

Effects of adjuvants on the effectiveness and rainfastness of rimsulfuron in potato

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Summary Adjuvants are used with herbicides to increase their efficacy. In this study, it was demonstrated that the application of 0.1% of the non-ionic surfactant (NIS, Contact) and 0.5 L ha⁻¹ of a crop oil concentrate (COC, Renol) did not improve the efficacy of rimsulfuron on *Amaranthus retroflexus*. In contrast, the same treatments enhanced performance and rainfastness of rimsulfuron in *Chenopodium album*. Increasing non-ionic surfactant concentration to 1 L ha⁻¹ increased rimsulfuron performance around 10-fold for *A. retroflexus* compared to around 3-fold for *C. album*. The same treatment reduced 12-fold the rainfastness of rimsulfuron on *A. retroflexus* while improving 2-fold the rainfastness of rimsulfuron on *C. album*. Measured ED₅₀ and ED₉₀ doses of rimsulfuron indicated that the addition of the 0.2 L ha⁻¹ of NIS improved the recommended (60 g a.i. ha⁻¹) and the reduced (30 g a.i. ha⁻¹) dose effect of rimsulfuron in potato crop in the field. The highest potato yield was recorded (60 tons per ha) when 60 g a.i. ha⁻¹ of rimsulfuron was applied at three growth stages [leaf development (S1) + vegetatively propagated organs (S4) + development of tuber (S7)] of the crop without using a NIS; not significant differences were measured when the same dose of rimsulfuron was applied at the three (S1, S4, and S7) and two (S1, S4) growth stages with NIS.

Additional keywords: chemical control, dose-response, growth stages, herbicide efficacy, surfactant

Introduction

The most important weeds in potato crop in Iran are *Amaranthus* spp., *Chenopodium album* L., *Portulaca oleracea* L., *Polygonum* spp., *Setaria* spp., *Echinochloa crus gali*, *Hordeum leporinum* and *Lolium* spp. (Hasaninasab Farzaneh *et al.*, 2018). Rimsulfuron is a sulfonylurea herbicide (applied at both pre- and post- emergence) which is selective and effective in potato crop for the control of a range of grass and broadleaved weeds except from *Solanum sarachoides* (L.) (Robinson *et al.*, 1996). Pre- and post- emergence application of rimsulfuron effectively controlled *C. album* and *A. retroflexus* (Tonks and Eberlin, 2001; Alebrahim *et al.*, 2012). On the other hand, the intensive use of metribuzin has caused an increasing number of resistant species (Alebrahim *et al.*, 2012), in-

cluding *S. sarachoides* and *Solanum triflorum* (Eberlein *et al.*, 1992). Also some potato cultivars are not tolerant to metribuzin (Arsenault and Ivany, 1996).

It is generally accepted that the optimization of herbicide use allows dose reductions. To optimize herbicide use, aspects such as the best time of application (Samadi Kalkhoran and Alebrahim, 2016) and appropriate use of adjuvants are investigated and in many studies have shown efficient weed control with reduced herbicide doses (Blachshaw *et al.*, 2006). An adjuvant is a biologically inert substance, but when it is added to herbicide spraying solutions could enhance retention, coverage, and efficacy of the applied herbicide (Green and Beestman, 2007). Improving the penetrability of the active ingredients will increase the effect of herbicide and will reduce side effects risk (Penner, 2000). Numerous types of adjuvants exist such as surfactants, oils, and fertilizers while surfactants are classified as non-ionic, anionic, cationic, or zwitterionic ones (Schramm, 2003). Herbicide applications carry the risk of reduced efficacy if

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rainfall occurs shortly after application. Adjuvants would affect the herbicide's rainfastness which is another reason to consider when selecting an adjuvant (Kudsk *et al.*, 1989).

Rimsulfuron needs an adjuvant to optimize its efficacy and rainfastness similarly to other ALS inhibitors (Green and Green 1993; Mathiassen and Kudsk, 2002; Pannacci, 2010). Since the type and the concentration of the applied adjuvant could influence rimsulfuron activity, Tonks and Eberlein (2001) applied rimsulfuron at 4 different dosages (9, 18, 26, 35 g ha⁻¹) with different types of adjuvants such as a nonionic surfactant (NIS), a crop oil concentrate (COC), a methylated seed oil (MSO), or an organosilicon surfactant (SIL). The mean control of the common lambsquarters (*C. album*) reached 75%, regardless of the type of adjuvant or rimsulfuron dose.

Amaranthus retroflexus and *C. album* are two problematic weeds in cultivation of potato (Alebrahim *et al.*, 2012), given the limited available herbicides for their control. Therefore, it is important to investigate solutions for their effective control. The objectives of the current study are to demonstrate the efficacy and rainfastness of optimized doses of rimsulfuron when applied together with NIS and COC adjuvants in controlling *A. retroflexus* and *C. album* in greenhouse and field experiments.

Materials and methods

First outdoor pot experiment

The experiments were carried out at the Department of Agroecology, the University of Aarhus, Denmark (55° 19' N, 11° 23' E) in 2011. Two experiments were conducted in pots outdoors. *Chenopodium album* and *A. retroflexus* seeds were obtained from the seedbank of the University of Aarhus, Denmark. For each plant species, twenty seeds were sown per pot in 2 L plastic pots filled using an automatic seed sowing machine. The potting mixture included: sandy loam soil, sand, and peat (2:1:1 w/w/w respective-

ly, 4.2% organic matter and a pH of 6.9). The pots were sub-irrigated five times a day by deionized water after seedling emergence, only four plants were kept in each pot. At four to six-leaf growth stages, plants were treated by the herbicide. Commercial rimsulfuron (Titus DF, 250 g kg⁻¹) were used in a laboratory pot sprayer equipped with two flat-fan nozzles (4110-14; Hardi; Taastrup, Denmark) working at 260 kpa and delivering 155.3 l ha⁻¹. Rimsulfuron was used solo and in a mixture of surfactants. The treatments used are shown in Table 1. The plants were subjected to 5 mm rain at different times by a rain simulator which was working at an intensity of 9 mmh⁻¹ (Pannacci *et al.*, 2010). A factorial experiment with three factors was applied: The first factor was the rimsulfuron doses (seven levels: 0, 1.872, 3.75, 7.5, 15, 30, 60 g a.i. ha⁻¹ for *C. album* and 0, 0.2343, 0.468, 0.9375, 1.875, 3.75, 7.5 g ha⁻¹ for *A. retroflexus*); the second factor was the type of surfactant (two levels: Contact (a non-ionic surfactant, 980 g/l linear alcohol ethoxylate, from Nufarm company (NIS), 0.1%), Renol (a crop oil concentrate (COC), 0.5 L ha⁻¹)); the third factor was the time of 5 mm rain (four levels: 0, 1, 2, 4 hours after treatment (HAT) (Table 1). The pots were located outdoors adopting a factorial experiment of a completely randomized block design with three replications. Plants were harvested three weeks after the herbicide application and fresh weight (all plants/pot) of the above ground biomass was measured. Afterwards, the fresh biomass was oven-dried at 75°C for 48 h and then the dry weight was measured.

Second outdoor pot experiment

In the second outdoor pot experiment, plants of *C. album* and *A. retroflexus* were sprayed with the same rimsulfuron doses and exposed to the same rain treatments, as in the first outdoor experiment. The NIS (Contact) was used in 0, 0.04, 0.2, and 1 L ha⁻¹ for *C. album* and *A. retroflexus* (Table 1). The plants were harvested three weeks after the herbicide application and fresh weight (all plants/pot) of the above ground biomass

Table 1. The list of treatments for all the experiments that refer to rimsulfuron and surfactants doses; the first and second outdoor pot experiments and the two field experiments. NIS: non-ionic surfactant, COC: crop oil concentrate, and HAT: hours after treatment, the application timings (see Table 2) were as follows: i) S1: Leaf development; ii) S1+S4: leaf development (S1) + vegetatively propagated organs (S4); and iii) S1+S4+S7: leaf development (S1) + vegetatively propagated organs (S4) + Development of tuber (S7).

First outdoor pot experiment				
Species	Rimsulfuron (g a.i. ha ⁻¹)	Contact (NIS)	Renol (COC)	Rain
<i>Chenopodium album</i>	0, 1.875, 3.75, 7.5, 15, 30, 60	0.1%	0.5 L ha ⁻¹	0, 1, 2, 4 HAT
<i>Amaranthus retroflexus</i>	0, 0.2343, 0.468, 0.9375, 1.875, 3.75, 7.5	0.1%	0.5 L ha ⁻¹	0, 1, 2, 4 HAT
Second outdoor pot experiment				
Species	Rimsulfuron (g a.i. ha ⁻¹)	Contact (NIS)	Renol (COC)	Rain
<i>Chenopodium album</i>	0, 1.875, 3.75, 7.5, 15, 30, 60	0.04, 0.2, 1 L ha ⁻¹	-	0, 1, 2, 4 HAT
<i>Amaranthus retroflexus</i>	0, 0.2343, 0.468, 0.9375, 1.875, 3.75, 7.5	0.04, 0.2, 1 L ha ⁻¹	-	0, 1, 2, 4 HAT
Field experiment (Reduced dose)				
Species	Rimsulfuron (g ai. ha ⁻¹)	Contact (NIS)	Renol (COC)	Application time
<i>Chenopodium album</i>	0, 5, 10, 15, 20, 25, 30	0.2 L ha ⁻¹	-	S1, S1+S4, S1+S4+S7
<i>Amaranthus retroflexus</i>	0, 5, 10, 15, 20, 25, 30	0.2 L ha ⁻¹	-	S1, S1+S4, S1+S4+S7
Field experiment (Recommended dose)				
Species	Rimsulfuron (g ai. ha ⁻¹)	Contact (NIS)	Renol (COC)	Application time
<i>Chenopodium album</i>	0, 10, 20, 30, 40, 50, 60	0.2 L ha ⁻¹	-	S1, S1+S4, S1+S4+S7
<i>Amaranthus retroflexus</i>	0, 10, 20, 30, 40, 50, 60	0.2 L ha ⁻¹	-	S1, S1+S4, S1+S4+S7

was measured. Afterwards, the fresh biomass was oven-dried at 75°C for 48 h and then the dry weight was measured.

Field experiments

Two field experiments were conducted at Sheikh Kalkhoran of Ardabil (48° 20' N, 38° 15' E) in Iran, on loam soil (42% sand, 32% silt, and 26% clay), in 2015. Soil organic matter and pH were 0.9% and 7.68, respectively. Fertilizers were applied through the irrigation system according to soil test recommendations during the growing season. Seed potatoes (cv. Agria) were planted at 10 cm depth and 25 cm distance in rows separated 75 cm apart from each other on April 21, 2015, after soil tillage on October 13, 2014. Plots were sprayed against in-

sects and diseases as needed and irrigated during the growing season with overhead sprinklers to obtain 65% minimum soil water content. Two factorial experiments of a complete randomized block design were conducted with three replications at a plot size of 2*4 m². There were three factors on *C. album* and *A. retroflexus* with reduced or the recommended doses. The first factor was rimsulfuron doses, either reduced (0, 5, 10, 15, 20, 25, 30 g ai. ha⁻¹) or the recommended (0, 10, 20, 30, 40, 50, and 60 g ai. ha⁻¹); the second factor was Contact surfactant doses (0 and 0.2 L ha⁻¹) and the third factor was the time of application (S1, S1+S4, S1+S4+S7) on *C. album* and *A. retroflexus* (Table 1). In both experiments, rimsulfuron was applied at leaf development (S1, one stage), leaf develop-

ment (S1) + vegetatively propagated organs (S4) (two stages), and leaf development (S1) + vegetatively propagated organs (S4) + development of tuber (S7) (three stages) (Meier *et al.*, 2009) (Table 2). Commercial rimsulfuron (Titus DF, 250 g kg⁻¹) was applied by using a back-pack sprayer equipped with two flat-fan nozzles (8001; Inter) worked at 260 kpa and delivering 250 L ha⁻¹. Weed control was evaluated by harvesting weed plants within a quadrat of (0.75× 0.50 m²) at three weeks after treatment. Three weeks after the herbicide application, all of the plants in each plot were harvested and dried in an oven at 75°C for 48 h and then weighed. For determination of total tuber yield per hectare, the tubers of center rows in each plot were harvested and weighted.

Statistical Analyses

The dose-response data were analyzed using the R (R Core Team, 2020) program (Version 4.0.1) with the drc package (Version 4.0.1). The log-logistic regression of dry weight of *C. album* and *A. retroflexus* on dose was fitted with a log-logistic regression using a three parameters log-logistic model (Streibig *et al.*, 1993):

$$y = \frac{d}{1 + \exp [b(\log(z) - \log(ED_{50}))]} \quad (1)$$

where y is dry weight z, d is the upper limit

where the dose is zero, ED₅₀ denotes the dose required for reducing dry weight at 50%, and bis proportional to the slopes of the curves around ED₅₀. The ED₅₀ parameter in Eq. (1) can be replaced by any ED level (Pannacci and Covarelli, 2009), (e.g., ED₁₀, ED₉₀).

The relative potency (RP) is the horizontal displacement between two curves at a chosen ED_x (Kudsk *et al.*, 1989). The biological exchange rate in a single application, i.e. the relative potency between the herbicides was calculated as follows:

$$RP = ED_{50xf} / EDC_{50xf+v} \quad (2)$$

Where, ED_{xf} = the ED_x of herbicide alone; and ED_{xf+v} = the ED_x of herbicide in mixture with a surfactant. If RP = 1, the addition of surfactant does not affect herbicide performance. If RP was significantly higher or lower than 1, the herbicide in the mixture with the surfactant was more or less potent than the herbicide alone, respectively. Similarly, the rain-fastness can be assessed by calculating the ratio between the ED_x dose with rain and the corresponding ED_x dose without rain.

Statistical analyses of yield data were performed using SAS (9.1) software. An ANOVA was performed using PROC GLM (PC-SAS) and when the F test indicated significant effects, means were compared using LSD Fisher (*P* < 0.05) test.

Table 2. Application times of rimsulfuron in relation to the principal potato growth stages in the field experiments.

Stage	Description
0	Germination / sprouting / bud development
1	Leaf development (main shoot)
2	Formation of side shoots / tillering
3	Stem elongation or rosette growth/shoot development (main shoot)
4	Development of harvestable vegetative plant parts or vegetatively propagated organs/ booting (main shoot)
5	Inflorescence emergence (main shoot) / heading
6	Flowering (main shoot)
7	Development of fruit
8	Ripening or maturity of fruit and seed
9	Senescence, beginning of dormancy

Results

First outdoor pot experiment

Regarding the efficacy, the results showed no significant improvement on rimsulfuron performance on *A. retroflexus* with the addition of the adjuvant 0.1% NIS or 0.5 COC (compare ED₅₀ values of the 'no rain' treatments) (Table 3). In contrast, the inclusion of the 0.1% NIS adjuvant significantly improved the performance of rimsulfuron on *C. album* (Table 3).

Regarding the rainfastness, 0.1% NIS and 0.5 COC provided a high level of rainfastness comparable to that of COC on *A. retroflexus*

(Table 3). In *C. album*, the ED₅₀ doses were much higher in comparison with *A. retroflexus* and the non-ionic surfactant strongly improved the efficacy of rimsulfuron and had a strong effect on rainfastness while no significant impact of rain with Renol was shown (Table 3). Also, the results showed that rainfastness was low without adjuvant and with 0.5 L ha⁻¹ COC, but the inclusion of 0.1% NIS significantly improved the rainfastness; full rainfastness of rimsulfuron was obtained only after 4 hours (Table 3).

Second outdoor pot experiment

In the second pot experiment, the re-

Table 3. The effect of NIS and COC adjuvants on the effectiveness and rainfastness of rimsulfuron [applied at various timings: 1, 2, 4 HAT (hours after treatment)] on *Amaranthus retroflexus* and *Chenopodium album*. Relative rainfastness is the necessary length of a rain-free period following a herbicide application. Different superscripts in the ED₅₀ column indicate differences between ED₅₀ values for each weed species.

<i>Amaranthus retroflexus</i>				
Adjuvant	Rain	ED ₅₀ (g a.i. ha ⁻¹)	Confidence intervals	Relative rainfastness
None	No rain	0.28 ^{abc}	0.201-0.368	1.00
	1 HAT	4.68 ^{ijk}	3.318-6.036	16.71
	2 HAT	1.59 ^{fgh}	1.069-2.103	5.68
	4 HAT	1.34 ^f	0.937-1.743	4.79
0.1 % NIS	No rain	0.26 ^{ab}	0.182-0.345	1.00
	1 HAT	0.55 ^{de}	0.372-0.732	2.12
	2 HAT	0.51 ^d	0.363-0.657	1.96
	4 HAT	0.28 ^{abc}	0.184-0.382	1.08
0.5 L ha ⁻¹ COC	No rain	0.25 ^a	0.179-0.330	1.00
	1 HAT	3.76 ^{ij}	2.294-5.235	15.04
	2 HAT	3.74 ⁱ	2.407-5.064	14.96
	4 HAT	1.44 ^{fg}	0.910-1.970	5.76
<i>Chenopodium album</i>				
None	No rain	26.47 ^{e-i}	-14.78-67.72	1.00
	1 HAT	24.56 ^{e-h}	6.13-42.98	0.93
	2 HAT	27.34 ^{e-k}	-3.60-58.29	1.03
	4 HAT	31.16 ^{e-l}	6.55-55.77	1.18
0.1 % NIS	No rain	1.89 ^a	1.11-2.69	1.00
	1 HAT	4.18 ^d	1.60-6.77	2.20
	2 HAT	2.06 ^{ab}	0.85-3.28	1.08
	4 HAT	2.36 ^{abc}	0.92-3.80	1.24
0.5 L ha ⁻¹ COC	No rain	13.28 ^e	1.60-24.96	1.00
	1 HAT	21.44 ^{efg}	5.09-37.79	1.61
	2 HAT	26.58 ^{e-j}	3.39-49.77	2.00
	4 HAT	16.69 ^{e-i}	-2.26-35.65	1.26

sults showed that increasing the concentration of the NIS up to 1 L ha⁻¹ improved the performance of rimsulfuron (Table 4). At 1 L ha⁻¹, the surfactant increased the efficacy of rimsulfuron on *A. retroflexus* around 10-fold compared to rimsulfuron alone. On the contrary, increasing the concentration of the NIS sharply improved the performance of rimsulfuron on *C. album* (Table 4). Herbicidal performance was slightly more enhanced as concentration increased from 0.04 to 1 L ha⁻¹. At 1 L ha⁻¹, surfactant increased rimsulfuron performance on *C. album* around 3-fold compared to rimsulfuron alone which was less compared to *A. retroflexus* (Table 4).

The rainfastness of rimsulfuron on *A. retroflexus* reduced with an increase in surfactant concentration up to 1 L ha⁻¹ up to 12-fold (Table 4). On the contrary, increasing the concentration of the NIS sharply improved the rainfastness of rimsulfuron on *C. album* to 2.5-fold (Table 4). Each species had some distinct differences to the single surfactant properties. Regarding herbicidal performance, the non-ionic surfactant was less efficient on *C. album* compared to *A. retroflexus*, but when tested for rainfastness showed a higher effectiveness especially at 1 L ha⁻¹ for *C. album* (Table 4). The spray deposit on the leaf surface is strongly related to cuticular

Table 4. The effect of NIS adjuvant doses on the effectiveness and rainfastness of rimsulfuron [applied at various timings: 1, 2, 4 HAT (hours after treatment)] on *Amaranthus retroflexus* and *Chenopodium album*. Relative rainfastness is the necessary length of a rain-free period following a herbicide application. Different superscripts in the ED₅₀ column indicate differences between ED₅₀ values for each weed species.

<i>Amaranthus retroflexus</i>				
Adjuvant	Rain	ED ₅₀ (g a.i. ha ⁻¹)	Confidence intervals	Relative rainfastness
0.04 L ha ⁻¹ NIS	No rain	0.33 ^{cd}	0.219-0.437	1.00
	1 HAT	0.96 ^{ij}	0.701-1.219	2.38
	2 HAT	0.59 ^{fg}	0.433-0.757	1.49
	4 HAT	0.43 ^{de}	0.302-0.553	1.16
0.2 L ha ⁻¹ NIS	No rain	0.12 ^b	0.051-0.196	1.00
	1 HAT	1.10 ^{jk}	0.789-1.406	4.22
	2 HAT	0.47 ^{def}	0.305-0.640	2.30
	4 HAT	0.43 ^{de}	0.306-0.559	1.73
1 L ha ⁻¹ NIS	No rain	0.03 ^a	-0.006-0.069	1.00
	1 HAT	0.73 ^{hi}	0.513-0.939	24.3
	2 HAT	0.70 ^{gh}	0.523-0.878	23.3
	4 HAT	0.29 ^c	0.191-0.396	9.67
<i>Chenopodium album</i>				
0.04 L ha ⁻¹ NIS	No rain	5.37 ^{b-f}	1.44-9.30	1.00
	1 HAT	23.38 ^{ij}	7.89-38.86	4.35
	2 HAT	23.91 ^{jk}	1.62-46.21	4.45
	4 HAT	13.47 ^{e-i}	6.15-20.79	2.51
0.2 L ha ⁻¹ NIS	No rain	3.66 ^{a-d}	2.26-5.05	1.00
	1 HAT	9.86 ^{d-h}	4.50-15.21	2.69
	2 HAT	6.61 ^{b-g}	3.39-9.83	1.81
	4 HAT	5.17 ^{a-f}	2.71-7.62	1.41
1 L ha ⁻¹ NIS	No rain	1.75 ^a	0.84-2.66	1.00
	1 HAT	4.20 ^{a-e}	2.24-6.16	2.40
	2 HAT	2.97 ^{abc}	1.46-4.47	1.70
	4 HAT	2.38 ^{ab}	1.21-3.56	1.36

structure and the adjuvant chemical tendency for retention on the leaf. Thus, the appropriate surfactant type and concentration increased rimsulfuron effectiveness by 10-fold. NIS efficacy was much higher compared to Renol. A surfactant concentration of 1 L ha⁻¹ was required for maximum herbicidal performance. However, regarding to rainfastness, the results were different between the weed species.

Field experiments

The results showed that increasing the doses of rimsulfuron up to 60 g ai. ha⁻¹ increased control of both *C. album* and *A. ret-*

roflexus. The assessment at three weeks after treatment demonstrate that rimsulfuron at 40, 50, and 60 g ai. ha⁻¹ in two (S1+S4) and three (S1+S4+S7) stages application provided 100% control of *C. album* and *A. retroflexus* (Figures 1, 2). Application of rimsulfuron at 25 and 30 g ai. ha⁻¹ (i.e. 0.25X and 0.5X of the recommended dose) applied at three crop stages (S1+S4+S7) provided excellent control of both weed species (Figures 1, 2). When rimsulfuron was combined with 0.2 L ha⁻¹ NIS, *C. album* and *A. retroflexus* control was only slightly increased.

Tables 5 and 6 show the ED₅₀ values of the surfactants applied alone and in combi-

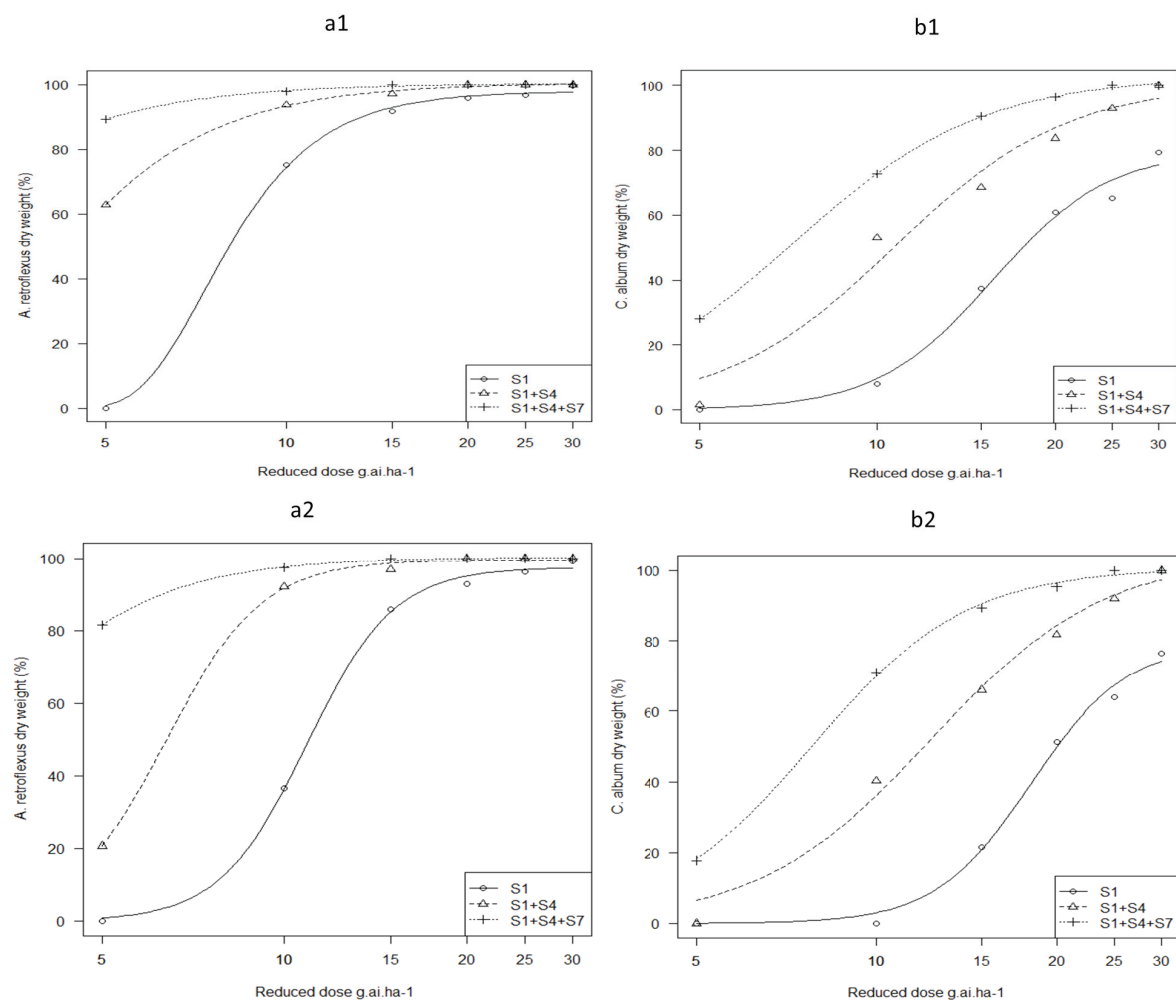


Figure 1. The effect of rimsulfuron application on dry weight of (a) *Amaranthus retroflexus* and (b) *Chenopodium album* when applied at a reduced dose (1X: 30 g a.i. ha⁻¹) without (a1, b1) and with (a2, b2) NIS surfactant (0.2 L ha⁻¹) at three cropping timings. The application timings (see Table 2) were as follows: i) S1: Leaf development; ii) S1+S4: leaf development (S1) + vegetatively propagated organs (S4); and iii) S1+S4+S7: leaf development (S1) + vegetatively propagated organs (S4) + Development of tuber (S7).

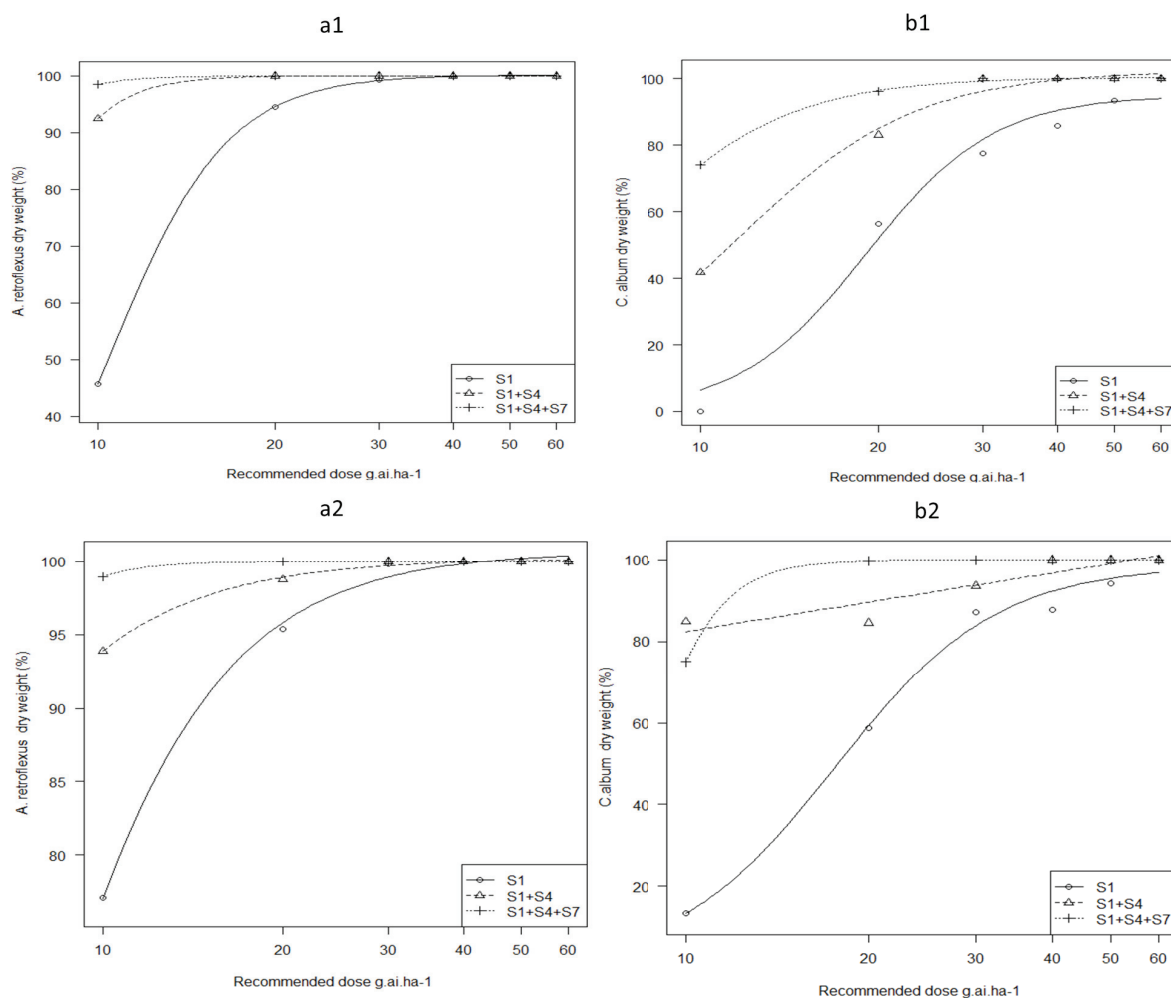


Figure 2. The effect of rimsulfuron application on dry weight of (a) *Amaranthus retroflexus* and (b) *Chenopodium album* when applied at the recommended dose (1X: 60 g a.i. ha⁻¹) without (a1, b1) and with (a2, b2) NIS surfactant (0.2 L ha⁻¹) at three cropping timings. The application timings (see Table 2) were as follows: i) S1: Leaf development; ii) S1+S4: leaf development (S1) + vegetatively propagated organs (S4); and iii) S1+S4+S7: leaf development (S1) + vegetatively propagated organs (S4) + Development of tuber (S7).

nation with rimsulfuron, at different growth stages of potato. The curves' upper limits were different for various doses and application time for each species, in some cases, the curves were crossing. The parameters ED_{10} , ED_{50} , ED_{90} , and b were estimated at each application time by fitting Eq. (1) for the *C. album*, and *A. retroflexus* biomass reduction. The ED_{50} values of rimsulfuron were significantly reduced two to three times for *A. retroflexus* at reduced dose of rimsulfuron. For *A. retroflexus*, the ED_{50} values of the reduced doses rimsulfuron experiment (applied at one, two, three stages without surfactant), were 10.88, 6.37 and 3.09 g ai ha⁻¹ vs. 7.27,

3.77 and 2.03 g ai ha⁻¹ (applied at one, two, three stages with 0.2 L ha⁻¹ NIS), (Table 5).

The reduced dose-response curves described the response well. The ranking of ED_{50} at reduced dose for the three application times was $S1 > S1+S4 > S1+S4+S7$ with and without surfactant (Table 5). Based on the ED_{50} values given in Table 5, surfactants can improve the efficiency of rimsulfuron at reduced dose compared to rimsulfuron alone. The ED_{50} values of rimsulfuron at reduced dose without surfactant were estimated at 18.11, 12.31, 7.81 g a.i. ha⁻¹ on *C. album* after application at one, two or three potato growth stages, respectively; when

Table 5. The estimated regression parameters of the reduced rimsulfuron dose effect (1X: 30 g a.i. ha⁻¹) on *Amaranthus retroflexus* and *Chenopodium album* dry weight, when applied with and without NIS surfactant (1L ha⁻¹) at three application times as follows: i) S1: Leaf development; ii) S1+S4: leaf development (S1) + vegetatively propagated organs (S4); and iii) S1+S4+S7: leaf development (S1) + vegetatively propagated organs (S4) + Development of tuber (S7). The response variable is 0-100-percent weed control (dry weight reduction). The Relative potency (Rp) is explained in section 2.4. Different superscripts in the ED₅₀ column indicate differences between ED₅₀ values within each weed species.

Reduced dose without surfactant on <i>Amaranthus retroflexus</i> dry weight						
Application time	slope	upper	ED ₁₀	ED ₅₀	ED ₉₀	Rp
S1	-6.04 ± 0.33	97.46 ± 0.78	7.56 ± 0.14	10.88 ± 0.09 ^f	15.64 ± 0.38	1.49
S1+S4	-5.48 ± 0.27	99.58 ± 0.59	4.27 ± 0.07	6.37 ± 0.09 ^d	9.52 ± 0.29	1.68
S1+S4+S7	-3.07 ± 0.76	100.29 ± 0.73	1.51 ± 0.44	3.09 ± 0.35 ^b	6.32 ± 0.43	1.52
Reduced dose with surfactant on <i>Amaranthus retroflexus</i> dry weight						
S1	-4.09 ± 0.13	97.94 ± 0.33	5.93 ± 0.09	7.27 ± 0.07 ^e	12.60 ± 0.16	1.00
S1+S4	-2.69 ± 0.14	100.49 ± 0.39	2.77 ± 0.08	3.77 ± 0.06 ^c	8.70 ± 0.28	1.00
S1+S4+S7	-2.38 ± 0.45	100.36 ± 0.42	1.43 ± 0.33	2.03 ± 0.33 ^a	5.22 ± 0.15	1.00
Reduced dose without surfactant on <i>Chenopodium album</i> dry weight						
S1	-5.40 ± 0.47	79.05 ± 2.86	12.06 ± 0.32	18.11 ± 0.40 ^f	27.20 ± 1.46	1.17
S1+S4	-3.00 ± 0.18	104.00 ± 2.66	5.92 ± 0.20	12.31 ± 0.34 ^d	25.59 ± 1.72	1.13
S1+S4+S7	-3.37 ± 0.18	100.64 ± 1.21	4.07 ± 0.15	7.81 ± 0.16 ^b	15.00 ± 0.68	1.08
Reduced dose with surfactant on <i>Chenopodium album</i> dry weight						
S1	-4.41 ± 0.58	79.74 ± 3.90	9.51 ± 0.47	15.46 ± 0.58 ^e	25.73 ± 2.43	1.00
S1+S4	-2.97 ± 0.27	100.36 ± 3.32	5.09 ± 0.27	10.66 ± 0.43 ^c	22.31 ± 2.22	1.00
S1+S4+S7	-2.71 ± 0.23	102.67 ± 2.15	3.19 ± 0.21	7.19 ± 0.25 ^a	16.17 ± 1.44	1.00

combined with surfactant the ED₅₀ values were 15.46, 10.66, 7.19 g a.i. ha⁻¹, respectively (Table 6). The ED₅₀ values at reduced dose and various time of application for *C. album* were higher than *A. retroflexus*. Table 6 shows the same ED₅₀ ranking of the potency of the three application times at the recommended dose of the dose-response curves of *C. album* and *A. retroflexus*. The results of rimsulfuron on *C. album* dry weight showed that the NIS surfactant could not improve the efficacy of the recommended dose of rimsulfuron at S1+S4 and S1+S4+S7. The estimated ED₅₀ doses demonstrated that a reduced dose of rimsulfuron at S1+S4 and S1+S4+S7 provided full control of the two species at 30 g a.i. ha⁻¹. The relative potency (RP) values were different when NIS were added to the herbicide. RP values showed that surfac-

tants can improve the efficacy of reduced and recommended doses of rimsulfuron for *A. retroflexus* at all application times, and reduced and recommended doses at all application times at S1 stage.

The effect of rimsulfuron application on total tuber yield, when applied at a reduced dose (1X: 30 g a.i. ha⁻¹) and the recommended dose (1X: 60 g a.i. ha⁻¹) without and with NIS surfactant (0.2 L ha⁻¹) at three crop stages (S1, S4, and S7), is presented in Figure 3. The highest potato yield was measured (60 tons per ha) when 60 g a.i. ha⁻¹ rimsulfuron was applied at all stages without using NIS. No significant differences were measured when the same dose of rimsulfuron was applied with NIS at three (S1, S4, and S7) and two (S1, S4) potato crop stages.

Table 6. The estimated regression parameters of the recommended rimsulfuron dose effect (1X: 60 g a.i. ha⁻¹) on *Amaranthus retroflexus* and *Chenopodium album* dry weight, when applied with and without NIS surfactant (1L ha⁻¹) at three application times as follows: i) S1: Leaf development; ii) S1+S4: leaf development (S1) + vegetatively propagated organs (S4); and iii) S1+S4+S7: leaf development (S1) + vegetatively propagated organs (S4) + Development of tuber (S7). The response variable is 0-100-percent weed control (dry weight reduction). The Relative potency (Rp) is explained in section 2.4. Different superscripts in the ED₅₀ column indicate differences between ED₅₀ values within each weed species.

Recommended dose without surfactant on <i>Amaranthus retroflexus</i> dry weight						
Application time	slope	upper	ED ₁₀	ED ₅₀	ED ₉₀	Rp
S1	-4.32 ± 0.25	100.19 ± 0.44	6.28 ± 0.17	10.41 ± 0.07 ^a	17.27 ± 0.55	1.63
S1+S2	-6.18 ± 8.04	100.02 ± 0.37	4.67 ± 4.61	6.67 ± 3.49 ^a	9.51 ± 0.61	2.07
S1+S2+S3	-6.73 ± 49.78	100.00 ± 0.36	3.87 ± 27.11	5.37 ± 24.61 ^a	7.44 ± 16.14	1.14
Recommended dose with surfactant on <i>Amaranthus retroflexus</i> dry weight						
S1	-2.60 ± 0.33	100.68 ± 0.64	2.73 ± 0.44	6.35 ± 0.36 ^a	14.76 ± 0.85	1.00
S1+S2	-2.37 ± 1.25	100.21 ± 0.68	1.27 ± 1.36	3.21 ± 1.86 ^a	8.11 ± 0.87	1.00
S1+S2+S3	-6.00 ± 43.54	100.00 ± 0.39	3.24 ± 26.42	4.67 ± 25.69 ^a	6.74 ± 19.15	1.00
Recommended dose without surfactant on <i>Chenopodium album</i> dry weight						
S1	-4.04 ± 0.35	94.93 ± 1.68	11.06 ± 0.49	19.05 ± 0.42 ^a	32.81 ± 1.96	1.08
S1+S2	-2.85 ± 0.23	102.37 ± 1.43	5.30 ± 0.34	11.44 ± 0.30 ^a	24.68 ± 1.83	0.88
S1+S2+S3	-3.10 ± 0.87	100.43 ± 1.27	3.54 ± 1.02	7.18 ± 0.67 ^a	14.57 ± 1.71	0.83
Recommended dose with surfactant on <i>Chenopodium album</i> dry weight						
S1	-3.27 ± 0.51	98.69 ± 3.53	9.02 ± 0.97	17.62 ± 0.92 ^a	3.44 ± 4.31	1.00
S1+S2	-0.24 ± 0.25	170.19 ± 145.92	0.001 ± 0.005	12.86 ± 89.96 ^a	9.79 ± 1.56	1.00
S1+S2+S3	-7.19 ± 26.69	100.00 ± 2.00	6.32 ± 10.72	8.58 ± 4.82 ^a	1.16 ± 6.68	1.00

Discussion

The optimum concentration of the active ingredient in post-emergence herbicides should be able to preserve its effectiveness for the critical period otherwise it could lead to inadequate weed control (Hess and Richard, 1990). Our results showed that ED₅₀ rimsulfuron was ranked as S1+S4+S7 < S1+S4 < S1 with and without surfactant. Renner and Powel (1998) concluded that post-emergence application of rimsulfuron at 18, 27 and 35 g ha⁻¹ provided full control of *A. retroflexus* and 77, 84, and 91% of *C. album*, respectively. Also, Robinson *et al.* (1996) reported that post-emergence application of rimsulfuron at 9, 18, 27, 35, 70 g ha⁻¹ controlled 67, 100, 100, 100, 100 % *A. retroflexus*, and 60, 90, 97, 90, 98% *C. album*, respectively. Rimsulfuron

at 30 g a.i ha⁻¹ controlled *A. retroflexus* and *C. album* 100% at S1+S4 and S1+S4+S7 stages. Lanfranconi *et al.* (1993) reported that rimsulfuron applied post-emergence at 9, 18, 27, 35, and 70 g ha⁻¹ controlled *A. retroflexus* 67, 100, 100, 100, 100% and *C. album* 60, 90, 97, 90, and 98%, respectively. Similar results were reported by Renner and Powell (1998) that concluded that post-emergence application of rimsulfuron at 18, 27, 35 g ha⁻¹ controlled *C. album* 77, 84 and 91% and of *A. retroflexus* 100, 100, and 100%, respectively. Khataami *et al.* (2017) reported that post-application of rimsulfuron provided 87.37, 99.75, and 96.87% control of *C. album* at 30, 40, and 50 g a.i ha⁻¹ and 86.73, 89.91 and 95.50% for *A. retroflexus*, respectively.

For the enhanced activity of a post-emergence herbicide, high absorption and

translocation are necessary. Using the appropriate type of adjuvants is necessary to increase the efficacy of most post-emergence herbicides by, mostly, surface tension reduction (Kudsk, 2008). Our results in greenhouse and field trials showed that NIS was more effective to improve the rimsulfuron performance and rainfastness on both weed species. Increase of NIS concentration increased rimsulfuron activity around 10-fold for *A. retroflexus* compared to around 3-fold for *C. album*; also it reduced the rainfastness of rimsulfuron on *A. retroflexus* while it improved the rainfastness of rimsulfuron on *C. album*.

Previous studies showed that NIS slightly improved the performance of rimsulfuron on *C. album* and *A. retroflexus* in field potato due to lower values of surface tension where ED_{50} was calculated. Hutchinson *et al.* (2004) suggested that using NIS with rimsulfuron controlled *C. album* and *A. retroflexus* by 89% and 97%, respectively. Tonks and Eberlin (2001) concluded that rimsulfuron applied at 4 different doses (9, 18, 26, or 35 g/ha) together with different types of surfactants, i.e. NIS, COC, a methylated seed oil (MSO), or an organosilicon surfactant (SIL), had moderate (average

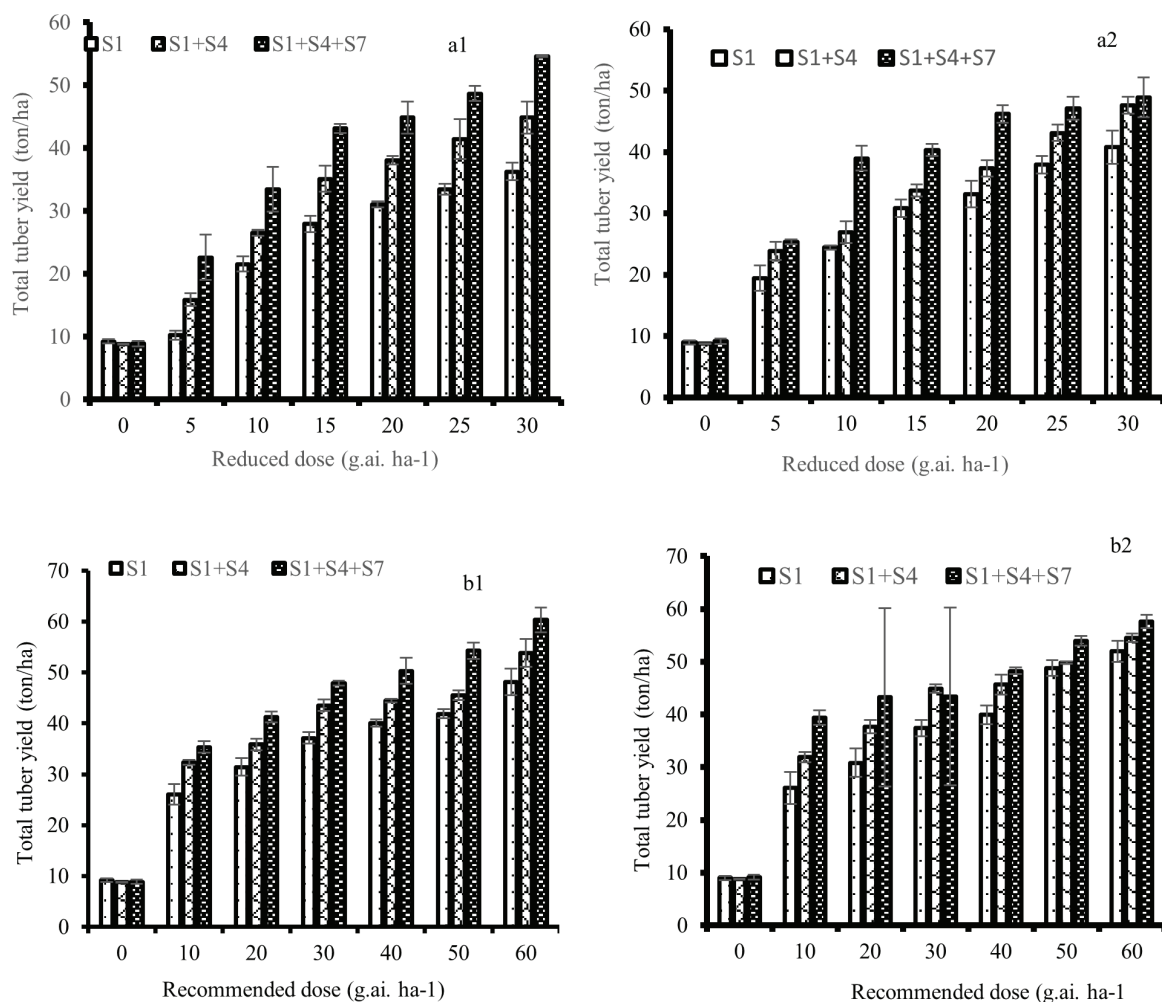


Figure 3. The effect of rimsulfuron application on total tuber yield, when applied at (a) a reduced dose (1X: 30 g a.i. ha⁻¹) and (b) the recommended dose (1X: 60 g a.i. ha⁻¹) without (a1, b1) and with (a2, b2) NIS surfactant (0.2 L ha⁻¹) at three cropping timings, The application timings (see Table 2) were as follows: i) S1: Leaf development; ii) S1+S4: leaf development (S1) + vegetatively propagated organs (S4); and iii) S1+S4+S7: leaf development (S1) + vegetatively propagated organs (S4) + Development of tuber (S7) (LSD=4.33).

75%) control of common lambsquarters, regardless of adjuvant or dose. Mamnoui *et al.* (2016) concluded that the use of rimsulfuron (60 g ha^{-1}) + 2.5 % citowet (non-ionic surfactant) controlled *A. retroflexus*, at an average of 54% and 96% in Jiroft and Karaj of Iran, respectively, in a two-year field experiment.

Chenopodium album had higher ED_{50} than *A. retroflexus*. One explanation is that *A. retroflexus* possess leaf areas that are easier to be wettable compared with those of the *C. album* (Ren *et al.*, 2007). The present results are in line with findings in previous similar experiments (Medd *et al.*, 2001). Harr *et al.* (1991) report there were 66% polar components in the leaf surface of *C. album*, in comparison with 55% for *A. retroflexus*. Other studies report that a) the hair covering on the abaxial side of the *C. album* leaves and crystalline structure of hair led to less herbicide retention and penetration into leaf tissues, b) *A. retroflexus* leaf surface possessed smooth cuticular layer; c) the angle of the spray droplet was 76° on the *C. album* leaves in comparison with of 54° on *A. retroflexus* (Harr *et al.*, 1991). Therefore, we can possibly assume that higher amounts of herbicide are required to be absorbed, transferred, and reach the target in the photosynthetic system in *C. album*. Hence, weak herbicide performance of *C. album* could be associated with lower wettability of the leaf surface.

On the other hand, due to the hairy cuticle of *C. album* it appears that utilization of a NIS adjuvant could increase the herbicide rainfastness. The improvement of the rimsulfuron efficacy by NIS could be associated with the solubilization, softening, or disordering of the nature of cuticular waxes by the utilization of the non-ionic surfactant. Hence, it is possible that the surfactant could lead to better cuticle penetration and stromal infiltration and subsequently, better absorption and translocation of rimsulfuron. Also, the non-ionic surfactant could possibly lower the surface tension of the spray droplet until the known as the Critical Micelle Concentration (CMC) (Sharma *et al.*, 1996; Penner, 2000).

Conclusions

Utilization of a NIS surfactant enhanced rimsulfuron efficacy and rainfastness on *C. album* and *A. retroflexus*. Increasing non-ionic surfactant concentration from 0.04 to 1 L ha^{-1} increased rimsulfuron activity around 10-fold for *A. retroflexus* compared to around 3-fold increase for *C. album*. Also, increasing rimsulfuron dosages up to 60 g ai ha^{-1} enhanced weed control to 100% at potato field and increased total tuber yield up to 60 ton ha^{-1} . The application time was critical, however, post-application of rimsulfuron at S1+S4 and S1+S4+S7 stages of potato enhanced weed control and potato yield.

Author Contribution

Mohammad Taghi Alebrahim conceived the ideas. Mohammad Taghi Alebrahim and Elham Samadi Kalkhoran assembled the data, analyzed the data. Roghayyeh Majd and Seyedeh Asieh Khatami helped to interpret the data. Mohammad Taghi Alebrahim and Elham Samadi Kalkhoran wrote the manuscript. Mohammad Taghi Alebrahim edited the manuscript. All authors improved and approved the manuscript.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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Επίδραση επιφανειοδραστικών στην αποτελεσματικότητα και την αντοχή στην έκπλυση του ζιζανιοκτόνου rimsulfuron στην πατάτα

M.T. Alebrahim, E.S. Kalkhoran, R. Majd και S.A. Khatami

Περίληψη Τα επιφανειοδραστικά χρησιμοποιούνται μαζί με ζιζανιοκτόνα για να αυξήσουν την αποτελεσματικότητά τους. Στην παρούσα μελέτη, αποδείχθηκε ότι η εφαρμογή 0,1% του μη ιονισμένου επιφανειοδραστικού (NIS, Contact) και 0,5 L ha⁻¹ συμπυκνώματος φυτικού ελαίου (COC, Renol) δεν βελτίωσε την αποτελεσματικότητα του rimsulfuron εναντίον του ζιζανίου *Amaranthus retroflexus*. Αντίθετα, οι ίδιες επεμβάσεις ενίσχυσαν την αποτελεσματικότητα και την αντοχή στην έκπλυση του rimsulfuron εναντίον του ζιζανίου *Chenopodium album*. Η αύξηση της συγκέντρωσης του μη ιονισμένου επιφανειοδραστικού σε 1L ha⁻¹ αύξησε την αποτελεσματικότητα του rimsulfuron περίπου κατά 10 φορές εναντίον του *A. retroflexus* ενώ κατά 3 περίπου φορές εναντίον του *C. album*. Η ίδια επέμβαση μείωσε κατά 12 φορές την αντοχή στην έκπλυση του rimsulfuron εναντίον του *A. retroflexus* ενώ τη βελτίωσε κατά 2 φορές εναντίον του *C. album*. Οι δόσεις ED₅₀ και ED₉₀ του rimsulfuron έδειξαν ότι η προσθήκη 0,2 L ha⁻¹ NIS βελτίωσε την αποτελεσματικότητα της συνιστώμενης (60 g δ.ο. ha⁻¹) και της μειωμένης δόσης (30 g δ.ο. ha⁻¹) του rimsulfuron σε καλλιέργεια πατάτας στον αγρό. Η υψηλότερη απόδοση της πατάτας καταγράφηκε (60 τόνοι ανά εκτάριο) όταν 60 g δ.ο. ha⁻¹ rimsulfuron εφαρμόστηκαν σε τρία στάδια ανάπτυξης [ανάπτυξη των φύλλων (S1), βλαστικά πολλαπλασιαστικά όργανα (S4) και ανάπτυξη κονδύλου (S7)] της καλλιέργειας χωρίς τη χρήση NIS. Δεν παρατηρήθηκαν σημαντικές διαφορές όταν εφαρμόστηκε η ίδια δόση rimsulfuron μαζί με NIS σε τρία (S1, S4 και S7) και δύο (S1, S4) στάδια ανάπτυξης της καλλιέργειας.

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