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Running title: Tiafenacil impact on rice

Impact of reduced rates of tiafenacil at vegetative growth stages on rice growth and yield

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Abstract

Tiafenacil is a new non-selective protoporphyrinogen IX oxidase (PPO)-inhibiting herbicide with both grass and broadleaf activity labeled for preplant application to corn, cotton, soybean, and wheat. Early season rice emergence and growth often coincide in the mid-southern U.S. with preplant herbicide application in cotton and soybean, thereby increasing the opportunity for off-target herbicide movement from adjacent fields. Field studies were conducted to identify any deleterious impacts of reduced rates of tiafenacil (12.5 to 0.4% of the lowest labeled application rate of 24.64 g ai ha^{-1}) applied to 1- or 3-leaf (lf) rice. Visual injury 1 week after treatment (WAT) for the 1- and 3-lf growth stages ranged from 50 to 7% and 20 to 2%, respectively, while at 2 WAT these respective ranges were 13 to 2% and no injury observed. Tiafenacil at applied rates had no negative season-long impact as early season visual injury observed was not manifested in a reduction in rice height 2 WAT or rough rice yield. Application of tiafenacil directly adjacent to rice in early vegetative stages of growth should be avoided as visual injury will occur. In cases where off-target movement does occur, however, impacted rice should be expected to fully recover with no impact on growth and yield, assuming adequate growing conditions and agronomic/pest management are provided.

Nomenclature: Tiafenacil; corn, *Zea mays* L.; cotton; *Gossypium hirsutum* L.; soybean, *Glycine max* (L.) Merr.; rice, *Oryza sativa* L.; wheat, *Triticum aestivum* L.

Keywords: herbicide injury; off-target movement; reduced rate

Introduction

By 2022, approximately 87% of all cropland acres in the United States were reported to be implementing some form of a conservation tillage production system, defined as tillage being reduced for at least one crop in a given field (Creech 2022). Of this conservation tillage system percentage, continuous no-till accounted for one-third of the hectares. Utilization of conservation tillage in crop production can lead to a potential 2888 million liter reduction in diesel equivalents per year as well as an 7.7 million metric ton yearly reduction in associated emissions (Creech 2022). Realized benefits of conservation tillage systems can include improved soil health, decreased erosion, maximized water infiltration, improvement in nutrient cycling, and a build-up in organic matter (Creech 2022; Farmaha et al. 2021; Lal 2015).

Conservation tillage systems rely greatly on herbicides for effective pre-plant weed management. Numerous herbicides or combinations of herbicides are currently labeled and recommended for pre-plant or “burndown’” control of many common and troublesome winter weed species encountered in corn, cotton, and soybean production fields (Anonymous, 2024 a, 2024 b, 2024 c; Anonymous 2023 a). Weed resistance issues and difficult to control species have necessitated identification of novel strategies and herbicides for continued successful pre-plant weed management in these production systems (Flessner et al. 2019; Johanning et al. 2016; Vollmer et al. 2019; Westerveld et al. 2021 a, 2021 b; Zimmer et al. 2018).

Tiafenacil, a new protoporphyrinogen IX oxidase (PPO)-inhibiting herbicide developed by FarmHannong Co., Ltd. (Seoul, Korea), exhibits nonselective contact activity on both weed and crop species (Anonymous 2023 b; Park et al. 2018). PPO-inhibiting herbicides halt the production of protoporphyrin IX (PPIX) from protoporphyrinogen IX (PPGIX), eventually preventing chlorophyll and heme biosynthesis. The increase in PPIX in the cytoplasm results in increases singlet oxygen which leads to lipid peroxidation, cell membrane destruction, and ultimately plant death (Shaner 2014). Tiafenacil is registered in the United States for preplant application to corn, cotton, soybean, and wheat as well as for defoliation of cotton (Adams et al. 2022; Anonymous 2023 b). Limited published research with tiafenacil has focused on weed management. Tiafenacil at 74 g ai ha^{-1} applied with varying urea ammonium nitrate (UAN) carrier volumes provided 85, 81, 92, and 90% control of barnyardgrass (*Echinochloa crus-galli* [L.] P. Beauv.), common lambsquarters (*Chenopodium album* L.), kochia (*Bassia scoparia* [L.]

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A.J. Scott), and redroot pigweed (*Amaranthus retroflexus* L.), respectively, 1 WAT (Mookodi et al. 2023). Tiafenacil applied at 50 g ha^{-1} alone resulted in 82% control of glyphosate-resistant (GR) downy brome (*Bromus tectorum* L.) (Geddes and Pittman 2023) 7 d after treatment (DAT) while the same rate co-applied with metribuzin at 400 g ha^{-1} resulted in 88% control of GR horseweed (*Erigeron canadensis* L.) (Westerveld et al. 2021 b).

Rice was planted on over 1 million hectares in the United States in 2023 (USDA 2023). Rice emergence and early season growth often coincide with preplant herbicide applications made in preparation for later planting of soybean or cotton and often occur in adjacent fields, thereby increasing opportunity for off-target herbicide movement. Drift or off-target movement was previously identified by survey respondents from two separate states as the biggest herbicide application challenge they face (Butts et al. 2021; Virk and Prostko 2022). Additionally, severe crop injury from off-target herbicide movement is possible upwards of 60 m downwind from both ground and aerial applications which can negatively impact yield, environmental stewardship, and other beneficial species (Butts et al. 2022). Consequently, it is imperative to understand the implications for crop growth and development if the crop were to be exposed to an herbicide drift event.

Serious deleterious effects of simulated off target movement of selective and nonselective herbicides to rice at various growth stages have been demonstrated (Bond et al. 2006; Ellis et al. 2003). Rice growth stage at time of herbicide exposure has also been shown to result in differential sensitivity to herbicides labeled for rice application. Patterson et al. (2023) reported that drill-seeded rice was more tolerant to application of benzobicyclon at the 4-lf or tillering growth stages than early growth stages. Lawrence et al. (2021) investigated the impacts of foliar application of sublethal rates of paraquat, a non-selective contact herbicide similar to tiafenacil, and fomesafen, a PPO herbicide like tiafenacil, to rice at the spike through panicle differentiation growth stage. Fomesafen injury three DAT exceeded 11% only with a preflood application. By 4 WAT, injury from fomesafen at any application timing ranged from only 2 to 5%. At 2 WAT, rice height was 95% of that of the nontreated control with fomesafen applied at spike to 1-lf growth stage, however, height ranged from 98% to 103% of the nontreated control for other timings. Rough rice yield was reduced with fomesafen applied later than the 2- to 3-lf growth stage. Paraquat application injured rice 37 to 47% regardless of application timing (Lawrence et al.

2021). Spike to one-lf and 2- to 3-lf timings still exhibited 45 and 52% paraquat injury, respectively, at 4 WAT. Rice height 2 WAT was more negatively affected with exposure to paraquat prior to flooding compared with post-flood. Total and whole milled rice yield was not affected by paraquat application at the spike to one-lf and 2- to 3-lf timings compared to nontreated plants.

To our knowledge published information exists on the impact of tiafenacil on rice growth and yield following foliar application at sublethal rates that may be encountered in off target movement events. Therefore, the objective of this research was to determine any negative impacts of foliar application of tiafenacil to rice as affected by growth stage at time of application.

Materials and Methods

Field experiments were conducted in 2022 at the LSU AgCenter Northeast Research Station near St. Joseph, LA (31.9184º N, 91.2335º W), the University of Arkansas System Division of Agriculture Lonoke Extension Center in Lonoke, AR (34.7843º N, 91.9001º W), and the Mississippi State University Delta Research and Extension Center in Stoneville, MS (33.4240º N, 90.9151º W) to determine the impact of reduced rates of tiafenacil (Reviton, HELM Agro US, Inc., Tampa, FL) applied at differing growth stages on rice growth and yield. Experiments were conducted in a randomized complete block design with treatments replicated three or four times. Treatments were applied via compressed air or CO_2-pressurized backpack sprayer at 140 liters ha^{-1}. Treatments included a factorial arrangement of reduced rates of tiafenacil at 0x, 1/8x, 1/16x, 1/32x, 1/64x, 1/128x, and 1/256x rate applied to one- or 3-lf rice. The 1x rate basis for reduced rate calculation was 24.64 g ha^{-1}. The tiafenacil label (Anonymous 2003 b) allows single application rates from 24.64 to 75.04 g ha^{-1}, however, previous unpublished research has indicated that the lower rate in combination with glyphosate provides adequate cost-effective control of most common winter weed species prior to planting (Donnie K. Miller, personal observation). Methylated seed oil (MSO) was added at 1% v/v to all treatments per label recommendations to maximize weed control (Anonymous 2023b). A comparison 1% MSO alone treatment was included but resulted in no impacts on parameters measured in comparison to the 0x rate and therefore was excluded from statistical analysis. Tiafenacil at designated rates was applied to 1- or 3-leaf rice cultivar ‘PVL02’ near St. Joseph on May 26 or June 1, cultivar ‘Full

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Page RT 7521' on May 18 or June 13 in Lonoke, and cultivar 'CLL16' on May 20 or June 9 in Stoneville. These timings were selected as being the most likely to exist when burndown of cotton and soybean ground normally occur in the mid-south (authors personal observations). Plots were maintained weed-free at St. Joseph with PRE (preemergence) application of clomazone (Command 3 ME, FMC, Philadelphia, PA) at 656 g ha^{-1} plus saflufenacil (Sharpen, BASF Corporation, Research Triangle Park, NC) at 50 g ha^{-1}, 2- to 3-lf application of quizalofop p-ethyl (Provisia, BASF Corporation, Research Triangle Paek, NC) at 119 g ha^{-1}, 3- to 4-lf application of halosulfuron plus prosulfuron (Gambit, Gowan, Yuma, AZ) at 83 g ha^{-1}, and a post-flood application of cyhalofop (Clincher, Corteva AgriScience, Indianapolis, IN) at 417 g ha^{-1}. Plots were maintained weed free at Lonoke with PRE application of imazethapyr (Preface, ADAMA, Raleigh, NC) at 105 g ha^{-1} and 4-lf application of imazethapyr (Preface, ADAMA, Raleigh, NC) at 105 g ha^{-1} plus halosulfuron plus prosulfuron (Gambit, Gowan, Yuma, AZ) at 111 g ha^{-1}. Plots were maintained weed free at Stoneville with PRE application of clomazone (Command 3 ME, FMC, Philadelphia, PA) at 559 g ha^{-1}, 2- to 3-lf application of imazethapyr (Newpath, BASF Corporation, Research Triangle Park, NC) at 105 g ha^{-1} plus quiclorac (Facet-L, BASF Corporation, Research Triangle Park, NC) at 420 g ha^{-1}, and 4-lf to one-tiller application of imazethapyr (Newpath, BASF Corporation, Research Triangle Park, NC) at 105 g ha^{-1} plus halosulfuron (Permit, Gowan, Yuma, AZ) at 39 g ha^{-1}.

Statistical Analysis

Parameter measurements included visual injury on a scale of 0=no injury and 100=plant death 1 and 3 WAT; plant height at 3 WAT for the 1-lf timing and 2 WAT for the 3-lf timing; and rough rice yield. The linear model (Equation 1) was fit to data.

$$y = \beta_0 + \beta_1 x + \varepsilon \qquad [1]$$

where y represents the response variable of interest (visual injury, plant height; or rough rice yield), x represents the rate of tiafenacil (g ai ha-1), β_1 is the slope, the amount by which the response variable changes when the tiafenacil rate increases by one unit, β_0 is the intercept, the value of the response variable when the tiafenacil rate = 0, and ε is the residual. The *lm()* function of the "stats" package was used to fit all linear models in R version 4.3.3 (R Core Team,

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2024). Data were analyzed by location and model parameters (slopes and intercepts) compared (Ritz et al., 2015) with no statistical differences detected between parameters of locations for herbicide rates applied at the same leaf stage (data not shown). Therefore, data were pooled across locations for curve fitting for a given application stage. In contrast, due to differences observed during application at 1-leaf and 3-leaf, data were analyzed separately for these stages. Model assumptions of linearity, homoscedasticity, independence, and normality were checked in each case.

Results and Discussion

Rice Injury

Visual rice injury was characterized by necrotic speckling of leaves contacted at time of application. When applied at the 1-lf growth stage, rice was injured 50% at the highest tiafenacil rate applied (1/8x), with each successive rate reduction resulting in 27, 17, 11, 8, and 7% injury 1 WAT (Figure 1). Exposure at the 3-lf growth stage resulted in 20, 11, 10, 4, 3 and 2% injury at these same rates (Figure 1). By 3 WAT, when applied at the 1-lf growth stage, rice injury was 13% at the highest tiafenacil rate applied (1/8x), with each successive rate reduction resulting in 7, 4, 3, 2, and 2% injury (Figure 2). Application at the 3-leaf growth stage resulted in no visual rice injury 3 WAT (Figure 2). Lawrence et al. 2021 reported lower levels of injury than the current study with injury no greater than 11 and 10% for the PPO herbicide fomesafen applied at 39 g ha^{-1} to rice at the spike to 1-lf and 2- to 3-lf growth stage 1 and 2 WAT, respectively. Differences in rice response may be due to natural sensitivity to the herbicides as tiafenacil exhibits effective activity on grass species while fomesafen exhibits primarily broadleaf activity (Anonymous 2023b; Anonymous 2019). By 4 WAT, injury was no greater than 5%, which was similar to decreasing injury in the current study with time. Paraquat applied at 10% of the labeled rate injured spike to 1-lf and 2- to 3-lf rice 44 to 47% at 1 and 2 WAT (Lawrence et al. 2021). At 4 WAT, injury at these timings was still 45 and 42%, respectively, indicating slower recovery from paraquat injury early season than tiafenacil.

Rice Height

Statistical analysis with respect to rice height indicated no negative impact of tiafenacil applied at either timing (Table 1). Rice height in the absence of tiafenacil averaged 26 and 35 cm at the 1- and 3-lf growth stage, respectively (Figure 3). Height following tiafenacil exposure ranged from 25 to 26 and 37 to 35 cm at these respective growth stages. Lawrence et al. 2021 reported at

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2 WAT, rice height was 95% of the nontreated control with fomesafen applied at spike to 1-lf growth stage. However, height ranged from 98% to 103% of the nontreated control for 2- to 3-lf through panicle differentiation timings. Rice height 2 WAT was more negatively affected with exposure to paraquat prior to flooding (spike to 1-lf through mid-POST (postemergence) timings) compared with post-flood (Lawrence et al. 2021). At the 2 WAT assessment timing, rice was exhibiting much greater levels of injury than did tiafenacil in the current research which may explain the differences in height impact.

Rice Yield

Similar to height, early season visual injury was not manifested in rough rice yield reduction following tiafenacil exposure (Table 1). Nontreated rice yield averaged 6926 and 6913 kg ha^{-1} for the early and late growth stage timings (Figure 4). Yield following tiafenacil exposure ranged from 7223 to 6935 and 7248 to 6923 kg ha^{-1} at these respective growth stages. Results were similar to those reported by Lawrence et al. (2021) where early season rice visual injury observed with fomesafen and paraquat was not reflected in rough rice yield reduction at the spike to 1-lf and 2- to 3- lf exposure timings.

Practical Implications

Visual rice injury levels 1 WAT were greater at the 1- than 3-lf growth stage application with tiafenacil rates ranging from 12.5 to 0.4% of the lower end of the labeled rate range (24.64 g ha^{-1}). Early season injury was evident quickly after application but lessened over time and was not manifested in height or rough rice yield reduction. In comparison to previous research conducted on the PPO inhibiting herbicide fomesafen (Lawrence et al. 2021), rice season-long response to off-target application of tiafenacil applied at rates evaluated would be similar between the two compounds, although the latter exhibits effective activity on grass species while the former exhibits primarily broadleaf activity (Anonymous 2023 b; Anonymous 2019). Application of tiafenacil directly adjacent to rice in early vegetative stages of growth should be avoided as visual injury will occur. However, based on the current results and previous research with other PPO inhibiting herbicides (Lawrence et al. 2021), tiafenacil appears to be a safer option for non-selective burndown weed control than paraquat in cotton or soybean fields near emerged rice prior to the 4-lf growth stage. In cases where off-target tiafenacil movement does occur, injured rice, similar to the response with fomesafen and paraquat in previous studies, should be expected to fully recover with no impact on growth and rough rice yield, assuming adequate growing conditions and agronomic/pest management are provided.

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Competing Interests

Competing interests: the authors declare none.

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Table 1. Linear regression parameters for rice visual injury 1 and 3 weeks after treatment (WAT), height, and rough rice yield following application of tiafenacil at 0x, 1/8x, 1/16x, 1/32x, 1/64x, 1/128x, and 1/256x of a 24.64 g ai ha^{-1} use rate applied to 1- or 3-leaf (lf) rice for data polled across locations of St. Joseph, LA, Lonoke, AR, and Stoneville, MS in 2022.

Parameter	Evaluation	Timing	Adjusted R^2		Estimate	Std. Error	t value	Pr(>|t|)
Injury	1 WAT	1-lf rice	0.72	Intercept	5.33	1.36	3.92	0.000183 ***
				Rate	14.63	1.01	14.47	< 2e-16 ***
		3-lf rice	0.33	Intercept	1.64	1.22	1.34	0.18
				Rate	5.86	0.91	6.44	7.75e-09 ***
	3 WAT	1-lf rice	0.3036	Intercept	1.41	0.82	1.72	0.09
				Rate	3.72	0.61	6.10	3.38e-08 ***
		3-lf rice		Intercept	Parameters not estimated (no injury, all values are 0)			
				Rate				
Height		1-lf rice	0.02	Intercept	25.62	0.62	41.01	<2e-16 ***
				Rate	-0.06	0.46	-0.13	0.90
		3-lf rice	0.01	Intercept	35.37	1.45	24.47	<2e-16 ***
				Rate	0.54	1.08	0.50	0.62
Yield		1-lf rice	0.01	Intercept	6926.18	314.86	22.00	<2e-16 ***
				Rate	96.24	232.83	0.41	0.68
		3-lf rice	0.01	Intercept	6912.60	308.10	22.44	<2e-16 ***
				Rate	108.80	226.50	0.48	0.63

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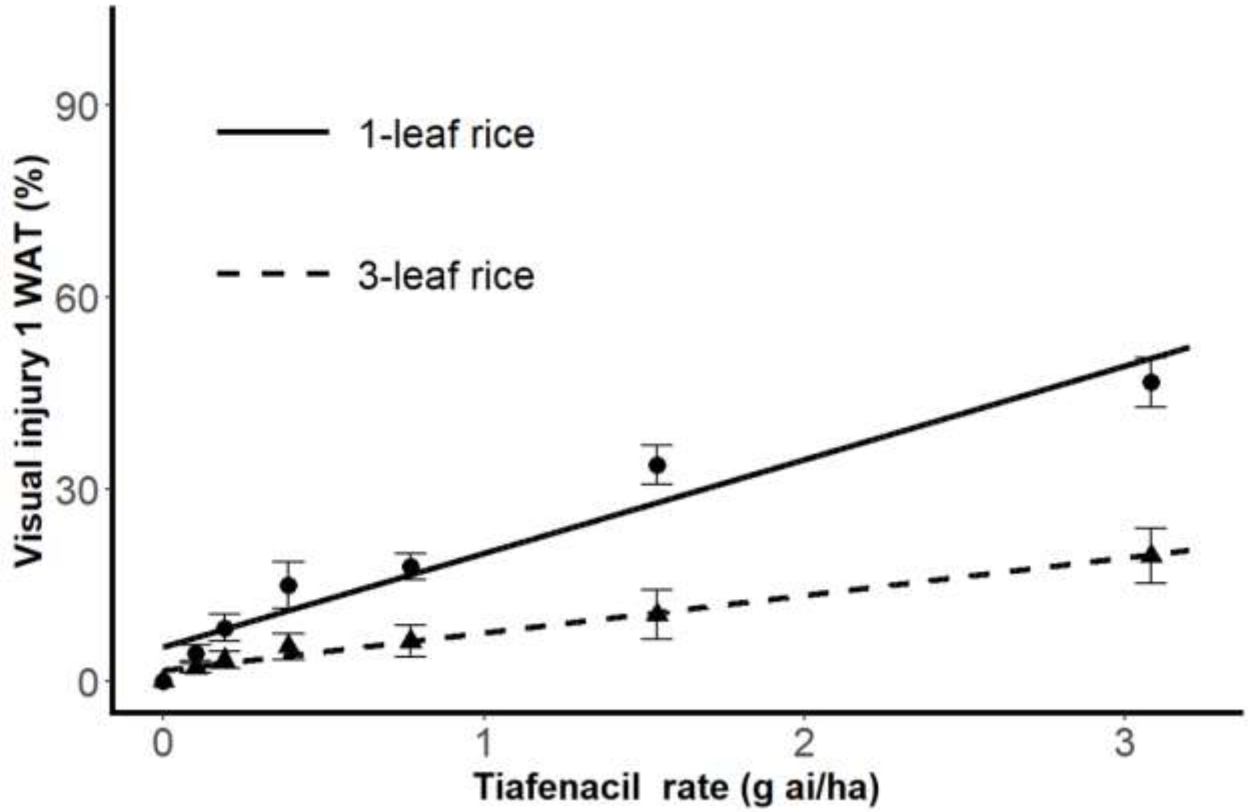

Figure 1. Visual rice injury 1 week after treatment (WAT) as impacted by tiafenacil at 0x, 1/8x, 1/16x, 1/32x, 1/64x, 1/128x, and 1/256x of a 24.64 g ai^{-1} ha use rate applied to 1- or 3-leaf (lf) rice for data pooled across locations of St. Joseph, LA, Lonoke, AR, and Stoneville, MS in 2022.

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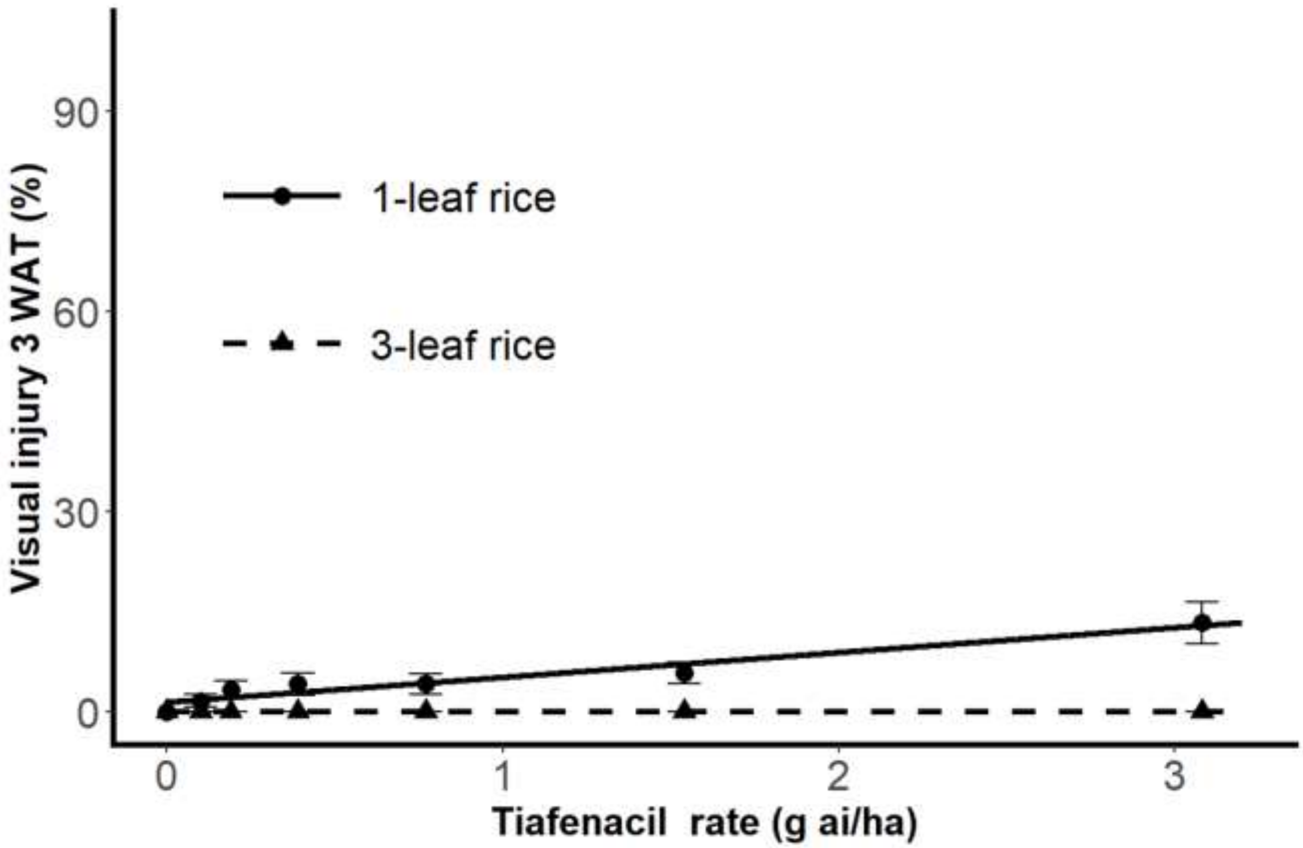

Figure 2. Visual rice injury 3 week after treatment (WAT) as impacted by tiafenacil at 0x, 1/8x, 1/16x, 1/32x, 1/64x, 1/128x, and 1/256x of a 24.64 g ai ha^{-1} use rate applied to 1- or 3-leaf (lf) rice for data pooled across locations of St. Joseph, LA, Lonoke, AR, and Stoneville, MS in 2022.

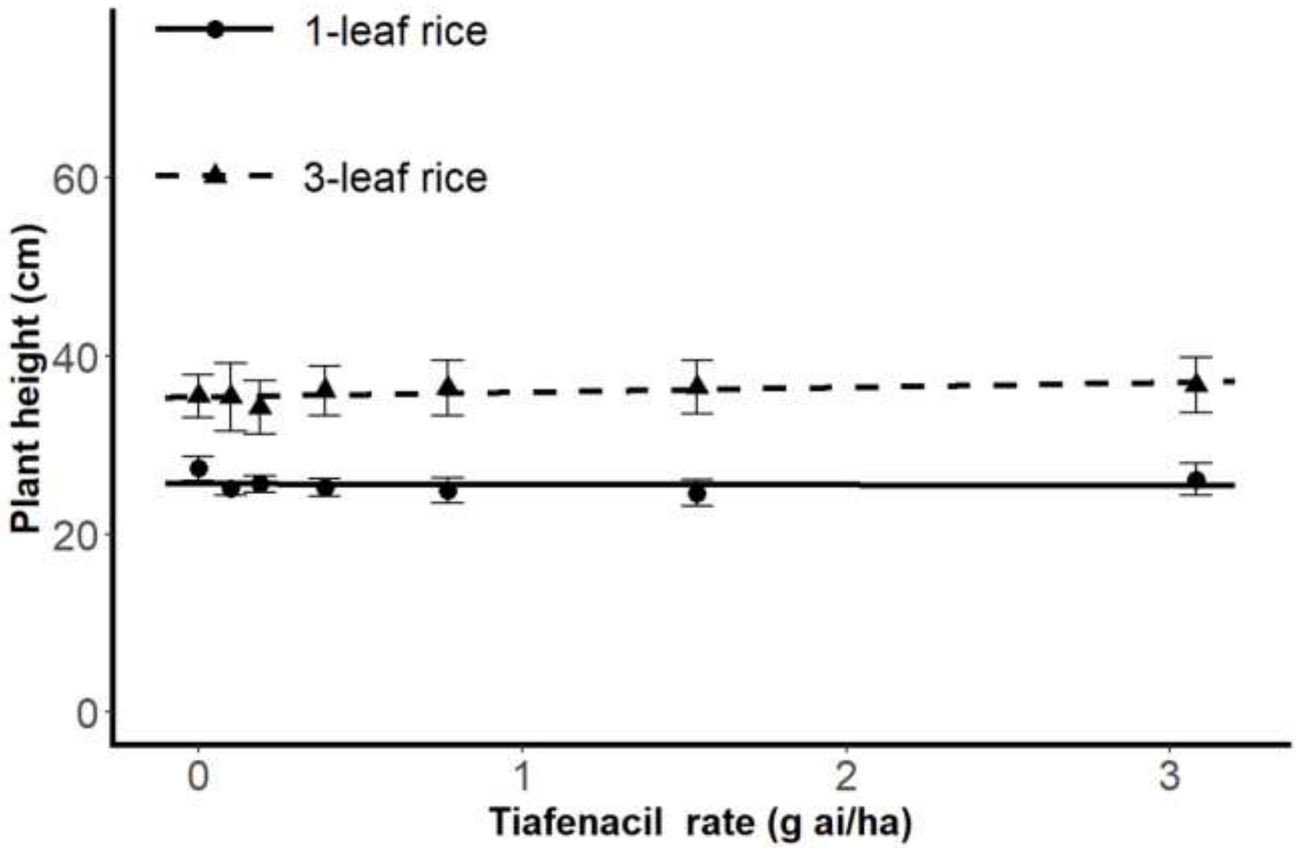

Figure 3. Rice height 3 weeks after treatment (WAT) for the 1-lf timing and 2 WAT for the 3-lf timing as impacted by tiafenacil at 0x, 1/8x, 1/16x, 1/32x, 1/64x, 1/128x, and 1/256x of a 24.64 g ai^{-1} ha use rate applied to 1- or 3-leaf (lf) rice for data pooled across locations of St. Joseph, LA, and Lonoke, AR in 2022.

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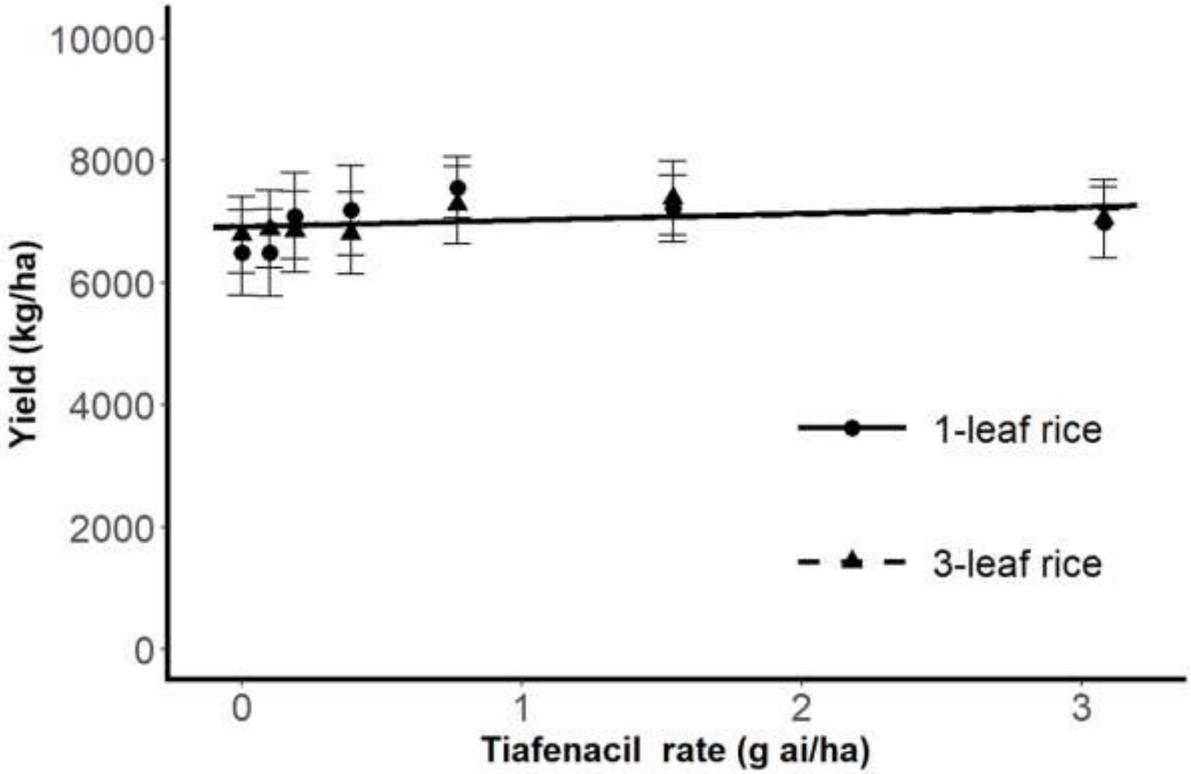

Figure 4. Rough rice yield as impacted by tiafenacil at 0x, 1/8x, 1/16x, 1/32x, 1/64x, 1/128x, and 1/256x of a 24.64 g ai^{-1} ha use rate applied to 1- or 3-leaf (lf) rice for data pooled across locations of St. Joseph, LA, Lonoke, AR, and Stoneville, MS in 2022.