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Herbicide Evaluation Against Giant Salvinia

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ABSTRACT

The response of giant salvinia (*Salvinia molesta* D. S. Mitchell) to 32 herbicide treatments was determined in an outdoor tank study at Lewisville, TX. Treatments included: endothall (as the dipotassium salt), endothall (as the mono(N,N-dimethylalkylamine salt)), diquat, glyphosate, imazapyr, copper, imazapyr + glyphosate, endothall (mono(N,N-dimethylalkylamine salt)) + glyphosate, diquat + copper, diquat + endothall (dipotassium salt), and diquat + endothall (mono(N,N-dimethylalkylamine salt)). Type of surfactant, rate of application and application technique were varied. Treatment with 1.12 kg ha^{-1} diquat, 8.97 kg ha^{-1} glyphosate, and all of the herbicide combinations controlled ≥98% salvinia 42 days after treatment (DAT). Diquat was the most effective herbicide; controlling salvinia regardless of rate, surfactant, application method (submersed vs. foliar application) and whether or not endothall (either formulation) or copper were included in the spray mixture. The least effective product evaluated against salvinia was imazapyr. Results demonstrated that several herbicides available for use in aquatic environments in the U.S. can be used to manage giant salvinia infestations.

Key words: Salvinia molesta, aquatic fern, herbicide, chemical control, exotic weed.

INTRODUCTION

Giant salvinia is a free-floating, aquatic fern native to Brazil that has recently established and become a nuisance in many lakes, rivers, and reservoirs in the Southeastern U.S. (Jacono 1999). This aggressive, non-indigenous species was most likely introduced into the U.S. through the water garden and the aquarium plant industry. Giant salvinia was first reported as an established population in a natural, outdoor environment in South Carolina in 1995 (Johnson 1995), and has since been found at over 60 locations in 28 drainages of ten states (AL, AZ, CA, GA, HI, FL, LA, MS, NC, and TX) (Jacono and Pitman 2001). Giant salvinia is considered one of the world's worst weeds due to its prolific growth rate, effective means of distribution and difficulty of control. The U.S. Department of Agriculture has listed giant salvinia as a Federal Noxious Weed which prohibits its importation into the U.S. as well as transport across state lines (Jacono 1999, Oliver 1993). However, it must be listed by individual states as a noxious species to prohibit sale and cultivation within that state. Since it is not currently designated as a noxious weed by all states, the spread of giant salvinia will likely continue throughout the southern U.S.

Herbicides will play a leading role in management and/or eradication strategies against this plant, however to date, traditional chemical techniques have provided limited effectiveness in the U.S. According to Thayer and Haller (1985), small floating plants like salvinia are difficult to treat chemically in part due to their small size and the fact that they can form dense vegetative mats several centimeters thick which shelter plants from surface-sprayed herbicide applications. Thomas and Room (1986) observed giant salvinia mats of up to 1 m thick. In addition, the upper surfaces of giant salvinia fronds are covered with numerous, cage-like hairs which can prevent optimal herbicide coverage (Holm et al. 1977, Thayer and Haller 1985, Oliver 1993). Paraquat (1,1'-dimethyl-4,4'-bipyridinium ion) has been used successfully to control giant salvinia in Australia, Kenya, Sri Lanka, Malaysia, and Papua New Guinea (Kam-Wing and Furtado 1977, Thomas and Room 1986, Oliver 1993). Diatloff et al. (1979) reported that 0.15 kg ha^{-1} diuron (N'-(3,4-diclorophenyl)-N,N-dimethylurea) mixed with surfactant (calcium dodecylbenzene) and kerosene gave complete control of giant salvinia in glasshouse trials in Australia. Although effective, neither paraquat nor diuron are registered by the U.S. Environmental Protection Agency (USEPA) for use in aquatic environments. Current information on the use and efficacy of USEPA-registered aquatic herbicides to manage this exotic weed in the U.S. is limited. The objective of this study was to evaluate the efficacy of several aquatic herbicides applied alone and in combination with one another for control of giant salvinia.

MATERIALS AND METHODS

Giant salvinia was collected from a locally-infested pond in Denton County, TX, and was transported to large, outdoor culture tanks at the Lewisville Aquatic Ecosystem Research Facility, Lewisville, TX. The tanks were surrounded by a wire-mesh enclosure to prevent the possible dispersal of salvinia by birds. The plants were grown in filtered Lake Lewisville water that was amended with Stearns Miracle-Gro® lawn food (36-6-6) at a rate to provide 10 mg L^{-1} of nitrogen in the water column. Nutrient amendments were based on recommendations by D. S. Mitchell[3] (pers. comm.) and were sufficient to maintain healthy plant cultures. These cultures were the source of plant material used for experimentation.

The herbicide study was conducted in 96, 80-L plastic containers (20-gal trash cans) filled with 75-L of nutrient-amend-

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ed water (same as culture conditions). The non-toxic dye, Aquashade®, was added to the water in each container at a rate of 1 mg L^{-1} to reduce light penetration and algal growth in the water column. Aquashade® also reduced the growth and buildup of epiphytic algae on the surfaces of submersed salvinia fronds. Algal growth on submersed fronds was shown to be phytostatic to lethal to salvinia grown in laboratory culture (J. F. Fairchild[4], pers. comm.). An equal amount of giant salvinia (approximately 310 g fresh weight; enough plant material to cover 75% of the water surface) was placed in each container and plants were allowed to acclimate to container conditions for 15 days prior to chemical treatment. The acclimation period allowed formation of a dense, single layer of salvinia that covered 100% of the water surface.

Six herbicide formulations applied alone, in combination, and with varying surfactants were evaluated in this study (Table 1). Single herbicide treatments included: the dipotassium salt of endothall (7-oxabicyclo[2.2.1] heptane-2,3-di-

[4]Fairchild, J. F., U.S. Geological Survey, Columbia Environmental Research Center. Columbia, MO.

TABLE 1. PERCENT CONTROL OF GIANT SALVINIA FOLLOWING CHEMICAL TREATMENT.

Treatment[2] (surfactant)	Rate[3] (kg ha^{-1})	Percent Control[1] 1 DAT	3 DAT	7 DAT	14 DAT	21 DAT	28 DAT	42 DAT
Untreated Control	0.0	0.0 i	0.0 k	0.0 j	0.0 l	0.0 g	0.0 h	0.0 e
Endothall-K (Cide-Kick)	5.04	10.0 hi	18.3 hi	50.0 fg	80.0 ghi	83.3 cd	80.0 cde	65.0 c
Endothall amine	High = 2.24	71.7 bc	71.7 ef	86.7 bcd	78.3 hi	80.0 d	60.0 g	56.7 c
(Cide-Kick)	Low = 0.56	23.3 gh	26.7 h	45.0 g	41.7 j	33.3 f	10.0 h	20.0 d
Diquat	High = 2.24	66.7 cd	83.3 b-e	94.3 ab	97.3 ab	100.0 a	100.0 a	100.0 a
(Cide-Kick)	Low = 1.12	45.0 ef	68.3 fg	80.0 de	81.7 f-i	92.0 abc	98.0 ab	100.0 a
Diquat (no surfactant)	2.24	7.0 i	73.3 def	91.0 abc	97.7 ab	100.0 a	100.0 a	100.0 a
Diquat submersed[4] (no surfactant)	1.12	1.0 i	5.3 jk	80.0 de	86.7 d-h	98.7 a	100.0 a	100.0 a
Diquat (SunEnergy)	1.12	11.7 hi	56.7 g	71.7 e	76.7 i	97.7 a	100.0 a	100.0 a
Glyphosate (Cide-Kick)	8.97	6.7 i	13.3 ij	56.7 f	76.7 i	78.3 d	78.3 def	99.3 a
Imazapyr (SunWet)	1.68	0.0 i	0.0 k	0.0 j	0.0 i	1.7 g	1.7 h	13.3 d
Copper (Cide-Kick)	4.49	97.0 a	95.0 ab	96.0 a	89.3 b-f	86.7 bcd	75.0 d-g	81.3 b
Herbicide Combinations:								
Endothall-K + diquat	1. 5.04 + 2.24	66.7 dc	83.3 b-e	91.7 abc	98.3 a	100.0 a	100.0 a	100.0 a
(Cide-Kick)	2. 5.04 + 1.12	53.3 de	65.0 fg	85.0 cd	86.7 d-h	98.0 a	99.3 a	100.0 a
	3. 2.52 + 2.24	71.7 bc	83.3 b-e	96.0 a	97.7 ab	100.0 a	100.0 a	100.0 a
	4. 2.52 + 1.12	56.7 de	71.7 ef	78.3 de	88.3 c-g	92.3 abc	99.3 a	100.0 a
Endothall amine + diquat	1. 2.24 + 2.24	95.3 a	97.0 a	98.0 a	99.0 a	100.0 a	100.0 a	100.0 a
(Cide-Kick)	2. 2.24 + 1.12	88.3 a	88.3 abc	93.3 abc	93.3 a-d	98.0 a	99.0 a	100.0 a
	3. 0.56 + 2.24	71.7 bc	94.3 ab	98.3 a	99.7 a	100.0 a	100.0 a	100.0 a
	4. 0.56 + 1.12	66.7 dc	76.7 c-f	85.0 cd	85.0 d-i	94.3 ab	96.3 abc	100.0 a
Endothall amine + glyphosate	1. 2.24 + 8.97	63.3 dc	91.7 ab	97.0 a	95.7 abc	91.0 abc	91.3 a-d	99.7 a
(Cide-Kick)	2. 2.24 + 4.49	61.7 dc	86.7 abc	97.3 a	93.3 a-d	92.7 abc	89.3 a-e	99.0 a
	3. 1.12 + 8.97	35.0 fg	70.0 f	90.0 abc	83.3 e-i	91.7 abc	81.7 b-e	98.7 a
	4. 1.12 + 4.49	36.7 fg	76.7 c-f	93.3 abc	83.3 e-i	83.3 dc	80.0 cde	99.0 a
Diquat + copper	1. 2.24 + 4.49	97.0 a	97.0 a	98.7 a	99.3 a	100.0 a	100.0 a	100.0 a
(Cide-Kick)	2. 2.24 + 2.25	88.3 a	89.3 ab	96.0 a	99.0 a	100.0 a	100.0 a	100.0 a
	3. 1.12 + 4.49	94.3 a	94.3 ab	95.3 ab	97.3 ab	100.0 a	100.0 a	100.0 a
	4. 1.12 + 2.25	85.0 ab	85.0 a-d	90.0 abc	91.7 a-e	100.0 a	100.0 a	100.0 a
Imazapyr + glyphosate	1. 1.68 + 8.97	0.0 i	0.0 k	18.3 h	31.7 k	56.7 e	73.3 efg	98.7 a
(SunWet)	2. 1.68 + 4.49	0.7 i	2.0 jk	8.3 ij	28.3 k	53.3 e	60.0 g	98.7 a
	3. 0.84 + 8.97	0.3 i	1.7 jk	13.3 hi	30.0 k	61.7 e	76.7 d-g	98.7 a
	4. 0.84 + 4.49	0.0 i	0.0 k	10.0 hi	28.3 k	41.7 f	61.7 fg	98.7 a
LSD (0.05)		13.7	12.0	8.7	8.4	10.2	16.7	10.3

[1]Salvinia control is expressed on a 0 to 100% scale where 0% equals no control and 100% equals complete control. Means in a column followed by the same letter do not significantly differ ($\alpha = 0.05$, Waller-Duncan *k*-ratio *t* test). DAT = Days after treatment

[2]Surfactants added to the spray mixture at the following rates: Cide-Kick, 0.5% v:v; SunEnergy, 4.68 L ha^{-1}; SunWet, 2.34 L ha^{-1}.

[3]Rates of endothall, glyphosate, and imazapyr are expressed as kg ae ha^{-1}; copper and diquat are expressed as kg ai ha^{-1} as copper and diquat cation, respectively.

[4]Submersed diquat application made by dispensing a calculated quantity of Reward formulation into the water column to achieve the target treatment rate. Rate equivalent to 0.5 mg L^{-1} diquat cation at a water depth of 0.46 m.

carboxylic acid as Aquathol® K) (hereafter referred to as endothall-K), the mono(N,N-dimethylalkylamine) salt of endothall (as Hydrothol® 191 hereafter referred to as endothall amine), diquat (6,7-dihydrodipyrido[1,2-α:2',1'-c]pyrazinedium ion as Reward®), glyphosate (N-(phosphonomethyl) glycine as Rodeo®), imazapyr ((±)-2-[4,5- dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-3-pyridinecarboxylic acid as Arsenal®), and copper (derived from copper-ethylenediamine complex and copper sulfate pentahydrate as Komeen®). Herbicide combination treatments included: imazapyr + glyphosate, endothall amine + glyphosate, diquat + copper, diquat + endothall-K, and diquat + endothall amine. Rates of application for all treatments are listed in Table 1 and are expressed as kg acid equivalent (ae) ha^{-1} unless otherwise noted. With the exception of imazapyr, all of the herbicides used in this study are registered by the U.S. Environmental Protection Agency for use in aquatic systems. American Cyanamid is currently pursuing aquatic registration for imazapyr. The non-ionic surfactant, Cide-Kick was added at a rate of 0.5% v:v to all treatments except those containing imazapyr, diquat + SunEnergy (a methylated seed oil and organosilicone surfactant blend), diquat alone (no surfactant) and diquat as a submersed application (no surfactant). As recommended by the manufacturer, a methylated seed oil (SunWet) was used as the surfactant at a rate of 2.3 L ha^{-1} with all treatments that contained imazapyr. Untreated controls were included.

All treatments (except diquat as a submersed application) were applied as a single spray dose using a CO_2-pressurized sprayer (R&D Sprayers, Opelousas, LA) equipped with a single-nozzle spray header and a solid-cone nozzle tip. The total spray volume was 1,870 L water ha^{-1} (200 gal water per acre). Care was taken so that treatments were evenly applied across plant surfaces. Shielding was placed on nearby experimental units when spraying to prevent cross contamination of spray materials between treatments. The submersed diquat application was made by dispensing (via pipette) a designated quantity of Reward® formulation directly into the water column (0.46 m depth) to achieve a final concentration of 0.5 mg L^{-1} which was equivalent to 1.12 kg diquat cation ha^{-1}. The water column was mixed thoroughly using a stirring rod after the Reward® formulation was dispensed. All treatments were applied on August 21, 1999.

A visual estimate of percent control (% dead salvinia) was recorded 1, 3, 7, 14, 21, 28, and 42 DAT. Salvinia control was expressed on a 0 to 100% scale where 0% equals no control and 100% equals complete control. A reading of 95% control or greater was regarded as an "acceptable" treatment response, however 100% plant control was considered ideal so as to prevent a recurrence of the weed problem in field situations. Observations of plant stunting, discoloration, wilting, plant deformity and re-growth were noted at each evaluation period. Salvinia biomass (all living plant material) was harvested at the conclusion of the study (42 DAT), dried to a constant weight (70C for 72 hr), and recorded as dry weight biomass. Temperature loggers (Optic StowAway Temp Loggers) were randomly placed in 9 experimental containers and were calibrated to record hourly water temperature from pre- through post- treatment (5 Aug 99 to 1 Oct 99).

Treatments were arranged in a randomized block design with 3 replicates. Data were subjected to analyses of variance procedures and means separated using Waller-Duncan *k*-ratio *t* test procedures at $\alpha = 0.05$ level of significance.

RESULTS AND DISCUSSION

Figure 1 shows the hourly water temperature data collected for the duration of the experiment. The highest water temperature, 31.3C, was recorded on August 12, 1999 with a low of 15.5C measured on the evening of September 30, 1999. The averaged daily temperature throughout the study was 25.8C. The upper and lower temperature thresholds for active giant salvinia growth are reported as 40C and 10C respectively (Oliver 1993), with the optimum range for growth from 25 to 28C (Cary and Weerts 1984, Holm et al. 1977). Our data show that water temperatures under the selected experimental conditions were conducive for active salvinia growth.

Six single-herbicide treatments (glyphosate and all of the diquat treatments) and all of the herbicide combination treatments provided 98.7 to 100% control of giant salvinia 42 DAT (Table 1). Initial treatment effects were observed at different times with each herbicide. Compared with untreated plants, treatment with copper, endothall amine, diquat, and all of the herbicide combinations except imazapyr + glyphosate, showed significant plant control as early as 1 DAT. Treatment with copper, copper + diquat (all rates), and endothall amine (2.24 kg ha^{-1}) + diquat (1.12 kg ha^{-1} and higher) were the most effective treatments 1 DAT with 85 to 97% salvinia control. Significant differences between untreated plants and those treated with endothall-K or glyphosate were first observed 3 DAT. Combining imazapyr with glyphosate significantly controlled salvinia by 7 DAT compared with untreat-

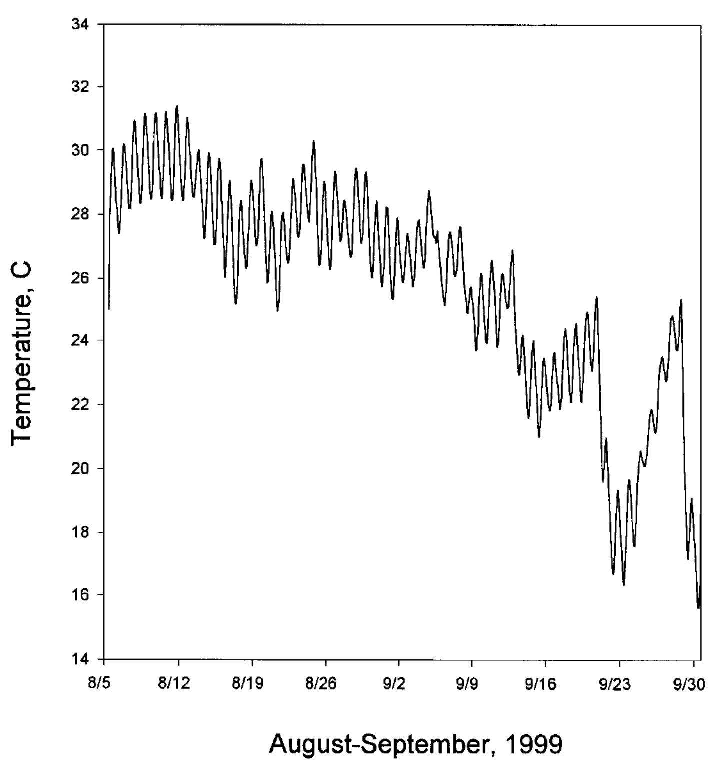

Figure 1. Mean hourly water temperature in experimental containers with giant salvinia. Plotted numbers represent the mean of 9 values.

ed plants, whereas imazapyr by itself did not show herbicide activity until 42 DAT.

Diquat with Cide-Kick as the surfactant improved salvinia control to 67% 1 DAT compared to the same rate of diquat applied alone (7% control). The low rate of diquat with Cide-Kick also performed better (45% control) than the same rate of diquat with SunEnergy as the surfactant (12% control) 1 DAT. By 3 DAT, there were no significant differences among diquat treatments with or without surfactant(s).

Herbicide rate did affect the performance of some treatments. Increasing the rate of endothall amine from 0.56 to 2.24 kg ha^{-1} improved control of salvinia. Initially, there was a significant difference in percent salvinia control between the high (2.24 kg ha^{-1}) and low (1.12 kg ha^{-1}) rates of diquat however, from 21 DAT until the end of the study, these two treatments performed similarly. For all herbicide combinations, the lowest rate of both products applied together was equally effective for controlling salvinia 42 DAT as combinations at higher rates.

All of the herbicide combinations were effective against salvinia although the advantage of tank mixing these products could not always be discerned. Since the low rate of diquat (1.12 kg ha^{-1}) applied by itself controlled 100% salvinia, an advantage of combining this rate of diquat with either endothall-K, endothall amine, or copper was not realized. Likewise, endothall amine combined with glyphosate provided significantly better salvinia control than endothall amine by itself, but not compared with glyphosate by itself. For imazapyr + glyphosate, treatment efficacy can most likely be attributed to the presence of glyphosate in the tank mix since imazapyr applied by itself was not effective against salvinia. Furthermore, all of the imazapyr + glyphosate combinations were statistically similar to glyphosate by itself 42 DAT. The herbicide combination data do suggest however, that a lower rate of glyphosate applied alone (4.49 kg ha^{-1}) may be effective for controlling salvinia. Further studies to identify lower rates of these herbicides applied alone and in combination with one another should be conducted.

Diquat as a submersed application was slower to manifest herbicide injury symptoms when compared with foliar-applied diquat. The first signs of herbicide activity were noted 7 DAT for diquat as a submersed application whereas a similar rate of diquat (1.12 kg ha^{-1}) applied as a foliar spray showed activity within 24 hrs (45% plant control 1 DAT). Although there was a delay in response, the end result of these two application methods (submersed versus foliar) was the same; 100% salvinia control.

Regrowth of plant tissues occurred with several treatments at varying times throughout the study. Although treatment with the high rate of endothall amine and with endothall-K controlled 80 to 83% of salvinia 21 DAT, new fronds emerged from surviving plant tissues as indicated by a decrease in percent control (57 to 65%) 42 DAT. Plants treated with the low rate of endothall amine and copper showed a similar regrowth response. Localized injury and regrowth of plant tissues is a typical response following treatment with contact herbicides (such as copper, endothall amine and endothall-K) since these products have limited translocation throughout plant tissues (Lembi and Ross 1985). Diquat is also a contact herbicide however, regrowth was not observed with this treatment and symptoms of herbicide injury progressed over time, suggesting herbicide movement within plant tissues. Regrowth was not observed with glyphosate nor any of the herbicide combination treatments.

Only 14 treatments had plant biomass remaining for harvest 42 DAT (Figure 2). Compared with untreated plants, imazapyr was the only treatment that did not significantly reduce salvinia biomass. Treatment with a low and high rate of endothall amine significantly reduced salvinia dry weight by 46 and 83% respectively, however remaining plant tissues were healthy and actively growing. Although the high rate of endothall amine performed significantly better than the low rate, the quantity of surviving plant material with either treatment rate was considered unacceptable. This quantity of surviving plant material would serve as an immediate source of plant material for re-infestation in field situations. All of the other treatments with surviving plant material (endothall-K, copper, glyphosate, imazapyr + glyphosate and endothall amine + glyphosate), reduced salvinia biomass by an average of 98% compared to untreated plants and would be less likely to provide sufficient biomass for re-infestation.

In conclusion, these data illustrate that treatment with 1.12 kg ha^{-1} diquat or 8.97 kg ha^{-1} glyphosate were equally effective for controlling salvinia. Both treatments controlled 99 to100% salvinia. Salvinia was controlled with diquat regardless of rate, surfactant, application method (submersed vs. foliar application) and whether or not endothall amine, endothall-K or copper were included in the spray mixture. Diquat as a submersed application may provide an alternate method of application for small ponds or for backwater areas with limited water exchange and low water turbidity that are difficult to treat with a boom sprayer. At the rates evaluated, treatment with copper, endothall-K, and endothall amine provided less than acceptable salvinia control (<95% control) by the end of the study.

The least effective compound evaluated for control of salvinia was imazapyr. Foliar necrosis was noted on 13% of plants 42 DAT however, new growth was evident at many growing points. Although imazapyr is a non-selective herbicide, salvinia was minimally affected by imazapyr at the rates applied in this study. The tolerance mechanism of salvinia to imazapyr is unknown however, the tolerance of other plant species to this herbicide is due to the ability to metabolize the active ingredient to an immobile compound which prevents translocation to the active growing points in the plant (Shaner and Mallipudi 1991). Although new, healthy salvinia growth was observed following imazapyr treatment, about 50% of new fronds were severely distorted and reduced with a "bottlebrush" appearance. Distorted fronds were not immediately visible on the surface vegetative mat but were evident at growing points underneath surface fronds. Similar symptoms have been reported on root tissues of other plants following treatment with imidazolinone herbicides and are a direct result of inhibition of cell growth and cell division due to inhibition of branched-chain amino acid synthesis (Shaner 1991). Uptake and translocation may also impact imazapyr tolerance in salvinia.

Regrowth did occur with several of the treatments evaluated in this study and emphasizes the importance of monitoring treatment efficacy with time. Initial treatment efficacy was not synonymous with long-term control as observed with copper,

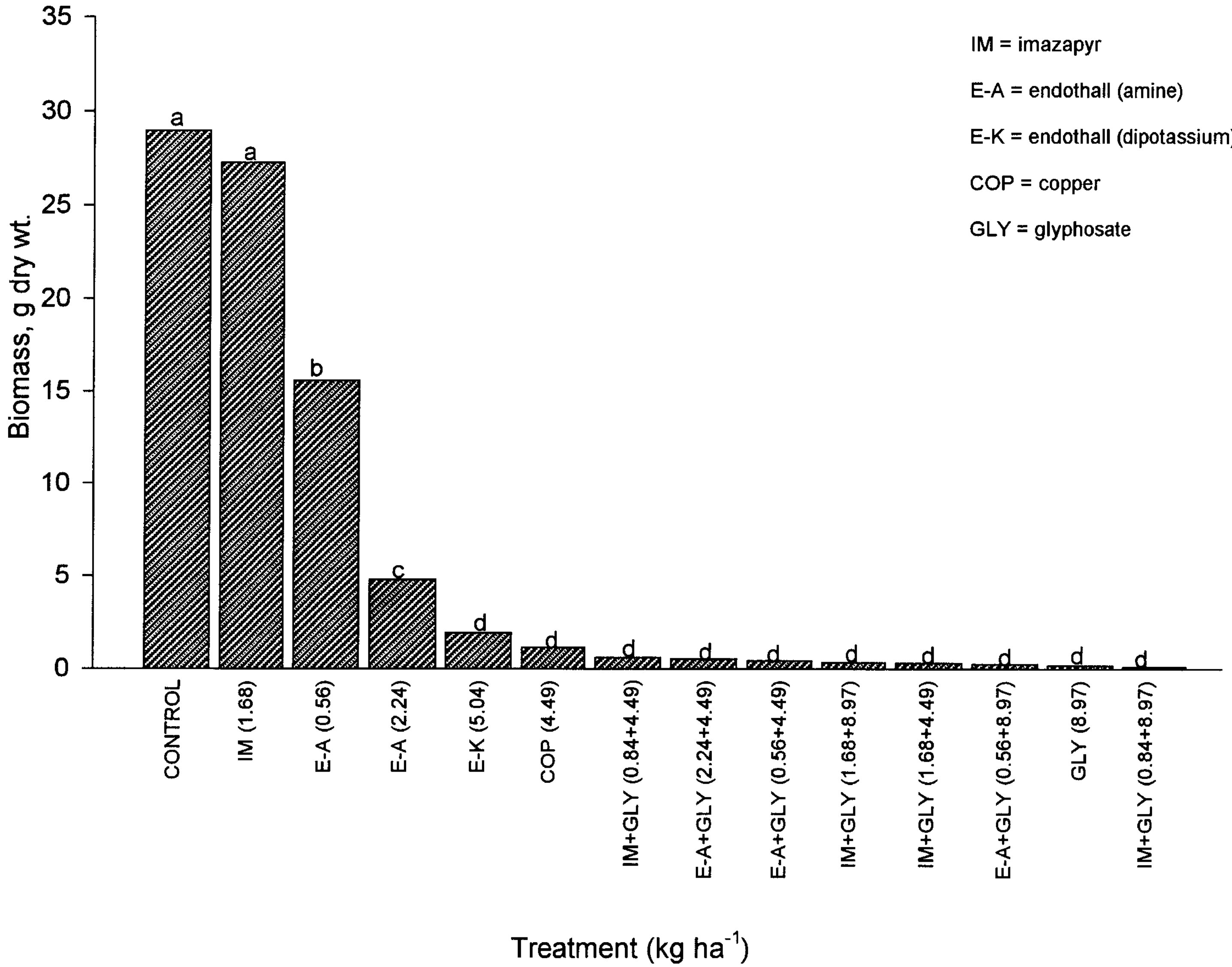

Figure 2. Dry weight biomass of salvinia 42 days after treatment with herbicides. Each bar represents the mean of three replicated treatments. Bars sharing the same letter do not differ significantly from each other. Waller-Duncan *k*-ratio *t* test was used to determine statistical significance at $\alpha = 0.05$. (Only those treatments with living biomass were included in this figure.)

endothall-K and endothall amine. Failure to monitor treatment efficacy for a sufficient time period following application may explain some of the product inconsistencies that have been reported with field applications of these herbicides.

All of the herbicide combination treatments evaluated in this study were effective against salvinia, however, some of these herbicides were equally effective when applied separately. Additional studies will be required to identify lower rates of application when products are combined with one another for control of salvinia.

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