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Research Article

Soil texture effects on tetflupyrolimet efficacy in turfgrass

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Abstract

Tetflupyrolimet is a novel herbicide that inhibits dihydroorotate dehydrogenase (DHODH), interfering with de novo pyrimidine biosynthesis in susceptible plants. While tetflupyrolimet efficacy for preemergence grassy weed control in rice (*Oryza sativa* L.) and managed turfgrass systems has been explored, there is minimal information regarding effects that edaphic factors may have on activity, particularly those pertaining to soil hydraulics. Dose–response experiments revealed 6- to 8-fold differences in tetflupyrolimet activity on annual bluegrass (*Poa annua* L.) due to soil texture, with higher activity reported following applications to sand compared with clay loam. Higher tetflupyrolimet activity in sand could be related to matric potential, as activity following applications to plants growing in sand exceeded that observed on clay loam across a wide range of volumetric water contents (15% to 60%). Once volumetric water content increased to ≥ 80%, no differences in tetflupyrolimet activity were detected between soils, suggesting that post-application irrigation could mitigate potential reductions in efficacy on finer-textured soils when moisture is limited. These findings underscore that soil texture and, consequently, moisture retention affect tetflupyrolimet activity to the extent that application rates could vary based on soil texture in turfgrass systems. Further research exploring a broader range of soil types and field conditions is warranted to refine tetflupyrolimet rate recommendations based on soil type.

Introduction

Tetflupyrolimet is a new herbicide with a unique mode of action (HRAC Group 28) that inhibits de novo pyrimidine biosynthesis in susceptible plants (Kang et al. 2023). The herbicide binds to dihydroorotate dehydrogenase (DHODH), an enzyme on the outer surface of the inner mitochondrial membrane (Reis et al. 2017), thereby obstructing the ubiquinone-mediated oxidation of dihydroorate to orotate (Zrenner et al. 2006). Tetflupyrolimet selectively controls annual grassy weeds in rice (*Oryza sativa* L.), including barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] and junglerice [*Echinochloa colona* (L.) Link], preemergence (Castner et al. 2024; Whitt et al. 2024).

In turfgrass systems, tetflupyrolimet offers a novel mode of action for effective preemergence control of annual bluegrass (*Poa annua* L.) and smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.] for 11 to 13 wk (Pritchard et al. 2025). Given that herbicide resistance is an emerging issue in managed turfgrass, particularly in *P. annua* (Brosnan et al. 2020; McCurdy et al. 2023; Rutland et al. 2023), tetflupyrolimet offers a new herbicide for resistance management, particularly in warm-season turfgrasses. No injury was observed following tetflupyrolimet applications up to 4,800 g ha^{-1} on hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy] or manilagrass [*Zoysia matrella* (L.) Merr.] (Pritchard et al. 2025). Weed control and turfgrass tolerance with tetflupyrolimet could satisfy the desire among turfgrass managers for new herbicides to reduce resistance concerns (Allen et al. 2022).

Managed turfgrass systems such as golf courses are constructed on soils varying in texture. Golf course putting greens and teeing grounds are often constructed with engineered sand root zones containing ≤ 8% silt and clay by volume (Shaddox et al. 2023; United States Golf Association 2018). Golf course fairways and roughs are primarily established on native soils that can vary widely in both texture and other edaphic parameters (Soil Survey Staff 2024). Given that sand root zones are designed to optimize internal drainage and aeration under concentrated traffic (Ok et al. 2004), sand is often introduced to native soil sites via applications of topdressing to improve turfgrass quality and playability (Green et al. 2019; Klingenberg 2009). Differences in soil texture can impact efficacy of herbicides, including atrazine (Blumhorst et al. 1990), pendimethalin (Blumhorst et al. 1990), metribuzin (Weber et al. 1987), and pronamide (Dutt and Harvey 1980). Commodity agricultural labels for these active ingredients often offer use directions based on soil texture (Anonymous 2008, 2017, 2021a, 2022a). For example, label rates for atrazine (AAtrex®4L, Syngenta Crop Protection, Greensboro, NC, USA) can vary as much 673 g ha^{-1} due to soil texture (Anonymous 2022a). Rate specificity based on soil texture is not present within label directions for these same active ingredients in managed turfgrass (Anonymous 2019, 2021b, 2022b). While rate specificity for varied soil textures is not required by federal guidelines and could be cost-prohibitive or logistically difficult, research aiming to improve sustainable use of new herbicides in turfgrass is warranted (USEPA 2024).[1]

Textural differences can affect soil hydraulics, particularly soil moisture availability, that can influence herbicide performance. Pyroxasulfone efficacy for preemergence weed control in corn (*Zea mays* L.) is affected by soil organic matter content and clod size, edaphic parameters that influence soil moisture retention following rainfall (Yamaji et al. 2016). Soil moisture deficits were attributed to reduced *Digitaria* spp. control with fenoxaprop applied at early- and mid-postemergence timings, whereas applications before a heavy rainfall increased efficacy at a late-postemergence timing (Neal et al. 1990). Foramsulfuron efficacy on goosegrass [*Eleusine indica* (L.) Gaertn.] is maximized under conditions of elevated soil moisture (≥ 20%) and low evaporative demand (Shekoofa et al. 2020). Post-application irrigation increased efficacy of pendimethalin for preemergence *D. ischaemum* control, likely by moving foliar residues intercepted by the turfgrass canopy after treatment into the soil (Gasper et al. 1994). Indaziflam and flumioxazin efficacy for kochia [*Bassia scoparia* (L.) A.J. Scott] control decreased in drier soils (Sebastian et al. 2017). A drought-tolerant species, *B. scoparia* was able to germinate in soils where moisture content limited water available for herbicide solubilization to soil solution (Everitt et al. 1983). Low soil moisture content can increase herbicide adsorption to soil, reducing ability for root uptake (Dao and Lavy 1978).

There is minimal information available regarding the effects of edaphic factors such as soil texture and moisture retention on tetflupyrolimet efficacy for weed control in turfgrass. Considering that tetflupyrolimet is a promising tool for turfgrass managers, particularly those challenged with herbicide-resistant weeds, understanding the effects of soil texture and moisture retention on performance is needed to optimize efficacy. We hypothesized that tetflupyrolimet efficacy would vary among soils of differing textures and hydraulic properties. This paper presents a series of experiments designed to explore that hypothesis in detail.

Material and Methods

Soil Selection

All experiments were conducted using two distinctly different soils: a Sequatchie clay loam (fine-loamy, siliceous, semiactive, thermic Humic Hapludults) with 26.1% sand, 41% silt, and 32.1% clay, and a United States Golf Association–specified silica sand (United States Golf Association 2018). This sand medium contained 98.3% sand, 1.2% silt, 0.5% clay, and 0.5% organic matter (Table 1). A complete analysis of the physical and chemical properties of each soil is presented in Table 1. Additionally, soil moisture retention curves for each soil are presented in Figure 1. Nutrient analyses for both soils are presented in Supplementary Table 1.

Dose–Response Studies

Experiments were conducted in a controlled glasshouse environment in Knoxville, TN, USA (35.94°N, 83.93°W) evaluating the response of herbicide-susceptible *P. annua* to increasing doses of tetflupyrolimet in two different soils. Experiments were repeated in both time and space during spring 2023 under conditions of natural and supplemental light for a 16/8-h (day/night) photoperiod (PKB, Arize Element L1000 Next-Gen, Current Lighting Solutions, Cleveland, OH, USA).

Each experiment was arranged in a randomized complete block design with five replications repeated in time and space. Greenhouse pots (1,065 cm^3) were separately filled with each soil and irrigated thereafter to ensure settling throughout the profile. After 3 d of irrigation cycling, pots were surface seeded with *P. annua* (University Park, PA, USA) before being treated with tetflupyrolimet (Dodhylex™ Active, FMC Corporation, Philadelphia, PA, USA) at rates of 0, 25, 50, 100, 200, 400, 800, 1,600, 3,200, or 6,400 g ha^{-1} using an enclosed spray chamber (Generation III Research Sprayer, DeVries Manufacturing, Hollandale, MN, USA), calibrated to deliver 215 L ha^{-1} using a single flat-fan nozzle (8004EVS, TeeJet® Spraying Systems, Wheaton, IL, USA).

Temperature conditions in the glasshouse were monitored using greenhouse control sensors (PRIVA, Vineland Station, ON, Canada), whereas a quantum sensor (SQ-500 Full-Spectrum Quantum Sensor, Apogee Instruments, Logan, UT, USA) was used to record photosynthetically active radiation (Table 2). Irrigation was supplied via misting heads (Ein Dor Mini-Sprinklers, Tavlit Plastic, Yavne, Israel) connected to a timer (Galcon 8056AC-6S Timer, Galcon USA, San Rafael, CA, USA) that was configured to apply light (0.4 to 0.6 cm h^{-1}) irrigation cycles throughout the day.

Poa annua control was visually evaluated using a 0% (i.e., no control) to 100% (i.e., complete plant death) scale relative to nontreated check pots (i.e., 0 g ha^{-1} tetflupyrolimet) in each replication 42 d after treatment (DAT). After control assessments were made, aboveground biomass was harvested at the soil surface of each pot, bagged, dried in a forced-air oven (Laboratory Oven, Grieve Corporation, Round Lake, IL, USA) for 72 h at 105 C, and weighed. Aboveground biomass data were expressed as a percentage of nontreated check pots in each replication.

Aboveground biomass and *P. annua* control data were subjected to nonlinear regression analysis using Prism software (v. 10.1.1. GraphPad, Boston, MA, USA). Data from each soil type were fit to an EC anything model (https://www.graphpad.com/guides/prism/latest/curve-fitting/reg_ecanything.htm) that was used to calculate doses of tetflupyrolimet required to achieve 90% *P. annua* control and 90% reductions in aboveground biomass. Confidence intervals (95%) were used to compare values between soil types.

Soil Moisture Effects on Tetflupyrolimet

Laboratory research was conducted in 2024 to evaluate the effect of soil moisture on tetflupyrolimet activity in different soil types. The experiment was arranged in a completely randomized design with four replications and repeated in time. Treatments included the factorial combination of two soil types (Table 1) and 10 soil moisture treatments.

[1]Pesticides; Data Requirements for Conventional Chemicals, 40 CFR part 158 subpart A, 21 U.S.C. 346a (2007), https://www.ecfr.gov/current/title-40/chapter-I/subchapter-E/part-158, accessed: February 9, 2025; Labeling Requirements for Pesticides and Devices, 40 CFR part 156, 7 U.S.C. 136-136y (2008), https://www.ecfr.gov/current/title-40/chapter-I/subchapter-E/part-156, accessed: February 9, 2025.

Table 1. Physical and chemical properties of soils used in glasshouse and laboratory experiments exploring effects of various edaphic factors on tetflupyrolimet (Dodhylex™ Active) efficacy for grassy weed control.[a]

Soil type	Sand	Silt	Clay	Organic matter	Total porosity	Air-filled porosity	Capillary porosity	Total exchange capacity	Saturated hydraulic conductivity	pH
	%							meq 100 g^{-1}	cm h^{-1}	(H_2O 1:1)
Clay loam	26.1	41.0	32.1	2.2	54.5	18.5	36.0	6.7	25.1[b]	5.7
Sand	98.3	1.2	0.5	0.5	43.7	27.6	16.1	1.6	70.6	4.8

[a]Organic matter, total exchange capacity, and pH analyses conducted by Brookside Laboratories (New Bremen, OH, USA). Soil texture, porosity, and saturated hydraulic conductivity analyses conducted by A. McNitt and SerenSoil (State College, PA, USA).
[b]Testing after compacting soil to 75% compaction using ASTM D698-12.

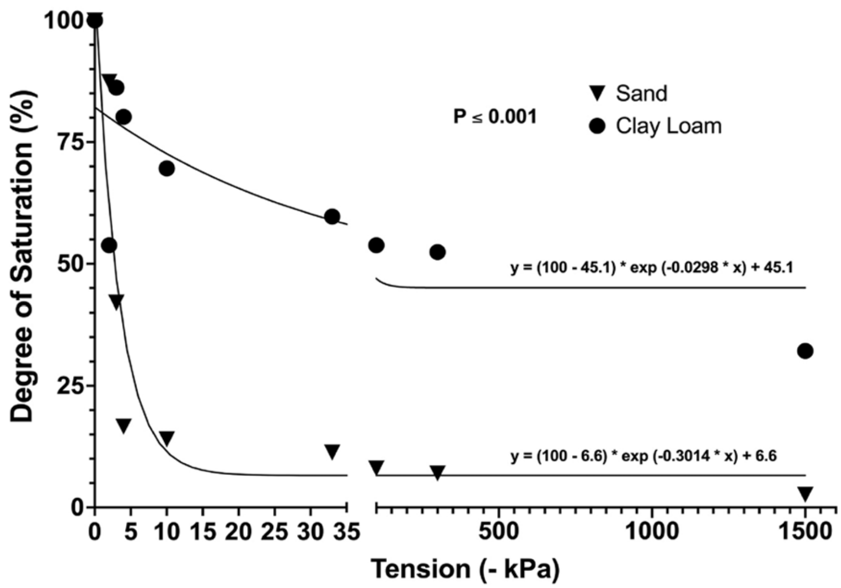

Figure 1. Soil moisture retention curves for the two soils used in glasshouse and laboratory experiments exploring effects of various edaphic factor on tetflupyrolimet (Dodhylex™ Active) efficacy for grassy weed control. Soil moisture retention curves generated by Turf & Soil Diagnostics (Trumansburg, NY, USA) using ASTM D6836. Data were fit to a one-phase exponential decay model in GraphPad Prism (v. 10.1.1. GraphPad, Boston, MA, USA) and compared using a global sums-of-squares *F*-test at α = 0.05.

Petri dishes (100 by 15 mm, Fisherbrand™ Petri Dishes with Clear Lid, Thermo-Fisher Scientific, St Louis, MO, USA) were filled with 50 cm^3 of each soil. Bulk density values within petri dishes were 1.23 and 1.48 g cm^{-3} for the clay loam and sand, respectively. Distilled water was added to each plate using a syringe (10 ml Fisherbrand™ Sterile Syringes for Single Use, Thermo-Fisher Scientific, St Louis, MO, USA) to create volumetric water content treatments: 0%, 5%, 10%, 15%, 20%, 30%, 40%, 60%, 80%, and 100%. In this study, volumetric water content refers to the volume of water added to each petri dish relative to the volume of soil (v/v). Ten perennial ryegrass (*Lolium perenne* L.) seeds were added to each plate to serve as a bioindicator of tetflupyrolimet activity after treatment at 50 g ha^{-1} using the previously described enclosed spray chamber. Non-treated controls (0 g ha^{-1} tetflupyrolimet) were included at each volumetric water content for comparison. In the dose–response experiment discussed earlier, differences in *P. annua* control among soil types were greatest at 50 g ha^{-1} (Figure 2). *Lolium perenne* seeds were selected for this assay because they germinate more quickly than *P. annua*, and pilot experiments indicated that both species were sensitive to tetflupyrolimet.

After herbicide application, petri dishes were sealed with Parafilm (2 in. All-Purpose Laboratory Film, Amcor, Menasha, WI, USA) and placed inside a growth chamber (G1000-Germinator, Conviron, Winnipeg, MB, Canada) that provided a constant 16 C air temperature and 16-h photoperiod. The number of *L. perenne* seeds germinating in each plate were counted at 15 DAT. Data were subjected to ANOVA in R (v. 6.2) to discern effects of soil type, volumetric water content, and their interaction on tetflupyrolimet activity. For each soil, *L. perenne* germination means were plotted across volumetric water content in GraphPad Prism with means separated using standard error assessments.

Results and Discussion

Soil-Type Dose Response

Significant differences in *P. annua* control were detected between soils treated with increasing doses of tetflupyrolimet from rates of 25 to 400 g ha^{-1} in this study (Figure 2; Table 3). Tetflupyrolimet rates of 38 and 231 g ha^{-1} were required to control *P. annua* 90% in sand and clay loam, respectively. Similarly, rates of tetflupyrolimet required to reduce *P. annua* biomass 90% also varied between soil types (Figure 2; Table 3). A rate of 30 g ha^{-1} was required for a 90% biomass reduction in sand compared with 237 g ha^{-1} in clay loam, representing a near 8-fold documented difference in herbicide activity between soil textures. By 42 DAT, tetflupyrolimet at 400 g ha^{-1} controlled *P. annua* on both soil types similar to field reports in turfgrass (Pritchard et al. 2025).

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Table 2. Conditions inside glasshouses during dose–response experiments evaluating efficacy of tetflupyrolimet (Dodhylex™ Active) for preemergence control of herbicide-susceptible *Poa annua* in two soil types.[a]

Parameter	Experimental run 1	Experimental run 2
Irrigation[b] (cm d^{-1})	0.43	0.58
Temperature[c] (C)	22.6	23.6
Photosynthetically active radiation[d] (μmol m^{-2} s^{-1})	495	716

[a]Experiments conducted in Knoxville, TN, USA (35.94°N, 83.93°W) during spring 2023.
[b]Irrigation delivered via misting heads (Ein Dor Mini-Sprinklers, Tavlit Plastic, Yavne, Israel) connected to a timer (Galcon 8056AC-6S Timer, Galcon USA, San Rafael, CA, USA).
[c]Measurements made using greenhouse control sensors (PRIVA, Vineland Station, ON, Canada).
[d]Data are the daily averages collected using a quantum sensor (SQ-500 Full-Spectrum Quantum Sensor, Apogee Instruments, Logan, UT, USA).

Our experiments identified 6- to 8-fold differences in tetflupyrolimet activity on *P. annua* due to soil texture. Soil texture effects on herbicide efficacy have been documented for other preemergence herbicides. For example, differences in efficacy have been documented with atrazine and pendimethalin in corn production where humic matter, organic matter, and cation exchange capacity were significantly correlated with increasing herbicide rates required to reach 80% weed control (Blumhorst et al. 1990). In addition, higher rates of metribuzin were needed for effective weed control as humic and organic matter content increased across 201 soils evaluated representative of the corn, wheat (*Triticum* spp.), and cotton (*Gossypium hirsutum* L.) production belts of the United States (Weber et al. 1987). To date, minimal information has been published regarding the effect of soil type on tetflupyrolimet; efficacy in rice production has been reported on a single soil type (clay) (Lombardi and Al-Khatib 2024). Similarly, tetflupyrolimet efficacy in turfgrass has only been evaluated on silt and clay loam soils (Pritchard et al. 2025).

Soil Moisture Impacting Tetflupyrolimet Efficacy

A significant soil type by volumetric water content by herbicide treatment interaction was detected ($P \leq 0.0001$) in *L. perenne* germination data and is presented in Figure 3. When no herbicide was present, a minimum of 5% volumetric water content (v/v) was required for *L. perenne* germination in sand, whereas 15% volumetric water content was required for similar germination in clay loam. While not measured directly, this difference could be a function of water being held at greater matric potential in the clay loam compared with the sand root zone. Although total porosity was similar among these two soils, the sand root zone contained a greater quantity of macropores (27.6% compared with 18.5%) leading to greater saturated hydraulic conductivity and reduced soil moisture retention (Table 1; Figure 1). While herbicide sorption and bioavailability can differ among soil textures, these proxy measures suggest that less energy may be required for *L. perenne* to access moisture in this sand root zone compared with clay loam. In the absence of tetflupyrolimet, *L. perenne* could not germinate in clay loam at ≤ 10% volumetric water content, whereas germination was ≥ 75% in a sand root zone maintained under the same conditions (Figure 3). Similar to field reports on *D. ischaemum* (Pritchard et al. 2025), overall activity of tetflupyrolimet (50 g ha^{-1}) in the current laboratory study increased in both soils as volumetric water content increased (Figure 3). However, tetflupyrolimet activity in sand was greater than clay loam at each soil moisture content from 15% to 60% (Figure 3).

Higher tetflupyrolimet activity in sand could be related to matric potential, as activity on *L. perenne* was higher in sand (compared with clay loam) across a wide range of volumetric water contents (15% to 60%). Once volumetric water content increased to ≥ 80%, no differences in tetflupyrolimet activity were detected among soils, with *L. perenne* germination measuring 0% (Figure 3). Similar to what has been reported with other preemergence herbicides (Gasper et al. 1994; Olson et al. 2000; Sebastian et al. 2017), this response indicates that post-application irrigation could mitigate potential reductions in efficacy on heavier soils, particularly when soil moisture is limited.

While this study provides valuable information regarding the effects of soil type on tetflupyrolimet efficacy in turfgrass, this research has limitations. First, only two soil types were included in our experiments. Future research exploring tetflupyrolimet efficacy on different soils is warranted, particularly those with edaphic parameters different from those presented in Table 1. It should be noted that pilot experiments found no significant

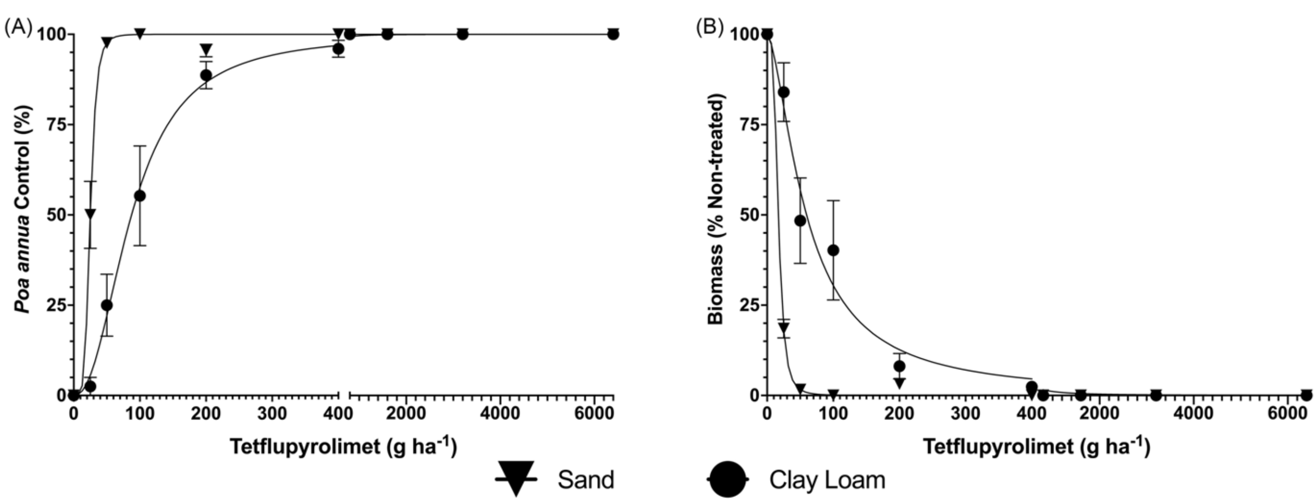

Figure 2. Visual control of *Poa annua* (A) and aboveground biomass (B) response to increasing doses of tetflupyrolimet (Dodhylex™ Active) applied preemergence to herbicide-susceptible *Poa annua* planted in a sand that conformed to United States Golf Association specifications, as well as a clay loam soil native to Knoxville, TN, USA. Edaphic factors for each soil type are presented in Table 1. Data pooled from two experimental runs conducted in a glasshouse in 2023. Bars represent standard error of each mean.

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Table 3. Rate of tetflupyrolimet (Dodhylex™ Active) to achieve 90% *Poa annua* control or 90% reductions in *P. annua* biomass (EC_{90}) in glasshouse experiments conducted in Knoxville, TN, USA (35.94°N, 83.93°W) during spring 2023.

	Sand		Clay loam	
Parameter	Control (%)	Biomass reduction (%)	Control (%)	Biomass reduction (%)
	——— % ———			
EC_{90} (g ha^{-1})	38	30	231	237
Confidence interval (95%)	~ to 47	~ to 33	175–317	157–383
R^2	0.92	0.99	0.86	0.77

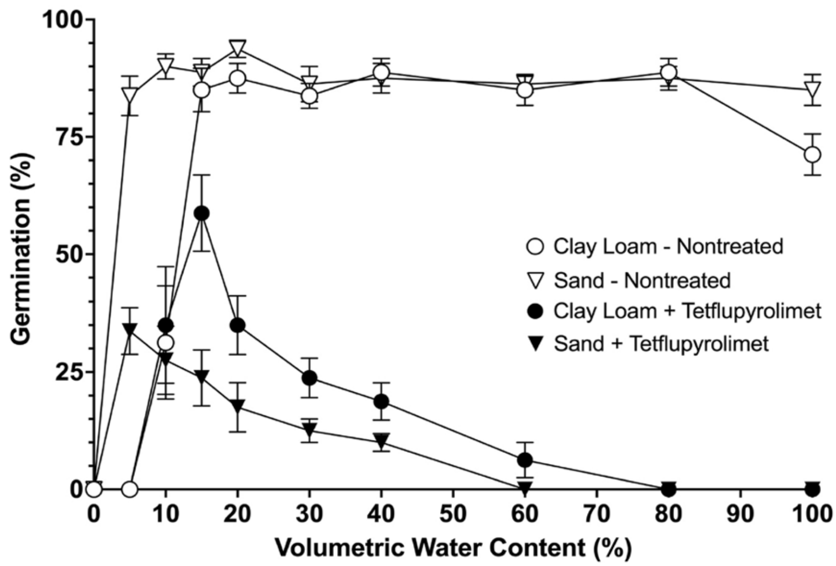

Figure 3. Effect of tetflupyrolimet (50 g ha^{-1}) on *Lolium perenne* germination in clay loam soil or sand varying in volumetric water content during repeated growth chamber experiments conducted in Knoxville, TN, USA, during 2024. Bars represent standard error of each mean.

differences in tetflupyrolimet efficacy due to soil pH, total exchange capacity, or calcium content (data not shown). Second, matric potential was not directly measured in our experiment. Similar to research with *B. scoparia* (Sebastian et al. 2017), direct assessments of matric potential on tetflupyrolimet efficacy are warranted. Further work to better characterize sorption and mobility of tetflupyrolimet in soils of varying texture, particularly those common in rice production, would enhance general understanding of this novel molecule.

Overall, our experiments highlighted a 6- to 8-fold difference in tetflupyrolimet activity on *P. annua* following treatments to plants growing in a sand root zone compared with a clay loam. These data suggest that tetflupyrolimet application rates in sand could differ from those recommended for use in finer-textured soils, such as clay loam. Outlining optimal application rates based on soil texture may be difficult in managed turfgrass landscapes containing mixed-textured soils. Greater activity of tetflupyrolimet in sand offers several benefits for turfgrass managers, including its suitability for use on golf course putting greens, which are predominantly constructed on sand profiles. Use of tetflupyrolimet on putting greens could address widespread infestations of acetolactate synthase-resistant *P. annua* on these surfaces (Singh et al. 2021). Second, new golf courses are often constructed on sandy sites given that they offer a growing medium that can withstand traffic and provide optimal ball-to-surface interactions. Greater tetflupyrolimet activity in these sandy mediums could allow for reduced application rates to be used for acceptable weed control. However, surface organic matter accumulation within turfgrass systems established on sand can be significant; for example, sand-based putting greens in Tennessee contain 5.8% to 10.1% total organic material in the uppermost 2 cm of the soil profile (Kahiu et al. 2024). While our pilot experiments revealed few differences in tetflupyrolimet efficacy due to total exchange capacity (data not shown), additional research exploring the effects of organic matter on the enhanced efficacy of tetflupyrolimet in sand root zones is warranted.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wsc.2025.10043

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Competing interests. The authors of this publication state that FMC Corporation owns the trademark for tetflupyrolimet (Dodhylex™ Active) and provided financial support of the research presented in this publication. Additionally, AP is an employee of FMC Corporation.

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