DOI: 10.1017/wet.2024.21

Control of *Echinochloa spp.* and *Leptochloa fascicularis* with the Novel Dihydroorotate Dehydrogenase Inhibitor Herbicide Tetflupyrolimet in California Water-seeded Rice

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Short title: Tetflupyrolimet in rice

Nomenclature: tetflupyrolimet; carfentrazone; watergrass species, *Echinochloa spp.*; bearded sprangletop, *Leptochloa fusca* (L.) *Kunth ssp. fascicularis* (Lam.) N. Snow; rice, *Oryza sativa*

Abstract

The spread of herbicide-resistant weeds is considered a major problem for rice production in California and there is a need for new herbicides. Tetflupyrolimet is a new herbicide with a novel dihydroorotate dehydrogenase (DHODH) inhibiting site of action (SOA) that has strong activity on grasses. Three field studies were conducted at the California Rice Experiment Station in Biggs, CA, in 2022 and 2023 to 1) determine control of watergrass species and bearded sprangletop with tetflupyrolimet 2) characterize the effects of tetflupyrolimet combined with other herbicides on weed control and rice, and 3) determine response of rice cultivars to tetflupyrolimet. In the first study, tetflupyrolimet was applied at preemergence (PRE) or at the 1- to 2-leaf stage of rice (POST) at 0.1, 0.125, or 0.15 kg ai ha^{-1} followed by carfentrazone. Tetflupyrolimet provided ≥ 99% control of watergrass species and 100% bearded sprangletop control regardless of the rate or application timing, while showing no crop injury symptoms or yield reduction. In the second study, tetflupyrolimet was applied PRE or POST at 0.1 or 0.15 kg ai ha^{-1} followed by herbicides labeled for use in California rice production. Tetflupyrolimet provided ≥ 98% control of watergrass species, which was better than the grower standard treatment, and ≥ 97% control of bearded sprangletop. In the third study, tetflupyrolimet was applied PRE or POST at 0.125, 0.15, 0.25, or 0.3 kg ai ha^{-1} followed by carfentrazone. The six California rice cultivars evaluated – 'M-105,' 'M-206,' 'M-209,' 'M-211,' 'L-208,' and 'CM-203' – did not show any trend of crop injury caused by tetflupyrolimet. Overall, tetflupyrolimet provided a high level of control of watergrass species and bearded sprangletop without causing visual rice injury or yield reductions, regardless of rice cultivar, when applied alone or in combination with commonly used sedge and broadleaf herbicides in California water-seeded rice.

Keywords: Herbicide resistance; weed control; varietal response

Introduction

The Sacramento Valley of California has nearly 200,000 hectares of rice (*Oryza sativa* L.) with a farm gate value of close to $1 billion (CDFA 2021). Rice grown in California is mainly medium grain cultivars. In the water-seeded rice production system, pre-germinated rice seeds are aerially broadcast onto fields continuously flooded with 5 to 10 cm of water, depending on specific management strategies. Over half of the soils in California's rice producing region have impeded drainage with a typical infiltration rate of 1 to 5 mm day^{-1}, these fields are poorly suited to most upland crops and often are continuously planted with rice (Hill et al. 2006). These soil conditions allow growers to continuously flood their fields for suppression of highly competitive grass weeds, which also contributes to this system's high productivity (Hill et al. 2006; Strand 2013).

The semi-aquatic conditions in California rice fields have led to well adapted weed populations of grasses (*Echinochloa crus-galli*, barnyardgrass; *Echinochloa oryzoides*, early watergrass; *Echinochloa phyllopogon*, late watergrass; and *Leptochloa fusca* (L.) Kunth ssp. *fascicularis* (L.) N. Snow, bearded sprangletop), sedges (*Schoenoplectus mucronatus*, ricefield bulrush; and *Cyperus difformis*, smallflower umbrellasedge), and broadleaf weeds (*Heteranthera limosa*, ducksalad; and *Ammannia* spp., redstems) (Brim-DeForest et al. 2017b; Ceseski et al. 2022). The aforementioned grass weed species have especially been found to heavily compete with rice, if unmanaged, causing a significant decrease in yields (Smith 1983; Stauber et al. 1991; Gibson et al. 2002; Oerke 2006; Brim-DeForest 2017a; Kanter et al. 2021).

California's unique crop diversity paired with strict regulatory structures have limited the number of herbicide active ingredients available to rice growers because of the potential for herbicide drift to nearby orchards as well as heightened regulations regarding environmental toxicology (Hill et al. 2006; Prather et al. 2000). With a total of 14 active ingredients registered for use in rice in California, six are within the same site of action group 2 or acetolactate synthase-inhibiting herbicides (Espino et al. 2019). Due to limited residual activity of these products and a narrow weed control spectrum, common weed control strategies include the application of multiple herbicides to achieve effective control of grass, sedge, and broadleaf weeds in rice fields. The reliance on limited herbicidal chemistries for decades in continuous rice has selected for weed populations that are resistant to these herbicides (Becerra-Alvarez et al.

2022; Brim-DeForest et al. 2022). Multiple cases of herbicide resistance have been detected in all aforementioned grass and sedge weed species and redstem, to various active ingredients throughout California rice fields (Fischer et al. 2000; Yasuor et al. 2008, 2009; Abdallah et al. 2014; Hanson et al. 2014; Heap 2014; Valverde et al. 2014; Becerra-Alvarez et al. 2023). The drastic rise of herbicide resistance in rice weeds has proven to be a major problem for rice growers by increasing the cost of herbicide treatment programs.

A decades long lapse in development of novel SOAs due to the increased cost of development of new active ingredients, increased toxicological and environmental regulations, and the consolidation of agrichemical industry to a few dominating companies, has left growers overusing the same active ingredients and modes of action, therefore exacerbating the effects of herbicide resistance in agriculture (Dayan 2019; Davis and Frisvold 2017; Duke 2012). Herbicide discovery, however, has since been revived and led to the introduction of a few new chemicals including tetflupyrolimet, a novel dihydroorotate dehydrogenase (DHODH) inhibitor that has herbicidal activity on grasses (Dayan et al. 2019; Satterfield et al. 2014). Tetflupyrolimet was discovered in 2014 through high-volume sourced greenhouse screening (Gaines et al. 2021; Selby et al. 2023).

Tetflupyrolimet is in the aryl pyrrolinone anilide chemical family and disrupts the de novo pyrimidine nucleotide biosynthesis pathway at the DHODH step, which is the only redox reaction of the pathway, causing both an over accumulation of dihydroorotate (DHO) and a deficiency of uridine-5'-monophosphate (UMP) (Nagy et al. 1992; Björnberg et al. 1997; Dayan 2019). The de novo pyrimidine nucleotide biosynthesis pathway is an essential process for metabolism, gene expression, and the production of substrates for DNA, RNA, and multiple biosynthesis pathways (Zrenner et al. 2006; Santosos and Thornburg 1998). There are six enzymatic steps in the pathway and some organisms have significantly different enzymes for these steps (Santosos and Thornburg 1998; Nara et al. 2000; Doremus 1986). Most of pyrimidine biosynthesis in plants occurs in the chloroplast, however DHODH is localized in the outer surface of the inner mitochondrial membrane (Kafer and Thornburg 1999; Chen and Jones 1976; Doremus and Jagendorf 1985; Miersch et al. 1986). The few peer reviewed articles that mention tetflupyrolimet's herbicidal activity note that the compound provides excellent grass control and safety on rice (Selby et al. 2023; Dayan 2019). For example, tetflupyrolimet's activity on foxtail was reported as 10-fold greater than on rice (Dayan 2019). This may suggest that rice can metabolize tetflupyrolimet, which may result in a high level of resistance in *Oryza* spp.

Tetflupyrolimet was designed as a preemergence (PRE) and early post-emergence (POST) granular herbicide in rice; however, weed control and crop response to tetflupyrolimet are not well studied. The objectives of this research were to 1) determine the control of watergrass species and bearded sprangletop with various rates of tetflupyrolimet applied at the PRE or POST timings 2) characterize the effects of tetflupyrolimet on weed control and rice when applied in combination with other rice herbicides and 3) determine response of rice cultivars to tetflupyrolimet in a water-seeded rice system.

Materials and Methods

Site Conditions and Preparation

Three field experiments were conducted during the 2022 and 2023 growing seasons at two sites at the California Rice Experiment Station (CRES) near Biggs, CA. Site one (39.46°N, 121.74°W) was located on the west end of the station property and site two (39.45°N, 121.72°W) was on the station's east end. Soils at both sites are classified as Esquon-Neerdobe (fine, smectitic, thermic Xeric Epiaquerts and Duraquerts) clay. The soil at site one had a pH of 5.2 and 1.9% organic matter, while soil at site two had a pH of 5.1 and 1.9% organic matter. The average minimum and maximum daily temperatures in Biggs, CA during the growing season (May to October) in 2022 were 16.6 C and 34.0 C and in 2023 were 13.0 °C and 30.3 °C, respectively. The sites' weed seedbank has been described in Brim-DeForest et al. (2017a, 2017b) and contains watergrass species, bearded sprangletop, ricefield bulrush, smallflower umbrellasedge, ducksalad, and redstem.

Field preparation in both years began with a pass of a single offset stubble disk once the winter flood was drained and the soil was dry enough to allow for equipment to pass. Prior to planting, field operations consisted of one pass with a chisel plow and two passes with a single-offset disk, followed by a land plane to smooth the soil surface. Site one was fertilized with 169 kg N ha^{-1} as aqua-ammonia (20-0-0) and site two was fertilized with 114 kg N ha^{-1} as 34-17-0 in both years. Prior to flooding the field in the spring, a corrugated roller was used to pack the soil and eliminate large clods on the soil surface. Plots were 3 m by 6 m and surrounded by small levees pulled by a ridger to prevent herbicide cross contamination to other plots. Standard agronomic and pest management practices were followed based on the University of California rice production guidelines (UCANR 2023).

Plant Material

Rice seeds were soaked in water for 24 hours allowing for pre-germination then the water was drained. Depending on the study, seeds were either evenly broadcasted by hand or aerially broadcasted at a rate of 168 kg ha^{-1} into a 10 cm flooded field. Rice cultivar 'M-209' was used in the watergrass species and bearded sprangletop control study as well as the evaluation of tetflupyrolimet's interaction with common herbicides study. The rice varietal response to tetflupyrolimet study included one short, four medium, and one long grain cultivars with two different maturity timings to cover an array of genetic backgrounds that are grown in California. Rice grain was harvested from each 18 m^2 plot with a specialized small plot combine with a swath width of 2.3 m (Almaco, Nevada, Iowa, USA). Rice grain yield for all experiments was adjusted to 14% moisture.

Herbicide Application

Herbicide applications were timed according to the University of California rice production guidelines (UCANR 2023). Granular herbicides were evenly broadcasted by hand. Foliar herbicides were applied with a CO_2-pressurized 2 m boom equipped with six 8002VS flat-fan nozzles (TeeJet Technologies, Springfield, Illinois, USA) calibrated to deliver 187 L ha^{-1} at 193 kPa. For POST combination treatments, the spray mixture included 1.25 % v/v crop oil concentrate (COC, Agri-Dex ®, Collierville, TN, USA). Treatments including propanil or triclopyr required the 10 cm flood to be reduced in order to broaden the coverage of weeds below the water's surface, therefore, these plots were drained prior to the application then reflooded to 10 cm 48 hours after application.

Study 1: Watergrass species and bearded sprangletop control study

This study aimed to determine the control of barnyardgrass, early watergrass, late watergrass, and bearded sprangletop with various rates of tetflupyrolimet applied at the PRE or POST timings. Study 1 was a single-factor randomized complete block design with three replicates conducted twice in 2023 at the aforementioned sites. Before flooding, 1,000 seeds of bearded sprangletop were evenly broadcasted by hand and raked into each plot to increase the population of this target weed species. Plots were seeded with rice cultivar ‘M-209’ by hand on May 20, 2023, for site one and aerially broadcasted on June 2, 2023, for site two.

Tetflupyrolimet (FMC Corp., Philadelphia, Pennsylvania, USA) was applied as a 1% by weight granular formulation of the herbicide at PRE and POST and three rates followed by 0.53 kg ha^{-1} carfentrazone (SHARK® H2O, FMC Corp., Philadelphia, Pennsylvania, USA) applied as a granular at 2 to 3 leaf annual grass to control sedge and broadleaf weeds (Table 1). The same formulation of tetflupyrolimet was used in all three experiments. In addition, clomazone (CERANO® 5 MEG, Wilbur-Ellis Company LLC, Fresno, California, USA) and penoxsulam (Granite® GR, Corteva AgriScience, Indianapolis, IN, USA) was included as a grower standard treatment for comparison. A treatment of carfentrazone alone at the same rate and timing as mentioned previously was added to compare a plot with grass weeds only since this herbicide does not have control grasses.

Visual weed control ratings were conducted for watergrass species and bearded sprangletop at 14, 28, 42, and 56 days after PRE or POST tetflupyrolimet treatment (DAT) on a percent control scale ranging from 0 (no control) to 100 (complete control or no weeds present). Barnyardgrass, early watergrass, and late watergrass control ratings were grouped together as watergrass species because they are hard to differentiate at early growth stages (Fischer et al. 2000). Visual rice phytotoxity ratings were conducted at 7, 14, and 28 DAT for general, chlorosis, bleaching, stunting, stand reduction, and necrosis on a scale ranging from 0 (no injury) to 100 (plant kill) as compared to the control plots (Frans 1986). Rice plant counts were conducted at each site at 4-leaf stage of rice (LSR) in the treated plots. Plant counts were measured in every plot by randomly laying out four 645 cm^{2} quadrats. Rice plant counts were averaged between the four subplot counts and density was converted to plants m^{-2}. The control plots were measured in the same manner for weed counts of watergrass species and bearded sprangletop. Weed counts were averaged at 7, 14, and 28 DAT for every control plot to get density in number of weeds m^{-2}. Additionally, the control plots were visually estimated for percent weed coverage for watergrass species, bearded sprangletop, ricefield bulrush, smallflower umbrellasedge, ducksalad, and redstem on a percent coverage scale of 0 (no weeds present) to 100 (complete plot coverage).

Study 2: Evaluation of tetflupyrolimet's interaction with common herbicides study

The objective of this study was to characterize the effects of tetflupyrolimet on weed control and rice when applied in combination with other commonly used sedge and broadleaf rice herbicides. Study 2 was a single factor randomized complete block design with three replicates conducted at site two in 2022 and 2023. Seeds of rice cultivar 'M-209' were aerially broadcasted on May 23, 2022, and June 1, 2023. Tetflupyrolimet was applied at two timings and two rates (Table 2).

Tetflupyrolimet was applied in combination with or followed by recommended rates of carfentrazone, clomazone, thiobencarb (Bolero® UltraMax, Valent USA, San Ramon, CA, U.S.A.), propanil (SUPERWHAM! CA, UPL NA Inc, King of Prussia, PA, USA), triclopyr (Grandstand® CA, Corteva AgriScience, Indianapolis, IN, USA), bensulfuron (LONDAX®, UPL NA Inc, King of Prussia, PA, USA), and benzobicyclon plus halosulfuron (BUTTE®, Gowan Company LLC, Yuma, Arizona, USA) at their respective recommended application timings (Table 2). These treatments were compared to a grower standard of benzobicyclon plus halosulfuron followed by propanil followed by a mixture of propanil and triclopyr as well as an nontreated control.

Visual ratings for weed control were conducted the same as the previous study but included the weed species ricefield bulrush, smallflower umbrellasedge, ducksalad, and redstem. Visual ratings of rice response as well as rice plant counts and weed quantification were conducted in the same manner described in the previous study.

Study 3: Rice varietal response to tetflupyrolimet study

This experiment was a two-factor split-plot design, where cultivar was the main plot and the herbicide treatments were the subplots, with three replicates conducted in 2022 and 2023 at site two. Seeding dates were May 27, 2022, and May 31, 2023. Seeds of rice cultivars 'M-105,' 'M-206,' 'M-209,' 'M-211,' 'L-208,' and 'CM-203' were broadcasted by hand.

Tetflupyrolimet was applied as a granular formulation of 1% at two timings and four rates followed by carfentrazone applied at 0.53 kg ha^{-1} at 2 to 3 LSR to control sedge and broadleaf weeds (Table 3). In addition, a standard herbicide treatment of benzobicyclon plus halosulfuron followed by propanil and triclopyr was included for a weed free comparison along with a treatment of carfentrazone alone at the same rate and timing as in Study 1. This standalone carfentrazone treatment provided good suppression of broadleaves and sedges and was used in comparison to the grower standard treatment to assess impact of grass weeds on yield. Visual ratings of rice injury, rice plant counts, and weed quantification were measured in the same manner as described in the previous studies.

Statistical Analysis

The data for the three experiments were tested for homogeneity of variance and analyzed using ANOVA and linear regression in R (R Core Team 2023). Means separation was performed using Tukey-Kramer's honestly significant difference (HSD) at 95% significance level. Linear models were fit with the *lme4* (Bates et al. 2015) and *lmerTest* (Kuznetsova et al. 2017) packages. Marginal means were estimated with the *emmeans* (Lenth 2023) package and the *multcomp* (Hothorn et al. 2008) package was used to generate multiple comparisons among means. Control plots were excluded from the weed control and rice injury ANOVA because all values were 0. Study 1 had herbicide treatment, site, and time of rating used as fixed effects and block used as a random effect. Study 2 had herbicide treatment, year, and time of rating used as fixed effects and block used as a random effect. Study 3 had herbicide treatment, cultivar, treatment by cultivar, year, and time of rating used as fixed effects and block used as a random effect.

Results and Discussion

Study 1: Watergrass species and bearded sprangletop control study

The weed control data showed no significant interaction between sites. The rice response data, however, showed significant treatment by site interaction for bleaching symptoms but not for chlorosis, stunting, stand reduction, necrosis, and yield. Therefore, the data for bleaching were analyzed separately by site while weed control data and all other injury symptoms and yield for both sites were combined.

Weed population composition varied at the two sites for this experiment. Site one had control plots dominated by sedges and broadleaf weeds, averaging 73% coverage, while watergrass species abundance averaging 2% and bearded sprangletop abundance averaging 5% based on the treated control plots (data not shown). The control plots at site two had no sedge or broadleaf weeds and were dominated by watergrass species and bearded sprangletop, averaging 32 and 15%, respectively (data not shown). Weed populations could differ at these two sites because of differences in management practices, flooding time, and planting dates.

All treatments, including the grower standard, across both sites provided complete season-long watergrass species control (data not shown). The grower standard treatment had 100% control of bearded sprangletop early in the season, then decreased to 99% control by the end of rice heading stage. Every treatment that included tetflupyrolimet had a season-long complete control of bearded sprangletop. All treatments were similar for control of bearded sprangletop and no PRE herbicide applications showed escapes. Other experiments have made observations of bearded sprangletop escapes from PRE herbicide application due to the delayed emergence of some populations of this species, which suggests tetflupyrolimet has longer-lasting control than other graminicides (Driver et al. 2020). Tetflupyrolimet's season-long control of these problem grass weed species, both at the PRE and POST timings, may be useful for growers who want to rotate a new SOA in their herbicide program. Tetflupyrolimet provides an opportunity to eliminate these problem grass weeds that have resistance as outlined in a field survey of California rice weeds by Becerra-Alvarez et al. in 2022 and 2023. Becerra-Alvarez also tested tetflupyrolimet against all submitted grass samples, finding complete control in all samples (A Becerra-Alvarez, unpublished data).

Rice injury symptoms observed were bleaching, chlorosis, stunting, and stand reduction across both sites. At both sites, moderate early bleaching was observed in the grower standard treatments (clomazone followed by penoxsulam) and then subsided later in the season (Table 4). The injury is not surprising due to the extensive characterization of rice's response to the bleaching herbicide, clomazone (Jordan et al. 1998). The grower standard treatment also showed moderate stunting at 28 DAT due to the early POST application of penoxsulam, which is known to cause stunting and chlorosis in rice (Bond et al. 2007). PRE and POST tetflupyrolimet treatments did not show any bleaching throughout the season. Chlorosis, stunting, and stand reduction symptoms in all tetflupyrolimet treatments averaged across both sites were overall minimum, ranging from 0 to 8% by 28 DAT (Table 5). All symptoms observed were slight, and the rice was fully recovered by 42 DAT (data not shown). There was no significant interaction between treatments for any of these symptoms and no trend of increased symptoms with increased rate or varied application timing. The work done by Selby et al. in 2023 supports the observation that tetflupyrolimet shows no significant chlorosis or necrosis in rice. These slight symptoms were not surprising and were possibly due to the cooler nights recorded around Biggs, CA in 2023, averaging 14 °C during the germination and early vegetative stages (Das 2015; Ceseski et al. 2022).

Yield for the grower standard treatment averaged 5,390 kg ha^{-1} while yields of tetflupyrolimet treatments were not significantly different and ranged between 5,770 to 6,300 kg ha^{-1}. The similarities of yield data indicates that the slight early injury observed in tetflupyrolimet treatments did not affect yield. As discussed previously, the 2023 growing season experienced colder than usual temperatures, which could be a contributing factor of the lower yield measured in this study (Delerce et al. 2016). Although temperature alone could not account for this experiment's low yields, a late planting date and rice lodging after heading also may have contributed to the low yields (Lang et al. 2012; UCANR 2023).

Tetflupyrolimet provided excellent season-long control of watergrass species and bearded sprangletop regardless of application timing. There was no trend of late season escapes of bearded sprangletop in tetflupyrolimet treatments, unlike other bearded sprangletop control herbicides such as clomazone and thiobencarb.

Study 2: Evaluation of tetflupyrolimet's interaction with common herbicides study

There was significant treatment-by-year interaction for weed control, so the data were analyzed separately by year for watergrass species, bearded sprangletop, ricefield bulrush, smallflower umbrellasedge, ducksalad, and redstem. There was also significant treatment-by-year interaction for yield, while no significant interaction was detected for rice chlorosis, bleaching, stunting, stand reduction, and necrosis. Therefore, all weed control and yield data were analyzed separately by year while all rice injury symptom data were combined.

Weed population composition varied each year: in 2022, there was a lower density of sedge and broadleaves than in 2023; however, the dominant species for both years was watergrass species. In 2022, the untreated control plots had an abundance of watergrass species and bearded sprangletop cover, averaging 62% of the plot, while the sedges and broadleaves had an average of 23% relative cover by 4 LSR (data not shown). In 2023, the untreated controls plots had a higher abundance of both grasses, averaging 74%, as well as sedges and broadleaves, averaging 45% abundance (data not shown). This shift in weed population composition is not surprising and has been observed before in previous experiments near this site due to differences in soil moisture and temperature throughout the growing season (Becerra-Alvarez et al. 2022; Brim-Deforest et al. 2017a; Lundy et al. 2014).

In 2022, the grower standard treatment showed 94% control of watergrass species throughout the season (Table 6). The grower standard treatment had significantly lower control than all treatments that included tetflupyrolimet, which had 98 to 100% control of watergrass species throughout the season. The grower standard treatment showed complete control of bearded sprangletop at 14 DAT, but decreased to 99% control by 56 DAT. The PRE tetflupyrolimet treatments showed a similar trend with bearded sprangletop control, shifting from complete control at 14 DAT to decreasing by a few percent points, ranging from 97 to 100%. However, treatments that included a POST application of tetflupyrolimet combined with a PRE herbicide with herbicidal activity on grasses maintained complete control throughout the season (Table 6).

In 2023, the grower standard treatment maintained complete control of watergrass species throughout the entire season (Table 7). Tetflupyrolimet treatments had complete or nearly complete control of watergrass species by 14 DAT, but by 56 DAT, complete control was observed in all treatments regardless of tetflupyrolimet application timing. The grower standard treatment had near complete control of bearded sprangletop at 14 DAT, which later increased to complete control by 56 DAT. Treatments including both PRE and POST applications of tetflupyrolimet had a season-long complete control of bearded sprangletop.

Excellent grass control by tetflupyrolimet is consistent even when combined with other herbicides with or without activity on grasses. Mixing tetflupyrolimet with graminicides does not appear to adversely affect POST graminicides unlike the combination of other rice herbicides, such propanil tank mixed with acetyl coenzyme A carboxylase-inhibiting herbicides that was reported by Matzebacher et al. (2015). Because tetflupyrolimet has activity on grasses with little activity on sedge or broadleaf weeds, a combination of tetflupyrolimet with other herbicides that control sedge and broadleaf weeds is required for complete control of the weed species that are common in California rice fields.

In 2022, the grower standard treatment showed season long complete control of ricefield bulrush (Table 6). All other treatments showed complete control of ricefield bulrush at 14 DAT, which then decreased by 56 DAT and ranged from 88 to 97% control in treatments that did not include benzobicyclon plus halosulfuron, which is an herbicide treatment with known activity on ricefield bulrush (Espino et al. 2019). The control of smallflower umbrellasedge was similar to results of ricefield bulrush control where complete control was obtained by the grower standard and all other treatments at 14 DAT, followed by a minimal decrease in control by 56 DAT for tetflupyrolimet followed by carfentrazone, tetflupyrolimet followed by bensulfuron followed by propanil, tetflupyrolimet followed by triclopyr plus propanil, and clomazone followed by tetflupyrolimet followed by propanil. The only significantly different treatment for smallflower umbrellasedge control was tetflupyrolimet followed by carfentrazone, which still had 72% control of smallflower umbrellasedge. The lessened control of smallflower umbrellasedge for this treatment is unlikely to be from herbicide resistance because previous greenhouse trials reported that this species did not show resistance to carfentrazone (Becerra-Alvarez et al. 2023). Complete season long control of ducksalad was achieved by the grower standard treatment as well as all other treatments besides tetflupyrolimet followed by carfentrazone, which showed 90% control at 56 DAT. Control of redstem by the grower standard treatment shifted from complete control at 14 DAT to near complete control by 56 DAT. All other treatments not including benzobicyclon plus halosulfuron had complete season long control of redstem. PRE tetflupyrolimet followed by POST benzobicyclon plus halosulfuron had moderate control of redstem at 82%, while PRE benzobicyclon plus halosulfuron followed by POST tetflupyrolimet had minimal control of redstem at 33%. Redstem is known to emerge later in the season, missing the PRE applications (Brim-DeForest et al. 2017b; Espino et al. 2019). The delayed emergence explains why greater control is achieved when benzobicyclon plus halosulfuron is applied POST rather than PRE, since it has slight control of this species while tetflupyrolimet has no control of redstem. Therefore, herbicides, such as propanil and triclopyr, are needed to successfully control redstem.

In 2023, control of ricefield bulrush by the grower standard at 14 DAT was 98% and 100% at 56 DAT (Table 7). There was a wide range of 40 to 100% control of ricefield bulrush for all other treatments. Ricefield bulrush control was 65, 50, and 40% with tetflupyrolimet followed by triclopyr and propanil, clomazone followed by tetflupyrolimet followed by propanil, and tetflupyrolimet followed by benzobicyclon plus halosulfuron, respectively. The low ricefield bulrush control by these treatments was largely because none of the PRE herbicides in these treatments have good activity on sedges (Espino et al. 2019). Furthermore, the 14 DAT rating was only 2 to 3 days after the follow up herbicide application which was not enough time to completely control ricefield bulrush. By 56 DAT, near complete or complete control was observed in all treatments except tetflupyrolimet followed by carfentrazone, which gave 77% control.

In 2023, smallflower umbrellasedge control by the grower standard increased from 96% control at 14 DAT to complete control by 56 DAT. All other treatments showed either near complete or complete control of smallflower umbrellasedge throughout the season. The grower standard showed complete control of ducksalad throughout the entire season. In all the other treatments, there was complete control of ducksalad at 14 DAT besides tetflupyrolimet followed by triclopyr (43%) and clomazone followed by tetflupyrolimet followed by propanil (50%). This varying control is once again because of the application timings, where the PRE herbicides do not have activity on ducksalad but by 56 DAT, an application of propanil or triclopyr has been made. Near complete control was shown at 56 DAT in all treatments excluding tetflupyrolimet followed by carfentrazone, which was significantly lower from most other treatments at 83%. The grower standard treatment showed no control of redstem at 14 DAT due to the weak activity of benzobicyclon plus halosulfuron on redstem (Becerra-Alvarez et al. 2023; Espino et al. 2019), however by 56 DAT, redstem was completely controlled by the subsequent propanil and triclopyr applications. All other treatments had complete control of redstem at 14 DAT. However, by 56 DAT, control of redstem in treatments that did not include an application of propanil decreased, ranging from 63 to 73%, while the treatments that did include an application of propanil achieved near complete control (92 to 97%). The control of grass, sedge, and broadleaf weeds by the combination of herbicides used in this experiment showed acceptable control in both years. There have been a multitude of both herbicide synergism and antagonism cases in rice across the world, such as the synergism of barnyardgrass and red rice control when mixing imazethapyr, propanil, and thiobencarb (Fish et al. 2015). This suggests that tetflupyrolimet may be more user friendly for applicators and growers than other available rice herbicides, however, it is crucial to understand the weed populations dynamics in a field when choosing herbicide programs to ensure the effective control of all weed species present.

The grower standard treatment showed slight rice injury symptoms of stunting and stand reduction by 28 DAT, which completely recovered by 42 DAT (data not shown). No tetflupyrolimet treatments showed any evidence of stand reduction at 14 DAT. At 28 DAT, tetflupyrolimet followed by thiobencarb followed by propanil showed 16% injury compared to the nontreated control. Because of the ability of thiobencarb to reduce shoot growth, the application of thiobencarb could have had damaged the root system of the rice causing death of some plants that were not completely anchored to the seedbed (Mabbayad and Moody 1992). There was no chlorosis observed for any herbicide treatment at 14 DAT, however at 28 DAT, only three treatments – tetflupyrolimet followed by benzobicyclon plus halosulfuron, tetflupyrolimet followed by thiobencarb followed by propanil, and benzobicyclon plus halosulfuron followed by tetflupyrolimet – showed very slight chlorosis. Rice plants, however, completely recovered from chlorosis by 42 DAT. Moderate (42%) bleaching was observed in the clomazone followed by tetflupyrolimet followed by propanil treatment at 7 DAT but fully recovered by 14 DAT, which was not surprising because clomazone is known to cause bleaching of rice after its application (Becerra-Alvarez et al. 2022). There were no bleaching symptoms observed in any other treatments. No significant stunting was observed at 14 DAT for any treatment. At 28 DAT, tetflupyrolimet followed by thiobencarb followed by propanil showed slight stunting symptoms of 10% (data not shown). This response was not surprising because thiobencarb is known to show stunting in rice (Baltazar and Smith 1994). By 42 DAT, however, the stunted rice had completely recovered. There were no significant or lasting necrosis symptoms observed in this study.

The average yield for the nontreated control in 2022 was 3,690 kg ha^{-1}, which was significantly lower than all other treatments (Table 8). The grower standard treatment yielded 9,120 kg ha^{-1}, which was not significantly different from any tetflupyrolimet treatment. Of the tetflupyrolimet treatments, the lowest yielding treatment was clomazone followed by tetflupyrolimet followed by propanil at 7,740 kg ha^{-1} and the highest yielding treatment was tetflupyrolimet followed by thiobencarb followed by propanil treatment 9,550 kg ha^{-1}. The reduced yield of the clomazone followed by tetflupyrolimet followed by propanil treatment could be due to early bleaching resulting from the PRE clomazone application (data not shown). The greater yield from the tetflupyrolimet followed by thiobencarb followed by propanil treatment could be from superior weed control throughout the season that caused a lower level of weed competition to rice. However, in 2023, the only significant difference detected was that the yield of the nontreated control (2,940 kg ha^{-1}) was significantly lower than all other treatments (6,650 to 7,950 kg ha^{-1}). The difference of higher yields in 2022 and lower yields in 2023 could possibly be due to the cooler weather during the 2023 season compared to 2022 (Ceseski et al. 2022).

The introduction of tetflupyrolimet to the rice cropping system is contingent upon its ability to perform well in an herbicide program where sedge and broadleaf weeds can be controlled as well. Tetflupyrolimet applied in combination with benzobicyclon plus halosulfuron, thiobencarb followed by propanil, bensulfuron followed by propanil, triclopyr and propanil, or clomazone followed by propanil provided near perfect season long weed control. Excellent crop safety was displayed across each experiment, regardless of rate or timing. Tetflupyrolimet gave excellent grass control as both a preemergence and postemergence herbicide incorporated into a weed management program, however, if tetflupyrolimet is applied later than day of seeding, a higher rate is likely needed for the same grass control results.

Study 3: Rice varietal response to tetflupyrolimet study

There was significant interaction between treatment and year for necrosis and yield while there were no significant treatment by year interactions for bleaching, chlorosis, stunting, and stand reduction symptoms. Therefore, necrosis and yield data were analyzed separately by year and all other rice symptom data were combined.

In general, slight chlorosis symptoms in both years were observed in the grower standard treatment for 'CM-203,' 'M-206,' and 'M-209' at 14 DAT but rice plants completely recovered by 28 DAT (data not shown). The grower standard treatment also showed minimal stunting and stand reduction symptoms in all cultivars, which fully recovered from stunting shortly thereafter.

No tetflupyrolimet treatments, regardless of application timing or rate, had significant levels of chlorosis, bleaching, stunting, or stand reduction at any rating time.

In 2022, consistent necrosis on the tips of the rice leaves was observed. At 14 DAT, all treatments besides PRE tetflupyrolimet at 0.125 kg ai ha^{-1} showed minimal necrosis, however, it does not seem to be a trend of a specific cultivar showing necrotic symptoms (Table 9). Importantly, these necrosis symptoms also were observed in treatments that did not include tetflupyrolimet, which suggests that the necrosis symptoms were not related to application of tetflupyrolimet and also reiterates the findings of Selby et al. in 2023 that tetflupyrolimet does not cause injury in rice. These minimal symptoms persisted until the end of rice heading stage when they fully recovered before harvest. Average yield data for all tetflupyrolimet treatments were similar to the grower standard treatment within every cultivar (data not shown).

In 2023, there were no necrosis symptoms observed, which suggests that the necrosis symptoms observed in 2022 were not from tetflupyrolimet, but rather possibly abiotic factors (Table 8). Furthermore, no necrosis symptoms were observed in any of the other two experiments, regardless of year or site. Genetic variations within species can contribute to differential response of herbicides, however, no varietal response to tetflupyrolimet was observed in this study. Rice varietal response was reported in California when clomazone and triclopyr were used (Zhang et al. 2004; Pantone and Baker 1992). The yield data in 2023 for all tetflupyrolimet treatments (5,650 to 8,100 kg ha^{-1}) were comparable to the grower standard treatment (6,620 to 8,030 kg ha^{-1}) for every cultivar.

Out of the six rice cultivars evaluated – ‘M-105,’ ‘M-206,’ ‘M-209,’ ‘M-211,’ ‘L-208,’ and ‘CM-203’ – did not show any trend of crop injury caused by tetflupyrolimet. Tetflupyrolimet could be a valuable addition to weed control programs in California water seeded rice, regardless of cultivar grown.

Practical Implications

Rice growers in California have been battling herbicide resistant weeds, especially grasses, for decades which pose a great threat of yield and grain quality loss. The recently developed novel SOA herbicides, like tetflupyrolimet, can be rotated in existing herbicide programs to help growers more effectively control these problem weeds. The work done in this research determined the effectiveness of tetflupyrolimet on control of watergrass species and bearded sprangletop as well as a high level of crop safety in multiple rice cultivars. The research has also shown that tetflupyrolimet can be inputted into an herbicide program, which can obtain high levels of weed control for watergrass species, bearded sprangletop, ricefield bulrush, smallflower umbrellasedge, ducksalad, and redstem. Further research can be done to specifically identify synergistic or antagonist effects of tetflupyrolimet when applied with other herbicides to find the most effective herbicide program. Furthermore, tetflupyrolimet may also be a promising weed control tool for other crops besides rice and should be investigated.

Acknowledgements

The authors acknowledge the California Rice Experiment Station in Biggs, CA for assistance with field preparation and equipment. Also acknowledged are several past and present lab members, technicians, and student assistants who assisted with the labor and maintenance of this project.

Funding Statement

The authors acknowledge the California Rice Research Board and FMC Corp. for the funding of this project.

Conflicts of Interest: No conflicts of interest have been declared

References

Abdallah IS, Garcia A, Fischer AJ (2014). Rice field bulrush (*Schoenoplectus mucronatus* (L.) Palla) evolved multiple resistances to propanil and bensulfuron herbicides. J. Biol. Chem., 31, 788-99.

Baltazar AM, Smith RJ (1994). Propanil-resistant barnyardgrass (*Echinochloa crus-galli*) control in rice (*Oryza sativa*). Weed Technol., 8, 576-581.

Bates D, Mächler M, Bolker B, Walker S (2015). “Fitting linear mixed-effects models using lme4.” J. Stat. Soft., 67, 1–48.

Becerra-Alvarez A, Ceseski AR, Al-Khatib K (2022). Weed control and rice response from clomazone applied at different timings in a water-seeded system. Weed Technol., 36, 414-418.

Becerra-Alvarez, A Godar AS, Ceseski AR, Al-Khatib K (2023). Herbicide resistance management in rice: annual field survey of California rice weeds helps establish a weed management decision framework. Pestic. Outlook, 34, 51-57.

Björnberg O, Rowland P, Larsen S, Jensen KF (1997). Active site of dihydroorotate dehydrogenase A from *Lactococcus lactis* investigated by chemical modification and mutagenesis. Biochem., 36, 16197-16205.

Bond JA, Walker TW, Webster EP, Buehring NW, Harrell DL (2007). Rice cultivar response to penoxsulam. Weed Technol., 21, 961-965.

Brim-DeForest WB, Al-Khatib K, Fischer AJ (2017a). Predicting yield losses in rice mixed-weed species infestations in California. Weed Sci., 65, 61-72.

Brim-DeForest WB, Al-Khatib K, Linquist BA, Fischer AJ (2017b). Weed community dynamics and system productivity in alternative irrigation systems in California rice. Weed Sci., 65, 177-188.

Brim-DeForest WB, Al-Khatib K, Fischer AJ (2022). Emergence and early growth of multiple herbicide–resistant and-susceptible late watergrass (*Echinochloa phyllopogon*). Weed Technol., 36, 101-109.

[CDFA] California Department of Food and Agriculture (2021) California Agricultural Statistics Review 2020-2021. Sacramento, CA: California Department of Food and Agriculture

Ceseski AR, Godar AS, Al-Khatib K (2022). Combining stale seedbed with deep rice planting: a novel approach to herbicide resistance management?. Weed Technol., 36, 261-269.

Chen JJ, Jones ME (1976). The cellular location of dihydroorotate dehydrogenase: relation to de novo biosynthesis of pyrimidines. Arch. Biochem. Biophys., 176, 82-90.

Das S (2015) Variability of cold injuries in boro rice (*Oryza sativa* L.). Trends. Biosci., 8, 2465-2467. Print: ISSN 0974, 8.

Davis AS, Frisvold GB (2017). Are herbicides a once in a century method of weed control?. Pest. Manage. Sci., 73, 2209-2220.

Dayan F E (2019). Current status and future prospects in herbicide discovery. Plants, 8, 341.

Delerce S, Dorado H, Grillon A, Rebolledo MC, Prager SD, Patiño VH, Garcés Varón G, Jiménez D (2016) Assessing weather-yield relationships in rice at local scale using data mining approaches. PloS One, 11, e0161620.

Doremus HD (1986). Organization of the pathway of de novo pyrimidine nucleotide biosynthesis in pea (*Pisum sativum* L. cv Progress No. 9) leaves. Arch. Biochem. Biophys., 250, 112-119.

Doremus HD, Jagendorf A T (1985). Subcellular localization of the pathway of de novo pyrimidine nucleotide biosynthesis in pea leaves. Plant Physiol., 79, 856-861.

Driver KE, Al-Khatib K, Godar A (2020). Survey of bearded sprangletop (*Leptochloa fusca* spp. fasicularis) response to clomazone in California rice. Weed Technol., 34, 661-665.

Duke SO (2012). Why have no new herbicide modes of action appeared in recent years?. Pest. Manage. Sci., 68, 505-512.

Espino L, Greer C, Al-Khatib K, Godfrey L, Eckert J, Fischer A, Lawler S (2019). Rice: UC IPM pest management guidelines. Publication No. 3465. Davis: University of California Department of Agriculture and Natural Resources. 56 p

Fischer AJ, Ateh CM, Bayer DE, Hill JE (2000). Herbicide-resistant *Echinochloa oryzoides* and *E. phyllopogon* in California *Oryza sativa* fields. Weed Sci., 48, 225-230.

Fish JC, Webster EP, Blouin DC, Bond JA (2015). Imazethapyr co-application interactions in imidazolinone-resistant rice. Weed Technol., 689-696.

Frans R (1986). Experimental design and techniques for measuring and analyzing plant responses to weed control practices. Res. Methods Weed Sci, 29-46.

Gaines TA, Busi R, Küpper A (2021). Can new herbicide discovery allow weed management to outpace resistance evolution?. Pest. Manage. Sci., 77, 3036-3041.

Gibson KD, Fischer AJ, Foin TC, Hill JE (2002). Implications of delayed *Echinochloa* spp. germination and duration of competition for integrated weed management in water-seeded rice. Weed Res., 42, 351-358.

Hanson BD, Wright S, Sosnoskie LM, Fischer A, Jasieniuk M, Roncoroni JA, Hembree KJ, Orloff S, Shrestha A, Al-Khatib K (2014). Herbicide-resistant weeds challenge some signature cropping systems. Calif. Agric., 68, 142-152.

Heap I (2014). Global perspective of herbicide-resistant weeds. Pest. Manage. Sci., 70, 1306-1315.

Hill JE, Williams JF, Mutters RG, Greer (2006). The California rice cropping system: agronomic and natural resource issues for long-term sustainability. Paddy Water Environ., 4, 13-19.

Hothorn T, Bretz F, Westfall P (2008).Simultaneous inference in general parametric models. Biom. J., 50, 346–363.

Jordan DL, Bollich PK, Burns AB, Walker DM (1998). Rice (*Oryza sativa*) response to clomazone. Weed Sci., 46, 374-380.

Kafer C, Thornburg R (1999). Pyrimidine metabolism in plants. Paths to Pyrimidines, 15, 14-24.

Kanter J, Clark N, Lundy ME, Koundinya V, Leinfelder-Miles M, Long R, Light SE, Brim-DeForest WB, Linquist B, Putnam D, Hutmacher RB (2021). Top management challenges and concerns for agronomic crop production in California: Identifying critical issues for extension through needs assessment. Agron. J., 113, 5254-5270.

Kuznetsova A, Brockhoff PB, Christenson RHB (2017) LMERTEST package: tests in linear mixed effects models. J. Stat. Soft., 82, 1–26.

Lang YZ, Yang XD, Wang ME, Zhu QS (2012) Effects of lodging at different filling stages on rice yield and grain quality. Rice Sci., 19, 315-319.

Lenth RV (2020) EMMEANS: Estimated marginal means, aka least-square means. R Package v. 1.5.3.https://CRAN.R-project.org/package=emmeans

Lundy ME, Hill JE, Van Kessel C, Owen DA, Pedroso RM, Boddy LG, Fischer AJ, Linquist BA (2014) Site-specific, real-time temperatures improve the accuracy of weed emergence predictions in direct-seeded rice systems. Agric. Syst., 123, 12-21

Mabbayad MO, Moody K (1992). Herbicide seed treatment for weed control in wet-seeded rice. Int. J. Pest. Manage., 38, 9-12.

Matzenbacher FD, Kalsing A, Dalazen G, Markus C, Merotto Jr A. (2015). Antagonism is the predominant effect of herbicide mixtures used for imidazolinone-resistant barnyardgrass (*Echinochloa crus-galli*) control. Planta Daninha, 33, 587-597.

Miersch J, Krauss GJ, Metzger U (1986). Properties and subcellular localization of dihydroorotate dehydrogenase in cells of tomato suspension culture. J. Plant Physiol., 122, 55-66.

Nagy M, Lacroute F, Thomas D (1992). Divergent evolution of pyrimidine biosynthesis between anaerobic and aerobic yeasts. Proc. Natl. Acad. Sci., 89, 8966-8970.

Nara T, Hshimoto T, Aoki T (2000). Evolutionary implications of the mosaic pyrimidine-biosynthetic pathway in eukaryotes. Gene, 25, 209-222.

Oerke EC (2006). Crop losses to pests. J. Agric. Sci., 144, 31-43.

Prather T, DiTomaso J, Holt J (2000) Herbicide resistance: Definition and management strategies. Publication No. 8012. Davis: University of California Department of Agriculture and Natural Resources. 14 p

Pantone DJ, Baker JB (1992). Varietal tolerance of rice (*Oryza sativa*) to bromoxynil and triclopyr at different growth stages. Weed Technol., 6, 968-974.

R Development Core Team (2022) R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Satterfield AD, Selby TP, Travis DA, Patel KM, Taggi AE, inventor; FMC Corp, assignee (2014) December 2. US patent 10294202 B2

Santoso D, Thornburg R (1998). Uridine 5′-monophosphate synthase is transcriptionally regulated by pyrimidine levels in *Nicotiana plumbaginifolia*. Plant Physiol., 166, 815-821.

Selby TP, Satterfield AD, Puri A, Stevenson TM, Travis DA, Campbell MJ, Taggi AE, Hughes KA, Bereznak J (2023). Bioisosteric tactics in the discovery of tetflupyrolimet: a new mode-of-action herbicide. J. of Agri. and Food Chem. https://doi.org/10.1021/acs.jafc.3c01634

Smith RJ (1983). Competition of bearded sprangletop (*Leptochloa fascicularis*) with rice (*Oryza sativa*). Weed Sci., 31, 120-123.

Stauber LG, Smith RJ, Talbert RE (1991). Density and spatial interference of barnyardgrass (*Echinochloa crus-galli*) with rice (*Oryza* sativa). Weed Sci., 39, 163-168.

Strand L (2013). *Integrated Pest Management for Rice* (Vol. 3280). UCANR Publications.

[UCANR] University of California Division of Agriculture and Natural Resources (2023) Rice Production Manual 2023. Davis, CA: University of California Agronomy Research and Information Center Rice. 192 p

Valverde BE, Boddy LG, Pedroso RM, Eckert JW, Fischer AJ (2014). *Cyperus difformis* evolves resistance to propanil. Crop Prot., 62, 16-22.

Yasuor H, Osuna MD, Ortiz A, Saldain NE, Eckert JW, Fischer AJ (2009). Mechanism of resistance to penoxsulam in late watergrass [*Echinochloa phyllopogon* (Stapf) Koss.]. J. Agric. Food Chem., 57, 3653-3660.

Yasuor H, TenBrook PL, Tjeerdema RS, Fischer AJ (2008). Responses to clomazone and 5-ketoclomazone by *Echinochloa phyllopogon* resistant to multiple herbicides in Californian rice fields. Pest. Manage. Sci., 64, 1031-1039.

Zhang W, Webster EP, Blouin DC, Linscombe SD (2004). Differential tolerance of rice (*Oryza sativa*) cultivars to clomazone. Weed Technol., 18, 73-76.

Zrenner R, Stitt M, Sonnewald U, Boldt R (2006). Pyrimidine and purine biosynthesis and degradation in plants. Annu. Rev. Plant Biol., 57, 805-836.

Table 1. Herbicides, rates, and application timings for Study 1. Herbicides were applied at two sites near Biggs, California in 2023.

Herbicides	Rate	Application timing
	kg ai ha^{-1}	
Carfentrazone	0.53	2- to 3-leaf annual grass
Tetflupyrolimet	0.1	DOS[a]
Carfentrazone	0.53	2- to 3-leaf annual grass
Tetflupyrolimet	0.125	DOS
Carfentrazone	0.53	2- to 3-leaf annual grass
Tetflupyrolimet	0.125	2- to 3-leaf annual grass
Carfentrazone	0.53	2- to 3-leaf annual grass
Tetflupyrolimet	0.15	2- to 3-leaf annual grass
Carfentrazone	0.53	2- to 3-leaf annual grass
Clomazone	0.673	DOS
Penoxsulam	0.035	2- to 3-leaf annual grass

[a] DOS, day of seeding

Table 2. Herbicides, rates, and application timings Study 2 in 2022 and 2023 near Biggs, CA.

Herbicides	Rate	Application timing
	kg ai ha^{-1}	
Tetflupyrolimet	0.1	DOS[a]
Carfentrazone	0.53	2- to 4-leaf rice stage
Tetflupyrolimet	0.1	DOS
Benzobicyclon/ Halosulfuron	0.31	1- to 2-leaf rice stage
Tetflupyrolimet	0.1	DOS
Thiobencarb	3.9	1- to 2-leaf rice stage
Propanil	6.7	Mid-rice tillering
Tetflupyrolimet	0.1	DOS
Bensulfuron	0.12	1- to 2-leaf rice stage
Propanil	6.7	Mid-rice tillering
Tetflupyrolimet	0.1	DOS
Triclopyr	0.16	Mid-rice tillering
Propanil	6.7	Mid-rice tillering
Benzobicyclon/ Halosulfuron	0.31	DOS
Tetflupyrolimet	0.15	1- to 2-leaf rice stage
Clomazone	0.07	DOS
Tetflupyrolimet	0.15	1- to 2-leaf rice stage
Propanil	6.7	Mid-rice tillering
Benzobicyclon/ Halosulfuron	0.37	DOS
Propanil	4.48	Mid-rice tillering
Propanil	4.48	Mid-rice tillering
Triclopyr	0.16	Mid-rice tillering

[a] DOS, day of seeding

Table 3. Herbicides, rates, and application timings for Study 3 in 2022 and 2023 near Biggs, CA.

Herbicides	Rate	Application timing
	kg ai ha^{-1}	
Carfentrazone	0.53	1- to 2-leaf rice stage
Tetflupyrolimet	0.125	DOS[a]
Carfentrazone	0.53	1- to 2-leaf rice stage
Tetflupyrolimet	0.25	DOS
Carfentrazone	0.53	1- to 2-leaf rice stage
Tetflupyrolimet	0.15	1- to 2-leaf rice stage
Carfentrazone	0.53	1- to 2-leaf rice stage
Tetflupyrolimet	0.3	1- to 2-leaf rice stage
Carfentrazone	0.53	1- to 2-leaf rice stage
Benzobicyclon/ Halosulfuron	0.37	DOS
Propanil	4.48	Mid-tillering rice
Propanil	4.48	Mid-tillering rice
Triclopyr	0.16	Mid-tillering rice

[a] DOS, day of seeding

Table 4. Average rice bleaching at 14 and 28 days after treatment (DAT) for sites one and two for Study 1 near Biggs, CA in 2023.

Herbicides	Site 1[a]				Site 2[a]			
	DAT[c]							
	14		28		14		28	
	%							
Tetflupyrolimet (PRE 0.1 kg ai ha^{-1}) fb[b] carfentrazone	0	b	0	a	0	b	0	a
Tetflupyrolimet (PRE 0.125 kg ai ha^{-1}) fb carfentrazone	0	b	0	a	0	b	0	a
Tetflupyrolimet (POST 0.125 kg ai ha^{-1}) fb carfentrazone	0	b	0	a	0	b	0	a
Tetflupyrolimet (POST 0.15 kg ai ha^{-1}) fb carfentrazone	0	b	0	a	0	b	0	a
Clomazone fb penoxsulam	50	a	0	a	32	a	0	a

[a] Within columns, means accompanied by the same letter do not significantly differ with Tukey's honestly significant difference (HSD) at α = 0.05.

[b] fb, followed by

[c] DAT, days after treatment

Table 5. Average rice chlorosis, stunting, stand reduction, and necrosis at 14 and 28 days after treatment (DAT) Study 1 in 2023 at two sites near Biggs, CA.

Herbicides	Chlorosis[a]				Stunting[a]				Stand Reduction[a]				Necrosis[a]			
	DAT															
	14		28		14		28		14		28		14		28	
	%															
Tetflupyrolimet (PRE 0.1 kg ai ha^{-1}) fb[b] carfentrazone	0	a	1	a	0	a	1	a	1	a	0	a	0	a	0	a
Tetflupyrolimet (PRE 0.125 kg ai ha^{-1}) fb carfentrazone	0	a	2	a	0	a	5	a	0	a	8	a	0	a	0	a
Tetflupyrolimet (POST 0.125 kg ai ha^{-1}) fb carfentrazone	0	a	8	a	3	a	8	a	12	a	1	a	0	a	0	a
Tetflupyrolimet (POST 0.15 kg ai ha^{-1}) fb carfentrazone	2	a	2	a	0	a	3	a	0	a	0	a	0	a	0	a
Clomazone fb penoxsulam	0	a	3	a	0	a	12	a	3	a	1	a	0	a	0	a

[a] Within columns, means accompanied by the same letter do not significantly differ with Tukey's honestly significant difference (HSD) at α = 0.05.

[b] fb, followed by

Table 6. Average weed control at 14 and 56 DAT for Study 2 in 2022.

Herbicides	*Watergrass* species[a]		Bearded sprangletop[a]		Ricefield Bulrush[a]		Smallflower umbrellasedge[a]		Ducksalad[a]		Redstem[a]	
	DAT											
	14	56	14	56	14	56	14	56	14	56	14	56
	%											
Tetflupyrolimet fb[b] carfentrazone	99 a	99 a	100 a	98 a	100 a	88 a	100 a	72 b	100 a	90 a	100 a	100 a
Tetflupyrolimet fb benzobicyclon/ halosulfuron	99 a	99 a	100 a	100 a	100 a	100 a	100 a	100 a	100 a	100 a	100 a	82 a
Tetflupyrolimet fb thiobencarb fb propanil	99 a	99 a	100 a	100 a	100 a	97 a	100 a	100 a	100 a	100 a	100 a	100 a
Tetflupyrolimet fb bensulfuron fb propanil	100 a	100 a	100 a	97 a	100 a	99 a	100 a	96 a	100 a	100 a	100 a	100 a
Tetflupyrolimet fb triclopyr + propanil	100 a	100 a	100 a	99 a	100 a	99 a	100 a	97 a	100 a	100 a	100 a	100 a
Benzobicyclon/	98 a	98 a	10 a	100 a	100 a	100 a	10 a	10 a	100 a	100 a	10 a	33 b

halosulfuron fb tetflupyrolimet					0								0		0						0			
Clomazone fb tetflupyrolimet fb propanil	99	a	99	a	100	a	100	a	100	a	100	a	100	a	97	a	100	a	100	a	100	a	100	a
Benzobicyclon/ halosulfuron fb propanil fb propanil + triclopyr	94	b	94	b	100	a	99	a	100	a	100	a	100	a	100	a	100	a	100	a	100	a	99	a

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[a] Within columns, means accompanied by the same letter do not significantly differ with Tukey's honestly significant difference (HSD) at α = 0.05.

[b] fb, followed by

Table 7. Average weed control at 14 and 56 DAT for Study 2 in 2023.

Herbicides	Watergrass species[a]				Bearded sprangletop[a]				Ricefield Bulrush[a]				Smallflower umbrellasedge[a]				Ducksalad[a]				Redstem[a]			
	DAT																							
	14		56		14		56		14		56		14		56		14		56		14		56	
	%																							
Tetflupyrolimet fb[b] carfentrazone	100	a	100	a	100	a	100	a	95	a	77	a	100	a	83	a	100	a	83	b	100	a	97	a
Tetflupyrolimet fb benzobicyclon/ halosulfuron	100	a	100	a	100	a	100	a	40	a	100	a	100	a	100	a	100	a	100	a	100	a	63	a
Tetflupyrolimet fb thiobencarb fb propanil	99	a	100	a	100	a	100	a	98		100	a	100	a	100	a	100	a	100	a	100	a	65	a
Tetflupyrolimet fb bensulfuron fb propanil	100	a	100	a	100	a	100	a	100	a	100	a	100	a	100	a	100	a	100	a	100	a	92	a
Tetflupyrolimet fb triclopyr + propanil	100	a	100	a	100	a	100	a	65	a	100	a	100	a	100	a	43	a	98	ab	100	a	97	a
Benzobicyclon/	99	a	10	a	10	a	10	a	99	a	100	a	99	a	10	a	10	a	100	a	100	a	73	a

halosulfuron fb tetflupyrolimet			0		0		0								0		0							
Clomazone fb tetflupyrolimet fb propanil	100	a	100	a	100	a	100	a	50	a	98	a	100	a	98	a	50	a	97	ab	100	a	97	a
Benzobicyclon/ halosulfuron fb propanil fb propanil + triclopyr	100	a	100	a	99	b	100	a	98	a	100	a	96	b	100	a	100	a	100	a	0	b	100	a

[a] Within columns, means accompanied by the same letter do not significantly differ with Tukey’s honestly significant difference (HSD) at α = 0.05.

[b] fb, followed by

Table 8. Average rice yield in Study 2 in 2022.

Herbicides	Rate (lb ai ac^{-1})	Application Timing	Yield	
			kg ha^{-1}	
Untreated Control	-	-	3,690	a
Tetflupyrolimet	0.09	DOS[a]	7,830	bc
Carfentrazone	0.47	2-4 rice-leaf stage		
Tetflupyrolimet	0.09	DOS	9,250	bc
Benzobicyclon/ Halosulfuron	0.28	1-2 rice-leaf stage		
Tetflupyrolimet	0.09	DOS	9,550	c
Thiobencarb	3.48	1-2 rice-leaf stage		
Propanil	5.98	Mid-tillering rice		
Tetflupyrolimet	0.09	DOS	8,560	bc
Bensulfuron	0.11	1-2 rice-leaf stage		
Propanil	5.98	Mid-tillering rice		
Tetflupyrolimet	0.09	DOS	7,900	bc
Triclopyr	0.14	Mid-tillering rice		
Propanil	5.98	Mid-tillering rice		
Benzobicyclon/ Halosulfuron	0.28	DOS	8,560	bc
Tetflupyrolimet	0.13	1-2 rice-leaf stage		
Clomazone	0.06	DOS	7,740	b
Tetflupyrolimet	0.13	1-2 rice-leaf stage		
Propanil	5.98	Mid-tillering rice		
Benzobicyclon/ Halosulfuron	0.33	DOS	9,120	bc
Propanil	4.0	Mid-tillering rice		
Propanil	4.0	Mid-tillering rice + 7 days		
Triclopyr	0.14	Mid-tillering rice + 7 days		

[a] DOS, day of seeding

Table 9. Rice necrosis at 14 and 28 DAT observed in Study 3 in 2022 and 2023.

Herbicides	Application Timing	Cultivar[c]	Necrosis[a]							
			2022				2023			
			DAT							
			14		28		14		28	
			%							
Tetflupyrolimet (0.125 kg ai ha^{-1}) fb[b] carfentrazone	DOS[d]	M-105	0	a	5	a	0	a	0	a
		M-206	0	a	5	a	0	a	0	a
	1- to 2-leaf rice stage	M-209	0	a	5	a	0	a	0	a
		M-211	0	a	5	a	0	a	0	a
		L-208	0	a	5	a	0	a	0	a
		CM-203	0	a	5	a	0	a	0	a
Tetflupyrolimet (0.25 kg ai ha^{-1}) fb carfentrazone	DOS	M-105	0	a	5	a	0	a	0	a
		M-206	2	a	5	a	0	a	0	a
	1- to 2-leaf rice stage	M-209	2	a	5	a	0	a	0	a
		M-211	0	a	5	a	0	a	0	a
		L-208	2	a	5	a	0	a	0	a
		CM-203	0	a	5	a	0	a	0	a
Tetflupyrolimet (0.25 kg ai ha^{-1}) fb carfentrazone	1- to 2-leaf rice stage	M-105	5	bc	5	a	0	a	0	a
		M-206	10	a	7	a	0	a	0	a
		M-209	8	ab	5	a	0	a	0	a
	1- to 2-leaf rice stage	M-211	5	bc	5	a	0	a	0	a
		L-208	5	bc	5	a	0	a	0	a
		CM-203	7	b	7	a	0	a	0	a
Tetflupyrolimet (0.3 kg ai ha^{-1}) fb carfentrazone	1- to 2-leaf rice stage	M-105	7	b	5	a	0	a	0	a
		M-206	8	ab	5	a	0	a	0	a
	1- to 2-leaf rice stage	M-209	10	a	5	a	0	a	0	a
		M-211	8	ab	5	a	0	a	0	a
		L-208	5	bc	5	a	0	a	0	a
		CM-203	7	b	7	a	0	a	0	a
Benzobicyclon/ halosulfuron fb propanil fb propanil + triclopyr	DOS	M-105	7	b	5	a	0	a	0	a
		M-206	7	b	5	a	0	a	0	a
	Mid-tillering rice	M-209	10	a	5	a	0	a	0	a
		M-211	10	a	5	a	0	a	0	a
		L-208	5	bc	3	a	0	a	0	a
		CM-203	5	bc	7	a	0	a	0	a

[a] Within columns, means accompanied by the same letter do not significantly differ with Tukey's honestly significant difference (HSD) at α = 0.05.

[b] fb, followed by

[c] short ('CM-203'), medium ('M-105,' 'M-206,' 'M-209,' and 'M-211') , and long ('L-208') grain cultivars

[d] DOS, day of seeding