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Weed Management Programs with Pyroxasulfone in Field Corn (*Zea mays*)

Daniel O. Stephenson IV, Jason A. Bond, James L. Griffin, Randall L. Landry, Brandi C. Woolam, H. Matthew Edwards, and John M. Hardwick*

Field experiments were conducted in Louisiana and Mississippi from 2011 through 2013 to evaluate crop injury, weed control, and yield in field corn following pyroxasulfone applied PRE and POST. Pyroxasulfone PRE or POST did not injure corn at any evaluation. Barnyardgrass control was not improved with the addition of any POST treatment to pyroxasulfone alone or atrazine plus pyroxasulfone PRE; however, all POST treatments increased barnyardgrass control to at least 95% at all evaluations following atrazine PRE. All treatments that contained a PRE followed by POST application controlled browntop millet ≥90% at all evaluations. All POST treatments increased ivyleaf morningglory control to ≥92% following atrazine or pyroxasulfone alone PRE. However, control with atrazine plus pyroxasulfone PRE was similar or greater 28 d after POST than all treatments that received a POST application. In the absence of a POST treatment, pyroxasulfone or atrazine plus pyroxasulfone PRE controlled Palmer amaranth 93 to 96% at all evaluations, but atrazine alone PRE provided 84, 82, and 66% control 7, 14, and 28 d after POST, respectively. All programs that contained a PRE followed by POST herbicide treatment controlled Palmer amaranth >90% at all evaluations. Corn yield following all treatments except atrazine alone PRE and the nontreated were similar and ranged from 10990 to 12330 kg ha^{-1}. This research demonstrated that pyroxasulfone can be a valuable tool for weed management in a corn weed management program.

Nomenclature: Atrazine; glyphosate; pyroxasulfone; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv. ECHCG; browntop millet, *Urochloa ramosa* (L.) Nguyen PANRA; ivyleaf morningglory, *Ipomoea hederacea* Jacq. IPOHE; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; corn, *Zea mays* L.

Keywords: Residual herbicides, tank mixtures.

Surveyed producers from the United States reported that herbicides were applied to 97% to 98% of corn hectares in 2010 and 2014, with 27% to 77% of hectares receiving glyphosate, a photosystem II (PSII) inhibitor, a 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor, or a very long chain fatty acid synthesis (VLCFA) inhibitor (Anonymous 2017b, 2017c). Utilization of multiple herbicidal modes of action in a weed management plan, especially those that provide residual weed control, are important in a management program for herbicide-resistant weeds (Norsworthy et al. 2012). However, numerous weed species resistant to glyphosate, PSII inhibitors, and/or HPPD inhibitors have been documented in the United States (Heap 2017). In addition, multiple resistance to glyphosate and PSII inhibitors, or HPPD inhibitors and PSII inhibitors, has been documented in Palmer amaranth and tall waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer]. Furthermore, a population of tall waterhemp in Iowa was documented resistant to glyphosate, PSII, and HPPD inhibitors (Heap 2017). The aforementioned herbicide resistance is quite troubling for producers and scientists, because it encompasses one to three of the most widely utilized herbicidal modes of action in corn weed management programs. This highlights the importance of VLCFA inhibitors for weed management in corn.

Acetochlor, dimethenamid-P, and *S*-metolachlor have a long history of use in corn weed management programs (LSUAC-CES 2017; MSU-ES 2016). Recently, a new VLCFA inhibitor, pyroxasulfone, was

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* First, fourth, and fifth authors: Associate Professor and Research Associates, Louisiana State University Agricultural Center, Dean Lee Research and Extension Center, Alexandria, LA 71302; Second and sixth authors: Professor and Research Associate, Mississippi State University, Delta Research and Extension Center, P.O. Box 197, Stoneville, MS 38776; Third and seventh authors: Professor Emeritus and former Graduate Student, School of Plant, Environmental, and Soil Sciences, Louisiana State University Agricultural Center, Baton Rouge, LA 70803. Corresponding author's E-mail: dstephenson@agcenter.lsu.edu

commercialized in the United States (Anonymous 2017d). Pyroxasulfone is registered for use in corn, cotton (*Gossypium hirsutum* L.), fallow, soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.), with use rates of 49 and 210 g ai ha^{-1} (Anonymous 2017d; Shaner 2014; Tanetani et al. 2009, 2011). Mueller and Steckel (2011) evaluated the potential residual control of four VLCFA inhibitors and determined that the half-life (DT_{50}) values of acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor were 3.5 to 5 d, 5 to 9 d, 8.2 to 70 d, and 8.7 to 27 d, respectively. Considering the greater DT_{50} for pyroxasulfone compared to the other VLCFA inhibitors evaluated, these data suggest that pyroxasulfone can potentially provide longer residual control of susceptible weeds than the other herbicides evaluated.

Weeds controlled by pyroxasulfone include field sandbur (*Cenchrus spinifex* Cav.), Florida beggarweed [*Desmodium tortuosum* (Sw.) DC.], green foxtail [*Setaria viridis* (L.) Beauv.], Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot.], kochia [*Kochia scoparia* (L.) Schrad.], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], Palmer amaranth, puncturevine (*Tribulus terrestris* L.), shattercane [*Sorghum bicolor* (L.) Moench ssp. *arundinaceum* (Desv.) de Wet & Harlan], smallflower morningglory [*Jacquemontia tamnifolia* (L.) Griseb.], Texas millet [*Urochloa texana* (Buckl.) R. Webster], velvetleaf (*Abutilon theophrasti* Medik.), and tall waterhemp (Bond et al. 2014; Geier et al. 2006; Grey et al. 2014; Hulting et al. 2012; King and Garcia 2008; King et al. 2007; Knezevic et al. 2009; Steele et al. 2005). Crop safety following pyroxasulfone application varies by crop. Pyroxasulfone PRE or POST did not injure corn (Geier et al. 2006; Jha et al. 2015; King and Garcia 2008; Knezevic et al. 2009; Steele et al. 2005). In soybean, no injury was observed following pyroxasulfone PRE; however, 15% injury was reported following POST application (Grey et al. 2014; Mahoney et al. 2014; McNaughton et al. 2014; Stephenson et al. 2017). Peanut (*Arachis hypogaea* L.) injury increased from 5% to 48% following pyroxasulfone PRE as silt and clay content in the soil increased; however, pyroxasulfone POST injured peanut ≤10% (Prostko et al. 2011).

The utility of VLCFA inhibitors in corn, and the increased length of residual weed control offered by pyroxasulfone, potentially make it another tool for mitigation or management of herbicide-resistant weeds in corn. Others have reported crop safety and weed control with pyroxasulfone in corn when used along with other weed management methods (Geier et al. 2006; Jha et al. 2015; King and Garcia 2008; Knezevic et al. 2009; Steele et al. 2005), but they evaluated pyroxasulfone only as a PRE treatment. Little information is available concerning pyroxasulfone applied PRE and/or POST in a corn weed management system. Therefore, the objectives of this research were to evaluate crop injury, weed control, and yield following herbicide programs containing pyroxasulfone applied PRE and POST in field corn.

Materials and Methods

Experiments were conducted at the Louisiana State University Agricultural Center Dean Lee Research and Extension Center (31.178°N, 92.411°W) in Alexandria, Louisiana, in 2011, 2012, and 2013, and the Mississippi State University Delta Research and Extension Center (33.442°N, 90.909°W) in Stoneville, Mississippi, in 2011 and 2013. Soil in Louisiana was a Coushatta silt loam (fine-silty, mixed, superactive, thermic Fluventic Entrudepts), with a pH of 8.0 and 1.5% organic matter. Soil in Mississippi was a Dundee very fine sandy loam (fine-silty, mixed, active, thermic Typic Endoaqualf), with a pH of 6.1 and 1.2% organic matter.

The experimental design was a factorial arranged in a randomized complete block design with four replications. Factors consisted of four PRE and four POST treatments. The PRE treatments included atrazine (Aatrex 4L, Syngenta Crop Protection LLC, P.O. Box 18300, Greensboro, NC 27419) at 1,120 g ai ha^{-1}, pyroxasulfone (Zidua 85 WG, BASF Corporation, 26 Davis Dr., Research Triangle Park, NC 27709) at 150 g ai ha^{-1}, atrazine at 1,120 g ha^{-1} plus pyroxasulfone at 150 g ai ha^{-1}, and no PRE treatment. The POST treatments were atrazine at 1,120 g ha^{-1}, pyroxasulfone at 60 g ha^{-1}, atrazine at 1,120 g ha^{-1} plus pyroxasulfone at 60 g ha^{-1}, and no POST treatment, applied to 30-cm corn. Glyphosate (Roundup PowerMax 4.5 L, Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167) at 870 g ae ha^{-1} was co-applied with atrazine, pyroxasulfone, and atrazine plus pyroxasulfone POST treatments. Plot size was 9 m long with four 0.97-m rows in Louisiana, and 9 m long with four 1-m rows in Mississippi. Treatments at both locations were applied with a tractor-mounted compressed-air sprayer calibrated to deliver 187 L ha^{-1} at 5.6 km h^{-1} at 145 kPa using 11002 flat-fan nozzles (TeeJet Technologies, 200 W. North Ave., Glendale Heights, IL 60139). Dates of planting, emergence, PRE and POST treatment applications, and harvest are shown for each experiment in Table 1.

In Louisiana, 'Pioneer 31P42' was planted at 75,370 seeds ha^{-1} each year. In Mississippi, 'Pioneer 31G71' and 'Terral REV 27HR83' were planted in 2011 and 2013, respectively, both at 79,100 seeds ha^{-1}. Corn was seeded 4 to 5 cm deep at both locations. All experiments were conducted using conventional tillage methods and fertility programs based upon Louisiana State University AgCenter or Mississippi State University soil test analysis recommendations. Supplemental irrigation was utilized in Mississippi, but was not available in Louisiana.

Control of barnyardgrass and Palmer amaranth was evaluated at both locations. The Palmer amaranth population in Louisiana was susceptible to glyphosate; however, approximately 60% of the individual plants in the Palmer amaranth population in Mississippi were glyphosate-resistant. Browntop millet and ivyleaf morningglory were only evaluated in Mississippi. Weed densities ranged from 10 to 20 plants m^{-2} at both locations. At the time of POST herbicide application, weed height was 5 to 10 cm, and corn was 30 cm tall.

Visual estimates of corn injury and weed control were recorded 30 d after PRE application and 7, 14, and 28 d after POST application, using a scale of 0 (no injury/control) to 100 (complete death of all plants). Yield was determined using conventional harvesting equipment and was adjusted to 15% moisture before analysis.

Data were subjected to the GLIMMIX procedure in SAS (release 9.2, SAS Institute, Cary, NC). Fixed effects for the analysis of barnyardgrass and Palmer amaranth were PRE and POST treatments and their interaction. Random effects were location, year, replication within location, and year. For browntop millet and ivyleaf morningglory, fixed and random effects were identical, except all random effects containing location were removed. Least square means were calculated and separated with Tukey's HSD test at $P \leq 0.05$ for the effects.

Results and Discussion

Corn injury was not observed following any PRE or POST treatment at any evaluation (data not shown). Others also reported little to no injury to corn following pyroxasulfone application (Geier et al. 2006; Jha et al. 2015; King and Garcia 2008; Knezevic et al. 2009; Steele et al. 2005). Pyroxasulfone with or without atrazine PRE controlled barnyardgrass ≥93%, while atrazine alone provided ≤69% control 30 d after PRE treatment and 7, 14, and 28 d after POST treatment (Tables 2 and 3). Atrazine provides partial control of barnyardgrass, giant foxtail (*Setaria faberi* Herrm.), green foxtail, large crabgrass, witchgrass (*Panicum capillare* L.), and yellow foxtail [*Setaria pumila* (Poir.) Roemer & J.A. Schultes] when applied PPI or PRE on medium- or fine-textured soils (Anonymous 2017a), and both soils in Louisiana and Mississippi meet that description. Barnyardgrass control was not improved by following pyroxasulfone alone or atrazine plus pyroxasulfone PRE with any POST treatment; however, all POST treatments increased barnyardgrass control following atrazine PRE to ≥95% at all evaluation times (Table 3). Yamaji et al. (2014) reported barnyardgrass control of 100% 45 d after application of pyroxasulfone PRE at 125 and 250 g ha^{-1}. Similarly, pyroxasulfone PRE at 125 g ha^{-1} controlled green foxtail 95% 75 d after treatment (DAT) (Geier et al. 2006).

The addition of atrazine to pyroxasulfone PRE increased browntop millet control to 92% 30 d after PRE treatment, compared with 86% following pyroxasulfone alone (Table 2). In the absence of a

Table 1. Dates of planting, emergence, preemergence (PRE) and postemergence (POST) herbicide applications, and harvest for field corn studies conducted at each location.

Location	Year	Planting	Emergence	PRE application	POST application	Harvest
Alexandria, LA	2011	March 28	April 7	March 28	April 25	August 16
	2012	March 28	April 1	March 28	April 20	August 27
	2013	March 18	April 3	March 18	April 29	August 29
Stoneville, MS	2011	April 7	April 14	April 8	May 10	August 26
	2013	April 17	April 26	April 18	May 21	September 18

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Table 2. Barnyardgrass, browntop millet, ivyleaf morningglory, and Palmer amaranth control in field corn with preemergence (PRE) herbicides 30 d after treatment.[a]

PRE herbicide[b]	Barnyardgrass[c]	Browntop millet[c]	Ivyleaf morningglory[c]	Palmer amaranth[c]
	%			
Atrazine	69 c	78 c	88 b	94 a
Pyroxasulfone	93 b	86 b	86 b	95 a
Atrazine + pyroxasulfone	96 a	92 a	94 a	97 a

[a] Means followed by the same letter within a column are not significantly different according to Tukey's HSD test at $P \leq 0.05$. Nontreated check excluded from analysis of PRE herbicide treatments.

[b] Atrazine and pyroxasulfone applied at 1,120 and 150 g ai ha^{-1}, respectively.

[c] Barnyardgrass and Palmer amaranth control was evaluated in Louisiana and Mississippi. Browntop millet and ivyleaf morningglory control was evaluated only in Mississippi.

PRE treatment, all POST treatments controlled browntop millet 83% to 92% 7 and 14 d after POST. However, browntop millet control was 89% 28 d after POST following the co-application of glyphosate, atrazine, and pyroxasulfone POST compared to 77% control following glyphosate plus atrazine POST (Table 2), which may be attributed to the residual efficacy of pyroxasulfone. Similarly, Steele et al. (2005) reported 84% Texas millet control 28 DAT following pyroxasulfone PRE at 125 g ha^{-1}. All treatments that contained a PRE followed by POST application controlled browntop millet ≥90% at all evaluations, indicating the potential need for a PRE followed by POST program to control browntop millet in corn.

Ivyleaf morningglory control with atrazine plus pyroxasulfone PRE was 94% 30 d after PRE, while atrazine or pyroxasulfone alone PRE provided 88% and 86% control, respectively (Table 2). Yamaji et al. (2014) reported 92% ivyleaf morningglory control following pyroxasulfone PRE at 125 g ha^{-1} 28 d after application. In the absence of a PRE application, ivyleaf morningglory control with all POST

Table 3. Control of barnyardgrass and browntop millet in corn 7, 14, and 28 d after postemergence (POST) application in field corn as influenced by preemergence (PRE) and POST application of atrazine and pyroxasulfone.[a]

		Barnyardgrass[c]			Browntop millet[c]		
PRE herbicide[b]	POST herbicide[b]	7 DAT[d]	14 DAT	28 DAT	7 DAT	14 DAT	28 DAT
		%					
None	None	0 c	0 c	0 c	0 f	0 f	0 f
None	Atrazine	93 a	96 a	93 a	89 cd	83 d	77 d
None	Pyroxasulfone	96 a	97 a	96 a	92 abc	89 abcd	84 bcd
None	Atrazine + pyroxasulfone	93 a	94 a	96 a	90 bcd	86 bcd	89 abc
Atrazine	None	68 b	61 b	50 b	71 e	69 e	58 e
Atrazine	Atrazine	97 a	97 a	95 a	93 abc	90 abcd	83 bcd
Atrazine	Pyroxasulfone	97 a	97 a	95 a	96 ab	93 abc	92 ab
Atrazine	Atrazine + pyroxasulfone	97 a	98 a	96 a	95 abc	92 abcd	90 abc
Pyroxasulfone	None	95 a	96 a	93 a	83 d	82 d	78 cd
Pyroxasulfone	Atrazine	97 a	97 a	95 a	94 abc	92 abcd	90 ab
Pyroxasulfone	Pyroxasulfone	97 a	97 a	96 a	96 abc	96 a	93 ab
Pyroxasulfone	Atrazine + pyroxasulfone	97 a	98 a	96 a	97 a	93 abc	93 ab
Atrazine + pyroxasulfone	None	96 a	97 a	95 a	90 bcd	86 cd	86 bcd
Atrazine + pyroxasulfone	Atrazine	97 a	98 a	97 a	97 a	94 ab	93 ab
Atrazine + pyroxasulfone	Pyroxasulfone	97 a	98 a	97 a	97 a	97 a	97 a
Atrazine + pyroxasulfone	Atrazine + pyroxasulfone	97 a	98 a	97 a	97 a	97 a	96 a

[a] Means within each column followed by the same letter are not significantly different according to Tukey's HSD test at $P \leq 0.05$.

[b] Atrazine at 1,120 g ha^{-1} was applied in both PRE and POST treatments. Pyroxasulfone was applied PRE and POST at 150 and 60 g ha^{-1}, respectively. Glyphosate at 0.77 lb ae ha^{-1} was co-applied with all POST treatments except the nontreated.

[c] Barnyardgrass control was evaluated in Louisiana and Mississippi. Browntop millet control was evaluated only in Mississippi.

[d] Abbreviation: DAT, days after treatment.

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Table 4. Control of ivyleaf morningglory and Palmer amaranth in corn 7, 14, and 28 days after postemergence (POST) application in field corn as influenced by preemergence (PRE) and POST application of atrazine and pyroxasulfone.[a]

		Ivyleaf morningglory[c]			Palmer amaranth[c]		
PRE herbicide[b]	POST herbicide[b]	7 DAT[d]	14 DAT	28 DAT	7 DAT	14 DAT	28 DAT
		%					
None	None	0 e	0 g	0 f	0 e	0 d	0 e
None	Atrazine	89 c	88 cde	88 bcd	93 c	94 b	92 c
None	Pyroxasulfone	86 cd	85 ef	84 cde	94 bc	94 b	95 ab
None	Atrazine + pyroxasulfone	88 c	90 b-e	94 ab	94 c	95 ab	95 ab
Atrazine	None	89 c	85 def	82 de	84 d	82 c	66 d
Atrazine	Atrazine	95 ab	94 abc	93 ab	97 ab	97 ab	96 ab
Atrazine	Pyroxasulfone	95 ab	93 abc	93 ab	97 ab	97 ab	95 ab
Atrazine	Atrazine + pyroxasulfone	96 a	96 ab	95 ab	97 ab	98 a	97 ab
Pyroxasulfone	None	77 d	76 f	75 e	96 abc	94 b	93 bc
Pyroxasulfone	Atrazine	93 abc	92 a-e	93 ab	98 a	97 ab	97 ab
Pyroxasulfone	Pyroxasulfone	93 abc	93 a-d	92 abc	98 a	97 ab	97 ab
Pyroxasulfone	Atrazine + pyroxasulfone	95 ab	96 ab	95 ab	98 a	98 a	97 ab
Atrazine + pyroxasulfone	None	91 bc	93 a-d	92 abc	97 ab	96 ab	95 ab
Atrazine + pyroxasulfone	Atrazine	97 a	97 a	94 ab	98 a	97 ab	96 ab
Atrazine + pyroxasulfone	Pyroxasulfone	97 a	97 a	97 a	98 a	98 a	98 a
Atrazine + pyroxasulfone	Atrazine + pyroxasulfone	97 a	97 a	97 a	98 a	98 a	98 a

[a] Means within each column followed by the same letter are not significantly different according to Tukey's HSD test at $P \leq 0.05$.

[b] Atrazine at 1,120 g ha^{-1} was applied in both PRE and POST treatments. Pyroxasulfone was applied PRE and POST at 150 and 60 g ha^{-1}, respectively. Glyphosate at 0.77 lb ae ha^{-1} was co-applied with all POST treatments except the nontreated.

[c] Ivyleaf morningglory control evaluated only in Mississippi. Palmer amaranth control was evaluated in both Louisiana and Mississippi.

[d] Abbreviation: DAT, days after treatment.

treatments was similar 7 and 14 d after POST and ranged from 85% to 90% (Table 4). At 28 d after POST, glyphosate plus atrazine plus pyroxasulfone POST provided greater ivyleaf morningglory control than glyphosate plus pyroxasulfone alone POST, indicating the need for atrazine in the POST treatment. All POST treatments increased ivyleaf morningglory control to ≥92% following atrazine or pyroxasulfone alone PRE, but control following atrazine plus pyroxasulfone PRE was similar to or greater than control following all treatments that received a POST application 28 d after POST (Table 4). This observation supports data collected 30 d after PRE that atrazine plus pyroxasulfone PRE provides ≥90% control of ivyleaf morningglory.

All PRE treatments controlled Palmer amaranth 94% to 97% 30 d after PRE (Table 2). In the absence of a POST treatment, pyroxasulfone alone or atrazine plus pyroxasulfone PRE controlled Palmer amaranth 93% to 96% at all evaluation dates, but atrazine alone PRE provided 84%, 82%, and 66% control 7, 14, and 28 d after POST, respectively. Geier et al. (2006) observed 80% to 88% Palmer amaranth control 75 DAT with pyroxasulfone at 166 g ha^{-1} PRE. However, Steele et al. (2005) reported 97% Palmer amaranth control 63 DAT following pyroxasulfone PRE at 125 g ha^{-1}. Pyroxasulfone plus atrazine PRE controlled Palmer amaranth >96% 63 to 75 DAT (Geier et al. 2006; Steele et al. 2005). All programs that contained a PRE followed by POST herbicide treatment controlled Palmer amaranth >90% at all evaluations (Table 4). Grey et al. (2014) observed 93% control of glyphosate-resistant Palmer amaranth 100 to 124 d after planting following pyroxasulfone PRE at 120 g ha^{-1}. Results from these experiments indicate that pyroxasulfone applied PRE and/or POST is a good option for residual control of Palmer amaranth in corn.

Corn yields were similar following all treatments except atrazine alone PRE and the nontreated check, and ranged from 10,990 to 12,330 kg ha^{-1} (data not shown). Corn yield was 9,310 kg ha^{-1} following atrazine alone PRE, which was not different than the nontreated corn yield of 8,340 kg ha^{-1}. Corn yield following 166 g ha^{-1} of pyroxasulfone was 3,980 kg ha^{-1}, which was similar to yields following *S*-metolachlor plus atrazine (Geier et al. 2006).

King and Garcia (2008) reported that corn treated with pyroxasulfone at 166 or 209 g ha^{-1} PRE, or co-applied with glyphosate POST, yielded 90% to 102% of the weed-free yield. Knezevic et al. (2009) found that about 195 g ha^{-1} of pyroxasulfone PRE was needed to maintain corn yield at 95% of the weed-free yield. In our research, the lack of differences among treatments may be attributed to overall weed control ranging from 90% to 99%. Overall weed control following atrazine alone PRE ranged from 50% to 93%, with poor weed control observed for barnyardgrass, browntop millet, and Palmer amaranth, which supports corn yield data. Residual control of barnyardgrass, browntop millet, ivyleaf morningglory, and Palmer amaranth can be achieved with programs that contain pyroxasulfone PRE and/or POST in corn. In addition, no corn injury was observed following pyroxasulfone PRE or POST, indicating excellent crop safety. This research shows that pyroxasulfone can be a valuable tool for weed management in a corn weed management program.

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