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EFFECTIVENESS OF DIFFERENT ADJUVANTS ON EFFICACY OF STELLAR (TOPREMAZONE PLUS DICAMBA) APPLIED AT REDUCED RATES IN MAIZE (*Zea mays* L.)

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ABSTRACT. Field experiments were carried out in 2017 and 2018 on two individual farms that grew maize for grain, in Tetovo and Skopje locality, to determine the effectiveness of different adjuvants on the efficacy of Stellar applied at reduced rates. Herbicide treatment selectivity and influence on grain yield were estimated, as well. Both sites were naturally infested with a high population of *Polygonum lapathifolium* L., *Chenopodium album* L., *Echinochloa crus-galli* (L.) P. Beauv. and *Sorghum halepense* (L.) Pers. Overall efficacy of herbicides in control of weeds 28 DAT was ranged of 77% (Stellar + White oil applied at 0.125 + 0.2 L ha^{-1}) to 98% (Stellar + Trend applied at 0.75 + 1.0 L ha^{-1}) in Tetovo locality, and 64% (Stellar + White oil applied at 0.125 + 0.2 L ha^{-1}) to 99% (Stellar + DASH applied at 0.75 + 2.0 L ha^{-1}) in Skopje locality, respectively. In both localities, the efficacy of the full rate of Stellar (90 and 80%, respectively) was on the level of Stellar + White oil applied at 0.25 + 0.2 L ha^{-1} (90 and 78%, respectively). Herbicide efficacy 56 DAT was similar to the previous period of estimation. Efficacy of herbicide and herbicide plus adjuvants treatments in control of prevailing weeds 28 and 56 DAT ranged from 22–100% in Tetovo locality and 30–100% in Skopje locality, respectively. No visual maize injured was determined by any herbicide treatments in both localities for both years. Maize grain yields for each treatment in both localities generally reflected overall weed control.

Introduction

Maize (*Zea mays* L.) is the world's third most important cereal grain after wheat and rice (Kage *et al.*, 2013; Karavina *et al.*, 2014; Huma *et al.*, 2019). In North Macedonia, it is grown on an area of 33 967 hectares with an average grain yield of 4 277 kg ha^{-1} (State Statistical Office, 2020). Although there is a great potential for increasing its yield, as maize hybrids with high yield potential are under cultivation, the average yield is still far below as compared to the achievable potential of hybrids. Among various factors responsible for low yield, weed infestation is of supreme importance (Thobatsi, 2009; Peña-Asin *et al.*, 2013; Imoloame, Omolaiye, 2017; Iderawumi, Friday, 2018), particularly during the first weeks after sowing, in which, maize plants are strongly exposed to weed competition (Ghosheh *et al.*, 1996; Evans *et al.*, 2003; Sulewska *et al.*, 2012; Idziak, Woznica 2013), including such persistent species as *Chenopodium album, Echinochloa crus-galli* and *Sorghum halepense*. According to Dogan *et al.*, (2004) and Isik *et al.*, (2006), weeds occurrence in maize causes significant yield losses with an average of more than 29% in case of no weed control and more than 12% despite weed control applications. Averaged across the seven years (2007–2013), weed interference in maize in the United States and Canada caused an average of 50% yield loss, which equates to a loss of 148 million tons of maize valued at over U.S.$26.7 billion annually (Soltani *et al.*, 2016). Thus, poor maize competitiveness with weeds makes human intervention necessary.

The use of herbicides is the most effective and reliable method of weed control in maize fields (Kir, Doğan, 2009; Kierzek *et al.*, 2012; Noor *et al.*, 2012). For that purpose, in North Macedonia, many new herbicides for maize weed control were registered recently. One of them is Stellar (a.i. topremazone + dicamba). Dicamba is a well-known broadleaf weed control herbicide, which is either a benzoic acid (Golijan, 2015), or chlorophenoxy herbicide (Reigart, Roberts, 1999). Dicamba mimics a plant growth hormone, causing uncontrolled, abnormal and disorganized plant growth, disrupting normal plant functions that lead to plant death (Caux, 1993; Kelley, Riechers, 2007). On the other side, topremazone belongs to the new chemical class of pyrazolones or benzoylpyrazoles and was commercially introduced in 2006 (Grossmann, Ehrhardt, 2007; Zollinger, Ries, 2006). When applied as a post-emergence herbicide, it controls a wide spectrum of annual grass and broadleaf weeds (Ransom, Ishida, 2005; Porter *et al.*, 2005; Schonhammer *et al.*, 2006; Bollman *et al.*, 2007; Mahto *et al.*, 2020) and is safe to maize crop (Soltani *et al.*, 2007; Gitsopoulos *et al.*, 2010; Swetha *et al.*, 2015).

Sometimes, intensive herbicide use results in environmental pollution and the development of weed resistance. In addition, the cost of weed control is also too high (Zhang *et al.*, 2013). An effective way to reduce the side effect of the herbicide was to apply the lowest dose needed for biologically effective weed control (Kudsk, Streibig, 2003). Some previous studies showed that herbicide rates can be adjusted to the sensitivities of different weed species, weed growth stages, and environmental conditions and that the influences of these factors on herbicide efficacy can be quantified by conducting dose-response experiments (Christensen, Olesen, 1995; Kudsk, Streibig 2003; Pannacci, Covarelli 2009; Raimondi *et al.*, 2015).

In that direction, when herbicides are used at reduced rates (Praczyk, Adamczewski, 1996; Idziak, Woznica, 2013), added adjuvants to spraying liquid are necessary to improve the effectiveness of foliage-applied herbicidal treatment (Hazen, 2000; Penner, 2000; Curran, Lingenfelter, 2009; Idziak, Woznica, 2014), through increasing the retention of spray droplets, plant surface wettability and absorption of herbicide from spray deposit on plant surface into their cells (Sanyal *et al.*, 2006; Pacanoski, 2010; Whitford, Patton, 2016).

Although such studies have been carried out worldwide for more than 20 years (Kir, Dogan, 2009; Gołębiowska, Yıldırım, 2016), there is a lack of studies on the optimization of herbicide doses in maize in North Macedonia.

Because of that, the objective of this study was to determine the effectiveness of different adjuvants on the efficacy of Stellar applied at reduced rates and to determine its effect on maize weed control and grain yield.

Materials and Methods

Field experiments were carried out in 2017 and 2018 on two individual farms that cultivate maize for grain in Tetovo and Skopje locality, the Republic of North Macedonia, on Molic-vertic gleysol cumuligleyic and Fluvisol sandy loam, respectively (Filipovski, 2006) (Table 1).

Table 1. Localities, soil types and characteristics (%)

Characteristics	Locality	
	Tetovo	Skopje
Type	Molic-vertic gleysol cumuligleyic	Fluvisol sandy loam
Coarse	27.1	10.5
Fine sand	47.3	63.1
Clay+silt	25.6	26.4
Organic matter	1.86	2.66
pH	6.3	6.7

The seedbed was prepared by moldboard ploughing in the summer (immediately after wheat harvest), followed by two passes with a field cultivator, one in the autumn, and the second one in the spring, a few days before maize sowing. NPK 15:15:15 fertilizer was added before sowing at a rate of 400 kg ha^{-1}, while KAN fertilizer was added at a rate of 300 kg N ha^{-1} as ammonium nitrate (34% N) in two equal doses at 4–5 maize leaf stage (BBCH 14–15) and the beginning of stem elongation (BBCH 30). The experimental design was a randomized complete block with four replicates, and the area of the main plots was 21 m^2 (5 m long and 4.2 m wide, i.e., seven maize rows). The field studies were carried out with maize hybrid 'Kermes' produced by the KWC from Germany which was seeded in a well-prepared seedbed at a seeding rate of 25 kg ha^{-1} on May 10th, 2017 and April 28th, 2018 on Tetovo locality and May 17th, 2017 and May 3rd, 2018 in Skopje locality, respectively. The interrow/row spacing was 70/25 cm and the seeding depth was about 5 cm. The used herbicide was Stellar manufactured by the company BASF from Germany, and the following treatments were included in the study (Table 2).

All herbicide treatments were done POST in 4–6 maize leaf stage (BBCH 14–16), on June 10th, 2017 and May 28th, 2018 in Tetovo locality and, June 16th, 2017 and June 1st, 2018 in Skopje locality, respectively. During POST application broadleaved weeds were in the cotyledons – 4 leaf stage (BBCH 10–14), and grass weeds in the 3–5 leaf stage (BBCH 13–15). The full rate of Stellar (1.0 L ha^{-1}) was applied without adjuvant, while reduced Stellar rates (0.75; 0.50; 0.25 and 0.125 L ha^{-1}) were applied with recommended rates of all study adjuvants (White oil (COC) at 0.2; DASH (MSO) at 2.0 and Trend (NIS) at 1.0 L ha^{-1}). All herbicide and herbicide plus adjuvants treatments were applied with a CO_2-pressurized backpack sprayer calibrated to deliver a 300 L ha^{-1} aqueous solution at 220 kPa. An untreated control was included in the studies, as well. The estimation of weed population was done for 1 m^2 for each repetition. The control plots were left untreated during the entire experimental period.

Weed control efficacy was estimated at 28 and 56 days after treatment (DAT), by the weed plants counting from 1 m^2 area within each plot, and herbicide efficacy was calculated by Equitation 1 (Chinnusamy *et al.*, 2013).

Table 2. Trade names, herbicide active ingredients, adjuvants and time of application of herbicides in maize

Treatments	Herbicide active ingredients and adjuvants	Rate, L ha^{-1}	Time of application
Untreated control	–	–	–
Stellar	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) with no adjuvant	1.0	*POST
Stellar + White oil	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + crop oil concentrate (COC)	0.75 + 0.2	POST
Stellar + DASH	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + methylated rapeseed oil (MSO)	0.75 + 2.0	POST
Stellar + Trend	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + nonionic surfactant (NIS)	0.75 + 1.0	POST
Stellar + White oil	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + crop oil concentrate (COC)	0.50 + 0.2	POST
Stellar + DASH	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + methylated rapeseed oil (MSO)	0.50 + 2.0	POST
Stellar + Trend	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + nonionic surfactant (NIS)	0.50 + 1.0	POST
Stellar + White oil	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + crop oil concentrate (COC)	0.25 + 0.2	POST
Stellar + DASH	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + methylated rapeseed oil (MSO)	0.25 + 2.0	POST
Stellar + Trend	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + nonionic surfactant (NIS)	0.25 + 1.0	POST
Stellar + White oil	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + crop oil concentrate (COC)	0.125+0.2	POST
Stellar + DASH	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + methylated rapeseed oil (MSO)	0.125 + 2.0	POST
Stellar + Trend	topremazone (50 g a.i L^{-1}.) + dicamba (160 g a.i. L^{-1}) + nonionic surfactant (NIS)	0.125 + 1.0	POST

*POST – 4–6 maize leaf stage (BBCH 14–16)

$$W_{CE} = \frac{W_{up} - W_{tp}}{W_{up}} \times 100, \qquad (1)$$

where W_{CE} – weed control efficiency
W_{up} – number of weeds in the untreated plots
W_{tp} – number of weeds in the treated plots

Maize injuries were estimated visually using a 0 to 100% scale, where 0% = no maize injury and 100% = complete maize plant death (Frans *et al.*, 1986). Maize plants injury was rated 14 and 28 DAT. The injury was visually rated by determining the average percentage of deformation, plant stunting, bleaching, chlorosis, or necrosis (or all) occurring in treated maize plants when compared with nontreated plants. Maize grain yields were determined by hand harvesting the central part of each plot 3.5 m^2 (1.4 m × 2.5 m) when the crop was mature, and recording the fresh weight of the harvested sample. Harvest in both localities was conducted between early and mid-October. The yield was adjusted to 15% moisture. Efficacy comparisons, as well as maize grain yields, were made between the full rate of Stellar without adjuvant and the reduced Stellar rates treatments with adjuvants.

During the present study, meteorological conditions throughout POST applications at both localities in both years favoured the action of Stellar and its reduced rates in mixtures with adding adjuvants (Table 3).

All statistical analyses were performed by using R 3.5.1 software. The data were tested for homogeneity of variance and normality of distribution (Ramsey, Schafer, 1997) and were log-transformed as needed to obtain roughly equal variances and better symmetry before ANOVA was performed. Data were transformed back to their original scale for presentation. Means were separated by using the LSD test at 5% of probability.

Table 3. Meteorological conditions during POST applications at Tetovo and Skopje localities in 2017 and 2018

Days of POST applications											
Tetovo locality						Skopje locality					
2017			2018			2017			2018		
June 10th			May 28th			June 16th			June 1st		
P, mm	T, °C	AH, %	P, mm	T, °C	AH, %	P, mm	T, °C	AH, %	P, mm	T, °C	AH, %
2	24	48	1	22	53	0	26	41	2	24	45

P – precipitations, T – temperature, AH – air humidity

Results and Discussion

Weed population

The weed population in both localities for both years has consisted mainly of summer broadleaves and grasses, annual and some perennial weeds. The weed community varied across locations. In Tetovo locality, the weed population has consisted of 13 weed species, and the total number of weeds was 333 plants m$^{2-1}$ (Table 4). The most prevailing among the 13 weed species were *Polygonum lapathifolium* (162 plants m$^{2-1}$), *Echinochloa-crus galli* (82 plants m$^{2-1}$) and *Chenopodium album* (26 plants m$^{2-1}$). In the Skopje locality, the weediness was lower in comparison with the previous one. The total number of weeds was 105 plants m$^{2-1}$. The most prevailing among the 12 weed species were *Echinochloa-crus galli* (34 plants m$^{2-1}$), *Sorghum halepense* (20 plants m$^{2-1}$) and *Chenopodium album* (16 plants m$^{2-1}$).

Table 4. Weed population (species and no, m$^{2-1}$) in maize crop at Tetovo and Skopje localities, averaged over 2017 and 2018

Weed species	Tetovo	Skopje
Polygonum lapathifolium L.	162	–
Chenopodium album L.	26	16
Galinsoga parviflora Cav.	9	–
Amaranthus retroflexus L.	9	7
Amaranthus lividus L.	5	–
Solanum nigrum L.	4	–
Xanthium strumarium L.	2	2
Echinochloa crus-galli (L.) P. Beauv.	82	34
Convolvulus arvense L.	9	6
Cirsium arvense (L.) Scop.	6	–
Rubus caesius L.	2	–
Sorghum halepense (L.) Pers.	9	20
Cynodon dactylon (L.) Pers.	8	10
Sinapis arvensis L.	–	3
Polygonum aviculare L.	–	2
Anagallis arvensis L.	–	2
Abutilon theophrasti Med.	–	2
Diplotaxis muralis (L.) DC.	–	1
Total weed species	13	12
Total weeds, no, m$^{2-1}$	333	105

Weed control and herbicide efficacy

The criterion for herbicide efficacy was taken as the percentage of weeds that are controlled by any particular treatment in comparison with untreated control. Efficacy of POST herbicides varied among treatments, weed species, and localities, respectively. Data regarding overall performances of herbicides efficacy presented in Tables 5 and 6 showed that all investigated treatments had a significant (P <0.05) effect on weed density per m^2, 28 and 56 days after their applications. Also, our results indicate that Stellar + adjuvant treatments, except the minimum ones (Stellar at 0.125 + adjuvants) provided mainly greater control of weeds compared to the use of Stellar applied alone at a recommended rate without adjuvant.

However, in both localities, the maximum weeds (333 and 105, respectively) were recorded in untreated control plots. Among herbicide and herbicide plus adjuvants treatments 28 DAT, minimum weed density in Tetovo locality were recorded in plots treated with Stellar + Trend and Stellar + DASH, applied at 0.75 + 1.0 L ha^{-1} and 0.75 + 2.0 L ha^{-1}, respectively (7 and 10, respectively). On the other side, maximum weed density was recorded in plots treated with Stellar applied at 0.125 L ha^{-1} with all studied adjuvants (White oil, Trend and DASH, respectively) (78, 73 and 72, respectively). In Skopje locality, same as in the previous one, minimum weed density was counted in plots treated with Stellar + DASH (0.75 + 2.0 L ha^{-1}) – 1, followed by Stellar + Trend (0.75 + 1.0 L ha^{-1}) – 3, while maximum weed density in herbicide treatments was observed in plots treated with Stellar applied at 0.125 L ha^{-1} with White oil – 28.0, followed by Stellar + DASH (0.75 + 2.0 L ha^{-1}) – 22.3 and Stellar + Trend (0.125 + 1.0 L ha^{-1}) – 21.5, respectively.

Reduction of the weed density was in positive correlation with herbicide efficacy. Overall efficacy of herbicides in control of weeds 28 DAT was ranged of 77% (Stellar + White oil applied at 0.125 + 0.2 L ha^{-1}) to 98% (Stellar + Trend applied at 0.75 + 1.0 L ha^{-1}) in Tetovo locality, and 64% (Stellar + White oil applied at 0.125 + 0.2 L ha^{-1}) to 99% (Stellar + DASH applied at 0.75 + 2.0 L ha^{-1}) in Skopje locality, respectively. In both localities, the efficacy of the full rate of Stellar (90 and 80%, respectively) was on the level of Stellar + White oil applied at 0.25 + 0.2 L ha^{-1} (90 and 78%, respectively) (Table 5).

Table 5. Effect of herbicidal treatments on weed density per m^2 and herbicide efficacy 28 DAT in maize crop in Tetovo and Skopje localities in 2017 and 2018, averaged over years

Treatments	Rate, L ha^{-1}	Weed density per m^2		Herbicide efficacy, %	
		Tetovo	Skopje	Tetovo	Skopje
Untreated control	–	333	105	–	–
Stellar	1.0	32de	22de	90^{d}	80^{cd}
Stellar + White oil	0.75 + 0.2	18^{abc}	5^{a}	95^{abc}	96^{a}
Stellar + DASH	0.75 + 2.0	10^{ab}	1^{a}	97^{ab}	99^{a}
Stellar + Trend	0.75 + 1.0	7^{a}	3^{a}	98^{a}	97^{a}
Stellar + White oil	0.50 + 0.2	23^{cd}	19^{cde}	93^{bcd}	82^{c}
Stellar + DASH	0.50 + 2.0	13^{abc}	12^{b}	96^{abc}	89^{b}
Stellar + Trend	0.50 + 1.0	11^{a}	13^{bc}	97^{ab}	88^{b}
Stellar + White oil	0.25 + 0.2	35^{e}	23^{e}	90^{d}	78^{d}
Stellar + DASH	0.25 + 2.0	27^{cde}	17^{bcde}	92^{cd}	84^{bc}
Stellar + Trend	0.25 + 1.0	21^{bcd}	16^{bcd}	94^{abcd}	85^{bc}
Stellar + White oil	0.125 + 0.2	78^{f}	38^{f}	77^{e}	64^{f}
Stellar + DASH	0.125 + 2.0	72^{f}	32^{f}	79^{e}	69^{ef}
Stellar + Trend	0.125 + 1.0	73^{f}	32^{f}	78^{e}	70^{e}
$LSD_{0.05}$	–	11.81	6.84	4.38	5.75
Random effect interactions POST herbicide treatments x locality				*	

*Significant at the 5% level according to a Fisher's protected LSD test at P <0.05.
POST treatments were applied in the 4–6 maize leaf stage (BBCH 14–16).
Weed control efficacy was estimated at 28 DAT.
Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD at P <0.05.

Weed density 56 DAT, was similar to the previous period of estimation. In Tetovo locality, minimum weed density among herbicide and herbicide plus adjuvants treatments were recorded in plots treated with Stellar + Trend (0.75+1.0 L ha^{-1}) and Stellar + DASH (0.75 + 2.0 L ha^{-1}) – 5 and 7, respectively, while in Skopje locality, same as in the previous period of estimation, minimum weed density was observed in plots treated with Stellar + DASH (0.75 + 2.0 L ha^{-1}) and Stellar + Trend (0.75 + 1.0 L ha^{-1}) (1 and 2, respectively) (Table 6). From the other side, in Tetovo locality, maximum weed density were recorded in plots treated with Stellar + White oil (0.125 + 0.2 L ha^{-1}) – 72, followed by Stellar + DASH (0.125 + 2.0 L ha^{-1}) – 66 and Stellar + Trend (0.125 + 1.0 L ha^{-1}) – 65. Similar as in the Tetovo, in Skopje locality, maximum weed density in herbicide/adjuvants treatments were observed in plots treated with Stellar + White oil (0.125 + 0.2 L ha^{-1}) – 25 and Stellar + Trend (0.125 + 1.0 L ha^{-1}) and Stellar + DASH (0.125 + 2.0 L ha^{-1}) – 21 and 19, respectively. Overall herbicide efficacy 56 DAT was ranged of 78% (Stellar + White oil applied at 0.125 + 0.2 L ha^{-1}) to 99% (Stellar + Trend applied at 0.75 + 1.0 L ha^{-1}) in Tetovo locality and 76% (Stellar + White oil applied at 0.125 + 0.2 L ha^{-1}) to 99% (Stellar + DASH applied at 0.75 + 2.0 L ha^{-1}) in Skopje locality, respectively. Similar to in the previous period of efficacy estimation (28 DAT), in both localities, the efficacy of the full rate of Stellar (91 and 84%, respectively) was on the level of Stellar + White oil applied at 0.25 + 0.2 L ha^{-1} (89 and 82%, respectively) (Table 6).

Table 6. Effect of herbicidal treatments on weed density per m^2 and herbicide efficacy 56 DAT in maize crop in Tetovo and Skopje localities in 2017 and 2018, averaged over years

Treatments	Rate, L ha^{-1}	Weed density per m^2		Herbicide efficacy, %	
		Tetovo	Skopje	Tetovo	Skopje
Untreated control	–	333	105	–	–
Stellar	1.0	30de	17de	91^{cd}	84^{def}
Stellar + White oil	0.75 + 0.2	15^{ab}	6^{ab}	95^{abc}	94^{ab}
Stellar + DASH	0.75 + 2.0	7^{a}	1^{a}	98^{a}	99^{a}
Stellar + Trend	0.75 + 1.0	5^{a}	2^{a}	99^{a}	98^{a}
Stellar + White oil	0.50 + 0.2	20^{bc}	15^{cde}	94^{bc}	86^{cde}
Stellar + DASH	0.50 + 2.0	10^{a}	10^{bc}	97^{ab}	90^{bc}
Stellar + Trend	0.50 + 1.0	12^{ab}	10^{bc}	96^{ab}	90^{bc}
Stellar + White oil	0.25 + 0.2	34^{e}	18^{e}	89^{d}	83^{ef}
Stellar + DASH	0.25 + 2.0	28^{cde}	13^{cde}	91^{cd}	88^{cd}
Stellar + Trend	0.25 + 1.0	21^{bcd}	12^{cd}	94^{b}	89^{bcd}
Stellar + White oil	0.125 + 0.2	72^{f}	35^{g}	78^{e}	67^{g}
Stellar + DASH	0.125 + 2.0	66^{f}	29^{f}	80^{e}	72^{g}
Stellar + Trend	0.125 + 1.0	65^{f}	31^{fg}	81^{e}	70^{g}
$LSD_{0.05}$	–	9.49	5.29	4.25	5.22
Random effect interactions POST herbicide treatments x locality				*	

* Significant at the 5% level according to a Fisher's protected LSD test at P <0.05.
POST treatments were applied in the 4–6 maize leaf stage (BBCH 14–16).
Weed control efficacy was estimated at 28 DAT.
Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD at P <0.05.

For optimal weed control, topramezone should be applied with a certain adjuvant, and DASH (MSO) is the most recommended (Torma *et al.*, 2011). This herbicide has good field performance when applied with the MSO adjuvant (Zhou *et al.*, 2010; Zheng *et al.*, 2011; Zhang *et al.*, 2013), because significantly increases foliar absorption by weed plants (Grossmann, Ehrhardt, 2007). Some other reports also presented that a good efficacy could be achieved when this herbicide was tank-mixed with MSO adjuvant (Young *et al.*, 2007; Zollinger, Ries, 2006). Applied as a post-emergence herbicide, it controls a wide spectrum of annual grass and broadleaf weeds (Ransom, Ishida, 2005; Porter *et al.*, 2005; Schonhammer *et al.*, 2006; Bollman *et al.*, 2007). Weed control efficacy was significantly higher with the application of topramezone 336 SC at 25.2 and 33.6 g a.i. ha^{-1} + MSO adjuvant (94.8 and 95.4% based on weed dry weight (Tiwari *et al.*, 2018). Field research conducted by Zollinger, Ries, (2006) showed that topramezone applied at a 1X rate completely controlled *A. retroflexus*, *C. album*, *S. arvensis*, *K. scoparia*, *S. sarachoides*, and *X. strumarium*, while *A. artemisiifolia* control from topramezone applied alone was 95% through the growing season. In addition, topramezone gave 100% control of *Abutilon theophrasti* in maize crops (James, Cooper, 2012). Swetha *et al.*, (2018) recorded the lowest density of grasses (4.50 m^2) and broad-leaved weeds (3.56 m^2) in a mixture of topramezone + atrazine (25.2 + 250 g a.i ha^{-1}) + MSO adjuvant. Dobbels, Kapusta (1993) reported up to 100% control of *C. album*, *A. retroflexus* and *Setaria viridis* with nicosulfuron plus dicamba plus atrazine plus adjuvant X–77® (a mixture of alkylarylpolyoxyethylene glycols, free fatty acids, and isopropanol) in maize. However, nicosulfuron combination with companion herbicides such as dicamba plus X–77® provided inconsistent (0–100%) control of *A. theophrasti* in maize (Dobbels, Kapusta 1993). Nicosulfuron plus dicamba provided 90–98% control of *A. theophrasti*, 99% control of *A. artemisiifolia*, 74–99% control of *C. album* and 80–94% control of *S. viridis*. The control of *C. album* improved with the addition of either Agral 90® (Nonylphenoxy phenoxyethanol 90%) or Liberate® (non-ionic surfactant) (Soltani *et al.*, 2010).

However, limited research has been conducted about the biological efficacy of reduced rates of topramezone plus dicamba (Stellar) with different adjuvants on weeds in maize crops.

Weed control of predominant weeds

Efficacy of herbicide and herbicide plus adjuvants treatments in control of prevailing weeds at 28 and 56 DAT ranged from 22 to 100% in Tetovo locality (Table 7) and 30 to 100% in Skopje locality, respectively (Table 8).

Stellar at a recommended rate (1.0 L ha^{-1}) without adjuvants excellent controlled predominant broad-leaved *P. lapathifolium* and *C. album* in both localities and years (100%), except *E. crus-galli* (<65%) in Tetovo locality and *E. crus-galli* and *S. halepense* (<63 and <60%) in Skopje locality, respectively for both estimation periods. At the recommended dose topramezone provided good control on broadleaved weeds whether it was applied at the 2–3 leaf or 4–5 leaf stage of weeds (Zhang *et al.*, 2013). Similar results were reported by Bollman *et al.* (2008). Topramezone provided greater than 90% control of *C. album*, *A. theophrasti* and *A. artemisiifolia*.

In Tetovo locality, 28 DAT Stellar at 0.75; 0.50; 0.25 and 0.125 L ha^{-1} with all studied adjuvants provided control of *P. lapathifolium* between 100 and 88%. At the same time, control of *E. crus-galli* with Stellar at 0.75; 0.50 and 0.25 L ha^{-1} with Dash (MSO) and Trend (NIS) adjuvants was higher than 90%, which was quite effective than Stellar applied at the recommended rate (1.0 L ha^{-1}) without adjuvants (64%). Control of *E. crus-galli* with Stellar at 0.75; 0.50 and 0.25 L ha^{-1}

with White oil (COC) adjuvant was significantly lower in comparison with other adjuvants (between 86 and 76%), but statistically higher in comparison with Stellar applied at the recommended rate (1.0 L ha^{-1}) without adjuvants. From the other side, all adjuvants with Stellar at 0.125 L ha^{-1} showed the poorest control of *E. crus-galli* (<29%). Reduced rates of Stellar (0.75 and 0.50 L ha^{-1}) with Dash (MSO) and Trend (NIS) adjuvants resulted in maximum mortality (100%) of *C. album* compared with <89% control of this weed with Stellar at 0.75 and 0.50 L ha^{-1} with White oil (COC) adjuvant. Satisfactory efficacy in the control of *C. album* (>87%) was obtained with the lowest rates of Stellar (0.25 and 0.125 L ha^{-1}) with Dash (MSO) and Trend (NIS) adjuvants, which was not the case with the same Stellar rates (0.25 and 0.125 L ha^{-1}) and White oil (COC) adjuvant (77 and 68%, respectively) (Table 7).

56 DAT full rate of Stellar without adjuvants, as well as reduced rates of Stellar with adjuvants, provided similar levels of predominant weeds control as in the previous period of weed control estimation – 28 DAT. Reduced rates of Stellar (0.75 and 0.50 L ha^{-1}) with all studied adjuvants achieved complete control of *P. lapathifolium*. On the other side, Stellar applied alone at recommended rate (1.0 L ha^{-1}) excellent controlled broadleaved weeds, including predominant *Polygonum lapathifolium* and *Chenopodium album* and shows some activity on grass weeds, but without commercially acceptable control of those grasses (Goršić *et al.*, 2008; Soltani *et al.*, 2012). Stellar at 0.25 L ha^{-1} with all adjuvants gave 88–90% control of *P. lapathifolium*, but the efficacy of Stellar at 0.125 L ha^{-1} with all adjuvants gave only marginal control of this weed (between 66 and 74%). The lack of predominant *P. lapathifolium* control because this weed recovered after application of the lowest rate of Stellar (0.125 L ha^{-1}), regardless of adjuvants. Reduced rates of Stellar (0.25; 0.50 and 0.75 L ha^{-1}) with Dash (MSO) and Trend (NIS) adjuvants effectively controlled *E. crus-galli*; control ranged from 90–98%. Opposite, the same rates of Stellar with White oil (COC) adjuvant provided control levels of *E. crus-galli* between 79 and 89%. The three COC, MSO and NIS adjuvants added to the Stellar liquid spray at the lowest reduced rate (0.125 L ha^{-1}) showed the poorest *E. crus-galli* control (<26%). Concerning *C. album*, excellent control was achieved with Stellar at 0.75 and 0.50 L ha^{-1} with Dash (MSO) and Trend (NIS) adjuvants (100%), and with Stellar at 0.25 L ha^{-1} with Dash (MSO) and Trend (NIS) adjuvants (96–97%). White oil (COC) adjuvant only with Stelar at 0.75 and 0.50 L ha^{-1} provided good control levels of *C. album* (92 and 87%, respectively). Satisfactory efficacy (83%) was obtained with the Stellar at 0.125 L ha^{-1} with Dash (MSO) and Trend (NIS) adjuvants. The lowest *C. album* efficacy 56 DAT in Tetovo locality showed Stellar at 0.25 and 0.125 L ha^{-1} rate with White oil (COC) adjuvant (77 and 62%, respectively) (Table 7).

Table 7. Control of predominant *Polygonum lapathifolium*, *Echinochloa crus-galli* and *Chenopodium album* 28 and 56 DAT in maize crop in 2017 and 2018, averaged over years in Tetovo locality

Treatments	Rate, L ha^{-1}	Weed control, %					
		28 DAT			56 DAT		
		POLLA	ECHCG	CHEAL	POLLA	ECHCG	CHEAL
Untreated control	–	0	0	0	0	0	0
Stellar	1.0	100^{a}	64^{d}	100^{a}	100^{a}	65^{d}	100^{a}
Stellar + White oil	0.75 + 0.2	100^{a}	86^{b}	89^{c}	100^{a}	89^{b}	92^{c}
Stellar + DASH	0.75 + 2.0	100^{a}	96^{a}	100^{a}	100^{a}	98^{a}	100^{a}
Stellar + Trend	0.75 + 1.0	100^{a}	95^{a}	100^{a}	100^{a}	98^{a}	100^{a}
Stellar + White oil	0.50 + 0.2	99^{a}	79^{c}	84^{d}	100^{a}	80^{c}	87^{d}
Stellar + DASH	0.50 + 2.0	100^{a}	93^{a}	100^{a}	100^{a}	93^{ab}	100^{a}
Stellar + Trend	0.50 + 1.0	99^{a}	93^{a}	100^{a}	100^{a}	94^{ab}	100^{a}
Stellar + White oil	0.25 + 0.2	92^{cd}	76^{c}	77^{e}	88^{b}	79^{c}	77^{e}
Stellar + DASH	0.25 + 2.0	95^{b}	90^{ab}	95^{b}	90^{b}	90^{b}	97^{b}
Stellar + Trend	0.25 + 1.0	94^{bc}	90^{ab}	93^{b}	90^{b}	92^{ab}	96^{bc}
Stellar + White oil	0.125 + 0.2	88^{e}	24^{e}	68^{f}	66^{d}	22^{e}	62^{f}
Stellar + DASH	0.125 + 2.0	90de	29^{e}	87^{cd}	72^{c}	25^{e}	83^{d}
Stellar + Trend	0.125 + 1.0	90de	29^{e}	88^{c}	74^{c}	26^{e}	83^{d}
$LSD_{0.05}$		2.80	6.03	3.87	3.45	6.23	4.61
Random effect interactions POST herbicide treatments x DAT		NS					

DAT – days after treatments; POLLA – *Polygonum lapathifolium*; ECHCG – *Echinochloa crus-galli*; CHEAL – *Chenopodium album.*
NS – not significant according to a Fisher's protected LSD test at P <0.05.
Weed control efficacy was estimated at 28 and 56 DAT.
Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD at P <0.05.

In Skopje locality, 28 DAT Stellar at 0.75; 0.50 and 0.25 L ha^{-1} with Dash (MSO) and Trend (NIS) adjuvants provided control of *E. crus-galli* higher than 91%, significantly higher in comparison with 67% efficacy of Stellar applied at the recommended rate (1.0 L ha^{-1}) without adjuvants (Table 8). White oil (COC) adjuvant with Stellar at 0.75; 0.50 and 0.25 L ha^{-1} reduced the occurrence of *E. crus-galli* between 90 and 75%. The poorest control of *E. crus-galli* (<50%) was obtained in the lowest rate of Stellar (0.125 L ha^{-1}) with all studied adjuvants. The slightly higher efficacy of herbicide and herbicide plus adjuvants treatments was recorded in the control of *S. halepense* (Table 8). Both Dash (MSO) and Trend (NIS) adjuvants with Stellar at 0.75 and 0.50 L ha^{-1} provided nearly 100% control of *S. halepense,* while White oil (COC) adjuvant with the same rates of Stellar provided *S. halepense* control level of 95 and 91%, respectively. Reduced rates of Stellar (0.75; 0.50 and 0.25 L ha^{-1}) with COC, MSO and NIS adjuvants provided significantly higher control of *S. halepense* (between 80 and 100%) in comparison with 69% efficacy of Stellar applied at the recommended rate (1.0 L ha^{-1}) without adjuvants. Non-satisfactory efficacy in the control of *S. halepense* was recorded in the lowest rate of Stellar plus adjuvants treatments (between 55 and 67%). Stellar at 0.75; 0.50 and 0.25 L ha^{-1} with Dash (MSO) and Trend (NIS) adjuvants, as well as Stellar in full rate (1.0 L ha^{-1}) without adjuvant, resulted in nearly maximum mortality (98–100%) of *C. album* compared with 95, 93 and 89% control in Stellar at same rates with White oil (COC) adjuvant. Satisfactory control of *C. album* (90%) was obtained with the lowest rate of Stellar (0.125 L ha^{-1}) with Dash (MSO) and Trend (NIS) adjuvants, which was not the case with the same Stellar rate (0.125 L ha^{-1}) and White oil (COC) adjuvant (72%).

The trends in predominant weed control with a full rate of Stellar without adjuvant, as well as reduced rates of Stellar with adjuvants 56 DAT, were similar to weed control estimation 28 DAT. Stellar (0.75; 0.50 and 0.25 L ha^{-1}) tank-mixed with Dash (MSO) and Trend (NIS) adjuvants effectively controlled more than 92% of *E. crus-galli*. On the other side, the same rates of Stellar with White oil (COC) adjuvant provided control levels of *E. crus-galli* between 77 and 90%. Tank mixing Stellar (0.125 L ha^{-1}) with COC, MSO and NIS adjuvants, controlled *E. crus-galli* less than 42%. Stellar at 0.75 and 0.50 L ha^{-1} with Dash (MSO) and Trend (NIS) adjuvants achieved complete control of *S. halepense.* White oil (COC) adjuvant with Stellar at 0.75 and 0.50 L ha^{-1}, as well as Stellar at 0.25 L ha^{-1} with Dash (MSO) and Trend (NIS) adjuvants gave control of *S. halepense* between 88 and 92%. The lowest control of *S. halepense* (<58%) was recorded in the plots treated with Stellar at 0.125 L ha^{-1} with all studied adjuvants. Stellar at 0.75; 0.50 and 0.25 L ha^{-1} with all adjuvants achieved control of *C. album* bigger than 90%, while tank mixing Stellar (0.125 L ha^{-1}) with COC, MSO and NIS adjuvants, controlled *C. album* between 75 and 85% (Table 8).

Topramezone applied at 0.75X rate with MSO-type adjuvant completely controlled *A. retroflexus*, *C. album*, *S. arvensis, K. scoparia, S. sarachoides*, and *X. strumarium* (Zollinger, Ries, 2006). Spraying plants of *S. faberi*, *S. bicolor* and *S. nigrum* at the third leaf stage with topramezone (0.75 L ha^{-1}) and Dash HC (1.0 L ha^{-1}) caused strong photobleaching effects on shoots within 2–5 days after treatment. Consequently, the addition of an adjuvant such as Dash HC to the spray solution of topramezone was essential for excellent weed control (Grossmann, Ehrhardt, 2007).

As observations and previous experience with other herbicides suggested that most weed species could be controlled with significantly lower herbicide rates than recommended (Dogan *et al.*, 2005), a reduction in costs could be possible if effective minimum rates are determined for any herbicide.

Table 8. Control of predominant *Echinochloa crus-galli, Sorghum halepense* and *Chenopodium album* 28 and 56 DAT in maize crop in 2017 and 2018, averaged over years in Skopje locality

Treatments	Rate, L ha^{-1}	Weed control, %					
		28 DAT			56 DAT		
		ECHCG	SORHA	CHEAL	ECHCG	SORHA	CHEAL
Untreated control	–	0	0	0	0	0	0
Stellar	1.0	67^{d}	69^{f}	100^{a}	63^{f}	60^{d}	100^{a}
Stellar + White oil	0.75 + 0.2	90^{b}	95^{bc}	95^{abc}	90^{c}	92^{b}	100^{a}
Stellar + DASH	0.75 + 2.0	98^{a}	100^{a}	100^{a}	100^{a}	100^{a}	100^{a}
Stellar + Trend	0.75 + 1.0	98^{a}	100^{a}	100^{a}	100^{a}	100^{a}	100^{a}
Stellar + White oil	0.50 + 0.2	81^{c}	91^{d}	93^{bcd}	83^{d}	88^{b}	95^{b}
Stellar + DASH	0.50 + 2.0	95^{ab}	98^{ab}	100^{a}	98^{ab}	100^{a}	100^{a}
Stellar + Trend	0.50 + 1.0	93^{ab}	98^{ab}	100^{a}	98^{ab}	100^{a}	100^{a}
Stellar + White oil	0.25 + 0.2	75^{c}	80^{e}	89^{d}	77^{e}	75^{c}	90^{c}
Stellar + DASH	0.25 + 2.0	91^{ab}	93^{cd}	98^{ab}	92^{c}	90^{b}	95^{b}
Stellar + Trend	0.25 + 1.0	91^{ab}	91^{d}	98^{ab}	94^{bc}	90^{b}	97^{ab}
Stellar + White oil	0.125 + 0.2	38^{f}	55^{g}	72^{e}	30^{h}	44^{e}	75^{e}
Stellar + DASH	0.125 + 2.0	47^{e}	66^{f}	90^{cd}	40^{g}	58^{d}	85^{d}
Stellar + Trend	0.125 + 1.0	50^{e}	67^{f}	90^{cd}	42^{g}	58^{d}	88^{cd}
$LSD_{0.05}$		7.75	3.49	5.80	5.15	4.75	4.38
Random effect interactions POST herbicide treatments x DAT				NS			

DAT–days after treatments; ECHCG–*Echinochloa crus-galli*; SORHA–*Sorghum halepense* CHEAL–*Chenopodium album.*
NS–not significant according to a Fisher's protected LSD test at P <0.05.
Weed control efficacy was estimated at 28 and 56 DAT.
Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD at P <0.05.

Maize injury and grain yield

Taking into consideration fact that all investigated herbicide and herbicide plus adjuvants treatments were applied in properly maize growth stages possesses high selectivity to maize, no visual injured were determined by any rates in both localities for both years (Table 9). Maize grain yields for each treatment in both localities for both years generally reflected overall weed control. In Tetovo locality, the highest grain yield among herbicide and herbicide plus adjuvants treatments were recorded in plots treated with Stellar + Trend at 0.75 + 1.0L ha^{-1} and Stellar + DASH at 0.75 + 2.0 L ha^{-1} (8300 and 8250 kg ha^{-1}, respectively, while in Skopje locality, same as in the previous case, the highest grain yield were observed in plots treated with Stellar + DASH at 0.75 + 2.0 L ha^{-1} and Stellar + Trend at 0.75 + 1.0 L ha^{-1} (8570 and 8510 kg ha^{-1}, respectively) (Table 9). From the other side, in Tetovo locality, the lowest grain yield were recorded in plots treated with Stellar + White oil (0.125 + 0.2 L ha^{-1}) – 4710 kg ha^{-1}, followed by Stellar + DASH (0.125 + 2.0 L ha^{-1}) – 5180 kg ha^{-1} and Stellar + Trend (0.125 + 1.0 L ha^{-1}) – 5270 kg ha^{-1}. Similar to in the Tetovo, in the Skopje locality, the lowest grain yield in herbicide and herbicide plus adjuvants treatments were observed in plots treated with Stellar + White oil (0.125 + 0.2 L ha^{-1}) – 4460 kg ha^{-1} and Stellar + Trend (0.125 + 1.0 L ha^{-1}) and Stellar + DASH (0.125 + 2.0 L ha^{-1}) – 4590 and 4630 kg ha^{-1}, respectively. In both localities, grain yield of the full rate of Stellar (5980 and 5530 kg ha^{-1}, respectively) was on the level of Stellar + White oil applied at 0.25 + 0.2 L ha^{-1} (5870 and 5440 kg ha^{-1}, respectively) (Table 9). Topramezone 336 g L^{-1} SC applied at 20.1, 25.2 and 33.6 g a.i. ha^{-1} + MSO adjuvant produce a significantly higher yield than the lowest dose 13.4 g a.i. ha^{-1}. + MSO Adjuvant (Tiwari *et al.,* 2018). Post-emergence application of topramezone at 25.20 g ha^{-1} + MSO recorded a grain yield of 47.12 g ha^{-1} which was comparable with the hand weeding at 20 and 40 DAS (49.41 g ha^{-1}) (Mahto *et al.,* 2020). Nicosulfuron plus dicamba increased yield by at least 67% compared with the untreated control. The addition of Agral 90®and Liberate®to nicosulfuron plus dicamba increased yield by 24 and 17%, respectively (Soltani *et al.,* 2010).

Table 9. Maize plant injury as influenced by POST treatments and grain yield as influenced by POST treatments in maize crop in Tetovo and Skopje localities in 2017 and 2018, averaged over years [a–d]

Treatments	Rate, L ha^{-1}	Grain yield, kg ha^{-1}	
		Tetovo	Skopje
Untreated control	–	2570	3210
Stellar	1.0	5980^{e}	5530^{e}
Stellar + White oil	0.75 + 0.2	7420^{c}	7770^{b}
Stellar + DASH	0.75 + 2.0	8250^{a}	8570^{a}
Stellar + Trend	0.75 + 1.0	8300^{a}	8510^{a}
Stellar + White oil	0.50 + 0.2	7290^{c}	6020^{d}
Stellar + DASH	0.50 + 2.0	7960^{b}	7430^{c}
Stellar + Trend	0.50 + 1.0	7730^{b}	7390^{c}
Stellar + White oil	0.25 + 0.2	5870^{e}	5440^{e}
Stellar + DASH	0.25 + 2.0	6110^{e}	5880^{d}
Stellar + Trend	0.25 + 1.0	6300^{d}	5990^{d}
Stellar + White oil	0.125 + 0.2	4710^{g}	4460^{f}
Stellar + DASH	0.125 + 2.0	5180^{f}	4630^{f}
Stellar + Trend	0.125 + 1.0	5270^{f}	4590^{f}
$LSD_{0.05}$		250.41	238.09

POST – post-emergence; DAT – days after treatments.
Maize injury estimated at 14 and 28 DAT.
Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD at P <0.05.

Conclusion

Almost all reduced rates of Stellar (topremazone plus dicamba), except the lowest one 0.125 L ha^{-1} with the addition of properly chosen adjuvants, provided excellent control of all investigated weeds, including grasses, such as *Echinochloa crus-galli* and *Sorghum halepense.* The highest efficacy of 28 DAT was achieved in plots treated with herbicide Stellar + Trend applied at 0.75+1.0 L ha^{-1} 98% in Tetovo locality, while Stellar + DASH applied at 0.75+2.0 L ha^{-1} has shown slightly higher efficiencies 99% in Skopje locality. Therefore, the use of adjuvants in the spray liquid with different mechanisms of action, first, MSO and NIS, will improve Stellar efficacy even applied at the reduced rates, particularly in control of the monocotyledonous species in maize crop.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author contributions

ZP, AS, AM – study conception and design;
ZP – acquisition of data;
ZP, AS, AM – analysis and interpretation of data;
ZP, AM – drafting of the manuscript;
ZP, AS, AM – critical revision and approval of the final manuscript.

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