468

Hydroponic culture of wild rice (*Zizania palustris* L.) and its application to studies of silicon nutrition and fungal brown spot disease

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Malvick, D. K. and Percich, J. A. 1993. **Hydroponic culture of wild rice (*Zizania palustris* L.) and its application to studies of silicon nutrition and fungal brown spot disease.** Can. J. Plant Sci. **73**: 969–975. The mineral nutrient requirements of wild rice (*Z. palustris* var. *interior* L.) grown on flooded soils in Minnesota are poorly understood. A hydroponics culture system was developed to study the effects of silicon on the growth and fungal brown spot disease (FBS) resistance of wild rice. Wild rice was grown to maturity using a modified Hoagland's solution. Plants attained a height of 1.4 m and had healthy roots, leaves and inflorescences containing viable seeds. Plant height and biomass were approximately 80 and 46%, respectively, of plants grown in cultivated paddies. A method was developed to reliably infect leaves and stems of hydroponically grown wild rice with *Bipolaris oryzae*, the pathogen causing FBS. Silicon amendments did not significantly increase growth and had no apparent effect on resistance to FBS.

Key words: *Bipolaris oryzae*, hydroponic culture, plant nutrition, silicon, wild rice, *Zizania palustris*

Malvick, D. K. et Percich, J. A.1993. **Culture hydroponique du riz sauvage (*Zizania palustris* L.) et son application à des études sur la valeur fertilisante du silicium et sur la maladie des taches brunes,** Can. J. Plant Sci. **73**: 969–975. Les besoins nutritifs du riz sauvage (*Zizania palustris* var. *interior* L.) cultivé sur sol inondé au Minnesota sont encore très peu compris. Un dispositif hydroponique a été mis au point pour étudier les effets du silicium sur la croissance du riz sauvage et sur sa résistance à la maladie des taches brunes. Le riz était cultivé jusqu'à maturité dans une solution de Hoagland modifiée. Les plantes ont atteint une hauteur de 1,4 m et produisaient des racines, des feuilles et des inflorescences vigoureuses, ces dernières contenant des semences viables. La hauteur des plantes et leur biomasse se situaient, respectivement, à 80 et 46% de celles obtenues en rizière. Une méthode a été mise au point infecter à coup sûr les feuilles et les tiges du riz sauvage en culture hydroponique avec *Bipolaris oryzae*, le champignon responsable de la maladie des taches brune. L'apport de silicium n'a pas (significativement amélioré la croissance et n'avait pas non plus d'effet visible sur la résistance à la maladie des taches brunes.

Mots clés: *Bipolaris oryzae*, culture hydroponique, nutrition végétale, silicium, riz sauvage, *Zizania palustris*

Wild rice (*Zizania palustris* var. *interior* L.) is a native, outcrossing aquatic grass which grows in shallow lakes and slow moving streams in the Great Lakes region of the US and Canada. It is also grown commercially in cultivated paddies in Minnesota and California. The cultivation of wild rice began in Minnesota in the 1950s and has increased substantially since that time. In 1990 Minnesota produced 2180 t of processed wild rice on 8100 ha (Rock et al. 1991). Plant nutrition and fungal brown spot disease (FBS), caused by the facultative pathogen *Bipolaris oryzae* (Breda de Haan) Shoemaker, the

anamorph of *Cochiobolus miyabeanus* (Itô & Kuribayashi in Ito) Drech. ex Dastur., are considered to be the most important factors limiting wild rice production in Minnesota (Johnson and Percich 1992).

Wild rice is cultivated mainly on organic peat soils (Histosols) in Minnesota. Mineral soils are common where wild rice grows naturally, and FBS is uncommon in these uncultivated habitats (Oelke et al. 1982; Aiken et al. 1988). Mineral nutrient deficiencies in Minnesota's organic soils may contribute to the serious problems with FBS that frequently occur in cultivated wild rice paddies (Percich et al. 1988). Silicon applied to Histosols in Florida apparently reduced severity of FBS and increased growth and yield of *Oryza sativa* L. (Snyder et al. 1986; Anderson et al. 1987; Datnoff et al. 1991). Experiments with Minnesota Histosols suggest that silicon amendments can increase growth of wild rice and decrease susceptibility to FBS (Percich et al. 1988). Field and greenhouse studies have also provided information about the management of N, P, and K for cultivation of wild rice on flooded Histosols in Minnesota (Grava and Raisanen 1978; Oelke et al. 1982; Percich et al. 1988). The requirements for micro-mineral nutrients such as silicon and their effects on plant growth and development, and disease resistance of wild rice are poorly understood (Johnson and Percich 1992).

Defined nutrient media have been used for studies of growth and nutrition in many different plants (Asher and Edwards 1983) but not for wild rice. Hydroponic plant culture in controlled environmental growth chambers can be a precise method to study nutritional requirements and pathology. This study was undertaken to develop a hydroponic system to supplement field and greenhouse studies on nutrition and disease. The objectives were to: (i) identify and evaluate various nutrient solutions and the environmental conditions necessary to grow wild rice to maturity, and (ii) to evaluate the role of silicon on wild rice growth and FBS.

MATERIALS AND METHODS

Seed of wild rice var. K-2 was collected from central Minnesota and stored in tap water at 3.5°C for at least 12 wk to break dormancy prior to experimental use. After cold storage the seed was placed in fresh tap water at 22°C, and allowed to germinate and grow with a photoperiod of 12 h and a light intensity of 160 μmol m^{-2} s^{-1} for 2-3 wk. Healthy seedlings with primary roots and coleoptiles (4–6 cm each) were then placed into small plastic pots (5 × 5 × 5 cm) containing plastic mesh bottoms. Acetyl beads (Delrin, E. I. DuPont, Wilmington, DE) were placed to a depth of about 2 cm around the plants for support. Nine such pots were inserted into 6-L plastic buckets containing nutrient solution. Experiments were conducted in environmental chambers (Conviron, Winnipeg, MB) with a photoperiod of 16.5 h and a light intensity of 700 μmol m^{-2} s^{-1} from a mixture of 60 W incandescent and 160 W cool white and Gro-lux fluorescent bulbs (Sylvania, Danvers, MA) (ratio 6:5:3), 90–95% relative humidity (RH), and day and night temperatures of 21 and 12°C, respectively.

Five defined nutrient solutions prepared with deionized H_2O were evaluated: (1) an International Rice Research Institute (IRRI) solution with 2× Fe (Yoshida et al. 1976), (2) a modified Shive's solution (Veltrup 1976); (3) and (4) two modifications of Hoagland's solution (Hoagland and Arnon 1938): HS-2 (Lee 1982) and HS-3 (Gerloff and Krombholz 1966); and (5) a modified Hoagland's solution (HS-1) formulated in our laboratory for wild rice. The macronutrient concentrations of HS-1 were 3.62 mmol L^{-1} N, as $Ca(NO_3)_2$, KNO_3, and $NH_4H_2PO_4$; 0.12 mmol P, as $NH_4H_2PO_4$; 1.5 mmol L^{-1} K, as KNO_3; Mg and S, 0.5 mmol L^{-1}, as $MgSO_4$; and 1.0 mmol L^{-1} Ca, as $Ca(NO_3)_2$. The micronutrient concentrations were 9.0 μmol L^{-1} Mn, as $MnCl_2$; 46.3 μmol L^{-1} B, as H_3BO_3, 0.76 μmol L^{-1} Zn, as $ZnSO_4$; 0.31 μmol L^{-1} Cu, as $CuSO_4$; 0.5 μmol L^{-1} Mo, as Na_2MoO_4; and 14.9 μmol L^{-1} Fe, added twice weekly as a 1.0:0.8 mixture (wt/wt) of $FeSO_4$ and (L)tartaric acid. The five nutrient solutions were compared in duplicate in a completely randomized experiment. Each solution was placed into two 6-L buckets containing 27 seedlings. Plants in the solutions were evaluated after 6 wk on the basis of percent plant survival and mean fresh combined leaf and stem biomass per plant per bucket. Treatment means were compared with a Fisher's protected LSD test; the significance level was set at $P = 0.10$ due to heterogeneity among plants in this outcrossing species (Johnson and Percich 1992). The IRRI and HS-1 solutions were further compared in a

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In another experiment, nutrient solution HS-1 was amended individually with four silicon compounds to evaluate their affects on growth of wild rice. The amendments were: (i) 1.5 and 4 mmol L^{-1} Si added as sodium silicate, Na_2SiO_3-$5H_2O$ (Fisher Scientific, Pittsburgh, PA); (ii) 1.5 mmol L^{-1} Si added as calcium silicate, $CaSiO_3$ (Alfa Products, Danvers, MA); (iii) 1.2 mmol L^{-1} Si, as potassium silicate (soluble silicate Kasil No. 1, 20.74% SiO_2, PQ Corporation, Valley Forge, PA); and (iv) silicic acid, SiO_2–nH_2O, 0.17 g L^{-1} (Fisher Scientific). The nutrient solutions were prepared with glass-distilled H_2O and replaced weekly. The pH was adjusted to 5.0 twice per week with HCl and KOH, except for solutions amended with Kasil in which NaOH was used. Wild rice was grown 7-8 wk to the early grain-elongation stage of development. Dry biomass was determined and plants were evaluated for vigor on a 1 to 3 point scale: 1 = dark green and turgid, 2 = slightly chlorotic and stunted; and 3 = flaccid and severely chlorotic and stunted. Experiments were conducted in a completely randomized design with seven plants per replication. There were six replications of the 2.0 mmol L^{-1} sodium silicate and unamended solutions, and four replications of the other four silicon treatments. Treatment means were compared with Fisher's protected LSD test ($P = 0.10$).

Single bulk samples of leaves and stems from two replications of plants at the early grain elongation stage of plant development in selected experiments were analyzed for elemental composition by the Research Analytical Laboratory at the University of Minnesota. For comparison, wild rice at the same growth stage from a cultivated paddy and a native habitat in the Mississippi River in northern Minnesota were included in the analyses. Nitrogen content was measured as total Kjeldahl nitrogen. Other nutrients, with silicon as the only exception, were measured by the dry ash method of multi-element ICP analysis (Dahlquist and Knoll 1978). Nutrient solution HS-1 amended with silicic acid was also analyzed using ICP methods. Silicon content of leaf and stem tissues was analyzed colorimetrically in duplicate as described by Elliott and Snyder (1991).

Plants cultured with and without silicon amendments as described above were tested for resistance to FBS. A single isolate of *B. oryzae* from an infected wild rice plant in Minnesota was cultured for 5–7 wk on potato dextrose agar (PDA) (Difco; Detroit, MI) at 22°C with a photoperiod of 12 h and a light intensity of 160 μM m^{-2} s^{-1}. Conidia were washed from the PDA surface, suspended in sterile, deionized water and adjusted to 1.0×10^4 conidia mL^{-1}. Plants grown with or without silicon amendments for 4 wk to the tillering stage of plant development were removed from the growth chambers and their leaves were sprayed to wetness with 95% ethanol to enhance leaf wetting and allowed to evaporate. The conidial suspension was sprayed onto the leaves to runoff. Inoculated and noninoculated plants were then placed in a growth chamber at 22°C with 100% RH where free water formed on leaf surfaces within 2-3 h. After 24–36 h at 100% RH, the plants were returned to an environment with 90–95% RH for lesion development. The number and size of lesions was recorded 10–12 d after inoculation. Each experiment consisted of two sets of seven plants grown in different buckets containing one of the four silicon compounds, and two sets grown without any silicon amendments. One set of seven plants grown with each silicon amendment was inoculated and one was left noninoculated. Experiments were completely randomized and replicated five times with seven plants per replication.

RESULTS

In the IRRI solution 26% of the plants survived at week 6 with a mean dry biomass per plant of 1.1 g. No plants survived in the Shive's solution. Percent survival of seedlings and mean dry biomass per plant in the modified Hoagland's solutions HS-1, HS-2, and HS-3 were 40.1, 18.2, and 3.7%, and 1.5, 0.4, and <0.1 g, respectively. Survival and dry biomass were significantly different between all pairs of nutrient solutions ($P = 0.10$). Because the IRRI and HS-1 solutions produced the highest survival and biomass of wild rice seedlings, they were compared in additional experiments.

The HS-1 and IRRI nutrient solutions produced plants with similar and not significantly different ($P = 0.10$) numbers of tillers per plant, dry root biomass per plant, and maximum height; 3.5 ± 0.9 vs. 3.4 ± 0.7,

1.0 ± 0.5 vs. 1.1 ± 0.4 g, and 1.2 vs. 1.1 m, respectively. Plants grown in solution HS-1 produced slightly but not significantly ($P = 0.10$) greater dry biomass of leaves and stems per plant, and higher numbers of seeds per plant than those grown in the IRRI solution; 7.8 ± 3.2 vs. 7.0 ± 2.2 g, and 59.7 ± 21.6 vs. 49.2 ± 29.1, respectively. The seeds were viable and produced seedlings that grew at a rate similar to seedlings produced from field-grown seed. Based on these results, HS-1 was chosen for studies of silicon amendments and FBS pathology.

Biomass, vigor and Si content of wild rice grown in HS-1 amended with the four silicon compounds were evaluated (Table 1). Regardless of differences in Si content of the tissues, no silicon amendment significantly increased dry biomass production over the control grown without Si. The 4.0 mM sodium silicate solution decreased growth and plants grown with this amendment produced significantly less dry biomass than those grown without any silicon amendment or with silicic acid. Calcium silicate was the most detrimental to plant vigor based on qualitative evaluations of chlorosis, loss of turgor, and stunting. Differences in growth due to genetic variability among plants, as indicated by the large standard deviations, may have obscured treatment differences.

The elemental composition of wild rice leaves and stems grown in HS-1, HS-1 amended with silicic acid, a cultivated Histosol paddy in central Minnesota, and a native river habitat was determined (Table 2). Freshly prepared HS-1 amended with silicic acid was also analyzed. Concentrations of several elements, e.g., Na, K, and Mn fluctuated among the plants grown in the different conditions; however, wild rice grew well and appeared healthy in all of them.

Inoculation of wild rice with *B. oryzae* in hydroponic culture resulted in FBS lesions on leaves characterized by oval necrotic spots surrounded by chlorotic halos. There were no clear differences in FBS lesion number, size, or extent of chlorosis on wild rice plants grown with or without the silicon amendments in spite of differences in tissue Si content (Table 1). The number, size, location, and distribution of lesions was extremely variable within and between treatments. This variability may have obscured slight differences in infection and disease development among the treatments. All five replications of the inoculation experiments yielded similar results. The following data from one experiment illustrate the variability in lesion number within treatments and the apparent lack of effect of Si on lesion number and development. The range in number of lesions per leaf, mean size of lesions, and percent leaves developing lesions on plants grown with or without silicic acid were 1–30, 8 mm^2, and 45%; and 2–58, 8 mm^2, and 30%, respectively, About 50% of the lesions had chlorotic halos.

Table 1. Dry weight, plant vigor, and Si content of wild rice grown in modified Hoagland's nutrient solution (HS-1) amended with four different silicon compounds

Silicon amendment	Biomass (g per plant)[z]		Plant vigor[y]	Si content (g kg^{-1})[x]
	Leaves + stems	Roots		
Control (no silicon added)	2.43 ± 1.55*b*	0.33 ± 0.22*ab*	1	0*a*
Silicic acid (0.17 g L^{-1})	2.82 ± 2.12*b*	0.45 ± 0.31*b*	1	35.90 ± 9.80*b*
Calcium silicate (1.5 mmol L^{-1})	2.47 ± 2.11*ab*	0.30 ± 0.23*ab*	3	46.60 ± 14.70*b*
Potassium silicate (1.5 mmol L^{-1})	1.92 ± 1.09*ab*	0.37 ± 0.22*b*	2	83.70 ± 33.10*c*
Sodium silicate (1.5 mmol L^{-1})	1.90 ± 1.42*ab*	0.22 ± 0.17*ab*	2	49.40 ± 17.90*b*
Sodium silicate (4 mmol L^{-1})	0.60 ± 0.41*a*	0.10 ± 0.00*a*	2	NM

[z]Plants were grown 7-8 wk to early grain-elongation stage of development.
[y]1 = dark green and turgid; 2 = slightly chlorotic and stunted; 3 = flaccid and severely chlorotic and stunted.
[x]Si content in combined leaf and stem tissue; NM = not measured.
a–c Means within a column followed by the same letter are not significantly different at $P = 0.10$ as determined by Fisher's protected LSD test.

Table 2. Elemental composition of wild rice aerial tissues grown in two modified Hoagland's solutions (HS-1 and HS-1 + Si) and two field environments, and elemental composition of HS-1 amended with silicic acid

Chemical element	HS-1	HS-1 + Si	Histosol paddy	Natural stand[y]	Solution[z] composition
	(mg kg^{-1} (except N and Si as g kg^{-1}))				HS-1 + Si
					— (mg L^{-1}) —
N	19.0	20.0	30.0	NM[x]	NM
Ca	3 539.0	5 528.0	4 000.0	2 735.0	46.3
Mg	1 215.0	1 888.0	1 321.0	915.0	14.2
Na	714.0	1 523.0	3 409.0	5 222.0	1.7
K	25 028.0	34 704.0	24 910.0	9 150.0	65.6
P	2 247.0	2 398.0	2 320.0	2 573.0	4.4
Fe	63.0	88.0	79.5	234.6	2.5
Al	<7.2	5.9	18.1	NM	<0.1
Mn	75.1	278.5	141.2	363.5	0.6
Cu	3.1	3.4	1.6	1.3	<0.1
Zn	41.0	54.0	57.9	14.5	0.2
B	12.7	25.3	16.7	3.1	0.5
Cd	2.3	3.0	<0.2	NM	<0.1
Cr	0.8	0.7	<0.4	NM	<0.1
Ni	<0.9	1.2	<0.4	NM	<0.1
Pb	<3.4	1.9	<1.1	NM	<0.1

[z]Solution HS-1 amended with silicic acid (0.17 g L^{-1}).
[y]Plants from a natural habitat in the Mississippi River near Grand Rapids, Minnesota.
[x]NM = not measured.

DISCUSSION

The results demonstrate that wild rice can be grown to maturity and produce viable seeds in defined nutrient solutions under controlled conditions. The overall height and dry biomass of these plants were approximately 80 and 46%, respectively, of plants at the same developmental stage grown under field conditions. These smaller plants can be advantageous because they are easier to work with in growth chambers. The reduced growth of plants in culture compared with field-grown plants could be due to crowding in the culture vessels. In one unreplicated experiment using HS-1 and the same culture methods as were used in the other experiments, total biomass of plants grown in hydroponic culture was increased by 47% when the 6-L containers that were used routinely in these studies were replaced by 10.5-L containers (Malvick and Percich, unpublished).

A modified Hoagland's nutrient solution (HS-1) supported the apparently healthy growth of wild rice in environmental chambers. This indicates that solution HS-1 supplied the elements required by wild rice for growth and development. The elemental composition of wild rice leaves and stems grown in solution HS-1, a cultivated paddy, and a natural river habitat in northern Minnesota was variable. The IRRI nutrient solution also supported growth of wild rice; however, plants grown in it tended to be smaller and have lower seed production than plants grown in HS-1. HS-1 differs from the two other modified Hoagland's solutions in that the nutrient concentrations and the chemical reagents vary among them.

Silicon amendments to soil decreased foliar fungal infection of *Oryza* rice (Datnoff et al. 1991). Field and greenhouse studies in Minnesota suggest that silicon amendments can also increase growth of wild rice, and possibly decrease susceptibility to fungal brown spot disease (FBS) (Johnson and Percich 1992). Our hydroponics studies indicate silicon amendments do not increase plant growth or reduce FBS. No difference in lesion

number or size was detected on plants grown with or without silicon amendments. Silicon amendments to the HS-1 solution resulted in tissue Si contents ranging from 2.9% for silicic acid treatments to 8.4% for potassium silicate, while the controls contained no detectable Si. Thus, plant growth and resistance to FBS did not increase over controls despite accumulation of silicon in plant tissues.

Results from this study contradict results from previous greenhouse and field studies involving calcium silicate slag amendments to soil (Snyder et al. 1986; Anderson et al. 1987; Percich et al. 1988; Datnoff et al. 1991). In those studies, increased tissue Si content was related to less disease and greater plant growth and yield. The reasons for these contrasting results is unclear; however, several hypothetical explanations may apply. First, calcium silicate slag contains many elements in addition to silicon (Snyder et al. 1986) and, perhaps, one or more of these interacts with silicon to result in enhanced growth and disease resistance. Second, the nutrient exchange and binding activities of soil may enhance the positive effects of silicon via supplying other elements for growth (Marschner 1986). Third, soil may bind elements in the calcium silicate amendments that are detrimental to the health of wild rice. In the present hydroponics study, plants grown with calcium silicate amendments were the least vigorous of all the silicon amendments. Last, an attempt was made in this study to optimize conditions for inoculation, infection and disease development. The favorable conditions for the pathogen may have enabled it to overcome silicon-mediated defenses.

Effects of silicon on pathology may have been masked in part by the methodology used in this study. Our visual measurements of lesion number and infection development may not have detected subtle effects of silicon on the infection process. More precise, e.g., microscopic and cytological, techniques may be needed to determine whether silicon affects fungal germination, growth, or infection (Samuels et al. 1991). The variability in numbers and distribution of lesions on leaves may also have concealed slight differences that occurred due to silicon. Further, the variability in infection and growth of plants in hydroponic culture was probably strongly influenced by the phenotypic heterogeneity found in wild rice (Johnson and Percich 1992). In conclusion, wild rice can be grown to maturity with defined nutrient solutions in hydroponic culture. Additional studies with soil and hydroponic culture may help to further clarify the role of silicon in plant growth and resistance to FBS.

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