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Performance of different herbicides on pondweed (*Potamogeton nodosus*) in rice

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Research Article

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Bensulfuron-methyl; bispyribac-sodium; butachlor; flucetosulfuron; metazosulfuron; metsulfuron-methyl; oxadiargyl; pendimethalin; penoxsulam; pretilachlor; pyribenzoxim; thiobencarb; triafamone plus ethoxysulfuron; pondweed, *Potamogeton nodosus* Poir. 'PTMNO'; rice, *Oryza sativa* L.

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Abstract

Pondweed is a rhizomatous perennial weed of aquatic habitats that recently adapted to rice ecosystems in northern Iran. Two field experiments were conducted at the Rice Research Institute of Iran to determine the impact of pondweed on rice yield and identify effective herbicides for pondweed control. The focus of the first study was to evaluate the herbicides commonly used in Iranian rice, including butachlor, pretilachlor, oxadiargyl, pendimethalin, thiobencarb, and bensulfuron-methyl. None of these herbicides effectively controlled pondweed, except bensulfuron, which reduced pondweed biomass by ≥95% and produced 26% higher rough rice grain yield than the nontreated plots. The second experiment evaluated the performance of acetolactate synthase–inhibiting herbicides on pondweed control, rough rice yield, and pondweed regrowth. Herbicide efficacy on pondweed varied from 36% to 100%. Five preemergence herbicides, bensulfuron at 45 g ai ha^{-1}, flucetosulfuron at 30 g ai ha^{-1}, triafamone plus ethoxysulfuron at 40 g ai ha^{-1}, and metsulfuron-methyl at 15 g ai ha^{-1}, provided ≥98% control of pondweed. Use of postemergence herbicides penoxsulam at 35 g ai ha^{-1}, bispyribac-sodium at 30 g ai ha^{-1}, and pyribenzoxim at 35 g ai ha^{-1} provided 36%, 89%, and 93% pondweed control, respectively. Rough rice yields ranged from 107% to 124% in herbicide-treated plots compared with the nontreated plots. Soil-applied herbicide treatments produced higher (≥119%) yield than the hand-weeded control or foliar-applied herbicides. Pondweed regrowth was affected by herbicides and was variable. Soil-applied residual herbicides metazosulfuron, flucetosulfuron, and metsulfuron provided complete control of pondweed and prevented regrowth. In contrast, pondweed regrowth in other soil- and foliar-applied herbicide treatments occurred, indicating their lesser translocation to underground vegetative rhizomes. This study shows that although most sulfonylurea herbicides can control pondweed effectively to achieve high rough rice yield, only a few soil-applied herbicides were able to prevent pondweed regrowth.

Introduction

Rice production is the most dominant economic, social, and agricultural activity in the northern part of Iran (Yaghoubi and Babaei 2013) and is the main occupation and source of income for approximately 700,000 families in the region. Approximately 437,000 ha of rice fields in Iran produce 1.99 million tons of rough rice yield (FAO 2019). Approximately 85% of rice fields are in Guilan and Mazandaran Provinces, located south of the Caspian Sea.

Weeds are the main constraint to rice production in Iran. The problem is perpetuated by continuous rice monoculture and a temperate climate favorable to various weeds. In addition to grasses, broadleafs, and sedges (Golmohammadi et al. 2020), ferns like water fern (*Azolla filiculoides* Lam.) and mosquito fern (*Azolla pinnata* R. Br.) are commonly found in transplanted rice in Iran.

Pondweed is a perennial broadleaf monocotyledonous weed belonging to the family of Potamogetonaceae, which reproduces by fragmentation, stolon, underground rhizomes, winter buds or turions, and seeds (Van Vierssen 1993; Zimdahl 2007). It is very common in swamps, ponds, streams, canals, ditches, and freshwater marshes in many areas of northern Iran. It has recently become adapted to flooded environments of rice production systems in this area (Yaghoubi and Babaei 2013). Approximately 10 species of Potamogeton have been documented in the country (Mozafarian 2018). This weed is highly adaptable to the transplanted rice ecosystem. Pondweed grows rapidly when rice fields are flooded after transplanting, and flowers and starts producing seeds in 10 wk. Once fields are drained 2 wk before rice harvest, pondweed foliage dries out rapidly. Re-irrigation of areas after rice harvest for ratooning or late-season rains stimulates the reemergence of pondweed seedlings. *Potamogeton* spp. have extensive creeping rhizome systems and floating or submerged leaves. They are among the 10 major aquatic weeds in the world (Durborow 2014; Lancar and Krake 2002; Zimdahl 2007). The species curly-leaf pondweed (*Potamogeton crispus* L.), sago pondweed [*Potamogeton pectinatus* (L.)

Börner], and pondweed have been reported as rice field weeds in Japan, Taiwan, the United States (DeDatta 1981), and Bhutan (Tshewang et al. 2016) and as cosmopolitan weeds in Europe and Asia (Barrett and Seaman 1980; Zhang 2003). A shift from small fields with natural drainage to mechanically leveled large ones with a compacted hardpan and less drainage capacity could be one reason for increased pondweed infestation in transplanted rice. Pondweed is tolerant to flooding; its growth is stimulated and maximized in anaerobic conditions (Harada and Ishizawa 2003; Mohammadvand et al. 2015). In addition, the lack of proper preventive measures coupled with the widespread use of tractor-operated rotavator equipment causes extensive fragmentation of pondweed rhizomes. Contaminated equipment contributes to movement of weed propagules and increases pondweed spread. Early-season emergence of pondweed may delay tillering in transplanting rice seedlings. Pondweed interference with rice may cause a 12% to 37% loss in rice grain yield (Tshewang et al. 2016; Yaghoubi 2016).

Weed management programs in Iran are currently based on a combination of cultural and chemical practices, including puddling, flooding, herbicide application, and hand-weeding. Paddy fields typically receive one of the herbicides butachlor, pretilachlor, thiobencarb, molinate, pendimethalin, oxadiazon, or oxadiargyl to control barnyardgrass, and also, more than 50% of the fields are treated with bensulfuron-methyl to control broadleaf or sedge species (Yaghoubi et al. 2010). Sulfonylurea use is increasing in Iran due to their high efficacy in controlling sedge and broadleaf weeds. In addition, almost all fields are hand-weeded one to two times each growing season, depending on rice genotype or type of weed flora. Hand-weeding has made herbicide use successful for approximately four decades without encountering herbicide-resistant weeds.

Decades of rice monoculture and the extensive use of the same or similar measures for weed control, such as continuous hand-weeding, flooding, and grass herbicides, have resulted in the development of increasingly problematic weed species in paddy fields. For example, watergrass [*Echinochloa oryzoides* (Ard.) Fritsch], a newly emerged weed for Iranian transplanted rice, has similar morphology to rice and is mistakenly transplanted with rice seedlings from the nursery to the field (Pouramir and Yaghoubi 2020). The time required for pondweed and barnyardgrass manual weeding in transplanted rice was reported to be 550 and 100 h ha^{-1}, respectively (Yaghoubi 2016).

Pondweed regrowth, even in submerged plots with a depth of approximately 10 cm water or more, has made the necessity of re-hand-weeding inevitable and unpleasant. The response of any weed species from the Potamogetonaceae family to herbicides recommended for rice has not been well documented in Iran. Thus the objective of this study was to investigate the efficacy of common rice herbicides and some newly registered herbicides in Iran, mainly sulfonylureas, for chemical control of pondweed and their effect on rice grain yield.

Materials and Methods

Site Description, Soil Properties, and Experimental Design

Four years of field experiments were conducted during 2016 to 2019 at the Rice Research Institute of Iran, Rasht (36°54′N, 40°50′E, −21 m asl), in a field that had a 40-yr history of growing transplanted rice. The soil was an alfisol containing 44% clay, 52% silt, 4% sand, and 2.3% organic carbon, with pH 7.2, available phosphorous 8.6 mg kg^{-1}, available potassium 172 mg kg^{-1}, and electrical conductivity 2.49 dS m^{-1}.

Table 1. Herbicide, formulation, trade name, dose, and manufacturer for field studies for control of pondweed in rice at Rice Research Institute of Iran.[a]

Herbicide	Rate	Formulation	Trade name	Manufacturer
	g ai ha^{-1}			
Butachlor	1,800	EC 60%	Macheti	Aryashimi, Iran
Pretilachlor	1,000	EC 50%	Rifit	Aryashimi, Iran
Thiobencarb	2,500	EC 50%	Saturn®	Moshkfam-fars, Iran
Pendimethalin	990	EC 33%	STAMP	Golsam, Iran
Oxadiargyl	105	EC 3%	topstar™	Golsam, Iran
Bensulfuron-methyl	45	DF 60%	Londax®	Golsam, Iran
Flucetosulfuron	30	WG 10%	Zechor	LG, Korea
Triafamone plus ethoxysulfuron	37.5	WG 30%	Council®	Bayer Crop Science, Germany
Pyrazosulfuron-ethyl	750	WP 10%	Saathi	UPL Mumbai, India
Metazosulfuron	82.5	WG 33%	Ginga	Nissan, Japan
Metsulfuron-methyl	15	WP 60%	—	Eastchem, China
Pyribenzoxim	35	EC 5%	PYRIMAX	Eastchem, China
Penoxsulam	35	OD 20%	Target	Eastchem, China
Bispyribac-sodium	30	SC 10%	NOMINEE®	Komia, Japan

[a]Abbreviations: DF, dry flowables; EC, emulsifiable concentrate; OD, oil dispersion; SC, suspension concentrate; WG, water-dispersible granules; WP, wettable powders.

In the first study (2016 and 2017), some herbicides commonly used in Iranian rice fields were evaluated for pondweed control. These included butachlor, pretilachlor, thiobencarb, oxadiargyl, pendimethalin, and bensulfuron (Table 1). Two treatments were added for comparison: a hand-weeded and a nontreated treatment. In the second experiment (2018 and 2019), acetolactate synthase (ALS)–inhibiting herbicides were applied for pondweed control, including flucetosulfuron, bensulfuron, metsulfuron, triafamone plus ethoxysulfuron, pyrazosulfuron-ethyl, metazosulfuron, bispyribac-sodium, pyribenzoxim, and penoxsulam (Table 1). Bensulfuron was registered in Iran approximately three decades ago, and all other sulfonylurea herbicides were registered in the past five years, except metazosulfuron and pyrazosulfuron-ethyl, which are still being investigated to register.

Most herbicides in both studies, except bispyribac-sodium, pyribenzoxim, and penoxsulam, were applied preemergence by pouring into flooded plots 3 d after transplanting (DAT), when there was no emerged pondweed or any other weed, using a handheld bottle with three holes designed to apply herbicides to transplanted rice soil. Postemergence herbicides bispyribac-sodium, pyribenzoxim, and penoxsulam were sprayed at the three- to five-leaf stage of pondweed 21 DAT. A backpack sprayer fitted with a TeeJet® (TeeJet Technologies, Wheaton, IL, USA) nozzle calibrated to deliver 170 L ha^{-1} was used.

The studies were arranged in a randomized complete block design with four replicates. The plot size was 10 × 5.4 m. The experimental plots were separated by an earthen levee covered with a high-density polyethylene film. The edges of the film were buried to prevent leaching of herbicides and water and cross-contamination of herbicides. Each plot had access to a canal for independent water management. Water entered from one end of each plot and was not allowed to overflow. Weeds in hand-weeded plots were

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removed manually at 14, 28, and 42 DAT, when their size was big enough for removal by hand. This trial focused strictly on pondweed control; therefore every weed other than pondweed that survived herbicide application was removed by hand.

Crop Management

Soil preparation consisted of flooding the land in early May, followed by two passes of wet plowing in opposite directions. Plots were then flooded until harrowing to puddle the soil 1 d before transplanting. Fertilizers were applied based on soil analyses and included 60 kg N ha^{-1} as urea, 50 kg P_2O_5 ha^{-1} as superphosphate triple, and 50 kg K_2O ha^{-1} as potassium sulfate broadcasted by hand. Thirty-two-day-old rice seedlings (cv. Hashemi traditional cultivar of indica type) that had been raised in the nursery were transplanted on May 25 of each year, spaced at a planting density of 20 hills m^{-2} with three seedlings per hill. Consistent with traditional transplanted rice practices in northern Iran, a permanent flood water level was maintained at 5 to 7 cm from 3 DAT until the physiological maturity of rice grains. The plots were drained approximately 2 wk before harvest. Recommended insect and disease control and other agronomic practices were implemented throughout the growing season as needed (Yaghoubi 2016). Planting date, rice cultivar, weeds present, and cultural practices were similar in both experiments. Also, transplanting and harvesting times over the two years of the experiment were similar, with less than 1 wk difference.

Plant Sampling

There were some visual crop injuries (chlorosis or necrosis); however, plants appeared visually to be recovered within 4 wk (data not shown). For both experiments, visual estimates of pondweed control were made 4 and 6 weeks after treatment (WAT) in each year on a scale of 0% to 100%, with 0% being no weed control and 100% being complete weed control. Also, the effect of treatments on pondweed biomass was determined at 4 and 6 WAT using a 0.25 m^2 quadrat at each end of the plot. Pondweed plants were cut at ground level, washed with water, and oven-dried at 75 C until a constant weight was achieved.

Plots were harvested when mature grain color changed to yellowish, at 18% to 20% moisture in mid-September. All plots were harvested by hand, excluding two borderlines, and air-dried for 24 h. Then the heads were threshed with a small stationary research thresher. Rice grain was weighed, and data were converted to kilograms per hectare and 14% moisture content.

Although pondweed is a perennial weed, it behaves like an annual weed in transplanted rice ecosystems, and by draining the rice fields to harvest, pondweed aerial parts dry out. By reflooding the plots after rice harvest, live rhizomes grow again. In this study, regrowth was counted 2 wk after the rice harvest.

Statistical Analyses

Data from both studies were subjected to analysis of variance (ANOVA) using the SAS program (SAS Institute Inc., Cary, NC, USA). Treatment and year were considered as fixed effects, and ANOVA results indicated that there was no significant interaction between treatments and years; therefore the data were pooled over years for analysis. Means were separated using Fisher's protected least significant difference (LSD) at the 5% significance level.

Results and Discussion

Experiment 1: Herbicide Screening for Pondweed Control

Visual pondweed control was affected by herbicide treatments. Pondweed did not show any toxicity symptoms following treatment with butachlor, pretilachlor, thiobencarb, and pendimethalin (Table 2). Oxadiargyl activity on pondweed decreased from 55% at 4 WAT to 42% at 6 WAT. Bensulfuron-methyl provided 99% and 96% pondweed control at 4 and 6 WAT, respectively (Table 1). Six WAT is the end of the critical weed control period in transplanted rice (Asghari and Mohammadsharifi 2001).

Pondweed biomass was affected by herbicide treatments. Thiobencarb provided the lowest (14%) and bensulfuron provided the highest (99%) reduction in pondweed biomass at 4 WAT. Pretilachlor, butachlor, pendimethalin, and oxadiargyl controlled pondweed 19%, 22%, 25%, and 58%, respectively. In a previous study, bensulfuron application alone or in combination with other common herbicides in rice fields, butachlor, pretilachlor, thiobencarb, or oxadiargyl, controlled pondweed ≥95% (Yaghoubi 2016).

At 4 WAT, pondweed density and biomass in the nontreated control was 75 plants m^{-2} and 140 g per m^{-2}, respectively (data not shown). Bensulfuron and oxadiargyl provided 99% and 24% reductions in pondweed biomass, respectively; other herbicides did not decrease pondweed biomass (Table 2). Pendimethalin, butachlor, pretilachlor, and thiobencarb have residual activity and control annual grasses and some broadleaf weeds but do not control perennials (Jordan and Kendig 1998; Baldwin 1995; Jordan et al. 1998).

Excellent control of rice broadleaf weeds by bensulfuron's sole application and its compatibility with grass killers butachlor, molinate, and thiobencarb in controlling most paddy weeds have been documented by many researchers (Kim and Im 2002; Rao et al. 2007; Yaghoubi 2016; Zhang 2003). DeDatta (1981) reported excellent control of roundleaf pondweed by simetryn plus thiobencarb or piperophos plus dimethametryn in Korean paddy fields. Although pondweed is susceptible to phenoxy herbicides (Hollingsworth 1978), this herbicide group is not popular among Iranian rice farmers, as the herbicides cause abnormal growth of rice seedlings, especially if the temperature drops below 12 C in the early season after transplanting (personal observation). Among the studied herbicides, only bensulfuron had consistent efficacy in pondweed control, which necessitates further research on other sulfonylureas herbicides.

Grain yield in all herbicide treatments was statistically similar, except with bensulfuron (Table 2). The maximum grain yield was obtained in the plots treated with bensulfuron, which had a statistically similar yield to oxadiargyl but higher than the hand-weeded control (Table 2). Grain yield in the nontreated plots was 26% less than in the bensulfuron-treated plots. The yield in the hand-weeded control was 9% more than in the nontreated plots, although it was not statistically different. Dense populations of barnyardgrass and bulrush in the hand-weeded control were present before hand-weeding (data not shown); therefore, with pondweed, more nutrient consumption occurred in this treatment, before the plants become big enough for removal by hand, and further yield reduction occurred.

Study 2: Sulfonylurea Herbicide Screening for Pondweed Control

All investigated herbicides reduced pondweed biomass ranging from 36% to 100% (Table 3). Penoxsulam as a postemergence

Table 2. Pondweed control at 4 and 6 WAT, percentage reduction in dry weight relative to the nontreated plot at 4 and 6 WAT, and rice grain yield.[a,b,c,d]

Treatment	Visual pondweed control		Pondweed biomass reduction[e]		Grain yield[f]
	4 WAT	6 WAT	4 WAT	6 WAT	
	%		%		% to nontreated
Pretilachlor	0 c	0 c	19 a	8 a	110 bc
Butachlor	0 c	0 c	22 a	3 a	111 b
Thiobencarb	0 c	0 c	14 a	1 a	112 b
Oxadiargyl	55 b	42 b	58 b	24 b	115 ab
Pendimethalin	0 c	0 c	25 a	5 a	106 bc
Bensulfuron-methyl	99 a	96 a	99 c	99 c	126 a
Hand-weeding	—	—	—	—	109 bc

[a]Abbreviation: WAT, weeks after treatment.
[b]Rough rice yield was 3,690 kg ha^{-1} in hand-weeded control.
[c]Data are averaged over 2 yr and four replicates.
[d]Means followed by the same letter within a column are not significantly different at P = 0.05 using least significant difference test.
[e]At 4 WAT, pondweed seedling density and biomass in the nontreated control was 75 plant m^{-2} and 140 g m^{-2}, respectively.
[f]Data are expressed as a percentage of the nontreated control for the respective treatment.

Table 3. Pondweed biomass reduction, regrowth, and rice grain yield as affected by herbicide treatments.[a,b,c]

Treatment	Pondweed		Rice yield,[e,f] 12 WAT
	Biomass reduction, 6 WAT	Regrowth,[d] 14 WAT	
	%	plant m^{-2}	
Bensulfuron-methyl	100 d	5 de	120 ab
Metazosulfuron	100 d	0 e	123 a
Flucetosulfuron	100 d	0 e	122 a
Metsulfuron-methyl	100 d	0 e	119 abc
Pyrazosulfuron-ethyl	98 d	12 bcd	124 a
Triafamone plus ethoxysulfuron	98 d	14 cd	121 ab
Bispyribac-sodium	89 bc	9 cd	114 bcd
Pyribenzoxim	93 c	19 b	113 cd
Penoxsulam	36 a	19 b	107 ed
Hand-weeding	100 d	18 b	114 bcd
Nontreated	—	54 a	—

[a]Abbreviation: WAT, weeks after treatment.
[b]Means are averaged over 2 yr and four replicates.
[c]Means followed by the same letter within a column are not significantly different at P = 0.05 using least significant difference test.
[d]Pondweed regrowth was measured by counting alive or green aerial tissue. Pondweed biomass was 157 g m^{-2}.
[e]Rough rice yield was 3,460 kg ha^{-1} in hand-weeded control.
[f]Data are expressed as a percentage of the nontreated for the respective treatment.

herbicide had the lowest efficacy, and all preemergence herbicides provided at least 98% control of pondweed. Bispyribac-sodium and pyribenzoxim, two other foliar-applied herbicides, provided 89% and 93% pondweed control, respectively. The results suggest that most ALS-inhibitor herbicides will prevent pondweed colonization where they are used to manage other weeds in transplanted rice.

Penoxsulam, a postemergence triazolopyrimidine sulfonamide herbicide, was developed to control annual grasses, sedges, and broadleaf weeds in rice culture (Jabusch and Tjeerdema 2005). It provides excellent barnyardgrass control, but inferior moderate broadleaf weed control was documented by other researchers (Durborow 2014; Ottis et al. 2003).

Bensulfuron applied with or without graminicides thiobencarb, butachlor, and oxadiargyl has been documented to provide greater than 95% control against pondweed (Yaghoubi 2016; Getsinger et al. 1994). Metsulfuron has been widely used in paddy fields (Chin 2001), cereal fields, grazing pasture, and forest lands for controlling broadleaf and grass weeds because of its high herbicidal activity and good selectivity (Brown 1990). It is one of the most mobile and persistent herbicides of the sulfonylurea compounds (Ismail and Chong 2003). Triafamone plus ethoxysulfuron, providing 98% control of pondweed, is one of the newly introduced herbicides for paddy rice weed control in Iran (Pouramir et al. 2020). Bispyribac-sodium, an acetohydroxy acid enzyme synthase or ALS inhibitor (Koger et al. 2007), is a member of the pyrimidinyloxybenzoic chemical family (Vencill 2002). It controls several broadleafs, sedges, and grasses, either annuals or perennials (Pearson et al. 2008).

Regrowth of plants partially injured by the herbicides was observed. Green or living tissues of pondweed at the end of the season in some treatments indicate incomplete control of pondweed and its potential survival, which might allow regrowth and reproduction. Green tissues or shoots of pondweed in the nontreated and hand-weeded plot was 54 and 18 seedlings m^{-2}, respectively (Table 3). Some soil-applied herbicides, including metazosulfuron, flucetosulfuron, and metsulfuron, did provide complete suppression of pondweed (Table 3), indicating a high residual activity of these herbicides and efficient translocation to underground organs. Bensulfuron, pyrazosulfuron, and triafamone plus ethoxysulfuron reduced pondweed regrowth by 91%, 78%, and 73%, respectively, compared to the nontreated plots. Bispyribac-sodium and penoxsulam reduced pondweed regrowth 83% and 33%, respectively. In a previous study, penoxsulam efficacy on suppressing pondweed was found to be less lasting than that of cinosulforun or bensulfuron (Maazi Kajal et al. 2012). Although bispyribac-sodium is a postemergence herbicide, it has soil residual activity also (Lassiter et al. 2004; Pearson et al. 2008). This feature may explain why bispyribac is more effective in preventing pondweed regrowth than pyribenzoxim, despite the higher efficacy of pyribenzoxim on pondweed control.

Root crown regrowth of different species of pondweed after removal from bensulfuron- or triclopyr-treated conditions has been documented (Getsinger et al. 1994; Hofstra and Clayton 2001; Sabbatini and Murphy 1996). The regrowth of leafy pondweed (*Potamogeton foliosus* Raf.) and sago pondweed was approximately twice as rapid in undrained treated tanks as in those drained before herbicide treatment (Oborn 1957). Skogerboe and Getsinger (2002) reported that sago pondweed and Illinois pondweed (*Potamogeton illinoensis* Morong) biomass was reduced following endothall application, but regrowth was observed at 8 wk after treatment.

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Regrowth of pondweed from tubers suggests a lack of herbicide translocation to tubers (Van and Stewart 1985), and regrowth from hand-weeded controls indicates the inefficiency of hand-weeding in removing and digging up the rhizomes from soil. Our results demonstrate greater efficacy of soil-applied herbicides compared with hand-weeding for pondweed regrowth control.

All investigated herbicides resulted in significantly higher grain yield compared to the nontreated plots (Table 3). The maximum grain yield was achieved by pyrazosulfuron, but the yield was similar to the yield obtained in plots treated with metazosulfuron, bensulfuron, flucetosulfuron, metsulfuron, and triafamone plus ethoxysulfuron. All soil-applied herbicide treatments provided significantly higher yield than foliage-applied herbicides penoxsulam, bispyribac-sodium, and pyribenzoxim, and even the hand-weeded control. The lowest grain yield was obtained in the nontreated plots, 14% less than in the hand-weeded plots. Tshewang et al. (2016) reported a 37% reduction in rice yield by roundleaf pondweed in Bhutan. In the current study, the paddy yield in plots treated with bispyribac-sodium, penoxsulam, and pyribenzoxim was 14%, 13%, and 7% higher than in the nontreated plots, respectively, showing that some differences in pondweed control did not translate to the reproductive stage and differences in grain yield (Table 3). Similarly, Jordan and Kendig (1998) reported that differences in barnyardgrass control among treatments did not always translate into grain yield.

Although some foliage-applied herbicides, such as pyribenzoxim, provided ≥93% control of aerial parts of pondweed, less yield in these treatments indicates the significance of pondweed competition with rice before being removed.

The lower yield of paddies with hand-weeded and foliar-applied treatments than in paddies with soil-applied herbicides indicates the importance of early-season competition between rice seedlings and weeds. These results also suggest the consumption of resources by weeds before being removed by hand or controlled by herbicides. Drainage is necessary before weeding, and this encourages nitrogen loss through denitrification. Chauhan and Abugho (2013) observed a 35% greater grain yield with herbicide use compared with hand-weeding in a dry-seeded rice system. Our previous study showed that pondweed damage to rice was dependent on the level of fertilizer, and at lower fertilizer levels than rice requirements, rough rice yield loss increased significantly (Yaghoubi et al. 2018).

Herbicide application for *Potamogeton* spp. control in aquatic environments is more common than in rice fields. Herbicides diquat, endothall, fluridone, and triclopyr control some submerged species of potamogeton, such as curly-leaf pondweed, and sago pondweed in aquatic ecosystems, but pondweed as an emerged plant is only susceptible to acrolein, endothal, penoxsulam, and glyphosate (Lancar and Krake 2002; Parsons et al. 2004; Sprecher et al. 1998). However, most of these cannot be used in rice fields, except triclopyr and penoxsulam.

This study has revealed that thiobencarb, butachlor, pretilachlor, oxadiargyl, and pendimethalin, the most commonly used herbicides for weed control in Iranian rice fields, do not provide adequate pondweed control, except bensulfuron. These graminicides are very efficient in barnyardgrass control and have reduced the time needed for hand-weeding to 90%. Bitarafan et al. (2012) reported that after four decades of using butachlor, molinate, thiobencarb, and propanil for barnyardgrass control in Iran, no resistance was detected.

Also, results showed various preemergence sulfonylurea herbicides, metsulfuron, flucetosulfuron, halosulfuroun, flucetosulfuron, pyrazosulfuron, triafamone plus ethoxysulfuron and postemergence bispyribac-sodium, pyribenzoxim, and penoxsulam sulfonylureas herbicides are effective on pondweed. Pondweed is often an early-season problem in transplanted rice and is susceptible to several soil-applied preemergence ALS-inhibitor herbicides. Thus, without extra time and costs associated with lowering flood irrigation water to allow hand-weeding or sufficient contact with foliage-applied herbicides, this weed can be controlled or eradicated by different soil-applied preemergence herbicides. However, soil-applied herbicides were superior in pondweed control over foliage-applied sulfonylureas, as shown by more inhibition of pondweed regrowth and higher grain yield. As pondweed is very susceptible to several ALS-inhibitor herbicides, the prevalence of this weed in rice fields could be attributed to the lack of use of these herbicides by many farmers in Iranian paddy fields. Recommending sulfonylureas herbicides for weed control in rice fields raises concerns about the evolution of sulfonylurea-resistant weeds. Because hand-weeding is carried out after herbicide application in almost all transplanted rice fields in Iran, potentially resistant seedlings are removed by hand, and there is not much concern about the evolution of sulfonylurea-resistant weeds in the paddy fields of Iran.

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