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Water-seeded rice response to pendimethalin applied at different rates and timings

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Abstract

Currently, a limited number of herbicides is available to treat water-seeded rice in California, with widespread resistance to most of those herbicides. Because no resistant grasses showed resistance to pendimethalin, a series of studies were conducted to evaluate water-seeded rice response to pendimethalin. In a field study conducted at the Rice Experiment Station at Biggs, California, in 2020 and 2021, three pendimethalin formulations, a granule (GR), emulsifiable concentrate (EC), and capsule suspension (CS), were applied at 1.1, 2.3, and 3.4 kg ai ha^{-1} rates, and at 5, 10, and 15 d after seeding onto water-seeded rice. In addition, a greenhouse study was conducted to examine the response of five common California rice cultivars to GR and CS formulation applications. *Echinochloa* control levels were reduced at 15 d after seeding after use of EC and CS formulations compared with earlier timings. In both years, rice grain yields were increased by 3,014 kg ha^{-1} after application of pendimethalin at 3.4 kg ai ha^{-1} when applied at 15 d after seeding compared with 5 and 10 d after seeding, and similar to 1.1 kg ai ha^{-1} applications. The GR and CS were safer formulations based on a reduction in injury and an increase in grain yields compared to the EC formulation. Differences in seedling vigor across cultivars appeared to incur an advantage after a pendimethalin application. However, most cultivars evaluated for stand reduction and dry biomass demonstrated tolerance to GR and CS formulation applications only after rice reached the 3-leaf stage. In contrast, an application at 1-leaf stage rice reduced stand up to 68%. Application rate, timing, and formulation are important factors to consider if the use of pendimethalin in water-seeded rice is to be pursued.

Introduction

Rice is an important staple food for many countries and is produced worldwide (Chauhan et al. 2017). Water-seeded rice is a common production system in California, Europe, Australia, and some Asian countries (Chauhan et al. 2017). The water-seeded system is useful for managing grasses, weedy rice, and other nonaquatic weeds (Hill et al. 2006; Rao et al. 2017). In California water-seeded rice, pregerminated rice seeds are air-seeded onto fields with a standing flood of 10 to 15 cm, the field will typically be continuously flooded throughout the growing season (Hill et al. 2006).

Weeds are a major management challenge encountered in rice production (Brim-Deforest et al. 2017a). Weedy grasses in California's water-seeded rice agroecosystem include barnyardgrass [*Echinochloa crus-galli* (L.) Beauv], early watergrass (*E. oryzoides*), late watergrass [*E. phyllopogon* (Stapff) Koss], and bearded sprangletop [*Leptochloa fusca* (L.) Kunth ssp. *fascicularis* (Lam.) N. Snow]. There is potential for up to 70% rice yield loss from season-long barnyardgrass competition (Smith 1988) and up to 36% rice yield loss from competition with bearded sprangletop (Smith 1983). Therefore, weedy grasses are the most economically important weeds in rice production (Brim-Deforest et al. 2017a).

In California, herbicides continue to be an important tool for weed management in water-seeded rice, but herbicide-resistant weeds have led to poor weed control with available herbicides (Becerra-Alvarez et al. 2023). An observed high incidence of resistant weed populations is common (Becerra-Alvarez et al. 2023). The high prevalence of resistance has developed due to the limited number of effective herbicide sites of action available and continuous rice production year after year with minimal to no crop rotations (Hill et al. 2006). Multiple herbicide resistance in *Echinochloa* species has made control in rice production a significant challenge. Therefore, new tools are needed to help implement herbicide resistance management through herbicide mode of action mixtures and herbicide mode of action rotations (Becerra-Alvarez et al. 2023).

Pendimethalin is a mitotic-inhibiting herbicide from the dinitroaniline chemistry, its use is a selective preemergent that ceases the seedling growth shortly after germination (Appleby and Valverde 1989). Pendimethalin has activity on *Echinochloa* species (Fischer et al. 2000) and bearded sprangletop (McCarty et al.1995). Currently, there is no recorded resistance to pendimethalin in California and controlled resistant populations, making it a potential new tool for herbicide resistance management in water-seeded rice (Becerra-Alvarez et al. 2023; Fischer et al. 2000).

Pendimethalin is registered for use in drill-seeded rice preemergence or early postemergence (Osterholt et al. 2019), however, it is not available for use on water-seeded rice because of the high crop injury potential (Fischer et al. 2000). In drill-seeded rice, pendimethalin application is suggested to occur 3 to 7 d after planting and at planting depths of 3.2 cm or greater to reduce injury (Bond et al. 2009; Koger et al. 2006). A deeper planting depth allows the seedlings to absorb water and grow before contacting pendimethalin on the soil surface (Bond et al. 2009). In water-seeded rice, rice seed is sown on the surface of the soil in high moisture levels, therefore, a postemergence application may reduce injury by allowing seedlings to establish before a pendimethalin application. The 1.1 kg ha^{-1} rate is the typical label rate used in drill-seeded rice for watergrass control (Bond et al. 2009). Pendimethalin degrades faster in anaerobic than aerobic conditions (Barrett and Lavy 1983). Higher than labeled rates may still provide adequate activity in anaerobic conditions. Therefore, 2× and 3× of the labeled rate were selected to evaluate rice response and weed control.

Herbicide formulation and application timing can be significant factors to reduce the rice injury to acceptable levels in a water-seeded system. Hatzinikolaou et al. (2004) recorded that the emulsifiable concentrate (EC) of pendimethalin had greater soil activity, but the water dispersible granule (GR) and capsule suspension formulation (CS) remained active in the soil longer, producing an extended soil residual activity. Hatzinikolaou et al. (2004) observed that the EC formulation resulted in a greater reduction in root length than GR and CS formulations, however, the GR and CS formulations also resulted in root length reduction in various plant species tested.

Tolerance to herbicides can also vary across rice cultivars. Koger et al. (2006) observed differential response to pendimethalin among three long grain rice cultivars, with the 'Wells' cultivar resulting in greater susceptibility to pendimethalin compared to 'Cocodrie' and 'Lemont' cultivars in a conventional tillage, dry-seeded system at different seeding depths. Bond et al. (2009) observed no differences with minimal to no rice injury among the same three long-grain cultivars in a stale seedbed dry-seeded field study.

It is important to examine the response from common California rice cultivars to pendimethalin to understand the practicability and limitations of its use in the water-seeded system. Thus, field and greenhouse studies were conducted to examine the response of water-seeded rice to a pendimethalin application. In the field study, we evaluate rice plant response to three pendimethalin formulations (GR, EC, and CS) at three different application timings and three pendimethalin rates. The greenhouse study assessed the response of five common California rice cultivars after a GR and CS pendimethalin application in a simulated water-seeded condition. The objectives of these studies were to characterize the response of water-seeded rice after a pendimethalin application and evaluate its potential use on water-seeded rice.

Materials and Methods

Field Study

The field study was conducted in 2020 and 2021 at the Rice Experiment Station in Biggs, CA. Soils at the study site are characterized as Esquon-Neerdobe (fine, smectitic, thermic Xeric Epiaquerts and Duraquerts), silty clay, made up of 27% sand, 39% silt, and 34% clay, pH 5.1, and with 2.8% organic matter. During the off-season winter months, in both years the field was flooded to 10 cm above the soil, after a pass with a single offset stubble disc and then drained in early spring of the following year. Field preparation in spring consisted of one pass with a chisel plow and two passes with a single offset disc, followed by a land plane to smooth the soil surface. A corrugated roller was used to pack the soil and eliminate large clods on the soil surface prior to planting. A granule fertilizer starter mixture application of ammonium sulfate and potassium sulfate (34% N, 17% P, 0% K) was applied by airplane at 336 kg ha^{-1} prior to the corrugated roller.

Seeds of the rice cultivar 'M-206' were pregerminated in steel bins filled with water until all the seeds were completely covered. For disease control, a 5% sodium hypochlorite solution was added to the water for the first hour, then drained and refilled with only water for the remaining 24 h. The seed was then drained until dry for 12 h, and air-seeded by aircraft at 140 kg ha^{-1} seeding rate in 2020 and 170 kg ha^{-1} seeding rate in 2021 onto the field with a 10-cm standing flood. Individual 3-m-wide by 6-m-long plots surrounded by 2.2-m-wide shared levees were made to prevent contamination from adjacent treatments in a replication. The flood was maintained the entire season and was lowered only to apply additional foliar herbicides for sedge and broadleaf control. Standard agronomic and pest management practices were followed based on the University of California rice production guidelines (UCANR 2023). Seeding dates were May 23, 2020, and June 5, 2021.

The study design was in a factorial arrangement of the treatments under a randomized complete block design with four replications. The treatment factors were three formulations, three application timings, and three application rates. The pendimethalin EC formulation was BAS 455 39H (BASF, Florham Park, NJ) with 0.4 kg L^{-1} of active ingredient, the CS formulation was BAS 455 48H (BASF) with 0.5 kg L^{-1} of active ingredient, and the GR was BAS 455 20H (BASF) with 2% of active ingredient per weight. Application timings were 5, 10, and 15 d after seeding (DAS), corresponding to 1-leaf, 2- to 3-leaf, and 3- to 4-leaf stage rice, respectively. The application rates were 1.1, 2.3, and 3.4 kg ai ha^{-1}.

The CS and EC formulations were applied with a CO_2-pressurized backpack sprayer calibrated at 206 kPa to deliver 187 L ha^{-1}. The sprayer boom was 3 m wide and equipped with six flat-fan TeeJet 8003VS tips (Spraying Systems Co., Glendale Heights, IL) traveling at 4.8 km h^{-1} and spraying onto the water surface. The GR formulation was spread by hand in each respective plot. Additional herbicides were applied for control of emerged grasses in 2020 and for control of other weed species not controlled by pendimethalin in both years. The observed population of grasses after treatment applications in 2020 deemed a necessary foliar herbicide application as a rescue treatment to acquire rice grain yield at the end of the season; however, this overspray may have biased the data to some degree. Copper sulfate crystals (Copper Sulfate Crystals MUP; Quimag Quimicos Aguila, Jalisco, Mexico) were applied by airplane at 17 kg ha^{-1} 3 DAS for algae control. In 2020, a mixture of cyhalofop-butyl at 0.3 kg ai ha^{-1} (Clincher CA; Corteva, Indianapolis, IN) and propanil at 1.7 kg ai ha^{-1} (SuperWham! CA; UPL, King of Prussia, PA) were applied at 21 DAS and a mixture of carfentrazone-ethyl at 0.1 kg ai ha^{-1} (Shark H_20; FMC, Philadelphia, PA) and triclopyr at 0.3 kg ai ha^{-1} (Grandstand CA; Corteva) was applied at 52 DAS for sedge and broadleaf control. In 2021, only carfentrazone-ethyl at 0.1 kg ai ha^{-1} and triclopyr at 0.3 kg ai ha^{-1} were applied for sedge and broadleaf control at 32 DAS.

Visual weed control of *Echinochloa* species and bearded sprangletop were recorded 14 and 56 d after pendimethalin treatment (DAT), on a scale of 0% to 100%, where 0% = no control and 100% = complete control. *Echinochloa* species counts in the nontreated plots were conducted 30 DAS by sampling twice in the plots within a 30-cm by 30-cm quadrat. Visual percent rice injury assessments were carried out at 20 DAT and 40 DAT by observing present symptomology, which included stand reduction and stunting, and compared with the nontreated, on a scale of 0% to 100%, where 0% = no injury and 100% = plant death. Rice tiller counts were conducted at 75 DAS by sampling twice within 30-cm by 30-cm quadrat in each plot, and data were scaled to a meter-squared area for presentation. Rice grain yield was collected in both years and adjusted to 14% moisture. The rice grain was hand harvested from two 1-m^2 quadrats in each plot and mechanically threshed (Large Vogel Plot Thresher; Almaco, Nevada, IA). The grain was then cleaned and weighed.

Greenhouse Experiment, Cultivar Response

The study of how rice cultivars respond to pendimethalin was conducted at the Rice Experiment Station greenhouse in Biggs, CA. A factorial arrangement of treatments in a completely randomized design was implemented. The factors were five cultivars, two formulations, two timings, and two rates. The rice cultivars consisted of 'S-102,' 'M-105,' 'M-205,' M-206, and 'M-209.' These rice cultivars represent common short-grain and medium-grain cultivars produced in California. CS and GR formulations were applied at 5 and 10 DAS at 1.1 kg ai ha^{-1} and 2.3 kg ai ha^{-1}, respectively. Three experimental runs were conducted separately over time. The first run was seeded on January 15, 2021, the second run on March 7, 2021, and the third run on April 20, 2021. Field soil with similar characteristics to that of the field site mentioned above was used to fill plastic containers (34 cm × 12 cm × 12 cm) with drainage openings on the bottom, and placed inside larger plastic containers (58 cm × 41 cm × 31 cm) with no drainage. Seeds were pregerminated by placing the different cultivar seeds inside cloth bags and in 18.9-L buckets completely submerged underwater for 24 h, and then seeds were air-dried before sowing. Twenty seeds were sown in each smaller container by placing the seed on the soil surface in a shallow flood onto the soil surface. The larger containers were immediately filled with water up to 10 cm above the soil level and maintained at that level throughout the study. Starting after the day of seeding, each smaller container was treated as a plot and was set in a completely randomized placement and re-randomized every 7 d. Copper sulfate crystals were applied by hand at 13 kg ha^{-1} 3 DAS for control of algae in each container for each run. The emerged rice seeds were counted before the pendimethalin applications and at 21 DAT to calculate the percent rice stand survival. At 20 DAT, plant height was measured from the soil surface to the far most extended leaf end in each plot. At 21 DAT, aboveground biomass was harvested from each plot and dry biomass was recorded.

The greenhouse was maintained at 33/25 ± 2C day/night temperature. A 16-h photoperiod was provided, and natural light was supplemented with metal halide lamps at 400 μ mol m^{-2} s^{-1} photosynthetic photon flux. The CS formulation was applied using a track-sprayer (Devries, Holland, MN) at 187 L ha^{-1} with a single TeeJet 8001EVS nozzle (Spraying Systems Co.) by placing the container inside the spray chamber with a height of 43 cm from the surface of the flood water to the spray nozzle. The GR formulation was spread by hand in each respective tub, calculated by the area of the larger plastic container.

Statistical Analysis

All statistical analysis was conducted using R software (R Development Core Team 2022) with the LMERTEST and EMMEANS packages (Kuznetsova et al. 2017; Lenth et al. 2020). Data were subjected to linear mixed effects regression models and mean separation, when appropriate, with Tukey's honestly significant difference test at $\alpha = 0.05$. In the field study, the model consisted of the three formulations, three rates, three application timings as fixed factors, and assessment dates as repeated measure, while replications were set as random separately each year. In the greenhouse study, the model consisted of two formulations, two rates, two application timings, and five cultivars as fixed factors, while experimental runs were treated as random. The normality of distribution was visually examined with quantile-quantile plots, and linearity was visually examined by plotting residuals.

Results and Discussion

Weed Control

There was interaction by year for *Echinochloa* species control (Table 1). In 2020, 330 ± 8 *Echinochloa* plants m^{-2} was observed in the nontreated plot, whereas in 2021, 180 ± 2 *Echinochloa* plants m^{-2} was observed by 56 DAT (Table 2). The field site previously recorded variations in weed species populations by year caused by differences in weather conditions and soil seedbank (Becerra-Alvarez et al. 2022; Brim-DeForest et al. 2017a). The cyhalofop and propanil application influenced the grass control levels observed in 2020.

Interaction effect across formulation with timing were observed for *Echinochloa* control both years (Table 1). The interaction of formulations with timings in 2020 demonstrated a reduction in *Echinochloa* control as application timing was delayed from 5 to 15 DAS with the EC formulation; however, the differences were not observed after application of GR and CS formulations (Table 2). In 2021, the interaction of formulations with timings demonstrated a decrease in *Echinochloa* control as application timing was delayed from 5 to 15 DAS with the EC and CS formulation, but again not with the GR formulation (Table 2). Application rates appeared to have an impact on grass control across timings in 2020 and across formulation in 2021 (Table 1). Interaction of rate with timing in 2020 and rate with formulation in 2021 were observed (Table 1). The *Echinochloa* control results are not consistent with those reported by Ahmed and Chauhan (2015), who repeatedly demonstrated an increase in grass control with an increase in pendimethalin rates in a dry-seeded rice system.

Transformations of sprangletop control data did not help meet the assumptions of normality of distribution, therefore, data are presented as if normality was met. Only pendimethalin timing and rate appeared to affect sprangletop control (Tables 1 and 3). The bearded sprangletop population is minimal and was previously observed by Brim-DeForest et al. (2017a). Therefore, the control results from pendimethalin may not be comparable to that of fields with greater sprangletop pressure. In this study, the flood was continuous and pendimethalin application was onto the water. The flood may have also been a factor in suppression of sprangletop (Driver et al. 2020).

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Table 1. Significance of main effects of formulation, timing, rate, and interactions among the main effects for grass weed control.[a,b]

	2020		2021	
Effect	*Echinochloa* control	Sprangletop control	*Echinochloa* control	Sprangletop control
	P-value			
Formulation	0.040	0.007	0.137	0.642
Timing	0.282	0.012	0.005	0.003
Rate	0.002	0.009	0.012	<0.001
Formulation × timing	<0.001	<0.001	0.002	0.053
Formulation × rate	0.162	0.750	0.003	0.348
Rate × timing	0.005	0.089	0.503	0.373
Formulation × timing × rate	0.464	0.489	0.408	0.920

[a]There was interaction by year.
[b]Transformations of the sprangletop control data did not help meet the assumptions of normality of distribution and data is presented as if normality was met.

Table 2. *Echinochloa* control as affected by the application of pendimethalin formulations by timings, averaged over rates in 2020 and 2021 on water-seeded rice.[a,b,c]

		2020	2021
Formulations	Timing	*Echinochloa* control	
14 DAT	DAS	%	
GR	5	34 abc	94 abc
	10	37 abc	82 abc
	15	31 abc	84 abc
EC	5	61 a	99 a
	10	68 ab	92 abc
	15	32 bc	83 bc
CS	5	20 c	97 ab
	10	28 bc	85 abc
	15	30 bc	80 c
56 DAT			
GR	5	74 a	84 ab
	10	72 a	84 ab
	15	73 a	71 b
EC	5	78 a	96 a
	10	79 a	87 ab
	15	75 a	75 b
CS	5	71 a	94 a
	10	67 a	85 ab
	15	72 a	70 b

[a]Abbreviations: CS, capsule suspension; DAS, days after seeding; DAT, days after treatment; EC, emulsifiable concentrate; GR, granule.
[b]Means with the same letter within each column do not significantly differ by Tukey's honestly significant difference test α = 0.05, averaged over the three rates.
[c]In 2020, 330 ± 8 *Echinochloa* spp. plants m^{-2} were present in the nontreated plots. In 2021, 180 ± 2 *Echinochloa* spp. plants m^{-2} were present in the nontreated plots.

Table 3. Sprangletop control as affected by application of three pendimethalin formulations and three timings averaged over rates in 2020 and 2021 on water-seeded rice.[a,b]

		2020	2021
Formulations	Timing	Sprangletop control	
14 DAT	DAS	%	
GR	5	32 d	94 ab
	10	83 ab	4 b
	15	77 ab	2 b
EC	5	55 c	15 ab
	10	91 a	8 b
	15	69 bc	4 b
CS	5	24 d	54 a
	10	75 ab	10 b
	15	76 ab	3 b
56 DAT			
GR	5	74 a	87 a
	10	84 a	82 a
	15	79 a	83 a
EC	5	85 a	93 a
	10	77 a	91 a
	15	80 a	84 a
CS	5	76 a	88 a
	10	74 a	90 a
	15	80 a	83 a

[a]Abbreviations: CS, capsule suspension; DAS, days after seeding; DAT, days after treatment; EC, emulsifiable concentrate; GR, granule.
[b]Means with the same letter within each column do not significantly differ according to Tukey's honestly significant difference test, α = 0.05, averaged over the three rates.

Rice Response

There was treatment interaction by year for visual rice injury but not across assessment dates (Table 4). Injury differed across formulation, rate, and timing (Table 4). Rice treated at the 15 DAS timing recorded the most reasonably accepted injury levels but differed across formulations (Table 4). The results demonstrate that different formulations result in varying rice injury levels, which is similar to the results reported by Hatzinikolaou et al. (2004), who evaluated pendimethalin injury on various grass crop species.

In 2020, tiller counts were 30 to 200 tillers m^{-2}. In 2021, however, tiller counts were 200 to 500 m^{-2} (Table 5). After a GR and CS application, rice tillers were similar across timings; however, after EC application at 15 DAS, tillers were increased. The rice treated at 15 DAS produced tiller counts similar to that of 10 DAS but not 5 DAS with pendimethalin applied at 2.3 and 3.4 kg ha^{-1} from the EC formulations (Table 5). Differences in formulations by application timings was evident and resulted in varying injury levels effected by the formulation.

The greater weedy grass pressure in 2020 may have been a factor in the increase on visual rice injury and decrease in rice stands compared to 2021. Weedy grasses interfere with rice growth early on and can reduce the rice stand and tillering capacity (Brim-DeForest et al. 2017b; Smith 1988). Rice treated with pendimethalin caused increased injury with increasing rates when applied at 5 and 10 DAS; however, at 15 DAS, injury was similar across rates, which suggests that after rice reaches the 3- to 4-leaf stage, pendimethalin injury may not affect rice development. Absorption of pendimethalin can cause greater growth disturbance at earlier seedling stages when the grass seedling coleoptile emerges at the surface of the soil and comes in contact with the herbicide as demonstrated by Knake and Wax (1968) with the grass weed giant foxtail. Pendimethalin remains on the upper soil surface due to its physiochemical properties (Makkar et al. 2019); therefore, once the

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Table 4. Visual rice injury as effected by the application of three pendimethalin formulations at three rates, and three timings in 2020 and 2021 on water-seeded rice.[a,b,c]

Formulation	Rate	Timing	2020	2021
			Visual injury	
	kg ha^{-1}	DAS	%	
GR	1.1	5	51 f-l	35 f-l
GR	2.3	5	71 b-j	56 b-j
GR	3.4	5	89 a-e	74 a-e
GR	1.1	10	41 j-l	26 j-l
GR	2.3	10	48 h-l	33 h-l
GR	3.4	10	67 c-k	51 c-k
GR	1.1	15	34 kl	18 kl
GR	2.3	15	36 kl	20 kl
GR	3.4	15	42 g-l	26 g-l
EC	1.1	5	99 a-d	83 a-d
EC	2.3	5	100 a	88 a
EC	3.4	5	100 a	90 a
EC	1.1	10	76 a-h	60 a-h
EC	2.3	10	95 ab	79 ab
EC	3.4	10	97 ab	81 ab
EC	1.1	15	37 i-l	21 i-l
EC	2.3	15	51 f-l	36 f-l
EC	3.4	15	60 e-l	45 e-l
CS	1.1	5	48 f-l	32 f-l
CS	2.3	5	95 a-e	79 a-e
CS	3.4	5	100 a-c	85 a-c
CS	1.1	10	36 j-l	21 j-l
CS	2.3	10	75 a-g	60 a-g
CS	3.4	10	80 a-f	64 a-f
CS	1.1	15	33 kl	17 kl
CS	2.3	15	38 i-l	23 i-l
CS	3.4	15	35 i-l	20 i-l

[a]Abbreviations: CS, capsule suspension; DAS, days after rice seeding; EC, emulsifiable concentrate; GR, granule.
[b]Interaction by year, $P = 0.016$, was observed for the visual injury. Model output recorded differences across formulations, $P < 0.001$, rates, $P < 0.001$, application timings, $P < 0.001$, formulations × rates, $P < 0.001$, formulations × application timings, $P < 0.001$, rates × application timings, $P < 0.001$, and formulations × rates × application timings, $P < 0.001$. There was no observed interaction across the two assessment dates of 20 and 40 d after treatment, $P = 0.644$; therefore, the data are presented as averaged over assessments.
[c]Means with the same letter within each column do not differ according to Tukey's honestly significant difference test, $\alpha = 0.05$.

Table 5. Rice tiller counts as effected by the application of three pendimethalin formulations at three rates, and three timings in 2020 and 2021 on water-seeded rice.[a–d]

Formulation	Timing	2020	2021
		Tiller count	
	DAS	m^2	
GR	5	88 ab	410 ab
GR	10	149 a	472 a
GR	15	164 a	486 a
EC	5	0 c	240 c
EC	10	3 bc	326 bc
EC	15	129 ab	452 ab
CS	5	6 bc	329 abc
CS	10	81 abc	403 abc
CS	15	145 ab	468 ab

[a]Abbreviations: CS, capsule suspension; DAS, days after seeding; EC, emulsifiable concentrate; GR, granule.
[b]Results presented are averaged over the three rates. Counts conducted 75 d after application.
[c]There was interaction by year, $P < 0.001$. Significance observed across formulations, $P = 0.011$, rates, $P = 0.007$, application timings, $P = 0.006$, formulations × rates, $P = 0.314$, formulations × application timings, $P < 0.001$, rates × application timings, $P = 0.089$, and formulations × rates × application timings, $P = 0.687$.
[d]Means with the same letter within each column do not differ according to Tukey's honestly significant difference test, $\alpha = 0.05$.

Table 6. Rice grain yield as effected by the application of three pendimethalin formulations averaged over three rates at three timings in 2020 and 2021 on water-seeded rice.[a–d]

Formulation	Timing	2020	2021
		Grain yield	
	DAS	kg ha^{-1}	
GR	5	2,170 abc	6,191 abc
GR	10	2,436 ab	6,457 ab
GR	15	3,485 a	7,506 a
EC	5	0 d	2,770 d
EC	10	216 cd	4,236 cd
EC	15	2,465 ab	6,486 ab
CS	5	656 bc	4,677 bc
CS	10	1,972 abc	5,992 abc
CS	15	2,572 ab	6,593 ab

[a]Abbreviations: CS, capsule suspension; DAS, days after seeding; EC, emulsifiable concentrate; GR, granule.
[b]Results presented are averaged over the three rates.
[c]Interaction by year was observed, $P < 0.001$. Model output recorded differences across formulations, $P < 0.001$, rates, $P < 0.001$, application timing, $P = 0.002$, rates × application timing, $P < 0.001$, and formulation × application timing, $P = 0.011$. No differences were observed for formulation × rate, $P = 0.066$, and formulations × rates × application timing, $P = 0.315$.
[d]Means with the same letter within each column do not differ according to Tukey's honestly significant difference test, $\alpha = 0.05$.

seedling growing points are further above the upper soil surface there is a potential to overcome pendimethalin injury.

An interaction with year and between formulation and timing for grain yield occurred (Table 6). In both years, rice grain yield was similar across timings with the GR and CS formulations, but not with the EC formulation (Table 6). Timing was most influential on grain yield with the EC formulation. Overall, similar grain yield was achieved from rice treated with the GR formulation across all rates and timings in 2020 and similarly in 2021 (Table 6). GR is formulated to slowly release the active ingredient, which results in a reduction of crop injury (Hatzinikolaou et al. 2004). The active ingredient is adsorbed onto inert materials and slowly activated (Hatzinikolaou et al. 2004). These characteristics of the GR formulation may have allowed more rice seedlings to establish by not being exposed to high concentrated levels of the active ingredient at once.

In addition, there was an interaction between rates with timings for grain yield (Table 7). Rice treated with 1.1 kg ha^{-1} at all timings produced similar grain yield in both years, and it was similar when treated with 2.3 kg ha^{-1} at 10 and 15 DAS, and with 3.4 kg ha^{-1} at 15 DAS (Table 7). Pendimethalin applied to rice at 3.4 kg ha^{-1} at 15 DAS resulted in an increased yield by 3,014 kg ha^{-1} of grain in both years when compared with the 5 and 10 DAS timings (Table 7). The results demonstrate that formulation, rate, and timing are important factors to achieve adequate grain yield in water-seeded rice with use of pendimethalin. An application of pendimethalin to dry-seeded rice in Bangladesh decreased grain yields by 44% to 50% when pendimethalin was applied 2 DAS compared with the weed-free check (Ahmed and Chauhan 2015). Application timing or soil saturation timing is an important influence on rice injury after a pendimethalin application in dry-seeded systems (Awan et al. 2016). In the water-seeded system, application timing is an important factor.

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Stand reduction was influenced by cultivar, formulation, rate, and timing (Table 8). In general, rice treated at 5 DAS resulted in up to

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Table 7. Rice grain yield as effected by the application of three pendimethalin rates averaged over three formulations at three timings in 2020 and 2021 on water-seeded rice.[a–d]

Application rate	Timing	2020	2021
		Grain yield	
kg ai ha^{-1}	DAS	kg ha^{-1}	
1.1	5	2,214 ab	6,235 ab
1.1	10	2,440 a	6,460 a
1.1	15	2,746 a	6,767 a
2.3	5	200 cd	4,221 cd
2.3	10	1,694 abc	5,715 abc
2.3	15	2,272 abc	6,293 abc
3.4	5	0 d	3,182 d
3.4	10	490 bcd	4,511 bcd
3.4	15	3,504 a	7,525 a

[a]Abbreviation: DAS, days after seeding.
[b]Results presented are averaged over the three formulations.
[c]Interaction by year was observed, P < 0.001. Model output recorded differences across formulations, P < 0.001, rates, P < 0.001, application timing, P = 0.002, rates × application timing, P < 0.001, and formulation ×application timing, P = 0.011. No differences were observed for formulation × rate, P = 0.066, and formulations × rates × application timing, P = 0.315.
[d]Means with the same letter within each column do not differ according to Tukey's honestly significant difference test, α = 0.05.

68% stand reduction across cultivars for both CS and GR formulations (Table 8). At 5 DAS, stand was reduced after application of both formulations for M-105, M-205, M-206, and M-209 cultivars (Table 8). Only S-102 at the 5 DAS timing resulted in less than 54% reduction (Table 8). At 10 DAS, S-102 and M-206 did not exhibit stand loss across rates, whereas M-105 resulted in a 21% decrease in stand after a 2.3 kg ha^{-1} application compared to 1.1 kg ha^{-1} (Table 8). However, the stand reduction after 10 DAS applications was zero to 29% for all cultivars (Table 8).

Koger et al. (2006) observed cultivar differences in pendimethalin applications on long-grain rice in a dry-seeded system. Relative tolerance was attributed to the mesocotyl length of seedling rice, which may vary by cultivar; however, planting depth is also an important factor in dry-seeded rice for achieving pendimethalin tolerance (Ceseski and Al-Khatib 2021; Ceseski et al. 2022; Koger et al. 2006). In water-seeded rice, a mesocotyl is not present on seedlings because the seeds are placed on the soil surface; however, differences in seedling vigor can be important for relative tolerance to pendimethalin. Ceseski and Al-Khatib (2021) observed that the M-205 and M-209 cultivars had greater seedling vigor than M-105 and M-206, when drill-seeded in a high-clay soil. Additionally, S-102 is a short-grain, very early maturing cultivar (fewer than 80 d to 50% heading) and higher cold temperature tolerance than other common short- and medium-grain rice cultivars (McKenzie et al. 1997). These cultivar characteristics can help us understand the observed relative tolerance to pendimethalin across cultivars in this study.

Dry biomass was affected by rate and timing (Table 9). The higher rate was an important factor in decreasing biomass for S-102 at the 5 DAS from CS and GR applications at 2.3 kg ha^{-1} (Table 9). Dry biomass was reduced by 77% at 5 DAS compared with the 10 DAS timing averaged across formulations, rates, and cultivars. However, biomass reduction was minimal and not significant at 10 DAS, except for M-205 at 2.3 kg ha^{-1} GR formulation (Table 9).

Awan et al. (2016) observed a decrease in rice seedling biomass in dry-seeded rice when pendimethalin was applied at 2.0 kg ha^{-1}, but not at 1.0 kg ha^{-1}. Similarly, in this study, biomass reduction was rate-dependent for M-205. Plant height measurements had no difference across treatments and were similar to the nontreated by time of biomass harvest (data not shown). Awan et al. (2016) did observe a decrease in plant height in plots treated with pendimethalin in a dry-seeded system with no recovery by the final evaluation.

Table 8. Percent stand reduction of five rice cultivars after application of two pendimethalin formulations at two rates and two application timings in a controlled water-seeded environment.[a,b]

	Rice stand survival							
	GR				CS			
	kg ai h^{-1}							
	1.1	2.3	1.1	2.3	1.1	2.3	1.1	2.3
Cultivar	5 DAS		10 DAS		5 DAS		10 DAS	
	% Reduction of the nontreated							
S-102	1	39	0	0	0	54	0	0
M-105	37	68	0	21	61	41	17	7
M-205	37	46	4	29	40	51	4	23
M-206	43	62	0	7	49	35	0	0
M-209	45	66	5	26	44	75	0	13
Tukey's HSD α = 0.05.								
Application timings, 37.								
Cultivar, 18.								
Cultivar × formulation, 18.								
Cultivar × rates, 23.								
Rates × application timings, 10.								

[a]Abbreviations: CS, capsule suspension; DAS, days after seeding; GR, granule; HSD, honestly significant difference.
[b]Means with differences above Tukey's HSD are significant when compared across the appropriate factors and interactions. Model output demonstrated differences across cultivar, P < 0.001, application timings, P < 0.001, cultivar × formulation, P = 0.045, cultivar × rates, P < 0.001, rates × application timings, P < 0.05. No differences were observed across formulations, P = 0.131, rates, P = 0.277, cultivar × application timings, P = 0.223, formulations × rates, P = 0.152, formulations × application timings, P = 0.469, cultivar × formulations × rates x application timings, P = 0.06.

Table 9. Dry aboveground biomass reduction of five rice cultivars after application of two pendimethalin formulations at two rates and two application timings in a controlled water-seeded environment.[a,b]

	Dry biomass							
	GR				CS			
	kg ai h^{-1}							
	1.1	2.3	1.1	2.3	1.1	2.3	1.1	2.3
Cultivar	5 DAS		10 DAS		5 DAS		10 DAS	
	% Reduction of the nontreated							
S-102	12	62	0	12	21	78	0	0
M-105	55	72	0	21	62	52	34	0
M-205	58	63	28	46	43	78	17	23
M-206	53	72	5	6	54	69	4	0
M-209	54	83	25	35	46	93	1	8
Tukey's HSD α = 0.05.								
Rates, 15.								
Application timing, 46.								
Cultivar × rate, 23.								
Rates × application timing, 26.								

[a]Abbreviations: CS, capsule suspension; DAS, days after seeding; GR, granule; HSD, honestly significant difference.
[b]Means with differences above Tukey's HSD are significant when compared across the appropriate factors and interactions. Model output demonstrated differences across rates, P = 0.008, application timings, P < 0.001, cultivar × rate, P = 0.006, rate × application timing, P = 0.004, and formulation × application timing, P < 0.05. No differences were observed across cultivar, P = 0.181, formulations, P = 0.614, cultivar × formulation, P = 0.337, cultivar × application timings, P = 0.481, formulation × rate, P = 0.755, and cultivar × formulation × rate × application timings, P = 0.159.

Practical Implications

Pendimethalin is currently not available for water-seeded rice, but it can be a valuable tool if it were to be introduced for management of herbicide-resistant grasses in California water-seeded rice. The CS and GR formulations are most appropriate for water-seeded rice. These results indicate rice crop injury is reduced with a postemergence application after the 3- to 4-leaf stage rice in a water-seeded system. Pendimethalin is not a stand-alone herbicide and will need to be accompanied by other available herbicides to achieve season-long weed control. In general, most rice cultivars tested were relatively tolerant to pendimethalin after a 3-leaf stage application; furthermore, cultivars with lower seedling vigor scores may become more injured from a pendimethalin postemergence application. The results provide supporting data for the registration of pendimethalin use in water-seeded rice production and provide a base knowledge from which further research should be conducted to enhance its use in this system.

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Competing interests. The authors declare none.

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