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Abstract

Straighthead is a physiological disorder of rice (*Oryza sativa* L.) that results in sterile florets with distorted lemma and palea, and the panicles or heads may not form at all in extreme cases. Heads remain upright at maturity, hence the name ‘straighthead’. The diseased panicles may not emerge from the flag leaf sheath when the disease is severe. Straighthead disease in rice results in poorly developed panicles and significant yield loss. Although other soil physicochemical factors involved, arsenic contamination in soil has also been reported to be closely associated with straighthead of rice. Monosodium methanearsonate has been a popular herbicide in cotton production in the USA, which has shown to cause injuries in rice that are similar to straighthead. Since toxicity of inorganic arsenic (iAs) is higher than other forms of arsenic, it may produce a more severe straighthead disorder in rice. The use of iAs-rich groundwater for irrigation, and the increase of iAs concentrations in agricultural soil in arsenic epidemic South and South-East Asia may cause a high incidence of straighthead in rice, resulting in a threat to sustainable rice production in this region.

Keywords: Rice (*Oryza sativa* L.), Straighthead, Arsenic, South-East Asia

Straighthead disease is a physiological disorder of rice (*Oryza sativa* L.) characterized by blank florets/spikelets and distorted lemma and palea. In extreme cases, the panicles or heads do not form at all. As a result, heads remain upright at maturity because of lack of grain development (Yan et al. 2005). The lemma and palea, or both, may be lacking, and are distorted and crescent-shaped if they are present, forming a characteristic symptom of straighthead called ‘parrot beak’ (Rasamivelona et al. 1995).

Straighthead occurs early in floret development while many other causes of sterility can occur after heading in an otherwise healthy floret. In fact, plants affected by straighthead appear healthy, even being darker green, as opposed to stunted or dried-up plants that have sterile panicles (Belefant-Miller and Beaty 2007). Straighthead was first reported in the USA in 1912 (Wells and Gilmour 1977). After that, the incidence of straighthead in rice was also reported in Portugal (Cunha and Baptista 1958), Japan (Baba and Harada 1954; Iwamoto 1969), Thailand (Weerapat 1979) and Australia (Batten et al. 2006; Dunn et al. 2006). The straighthead of rice leads to the reduction of grain yield and almost a total loss of yield in extreme cases (Rahman et al. 2008; Yan et al. 2005; Slaton et al. 2000; Wilson et al. 2001; Dilday et al. 2000). The yield reduction due to straighthead depends on rice varieties. It has been reported that the rice crop losses can range from 10 to 30% in medium-grain varieties and as high as 90% in long- and short-grain varieties (Batten et al. 2006).

Though the exact cause of straighthead is yet unknown, studies have shown that the disease increased by consistent flood (Wilson et al. 2001), low soil pH and free iron (Baba and Harada 1954) and rich organic matter in soil (Jones et al. 1938). Arsenic in soil is also another main factor that induces straighthead in rice (Wells and Gilmour 1977; Horton et al. 1983). In particular, straighthead has been frequently observed when rice is grown in soils where arsenical herbicides such as monosodium methanearsonate (MSMA) were previously applied (Gilmour and Wells 1980). MSMA has been a popular herbicide in cotton (*Gossypium* spp.) production in the USA. Therefore, rice fields with cotton growing history usually have residual arsenic which has been shown to cause injuries to rice that are similar to straighthead (Gilmour and Wells 1980).

Due to the inconsistency and unpredictability of naturally occurring straighthead, chemicals such as arsenical herbicides have been used to induce and study the straighthead symptoms in rice. It has also been reported that natural straighthead of rice is associated with nitrogen, phosphorus, and potassium (Baba et al. 1965), sulfates, iron and thiols (Iwamoto 1969), and some other nutrients (Evatt and Atkins 1957). Recently, Belefant-Miller and Beaty (2007) investigated the effect of nitrogen and some other plant nutrients on naturally occurring straighthead in several rice cultivars. The results showed that little or no straighthead was observed at higher nitrogen levels, while lower nitrogen levels produced moderate to high levels of straighthead. The reduction of natural straighthead by nitrogen has also been reported by other researchers (Dunn et al. 2006; Dilday et al. 2000; Yan et al. 2005). Organic matter is also considered to be a factor in the induction of straighthead (Kataoka et al. 1983; Groth and Lee 2003). The soil pH has been reported to be consistently lower in the straighthead soil than in non-straighthead soil (Belefant-Miller and Beaty 2007), and is believed to be related to the occurrence of straighthead (Baba and Harada 1954; Iwamoto 1969).

Straighthead of rice induced by arsenical herbicides

A number of studies have revealed that residual arsenicals of MSMA, a popular herbicide in cotton production in the USA, produce straighthead symptoms in rice (Gilmour and Wells 1980; Horton et al. 1983; Wells and Gilmour 1977). Therefore, application of MSMA to soil has become a common tool for rice (*Oryza Sativa* L.) straighthead evaluation. In a recent study, Yan et al. (2005) investigated differential response of rice germplasm to MSMA-induced straighthead. In another study, Yan et al. (2008) investigated the effect of MSMA on soil mineral availability and plant mineral uptake, and their influence on straighthead. Yan et al. (2005) reported that rice was highly susceptible to straighthead with ratings from 7.2 to 8.0 on a 1–9 scale when the plant was grown with 6.7 kg ha^{-1} arsenical herbicide (MSMA). They found that most of the grains became parrot beaked, many panicles failed to emerge, and plants became stubby with few seed set.

Straighthead of rice induced by inorganic arsenic

Studies about the influence of inorganic arsenic (iAs) in soil on straighthead of rice is limited. Belefant-Miller and Beaty (2007) reported almost twice as much arsenic in the rice kernels harvested from plants grown in straighthead soil than in non-straighthead soil, although total arsenic concentration in the straighthead soil was 4.5 mg kg^{-1} or less. Arsenate-induced straighthead symptoms, which mimic those induced by other means observed in the field, has also been reported in a glasshouse study (Batten et al. 2006). But the study did not demonstrate the amount of arsenate needed to induce straighthead symptoms in rice. It was also not clear from the study if arsenate-induced straighthead symptoms were the same as those that occur in the field by other means.

The iAs-induced (arsenate) straighthead in rice was studied in a controlled green house environment by Rahman et al. (2008). They investigated the effects of different concentrations of arsenate on straighthead incidence by application of a 0–6 rating scale calculated from sterile florets and the total number of grains. They observed symptoms of straighthead that were similar to those reported by Yan et al. (2005), indicating that iAs also produced straighthead, just as the residual arsenic of arsenical herbicide MSMA did. The results also revealed that straighthead was closely associated with the arsenic concentration in soil, and the severity of straighthead increased significantly with the increase of soil arsenic concentration. Straighthead resulted in sterile florets with distorted lemma and palea, reduced plant height, tillering, panicle length and crop yield (Fig. 1). Straighthead caused approximately 17–100% sterile florates/spikelets formation and about 16–100% loss of grain yield. Panicle formation was found to be reduced 21–95% by straighthead.

It has been evident from field studies that increasing soil arsenic concentration elevates the arsenic burden of aerial parts of the rice plant and in rice gain (Williams et al. 2006; Abedin et al. 2002). Some studies have revealed that arsenic in soil and irrigation water decreases the growth of rice plant and rice yield (Rahman et al. 2008; Rahman et al. 2007; Panaullah et al. 2009). The growth restrained of rice plant was for the toxicity of iAs (Panaullah et al. 2009; Xie and Huang 1998; Jha and Dubey 2004), while the yield reduction was due to straighthead (Gilmour and Wells 1980; Horton et al. 1983; Rahman et al. 2008). Although there is no direct evidence of iAs-induced straighthead in the field, increasing concentrations of iAs (arsenate and arsenite) in rice field soils of arsenic epidemic areas of South (S) and South-East (SE) Asia from contaminated underground irrigation water increases the possibility of widespread straighthead in this region.

Breeding rice cultivars resistant to straighthead disorder

Whether the cause of straighthead is arsenic or soil conditions (mineral nutrients), control of the disease is important to reduce yield loss of the rice crop. The major strategies proposed for straighthead control are: water management (Wilson et al. 2001), resistant cultivars (breeding) (Rasamivelona et al. 1995) and chemical application (Atkins et al. 1957). Chemical control is no longer feasible due to the unavailability of suitable chemicals (Agrama and Yan 2010; Belefant-Miller and Beaty 2007; Yan et al. 2008). A number of studies have shown that some rice varieties are more susceptible to straighthead symptoms than others. Therefore, cultivar resistance to straighthead is regarded as the most effective means of controlling straighthead in rice (Batten et al. 2006; Dunn et al. 2006; Rasamivelona et al. 1995; Slaton et al. 2000; Wilson et al. 2001; Yan et al. 2005). Breeding for straighthead resistance has been a consistent effort since the 1950s (Atkins et al. 1957; Agrama and Yan 2009). Effective breeding depends on the genetic study of the resistant germplasm. However, resistant germplasm, which produces normal yields even under severe straighthead infestation, had not been identified until a few years ago (Yan et al. 2005). Yan et al. (2005) noted that the resistant germplasm varied in subspecies, plant height, days of heading, and grain endosperm types. These variations among the straighthead resistance rice cultivars bring great flexibility to breeding.

The studies of Yan et al. (2005) also revealed that resistance to straighthead is ubiquitous in rice, and that resistant cultivars are more frequent in *indica* than in *japonica* cultivars. Batten et al. (2006) reported that resistance and susceptibility of rice to straighthead also depends on grain endosperm types. Long-grain varieties are more susceptible to straighthead than medium-grain varieties. Yan et al. (2005) predicted that straighthead resistance may also be influenced by days of heading and life cycle of the rice cultivars. The reason is that early varieties are exposed to arsenic for shorter time, and thus less arsenic is taken up by the early varieties compared to the late varieties. The identification of a wide variety of straighthead-resistance germplasms by Yan et al. (2005) was a great work in determining the genetic basis of resistance to this disorder.

Recently, the genetic diversity and relatedness of straighthead-resistant rice cultivars were studied by Agrama et al. (2010). They analyzed 1002 rice accessions sampled from the United States Department of Agriculture (USDA) core collection, evaluated for straighthead, and genotyped with 72 molecular markers. Among those, 42 accessions were found to be resistant to straighthead with no yield reduction even under severe infestation. The number of alleles averaged 5.9, and the 72 molecular markers were highly informative among the 42 resistant accessions. Thirty resistant accessions were identified as *indica* type while 10 were identified as temperate *japonica*. The other two were positioned between temperate and tropical *japonica* cultivars. These findings on phenotypic diversification and genetic relatedness among the straighthead resistant cultivars will be useful to make germplasm choices for transferring straighthead resistance to widely cultivated rice varieties.

Although the symptoms of straighthead induced by arsenic and soil conditions are almost identical, the extent and severity of the disease are different from these different causes. The growth of the rice plant drastically reduced by iAs, resulting in severe straighthead and a drastic yield reduction (Rahman et al. 2008). When straighthead is induced by other means, the plant grows normally and appears darker green and healthy. However, a yield loss of 30-90% also occurs in this case (Batten et al. 2006; Belefant-Miller and Beaty 2007). Since iAs-induced straighthead of rice is associated with the high bioavailability, uptake and toxicity of iAs, breeding arsenic-resistant rice cultivars is a good strategy for straighthead control. Identification of arsenic resistant germplasm and transfer of arsenic toxicity and straighthead resistances to widely cultivated rice varieties will be useful to reduce crop losses from straighthead.

Conclusion

Soil factors have been identified as the main reason for the induction of natural straighthead in rice at the field level. In addition, the residual arsenic of the arsenical herbicide MSMA has also been observed to produce straighthead-like symptoms in rice. Since MSMA is used mainly in cotton (*Gossypium* spp.) production, its use is restricted to the major cotton growing countries like USA. Therefore, MSMA-induced straighthead has been reported in the USA.

Although iAs-induced straighthead has not been reported yet at the field level, glass-house experiments have revealed iA-induced straighthead in rice. Significant grain yield loss for arsenate-induced straighthead was observed, starting at a soil arsenic concentration of 60 mg kg^{-1}, and the straighthead was found to increase with its increasing concentration in soil (Rahman et al. 2008). Therefore, high concentrations of iAs in the paddy soils of arsenic epidemic South and South-East Asia, especially in Bangladesh and West Bengal, and the increasing deposition of this toxic arsenic species from arsenic-contaminated underground irrigation water present potential threats for straighthead induction. It can be predicted from glass-house studies (Rahman et al. 2008) that iAs not only will contaminate rice, but also will be a major risk factor to sustainable rice production in this region.

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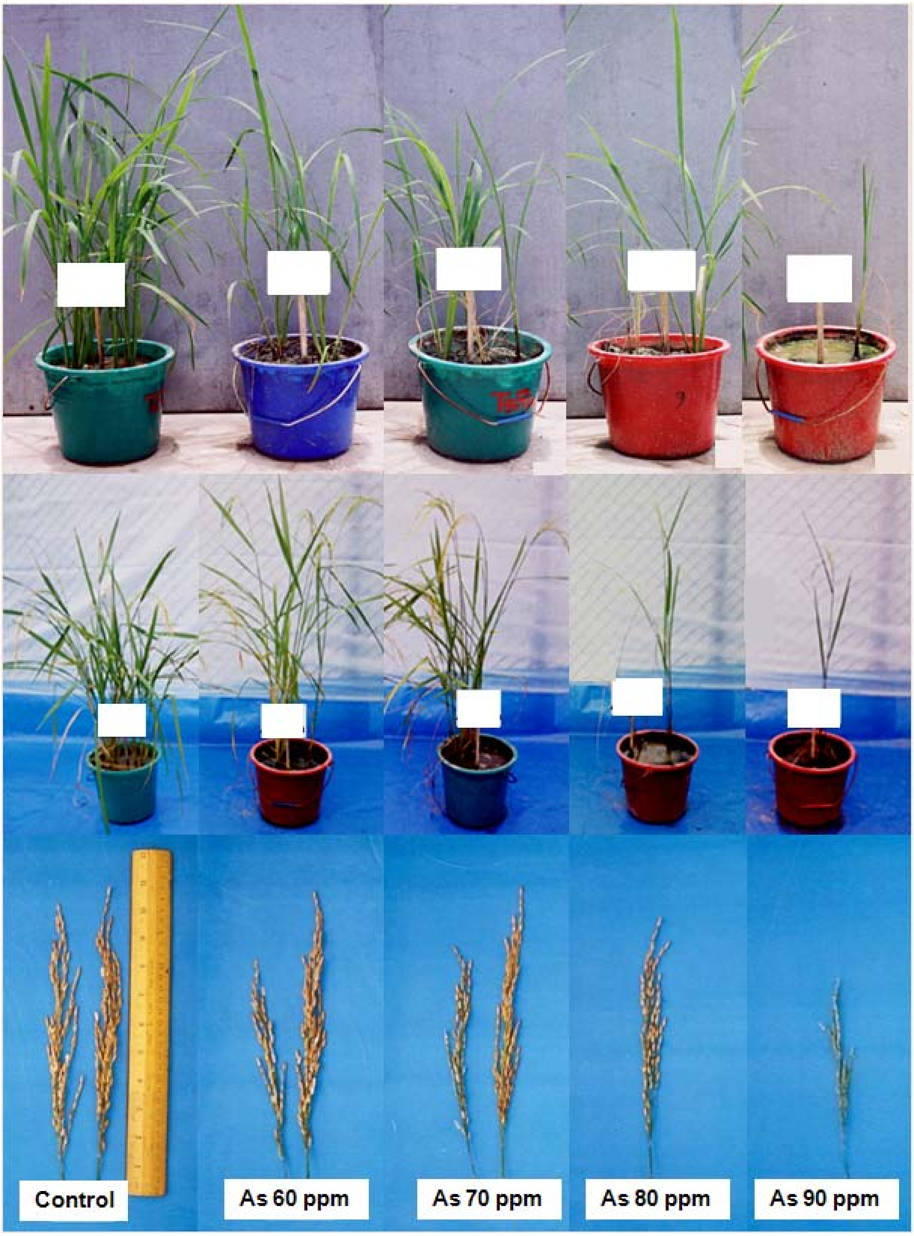

Fig. 1: Effect of arsenate-induced straighthead on growth and yield of rice (*Oryza sativa* L.). Approximately 17–100% of the florets were sterile due to arsenate-induced straighthead causing about 6–100% yield loss.