

1 **Arsenic-induced Straighthead: An Impending Threat to Sustainable**
2 **Rice Production in South and South-East Asia!**

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24 **Abstract**

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

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

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

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

61 Though the exact cause of straighthead is yet unknown, studies have shown that the disease
62 increased by consistent flood (Wilson et al. 2001), low soil pH and free iron (Baba and Harada
63 1954) and rich organic matter in soil (Jones et al. 1938). Arsenic in soil is also another main
64 factor that induces straighthead in rice (Wells and Gilmour 1977; Horton et al. 1983). In
65 particular, straighthead has been frequently observed when rice is grown in soils where arsenical
66 herbicides such as monosodium methanearsonate (MSMA) were previously applied (Gilmour
67 and Wells 1980). MSMA has been a popular herbicide in cotton (*Gossypium* spp.) production in
68 the USA. Therefore, rice fields with cotton growing history usually have residual arsenic which
69 has been shown to cause injuries to rice that are similar to straighthead (Gilmour and Wells
70 1980).

71 Due to the inconsistency and unpredictability of naturally occurring straighthead,
72 chemicals such as arsenical herbicides have been used to induce and study the straighthead
73 symptoms in rice. It has also been reported that natural straighthead of rice is associated with
74 nitrogen, phosphorus, and potassium (Baba et al. 1965), sulfates, iron and thiols (Iwamoto 1969),
75 and some other nutrients (Evatt and Atkins 1957). Recently, Belefant-Miller and Beaty (2007)
76 investigated the effect of nitrogen and some other plant nutrients on naturally occurring
77 straighthead in several rice cultivars. The results showed that little or no straighthead was
78 observed at higher nitrogen levels, while lower nitrogen levels produced moderate to high levels
79 of straighthead. The reduction of natural straighthead by nitrogen has also been reported by other
80 researchers (Dunn et al. 2006; Dilday et al. 2000; Yan et al. 2005). Organic matter is also
81 considered to be a factor in the induction of straighthead (Kataoka et al. 1983; Groth and Lee
82 2003). The soil pH has been reported to be consistently lower in the straighthead soil than in
83 non-straighthead soil (Belefant-Miller and Beaty 2007), and is believed to be related to the
84 occurrence of straighthead (Baba and Harada 1954; Iwamoto 1969).

85 86 **Straighthead of rice induced by arsenical herbicides**

87 A number of studies have revealed that residual arsenicals of MSMA, a popular herbicide
88 in cotton production in the USA, produce straighthead symptoms in rice (Gilmour and Wells
89 1980; Horton et al. 1983; Wells and Gilmour 1977). Therefore, application of MSMA to soil has
90 become a common tool for rice (*Oryza Sativa* L.) straighthead evaluation. In a recent study, Yan
91 et al. (2005) investigated differential response of rice germplasm to MSMA-induced
92 straighthead. In another study, Yan et al. (2008) investigated the effect of MSMA on soil mineral
93 availability and plant mineral uptake, and their influence on straighthead. Yan et al. (2005)
94 reported that rice was highly susceptible to straighthead with ratings from 7.2 to 8.0 on a 1–9
95 scale when the plant was grown with 6.7 kg ha⁻¹ arsenical herbicide (MSMA). They found that
96 most of the grains became parrot beaked, many panicles failed to emerge, and plants became
97 stubby with few seed set.

98 99 **Straighthead of rice induced by inorganic arsenic**

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

109 The iAs-induced (arsenate) straighthead in rice was studied in a controlled green house
110 environment by Rahman et al. (2008). They investigated the effects of different concentrations of
111 arsenate on straighthead incidence by application of a 0–6 rating scale calculated from sterile
112 florets and the total number of grains. They observed symptoms of straighthead that were
113 similar to those reported by Yan et al. (2005), indicating that iAs also produced straighthead, just
114 as the residual arsenic of arsenical herbicide MSMA did. The results also revealed that
115 straighthead was closely associated with the arsenic concentration in soil, and the severity of
116 straighthead increased significantly with the increase of soil arsenic concentration. Straighthead
117 resulted in sterile florets with distorted lemma and palea, reduced plant height, tillering, panicle

118 length and crop yield (Fig. 1). Straighthead caused approximately 17–100% sterile
119 floras/spikelets formation and about 16–100% loss of grain yield. Panicle formation was found
120 to be reduced 21–95% by straighthead.

121 It has been evident from field studies that increasing soil arsenic concentration elevates the
122 arsenic burden of aerial parts of the rice plant and in rice gain (Williams et al. 2006; Abedin et al.
123 2002). Some studies have revealed that arsenic in soil and irrigation water decreases the growth
124 of rice plant and rice yield (Rahman et al. 2008; Rahman et al. 2007; Panaullah et al. 2009). The
125 growth restrained of rice plant was for the toxicity of iAs (Panaullah et al. 2009; Xie and Huang
126 1998; Jha and Dubey 2004), while the yield reduction was due to straighthead (Gilmour and
127 Wells 1980; Horton et al. 1983; Rahman et al. 2008). Although there is no direct evidence of
128 iAs-induced straighthead in the field, increasing concentrations of iAs (arsenate and arsenite) in
129 rice field soils of arsenic epidemic areas of South (S) and South-East (SE) Asia from
130 contaminated underground irrigation water increases the possibility of widespread straighthead
131 in this region.

132

133 **Breeding rice cultivars resistant to straighthead disorder**

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

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

159 Recently, the genetic diversity and relatedness of straighthead-resistant rice cultivars were
160 studied by Agrama et al. (2010). They analyzed 1002 rice accessions sampled from the United
161 States Department of Agriculture (USDA) core collection, evaluated for straighthead, and
162 genotyped with 72 molecular markers. Among those, 42 accessions were found to be resistant to
163 straighthead with no yield reduction even under severe infestation. The number of alleles
164 averaged 5.9, and the 72 molecular markers were highly informative among the 42 resistant

165 accessions. Thirty resistant accessions were identified as *indica* type while 10 were identified as
166 temperate *japonica*. The other two were positioned between temperate and tropical *japonica*
167 cultivars. These findings on phenotypic diversification and genetic relatedness among the
168 straighthead resistant cultivars will be useful to make germplasm choices for transferring
169 straighthead resistance to widely cultivated rice varieties.

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

180

181 **Conclusion**

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

188 Although iAs-induced straighthead has not been reported yet at the field level, glass-house
189 experiments have revealed iA-induced straighthead in rice. Significant grain yield loss for
190 arsenate-induced straighthead was observed, starting at a soil arsenic concentration of 60 mg kg⁻¹,
191 and the straighthead was found to increase with its increasing concentration in soil (Rahman et
192 al. 2008). Therefore, high concentrations of iAs in the paddy soils of arsenic epidemic South and
193 South-East Asia, especially in Bangladesh and West Bengal, and the increasing deposition of this
194 toxic arsenic species from arsenic-contaminated underground irrigation water present potential
195 threats for straighthead induction. It can be predicted from glass-house studies (Rahman et al.
196 2008) that iAs not only will contaminate rice, but also will be a major risk factor to sustainable
197 rice production in this region.

198

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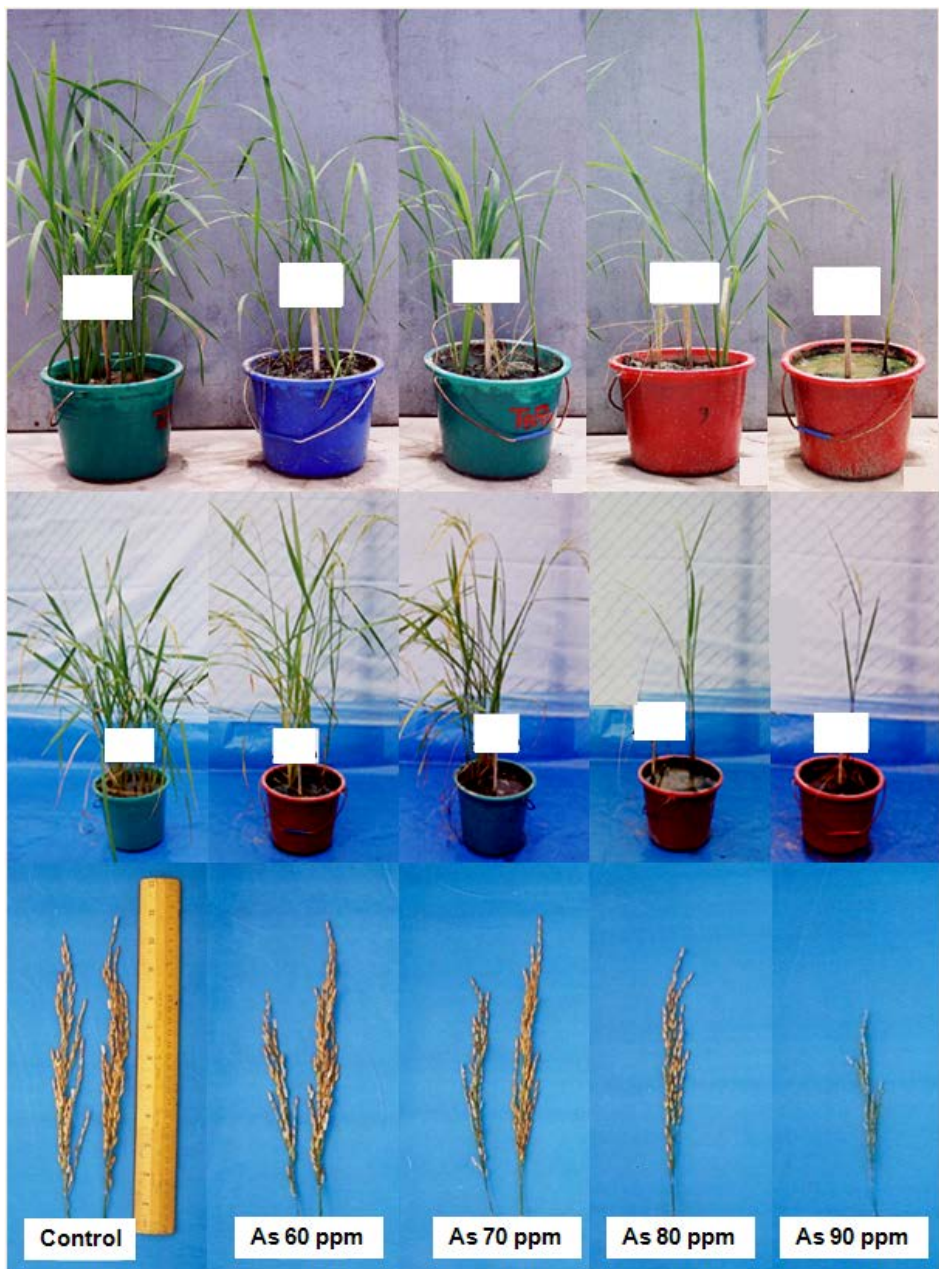
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 271 germplasm to straighthead induced by arsenic. *Crop Sci* 45: 1223-1228.



272
 273 **Fig. 1:** Effect of arsenate-induced straighthead on growth and yield of rice (*Oryza sativa* L.).
 274 Approximately 17–100% of the florets were sterile due to arsenate-induced straighthead
 275 causing about 6–100% yield loss.