang *et al.* 2014; Yu *et al*. 2013). A total of 193 putative effectors have been linked to genes that may be involved in the pathogenicity of *U. virens* and host-microbe interactions; 18 of these have been shown to inhibit plant hypersensitive response (Fan *et al*. 2016; Sun *et al*. 2013). Furthermore, compared to *M. oryzae and Fusariumgraminearum,* analyses of multiple *U. virens* genomes have revealed fewer genes for nutrient uptake, polysaccharide degradation, and metabolism and a relatively higher number of genes that code for secreted proteins related to toxins and are involved in secondary metabolism (Zhang *et al*. 2014). Research has also identified gene clusters for polyketide synthase and nonribosomal peptide synthetase, which may be crucial for *U. virens'* production of mycotoxin (Fu *et al*. 2015; Koiso*et al*. 1994; Lu *et al*. 2015; Zhang *et al.* 2014). The transcriptomes of the resistant (IR28) and susceptible (HXZ) rice cultivars' reactions to *U. virens* were compaired, and the results showed variations in the regulation of genes related to secondary and hormone metabolism.

Management Strategies

The key to effectively managing kernel smut and false smut is to use management techniques to minimize damage to a manageable degree. However, in contrast to other rice diseases, kernel smut and false smut are more challenging to control using individual management approaches due to a lack of useful management tools and an inadequate understanding of their in-season disease infection process. Uncertainties exist about the function and dynamics of kernel smut spores, particularly secondary sporidia, in the disease infection process as well as the influence of climate and plant growth stage on disease development. Because kernel smut and fake smut symptoms and indicators are only seen at or just before the cropping season, there are no scouting techniques available to detect and anticipate the development of these illnesses.

Pathogen exclusion

According to Whitney and Cartwright (2018), kernel smut is spread by seeds, and the main source of inoculum is infected seeds. Thus, a good way to keep disease out of a field is to utilize certified rice seeds that are free of the kernel smut pathogen. Visual inspection of collected seeds and microscopic verification of dark teliospores washed off from seed samples in water are the usual methods used to examine seed lots. Recently, a molecular detection technique based on polymerase chain reaction was created (Chen *et al*. 2016), which can help with the detection procedure. Growers are strongly advised not to utilize seeds collected from fields that previously had kernel smut infections. One way to lessen and possibly completely eradicate the kernel smut infection is to treat the seeds.Whitney's (1977) research, however, showed that fungicide seed treatments containing benomyl, maneb, and chlorothalonil were unsuccessful. Yet no standardized and successful seed treatment techniques have been created and put into practice for the commercial management of kernel smut. Despite the possibility that false smut in rice can spread through seeds, no research has shown that treating seeds can effectively prevent false smut (Jecmen 2014). Theoretically, using certified smut-free false seeds can be a useful way to keep illnesses out of the field where available, the application of appropriate nitrogen fertilizer and is also used as control agents.

Cultivar resistance

The most efficient way to control rice kernel smut is to employ cultivar resistance. The vulnerability of cultivars to kernel smut varies (Whitney and Cartwright 2018). Compared to medium- and short-grain cultivars, long-grain cultivars are more sensitive (Slaton et al. 2007; Whitney and Cartwright 2018). According to Whitney and Cartwright (2018), there appears to be a partial or positive correlation between cultivar susceptibility and the length of anthesis and the period of floret opening. Compared to medium- and short-grain cultivars, long-grain cultivars typically have longer anthesis durations and larger floret apertures. Commercial cultivars that are less vulnerable are accessible, but no highly resistant cultivars (Slaton *et al*., 2007; Zhou and Jo, 2014) have been created. The majority of cultivars cultivated in the US are either somewhat or highly sensitive to the fungus. Wells is one of the cultivars that are least prone to the illness (Slaton *et al*. 2007). None of the top 11 cultivars cultivated in Texas are resistant to kernel smut, but five of them are somewhat vulnerable (Zhou *et al*. 2020). Several nations, including China, Egypt, India, Pakistan, and the Philippines, have been found to be suppliers of resistant genotype material (El-kazzaz*et al*. 2014; Singh *et al*. 1998; Wang *et al*. 2020).

A rice genotype known as Jiangcheng 3A has just been described by Wang *et al*. (2020) to show resistance to kernel smut. Its infection rate can still, however, be above the US government's allowable limit of 3% for milled rice (USDA 2020a). Thus far, a relatively small amount of research has been done worldwide to create resistant cultivars as a viable and long-term approach to managing kernel smut. There aren't any public breeding initiatives for rice in the US at the moment aim to create cultivars that are more resistant to kernel smut. One of the challenges impeding research attempts to generate resistant cultivars is the lack of straightforward and trustworthy inoculation techniques for greenhouse and field screening. Different levels of kernel smut infection in rice plants have been shown to be induced by tests using different inoculation methods, such as injection, spraying, and dipping at different growth stages of the plants (Singh *et al.* 1998; X.-G. Zhou, unpublished data). However, a dependable and standardized inoculation method has not yet been developed.

There are rice cultivars that are quantitatively resistant to false smut, as opposed to kernel smut cultivar resistance. In transcriptome comparisons between the highly sensitive cultivar HXZ and the resistant cultivar IR28, quantitative trait loci have been identified against *U. virens*. Research has indicated that there may be possibilities for false smut resistance within the chitinase gene cluster (Hu *et al.* 2018; Li *et al.* 2011; Liang *et al*. 2014; Lore *et al*. 2013; Sun *et al*. 2020; Yesmin*et al.* 2015; Zhao *et al*. 2013). It seems that certain cultivars are less prone to fake smut. There aren't any public breeding initiatives for rice in the US at the moment that aimed to create cultivars that are more resistant to fake smut.

Fungicides

Prior research revealed that no fungicide was sufficiently effective to reduce kernel smut (Whitney and Cartwright 2018). Follic treatment with chlorothalonil, benomyl, maneb, and triphenyltin hydroxide during the heading stage was found to be unsuccessful by Templeton *et al*. (1960) and Whitney (1977). Fungicides have become a crucial tool for managing kernel smut with the introduction of propiconazole and other novel fungicides. Propiconazole can be administered as a midseason prophylactic treatment to control kernel smut (Brooks *et al*. 2009; Whitney and Cartwright 2018).

It has been demonstrated that fungicides containing propiconazole, such as QuiltXcel (propiconazole plus azoxystrobin), Quilt (propiconazole plus azoxystrobin), Stratego (propiconazole plus trifloxystrobin), and Tilt (propiconazole) are effective at controlling kernel smut (Zhou *et al*. 2020, 2021c). Farmers in the United States frequently utilize these fungicides, particularly tilt, to manage kernel smut. Zhou *et al*. (2020, 2021c) have demonstrated that Amistar Top, a novel fungicide containing azoxystrobin and difenoconazole as active ingredients, may effectively control kernel smut in the field by up to 68% when used in conjunction with propiconazole. Applying fungicides at the right time is essential to effectively controlling kernel smut. According to Zhou *et al*. (2021c), treatment during the mid-boot stage is the most effective; application prior to the mid-boot stage is less effective. In order to prevent rice from the infection of the kernel smut fungus, rice growers in the United States are advised to apply fungicide at the mid-boot stage (Harrell 2020). Two applications might be required when the kernel is under a lot of stress; the first would be made mid-boot and the second right before heading. It is advised in China to use fungicides at the initiation, full heading, and flowering stages in order to control kernel smut. The management of kernel smut is not always achieved by midseason fungicide spraying. There have been reports of decreased effectiveness or failure of propiconazole fungicides throughout the Southern United States. As a result, higher fungicide application rates are advised in order to control kernel smut. Therefore, more research is required to look at other fungal isolates from larger rice-producing regions in the US in order to determine whether fungicide resistance is existent and whether it is linked to a decrease in the effectiveness of fungicide management. Furthermore, research is being done to create novel compounds that effectively suppress kernel smut (Guo*et al*. 2018).

For farmers, however, managing kernel smut with fungicide spray could not be cost-effective. Applying fungicides in the middle of the season can be costly because they are applied before any visible signs of the illness appear and may not be as successful in controlling other fungal infections. But if farmers do nothing, they can lose a lot of output and quality in fields where there has already been a history of kernel smut. As a result, farmers may not always be able to justify the financial gains from using fungicides, and it can be challenging for them to make the best choices about fungicide use. Similarly, the application of fungicides like propiconazole is crucial for the management of fake smut.Apart from propiconazole, various fungicides have been found to be efficacious against false smut infections, such as azoxystrobin, copper oxychloride, cuproxat SC, difenoconazole, hexaconazole, prechloraz, simeconazole, and tebuconazole (Chen *et al*. 2013; Nakamura *et al*. 1994; Wang *et al*. 2019b; Zhou and Liu 2019). According to Nakamura *et al*. (1994), difenoconazole and azoxystrobin together were more effective than either fungicide by themselves at reducing false smut. The timing of fungicide application is crucial, just like with kernel smut. According to Dangi*et al*. (2020) and Kumar *et al*. (2018), the booting stage is the ideal period for fungicide application. Higher yields were reported by Raji*et al*. (2016) when propiconazole or trifloxystrobin + tebuconazole were applied during the booting stage. In China, applying the fungicide Wenquning six days prior to heading demonstrated a good degree of control (Liang *et al*. 2014). Two isolates of the false smut fungus with propiconazole resistance have been identified in China (Zhou *et al*. 2017), in contrast to kernel smut, where no fungicide resistance has been documented so far. The CYP51 gene, which is crucial for the synthesis of ergosterol in fungi, appears to be expressed more frequently in this resistance, which confers resistance to fungicides that inhibit sterol demethylation, such as propiconazole (Zhou *et al*. 2017).

Biological control

A little amount of study has been done on the control of rice kernel smut and false smut utilizing biological agents, plant extracts, and other biological products. After evaluating fifteen distinct bacterial and fungal isolates, El-Kazzaz*et al*. (2015a) concluded that Bacillus pumilus was the most promising biocontrol agent for managing the kernel smut fungus. The use of SA and a number of plant extracts from *Artemisiajudaica*, *Menthaviridis*, *Syzygiumaromaticum*, and *Eucalyptus globulus* have all been investigated as induced systemic resistance treatments for rice illnesses (El-kazzaz*et al*. 2015b). According to El-Naggar*et al*. (2015), biocontrol agents such *B. subtilis*, *Trichodermaviridae*, *T. koningii*, and *Antennariellaplacitae* have demonstrated efficacy against the fake smut fungus.

Cultural practice

Cultural customs can lessen the harm that kernel smut causes. Elevated nitrogen fertilizer tends to make rice crops more vulnerable to the disease known as kernel smut. Compared to rates of 157 kg/ha or less, the severity of kernel smut was substantially higher at the high nitrogen rate of

246 kg/ha. Likewise, Uppala*et al.* (2018a) found that applying nitrogen at a rate of 179 kg/ha can considerably lower the occurrence of kernel smut when compared to applying nitrogen at a rate of 247 kg/ha. Another strategy to lessen the damage caused by kernel smut is to plant rice early or use early maturing cultivars to prevent climatic conditions favorable for disease growth in the late season. According to Slaton *et al.* (2007), rice should be planted as soon as practicable.

Future Situations

Nearly all countries that grow rice have seen cases of kernel smut and fake smut as mild illnesses. However, due to changes in the methods used to produce rice, such as the use of hybrids and other susceptible semi-dwarf cultivars, excessive nitrogen fertilization, and short crop rotations, two major diseases that pose a threat to rice production in the United States and other countries are kernel smut and false smut. Decreased premiums, lowered grain quality, or even sales rejections often lead to significant financial losses. To gain a better understanding of the diseases infection process, epidemiology, and kernel smut fungus, very little work has been done. Because no single management technique can satisfactorily control kernel smut and false smut, managing these is currently difficult. The development and use of resistant cultivars is the most effective and economical approach to minimize the damage caused by kernel smut, false smut and maximize production returns.

Unfortunately, no cultivars or genotype sources with high levels of resistance have been identified so far. No extensive breeding efforts have been conducted for cultivars resistant to either smut. Therefore, more research is needed to identify new sources of resistance by screening a large number of germplasm lines, including those from other countries, and even wild species of *Oryza*. Further research is needed to develop and standardize a simple and reliable kernel smut inoculation technique that can be used for cultivar resistance screening in the greenhouse and field. New research is also needed to understand the genetics of kernel smut and false smut resistance in the host and to identify quantitative trait loci or genes potentially associated with resistance. The most efficient and cost-effective way to reduce the harm caused by kernel smut and fake smut and increase production returns is to develop and employ resistant cultivars. Sadly, no genetic sources or cultivars with high resistance levels have been found to date. It has not been possible to find cultivars resistant to either smut through considerable breeding. In order to find new sources of resistance, more study is required to screen a vast number of germplasm lines including those from other nations and even wild species of *Oryza*. Additional investigation is required to create and standardize a straightforward and trustworthy kernel smut inoculation method that can be applied for field and greenhouse cultivar resistance screening. Additionally, fresh study is required to comprehend the markers associated with resistance to false smut and kernel smut, which will help early breeding generations select for resistance. Advancements in genomes research have yielded insights into the pathogenicity and methods of infection of fake smut and kernel smut fungi. To gain a deeper understanding of the pathogens' virulence, the mechanism and genetics of rice resistance, and the effects of environmental factors on pathogen-host interactions, additional research is necessary. The creation of a forecasting model or system that can assist in predicting the likelihood of kernel smut and false smut incidence, which would then lead to the administration of fungicide, is another possible field of research. Rice seed microbiome study should be attempted in light of recent developments in microbiome research in order to comprehend the variations.

Funding: This work was supported by Salem University Research and Development Center, Lokoja.

The author(s) declare no conflict of interest.

References

Allen, T. W., Growth, D. E., Wamishe, Y. A., Espino, L., Jones, G., and Zhou, X. G. (2020). Disease loss estimatesfrom the rice producing states in United States: 2018 and 2019. *Proc. Rice Tech Wrkg. Grp.* 36:41.

Baite, M. S., Khokhar, M. K., and Meena, R. P. (2021). Management of false smut disease of rice: A review. I*ntechOpen*.

Biswas, A. (2003). Kernel smut disease of rice: Current status and future challenges. *Environ. Ecol.* 21:336-351.

Brooks, S. A., Anders, M. M., and Yeater, K. M. (2009).Effect of cultural management practices on *the severity of false smut and kernel smut of rice.*Plant Dis*. 93:1202-1208.

Carris, L. M., Castlebury, L. A., and Goates, B. J. (2006). Nonsystemic bunt fungi—*Tilletiaindica* and T. horrida: A review of history, systematics, and biology. *Annu. Rev. Phytopathol*. 44:113-133.

Castlebury, L. A., Carris, L. M., and Vánky, K. (2005). Phylogenetic analysis of *Tilletia* and allied genera in order Tilletiales (Ustilaginomycetes; Exobasidiomycetidae) based on large subunit nuclear rDNA sequences. *Mycologia*97:888-900.

Chahal, S. S. (2001). Epidemiology and management of two cereal bunts.*Indian Phytopathol*.54:12.

Chahal, S. S., Aulakh, K. S., and Mathur, S. B. 1993.Germination of teliospores of *Tilletiabarclayana*, the causal agent of kernel smut of rice, in relation to some physical factors.*J. Phytopathol*. 137:7. ISI,

Chen, Y., Yang, X., Yao, J., Kyaw, E. P., Zhang, A. F., Li, Y.-F., Gu, C.-Y., Zang, H.-Y., and Gao, T.-C.(2016). Simple and rapid detection of *Tilletiahorrida* causing rice kernel smut in rice seeds.*Sci. Rep.* 6:33258.

Chen, Y., Zhang, Y., Yao, J., Li, Y.-F., Yang, X., Wang, W.-X., Zhang, A.-F., and Cao, T.-C. (2013). Frequency distribution of sensitivity of Ustilaginoideavirens to four EBI fungicides, prochloraz, difenoconazole, propiconazole, and tubeconazole, and their efficacy in controlling rice false smut in Anhui Province of China. *Phytoparasitica* 41:277-284.

Dangi, B., Khanal, S., and Shah, S. (2020). A review of rice false smut, its distribution, identification and management practices. *Acta Sci. Agric*. 4:48-54.

Durán, R., and Fisher, G. W. (1961).The genus *Tilletia*.Washington State University Press, Pullman, WA.

El-Kazzaz, M. K., Salem, E. A., Ghoneim, K. E., Elsharkawy, M. M., El-Kot, G. A. E., and Kalboush, Z. A. E. (2015a). Biocontrol of *Tilletiabarclayana*, the causal agent of kernel smut disease in rice. Egypt. J. Biol. Pest Cont. 25:9.

El-kazzaz, M. K., Salem, E. A., Ghoneim, K. E., Elsharkawy, M. M., El-Kot, G. A. E. N., and Kalboush, Z. A. E. (2015b). Integrated control of rice kernel smut disease using plant extracts and salicylic acid. Arch. *Phytopathol.Plant Prot*. 48:664-675.

El-kazzaz, M. K., Wi-Kot, G. A. E., Ghoneim, K. E., Elsharkawy, M. M., Kalboush, Z. A. E., and Hyakumachi, M. (2014). Incidence of kernel smut caused by *Tilletiabarclayana* in Egyptian rice cultivars.*African J. Microbiol. Res*. 8:3052-3063.

El-Naggar, M., Elsharkawy, M., Almalla, R., El-Kot, G., Alwakil, A., and Badr, M. (2015).Control of *Ustilaginoideavirens*, the causal agent of rice false smut disease in Egypt.*Egypt. J. Biol. Pest Control* 25:555.

Elshafey, R. A. S. (2018). Biology of rice kernel smut disease causal organism *Tilletiabarclayana* and its molecular identification. *J. Phytopathol. Pest Manage*. 5:20.

Espino, L. (2019). Field sampling of kernel smut in rice and its effect on yield and quality.*Phytopathology* S109:1.

Fan, J., Yang, J., Wang, Y., Li, G., Li, Y., Huang, F., and Wang, W.-M. (2016). Current understanding on *Villosiclavavirens*, a unique flower-infecting fungus causing rice false smut disease. *Mol. Plant Pathol*. 17:1321-1330.

FAOSTAT.(2021). *FAOSTAT.*

Fu, X., Wang, X., Cui, Y., Wang, A., Lai, D., Liu, Y., Li, Q. X., Wang, B., and Zhou, L. (2015). A monoclonal antibody-based enzyme-linked immunosorbent assay for detection of ustiloxinA in rice false smut balls and rice samples. *Food Chem*. 181:140-145.

Goates, B. J. (2010). Survival of secondary sporidia of floret infecting *Tilletia*species: Implications for epidemiology. *Phytopathology* 100:655-662.

Guo, Z. F., Zhou, X. G., Liu, B. H., and Lei, X. Y. (2018).Development of novel chemical compounds for control of kernel smut of rice. 36th Proc. Rice Tech. Wrkg. Grp. 101-102.

Harrell, D. (2020). If you had smut in 2019, plan to protect crops this season. Rice Farming.

Hu, D., Liang, W., and Lai, C. (2018).Advances in the occurrence of rice false smut and its control.*Plant Prot*. 44:1-5.

Jecmen, A. C. (2014). Biology and control of rice false smut caused by *Ustilaginoideavirens* (Teleomorph*Vilosiclavavirens*).Graduate Thesis and Dissertations.

Jia, Q., Gu, Q., Zheng, L., Hsiang, T., Luo, C., and Huang, J. (2015). Genetic analysis of the population structure of the rice false smut fungus, *Villosiclavavirens*, in China using microsatellite markers mined from a genome assembly. *Plant Pathol*. 64:1440-1449.

Kämper, J., Kahmann, R., Bölker, M., et al(2006). Insights from the genome of the biotrophic fungal plant pathogen Ustilagomaydis. Nature 444:97-101.

Kemen, E., Gardiner, A., Schultz-Larsen, T., Kemen, A. C., Balmuth, A. L., Robert-Seilaniantz, A., Bailey, K., Holub, E., Studholme, D. J., MacLean, D., and Jones, J. D. G. (2011). Gene gain and loss during evolution of obligate parasitism in the white rust pathogen of *Arabidopsis thaliana*. *PLoS Biol*. 9:e1001094.

Khanal, S., Gaire, S. P. and Zhou, X.-G. (2023). Kernel Smut and False Smut: The Old-Emerging Diseases of Rice—A Review. Front. *Microbiol*.13:874128.

Khanal, S., Antony-Babu, S., Gaire, S. P., and Zhou, X.-G. (2022). Multi-Locus sequence analysis reveals diversity of the rice kernel smut populations in the United States. Front. *Microbiol*.13:874120.

Koiso, Y., Li, Y., Iwasaki, S., Hanaka, K., Kobayashi, T., Sonoda, R., Fujita, Y., Yaegashi, H., and Sato, Z. (1994). Ustiloxins, antimitotic cyclic peptides from false smut balls on rice panicles caused by*Ustilaginoideavirens*. *J. Antibiot*. 47:765-773.

Kumar, S., Kumari, S., and Sinha, B. S. (2018). Integrated management of false smut disease in rice: A review. *Int. J. Chem*. Stud. Sp4.

Ladhalakshmi, D., Laha, G. S., Singh, R., Karthikeyan, A., Mangrauthia, S. K., Sundaram, R. M., Thukkaiyannan, P., and Viraktamath, B. C. (2021). Isolation and characterization of *Ustilaginoideavirens* and survey of false smut disease of rice in India.*Phytoparasitica* 40:171-176.

Li, Y., Huang, S., Yang, J., and Wang, C. (2021).Analysis of quantitative trait loci for resistance to rice false smut.*ActaAgron.Sin*. 37:778-783.

Liang, Y., Zhang, X., Li, D., Huang, F., Hu, P., and Peng, Y. (2014).Integrated approach to control false smut in hybrid rice in Sichuan province. China. *Rice Sci*. 21:354-360.

Lore, J., Pannu, P., Jain, J., Hunjan, M., Kaur, R., and Mangat, G. (2013).Susceptibility of rice hybrids and inbred cultivars to false smut under field conditions.*Indian Phytopathol*. 66:397-399.

Lu, S., Sun, W., Meng, J., Wang, A., Wang, X., Tian, J., Fu, X., Dai, J., Liu, Y., Lai, D., and Zhou, L. (2015). Bioactive bis-naphtho-γ-pyrones from rice false smut pathogen *Ustilaginoideavirens*. *J. Agric. Food Chem*. 63:3501-3508.

Lu, M. H., Liu, W. C., and Zhu, F. (2018). Epidemic law and control technique of rice false smut in recent years. *China Plant Prot*. 38:44-47.

Monday Ahonsi and Adepoju A. A. (2002). False Smut on Upland Rice in Eight Rice Producing Locations of Edo State, Nigeria. *Journal of Sustainable Agriculture*. 20(3):81-94

Nakamura, K.-I., Izumiyama, N., Ohtsubo, K.-I., Koiso, Y., Iwasaki, S., Sonoda, R., Fujita, Y., Yaegashi, H., and Sato, Z. (1994). "Lupinosis"-like lesions in mice caused by ustiloxin, produced by *Ustilaginoiedavirens*: A morphological study. *Nat. Toxins* 2:22-28.

Padwick, G. W., and Khan, A. (1944).Notes on Indian fungi II.*Mycol*. Pap. 10:17.

Qin, P., Tu, B., Wang, Y., Deng, L., Quilichini, T. D., Li, T., Wang, H., Ma, B., and Li, S. (2013). ABCG15 encodes an ABC transporter protein and is essential for post-meiotic anther and pollen exine development in rice. *Plant Cell Physiol*. 54:138-154.

Que, Y., Xu, L., Wu, Q., Liu, Y., Ling, H., Liu, Y., Zhang, Y., Guo, J., Su, Y., Chen, J., Wang, S., and Zhang, C. (2024). Genome sequencing of *Sporisoriumscitamineum* provides insights into the pathogenic mechanisms of sugarcane smut. *BMC Genomics* 15:996.

Raji, P., Sumiya, K. V., Renjisha, K., Dhanya, S., and Narayanakutty, M. C. (2016).Evaluation of fungicides against false smut of rice caused by *Ustilaginoideavirens*.*Int. J. Appl. Nat. Sci*. 5.

Rush, M., Shahjahan, A., Jones, J., and Groth, D. (2000). Outbreak of false smut of rice in Louisiana.*Plant Dis*. 84:100.

Schneider, R., and Groth, D. E. (2018).False smut. Pages 49-50 in: Compendium of Rice Diseases and Pests, 2nd ed. D. E. Groth, R. D. Cartwright, Y. A. Wamishe, C. A. Greer, L. A. Calvert, C. M. Vera Cruz, V. Verdier, and M. O. Way, eds. American Phytopathological Society, St. Paul, MN.

Shetty, S., and Shetty, H. (1985).An alternative host for *Ustilaginoideavirens* (Cke.)Tak.*Int. Rice Res. Newslett*. 10.

Shi, J., Zhou, X.-G., Yan, Z., Tabien, R. E., Wilson, L. T., and Wang, L. (2021). Hybrid rice outperforms inbred rice in resistance to sheath blight and narrow brown leaf spot. *Plant Dis.* 105:2981-2989.

Singh, R., Dodan, D., and Sheoran, O. (1998). Kernel smut of rice: Present status. *Int. J. Trop. Plant Dis.* 16:149-168.

Singh, R., and Pavgi, M. (1973).Development of sorus in kernel bunt of rice.*Riso* 22:243-250.

Singh, V., Zhou, X. G., Ganie, Z., Valverde, B., Avila, L., Marchesan, E., Merotto, A., Zorrilla, G., Burgos, N., Norsworthy, J., and Bagavathiannan, M. (2017). Rice production in the Americas.Pages 137-168 in: Rice Production Worldwide.B. S. Chauan, K. Jabran, and G. Mahajan, eds. Springer International Publishing, Switzerland.

Slaton, N. A., DeLong, R. E., Norman, R. J., Cartwright, R. D., and Wilson, C. E. (2007). Cultivar and seeding date effects on kernel smut of rice. *Agro. J.* 99:521-529.

Snehlata, K., and Kumar, J. (2015).Evaluation of yield losses and management practices of false smut in rice (Oryza sativa).*Indian Phytopathol*. 68:45-49.

Statista.(2023). Worldwide production of grain in 2022/23, by type (in million metric tons).

Sun, X., Kang, S., Zhang, Y., Tan, X., Yu, Y., He, H., Zhang, X., Liu, Y., Wang, S., Sun, W., Cai, L., and Li, S. (2013). Genetic diversity and population structure of rice pathogen *Ustilaginoideavirens* in China. *PLoS One* 8:e76879.

Sun, W., Fan, J., Fang, A., Li, Y., Tariqjaveed, M., Li, D., Hu, D., and Wang, W.-M. (2020). *Ustilaginoideavirens*: Insights into an emerging rice pathogen. *Annu. Rev. Phytopathol*. 58:363-385.

Takahashi, Y. (1896). On *Ustilagovirensi* Cooke and a new species of *Tilletia*parasitic on rice plant. Bot. Mag. Tokyo 10:en16.

Tanaka, E., Ashizawa, T., Sonoda, R., and Tanaka, C. (2008).*Villosiclavavirens* gen. nov., comb. nov., the teleomorph of *Ustilaginoideavirens*, the causal agent of rice false smut.*Mycotaxon* 106:491-501.

Tang, Y., Jin, J., Hu, D., Yong, M., Xu, Y., and He, L. (2013). Elucidation of the infection process of *Ustilaginoideavirens* (teleomorph: *Villosiclavavirens*) in rice spikelets. *Plant Pathol*. 62:1-8.

Templeton, G. E., Johnston, T. H., and Henry, S. E. (1960).Kernel smut of rice. Arkansas Farm Res. 9:10.

Tullis, E. C., and Johnson, A. G. (1952).Synonymy of *Tilletiahorrida and Neovossiabarclayana*.*Mycologia* 44:773.

Uppala, L. S., Liu, B., and Zhou, X. G. (2018a).Effect of nitrogen fertilizer rate on rice kernel smut disease incidence.*Texas Rice* 2018:31-32.

Uppala, S., Liu, G., Liu, B., Wu, M., and Zhou, X. G.(2016). Texas rice kernel smut research. 2016:22.

USDA.(2020a). Rice Yearbook. https://www.ers.usda.gov/data-products/rice-yearbook/ Google Scholar

USDA.(2020b). Total U.S. rice production value from 2000 to 2019 (in 1000 U.S. dollars) [Graph].In Statista.

Wang, A., Pan, L., Niu, X., Shu, X., Yi, X., Yamamoto, N., Li, S., Deng, Q., Zhu, J., Liang, Y., Wang, L., Li, P., and Zheng, A. (2019a).Comparative secretome analysis of different smut fungi and identification of plant cell death-inducing secreted proteins from *Tilletiahorrida*.*BMC Plant Biol.* 19:360.

Wang, A., Pang, L., Wang, N., Ai, P., Yin, D., Li, S., Deng, Q., Zhu, J., Liang, Y., Zhu, J., Li, P., and Zheng, A. (2018a).The pathogenic mechanisms of *Tilletiahorrida* as revealed by comparative and functional genomics.*Sci. Rep*. 8:15413.

Wang, A., Shu, X., Niu, X., Zhao, W., Ai, P., Li, P., and Zheng, A. (2018b). Comparison of gene co-networks analysis provide a systems view of rice (*Oryza sativa L.*) response to *Tilletiahorrida* infection. PLoS One 13:e0202309.

Wang, A., Zha, Z., Yin, D., Shu, X., Ma, L., Wang, L., Li, P., and Zheng, A. (2020). Comparative transcriptome analysis of *Tilletiahorrida* infection in resistant and susceptible rice (*Oryza sativa L.*) male sterile lines reveals potential candidate genes and resistance mechanisms. *Genomics* 112:5214-5226.

Wang, F., Zhang, S., Liu, M.-G., Lin, X.-S., Liu, H.-J., Peng, Y.-L., Lin, Y., Huang, J.-B., and Luo, C.-X. (2014). Genetic diversity analysis reveals that geographical environment plays a more important role than rice cultivar in Villosiclavavirens population selection. *Appl. Environ. Microbiol*. 80:2811-2820.

Wang, L., Nysetvold, E., and Zhou, X.-G. (2021). Cultural media promoting sporulation of rice kernel smut fungus Tilletiabarclayana. *Eur. J. Plant Pathol*. 161:629-635.

Wang, N., Ai, P., Tang, Y., Zhang, J., Dai, X., Li, P., and Zheng, A. (2015). Draft genome sequence of the rice kernel smut *Tilletiahorrida* strain QB-1. *Genome Announc*. 3:e00621-15.

Wang, W.-M., Fan, J., and Jeyakumar, J. M. J. (2019b). Rice false smut: An increasing threat to grain yield and quality. *IntechOpen.*

Whitney, N. G. (1989). Taxonomy of the fungus causing kernel smut of rice.*Mycologia* 81:468.

Whitney, N. G., and Cartwright, R. D. (2018).Kernel smut.Pages 49-51 in: Compendium of Rice Diseases and Pests, Second Edition. D. E. Groth R. D. Cartwright Y. A. Wamishe, C. A. Greer, L. A. Calvert, C. M. Vera Cruz, V. Verdier, and M. O. Way, eds. American Phytopathological Society, St. Paul, MN. Google Scholar

Whitney, N. G., and Frederiksen, R. A. (1977).Kernel smut of rice.A comprehensive summary of the biology and control of *Tilletiahorrida*.Tex. Agric. Exp. Stn. Misc. Publ. 1231.

Yang, C., Li, L., Feng, A., Zhu, X., and Li, J. (2014).Transcriptional profiling of the responses to infection by the false smut fungus *Ustilaginoideavirens* in resistant and susceptible rice varieties.*Can. J. Plant Pathol.* 36:377-388.

Yesmin, K., Lore, J., and Pannu, P. (2015).Evaluation of rice genotypes for resistance against false smut.*Plant Dis. Res*. 30:46-49.

Yu, M., Chen, Z., Hu, J., Yin, X., Nie, Y., and Liu, Y. (2013). Genetic diversity and pathogenicity of Ustilaginoideavirens isolated from different rice false smut balls of a diseased spike. *ActaPhytophyl*.Sin. 43:561-573.

Zhang, Y., Zhang, K., Fang, A., Han, Y., Yang, J., Xue, M., Bao, J., Hu, D., Zhou, B., Sun, X., Li, S., Wen, M., Yao, N., Ma, L.-J., Liu, Y., Zhang, M., Huang, F., Luo, C., Zhou, L., Li, J., Chen, Z., Miao, J., Wang, S., Lai, J., Xu, J.-R., Hsiang, T., Peng, Y.-L., and Sun, W. (2014). Specific adaptation of *Ustilaginoideavirens* in occupying host florets revealed by comparative and functional genomics.*Nat. Commun*. 5:3849.

Zhao, Z., Liu, H., Wang, C., and Xu, J. R. (2013). Comparative analysis of fungal genomes reveals different plant cell wall degrading capacity in fungi. *BMC Genomics* 14:274.

Zhou, X. G., and Jo, Y. K. (2014).Disease management.Pages 44-57 in: 2014 Texas Rice Production Guidelines. M. O. Way, G. M. McCauley, X. G. Zhou, L. T. Wilson, and M. Brandy, eds. Texas

AgriLife Research and Texas Rice Research Foundation

Zhou, X. G., Khanal, S., and Imran, M. (2021b). Texas rice: Severe outbreaks of kernel smut in 2021. Agfax.com-Online Ag News Source.

Zhou, X. G., Liu, G., and Zhou, L. W. (2021c).Timing of fungicide applications for control of rice kernel smut and narrow brown leaf spot in main and ratoon crops, 2020.*Plant Dis. Manage. Rep*. 15:CF066

Zhou, X. G., Uppala, L. S., Liu, B., Guo, Z., Gaire, S., Lei, S., and Wang, L. (2020).In vitro and field evaluation of fungicides for control of rice kernel smut.Proc. Rice Tech. Wrkg. Grp. 36.

Zhou, X. G., Way, M. O., McClung, A., and Dou, F. (2021a).Texas organic rice production guidelines.Texas AgriLife Research.

Zhou, Y. X., Li, H. H., Yu, J. J., Yu, M. N., Song, T. Q., Du, Y., Qi, Z. Q., Zhang, R. S., Yin, X. L., and Liu, Y. F. (2017). First report of propiconazole resistance in field isolates of *Ustilaginoideavirens* on rice in Jiangsu Province of East China. *Plant Dis.* 101:840.

Figure 1: False smut (IRRI knowledge bank 2015)

Figure 2: kernel smut (LSU Ag Centre 2009)