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ORIGINAL PAPER

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EVALUATING GLUFOSINATE-AMMONIUM AND FLAME WEEDING FOR WEED CONTROL IN SWEET MARJORAM (*Origanum majorana* L.) CULTIVATION

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ABSTRACT

The objective of this four-year study was to compare the effects of flame weeding and spraying with glufosinate-ammonium on weed control in sweet marjoram field cultivation. The experiment was set up in a complete randomized four-replicate design with a plot area of 8 m^2. Moreover, the content of essential oil in marjoram herb obtained from the control plants, as well as the composition of this oil were also studied. Marjoram emergence began 13–17 days after sowing, and it was very uneven and in some years it was extendend up to 5 weeks. Flaming (90 kg propane · ha^{-1}) was applied in two times: immediately after noticing the first marjoram emergence or 5 days later, while glufosinate-ammonium (600 g · ha^{-1}) was applied on the same date as the first flaming. The tested methods of weeding significantly reduced the number and fresh weight of weeds growing 3–4 weeks after the start of marjoram emergence, i.e. in the period of its greatest sensitivity to weed competition. They had no soil residual activity and their effect on weeds disappeared after the first weeding. Among weeds occurring in the experiment, only barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) was partially tolerant to flaming. Flaming applied at the second time did not increase the effectiveness of weed control, but significantly decreased the number of emergence and the yield of marjoram herb. Essential oil content in marjoram grated herb varied considerably depending on the year, ranging from 1.35 to 2.34%. The oil contained from 33 to 36 identified compounds, among which *trans*-sabinene hydrate (28–34%) and terpinen-4-ol (17–21%) were clearly dominant.

Key words: weed flora, flaming, herbicide, marjoram growth, herb yield, essential oil

INTRODUCTION

Sweet marjoram is a perennial herb or subshrub of the Lamiaceae family, native to the Mediterranean Basin and now grown in many countries [Bina and Rahimi 2017]. In Poland, it belongs to the most important herbal and spice plants with a large area of its cultivation in the Lublin region [Newerli-Guz 2016]. Sweet marjoram has been used in cooking and human therapy since ancient times, but also today it attracts great attention and new methods of its cultivation and application are researched [Bina and Rahimi 2017, Postu et al. 2020, Wittmann et al. 2020, de Souza et al. 2021]. Under climatic conditions of Poland, marjoram is cultivated as an annual plant, as it freezes in winter [Rumińska 1991]. In previous years, it was grown from planting seedlings [Czarnecki i Załęcki 1986] but nowadays, less labor-intensive cultivation from sowing directly into the field prevails [Kucharski 2018]. In the field studies of Suchorska-Tropiło and

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Tołwiński [2001], the plants of four marjoram populations grown from seedlings reached the height of 22.3 to 31.7 cm, produced an average of 6.1 to 8.3 shoots, and were characterized by a diverse plant habit. In an experiment carried out by Nurzyńska-Wierdak and Dzida [2009] in the Lublin region, marjoram grown in the same way reached the height, depending on plant density and harvest time, from 29 to 34 cm, produced from 6.5 to 9.1 shoots per plant and from 12.0 to 15.9 main shoot branches.

In the cultivation of marjoram sown directly into the field, weed control is very difficult due to the slow and uneven emergence lasting 2–3 weeks and the initially slow growth of seedlings [Rumińska 1991, Kucharski 2018]. In Berbeć's [1969] pot experiment, the growth of marjoram was slow during the first several days after planting the seedlings and significantly increases in plant height, up to 10 cm and more in 10 days, were not recorded until the last ten days of June and in July. In another pot experiment carried out by Gregorczyk [1997], marjoram seeds started to emerge 9 days after sowing and then, during first three weeks of vegetation, the average weekly plant height increments ranged from about 1.0 to 1.5 cm only. In the following weeks, until the beginning of flowering, the plants grew faster and faster, and the daily height gain became more than 1 cm.

Currently in Poland, after marjoram emergence, it is allowed to use two herbicides, namely pyridate at the 11–13 marjoram BBCH phase against several annual species of dicotyledonous weeds, and fluazifop-P-butyl (12–14 BBCH) against the species of the *Poaceae* family [Strażyński 2020]. Previously, just before emergence (on sandy soils, at least 3 days before emergence), it was allowed to use diquat of total activity on weeds [Rumińska 1991]. Currently, glufosinate-ammonium, which proved to be useful in lemon balm (*Melissa officinalis* L.) [Kordana et al. 1997, Borowy and Kapłan 2022b] and summer savory (*Satureja hortensis* L.) [Borowy and Kapłan 2022a] sowings, could be a herbicide safer than diquat for humans and the environment [Sensemann 2007] for this treatment. In organic farming, where the use of herbicides is not allowed [Council Reg. 2007], they can sometimes be replaced by flame weeding [Carrubba and Militello 2013, Knežević 2016]. The use of flaming and ammonium-glufosinate leads to a reduction in mechanical soil cultivation, which is appreciated in organic [Kuepper 2001] and sustainable [Lal 2009] farming systems. When using these methods, the timing of the treatment is very important. The later it is done, the more weeds will emerge, and the more effective it would be. However, when the treatment is delayed for excessive time, the crop may emerge, which will prevent the use of both of these methods [Borowy and Kapłan 2022a, b]. Sometimes it is possible to flame the weeds after emergence of the crop [Knežević 2017].

So far, very little is known about the amount of manual labor involved in weeding herbal crops. Research conducted in Germany by Pank [1992] showed that manual labor inputs for weeding and hoeing of 1 ha of marjoram amounted to 590 hours, which constituted 95% of the total weeding effort, and that an efficient use of herbicides allowed for a reduction of these inputs by almost 90%. According to Dobrzański [1999], in Poland the manual labor incurred for weeding vegetable crops grown from direct sowing in the field and characterized by a long period of emergence as well as initially slow growth (carrot, leek, onion, parsley) range from 300 to 1200 worker hours per ha.

The most valuable component of sweet marjoram herb is essential oil. In the experiment conducted by Czarnecki and Załęcki [1986], dry herb of marjoram cultivated from direct sowing contained depending on the harvest date from 1.18 to 1.23% or from 1.23 to 1.38% of oil. In the study by Schorska-Tropiło and Tołpiński [2001], the content of oil in grated herb varied, depending on the population, from 0.90 to 1.72%, while the differences in the composition of the oil were smaller. In the studies conducted in the Lublin region, dry ungrated marjoram herb contained from 1.18 to 1.65% of oil [Nurzyńska-Wierdak and Dzida 2009, Nurzyńska et al. 2015], while grated herb contained 1.8–2.5% [Zawiślak 2008], 1.85–2.05% [Zawiślak and Dzida 2010] or 2.36% [Nurzyńska et al. 2015] of this compound. The oil obtained from herb harvested in the middle of July by Zawiślak [2008] contained 32 identified and 3 not identified compounds. The main compounds were *trans*-sabinene hydrate (29.4–50.3%), terpinen-4-ol (5.9–14.6%), sabinene (6.2–8.2%), linalyl acetate (4.2–8.5%), *cis*-sabinene hydrate (5.5–6.6%) and γ-terpinene (3.5–7.9%). The oil extracted from *Majoranae herba* by Nurzyńska et al. [2015] contained 41 identified compounds, the dominant one being the total content of *trans*-sabinene hydrate and linalool (46.8–51.6%). The other compounds present in significant amounts were terpinen-4-ol (6.4–8.8%), sabinene (5.4–6.6%), γ-terpinene (4.3–6.1%), *E*-caryophyllene (4.0–4.2%), limonene + β-phellandrene (3.5–3.8%), and α-terpinene (2.7–4.0%). The above-mentioned research concerned plants grown from planting the seedlings but there is a lack of such data relating to marjoram sown directly into the field.

There is very little information in the literature on the control of weeds in sweet marjoram cultivation and therefore the aim of this experiment was to evaluate the effect of flame weeding applied in two applications and spraying with glufosinate-ammonium on weed suppression and on the yield of marjoram sown directly into the field. The aim was also to determine the dynamics of marjoram growth, which is an important feature associated with the ability to compete against weeds. In addition, the content of essential oil in the grated herb obtained from hand-weeded marjoram plants was determined, as well as the composition of this oil.

MATERIALS AND METHODS

The experiment was conducted in the years 2016–2019 at the Felin Experimental Farm of the University of Life Sciences in Lublin, located in central-eastern Poland (215 m above sea level, 51°13'N, 22°39'E). Sweet marjoram (*Origanum majorana* L.) was cultivated on haplic Luvisol soil developed from loess deposits, containing 1.6% of organic matter and with pH (in 1 M KCl) of 6.4. Every year in the second half of April, on the day before sowing marjoram seeds, the experimental field was fertilized with 60 kg N · ha^{-1} (ammonium nitrate), 60 kg P_2O_5 · ha^{-1} (triple superphosphate) and 90 kg K_2O · ha^{-1} (concentrated potassium salt). Then the fertilizers were mixed with the soil by means of a cultivator and the soil surface was leveled with a rake. The seeds produced by the Polish seed company PNOS were sown by hand to a depth of 0.5 cm, slightly compressing the sowing, in 4 rows 4 m long with 50 cm distance between the rows (8 m^2 plot area), keeping the sowing rate of 5 kg · ha^{-1}. The exact sowing dates are given in Table 1. The experiment consisted of the following 4 treatments: flaming 13–17 days after sowing, flaming 18–21 days after sowing, spraying with glufosinate-ammonium, and hand weeding, what with 4 replications gave a total of 16 plots.

After some of the weeds emerged and immediately after noticing the first marjoram emergence, i.e. 13–17 days after sowing, flame weeding in the first term and spraying with glufosinate-ammonium were applied. At that time, the weeds were in the cotyledon and at the first true leaves stage. After another 5 days and more emergence of weeds and marjoram seedlings, flame weeding was applied for the second term.

Table 1. Schedule of the works performed in the experiment

Work	2016	2017	2018	2019
Sowing marjoram	April 23rd	April 25th	April 16th	April 27th
Spraying with glufosinate-ammonium and first term of flaming	May 7th	May 8th	May 2nd	May 13th
Second term of flaming	May 12th	May 13th	May 7th	May 18th
First assessment of weed infestation	May 28th	May 29th	May 23rd	June 1st
First plant height measurement	June 7th	June 1st	June 9th	June 10th
Second assessment of weed infestation	June 27th	June 24th	June 21st	June 30th
Counting marjoram emergence	June 28th	June 26th	June 24th	June 30th
Harvesting of marjoram herb	July 31st	July 26th	July 22nd	July 29th
Determination of essential oil content	October 19th	October 11th	October 1st	October 7th
Determination of composition of the oil	November 25th	–	November 23th	November 26th

Glufosinate-ammonium was sprayed at a dose of 600 g · ha^{-1} by means of a back-pack sprayer mounted with an XR TeeJet® nozzle at 1.5 bars pressure and 300 l of water · ha^{-1}. Flaming was carried out by hand using a universal Italian KIT 105-P flamer mounted with an open tubular burner with a diameter of 50 mm using 90 kg of propane · ha^{-1} at 2.5 bar pressure. For the first time, the weeds were counted by species in four 20 × 50 cm frames placed randomly in interrow spaces on each plot 34–37 days after sowing. During the counting the weeds were pulled out and their fresh weight was determined after the roots were cleared of soil. On the following day, the plots were hand weeded. For the second time, weed infestation was determined in the same way 26–30 days after the first measurement. In addition, in 2019, the amount of manual work incurred to weed the plots was determined. The plots were then weeded and kept weed-free until the end of the experiment. After 61–68 days from sowing, the marjoram seedlings growing on a randomly selected 1 running meter of each row in each plot were counted. On the first 10 days of June, i.e. about 5 weeks after the start of marjoram emergence, the height of 25 randomly selected plants was measured in each plot. Subsequent measurements were made every 10 days until harvest. The last measurement was made immediately before harvest. At the turn of July and August, the plants that started flowering were cut at the soil surface, and then their fresh weight was established. In addition, the first and second degree side shoots were counted for 25 plants per plot. The harvested plants were dried for one month in a shaded and ventilated place at about 32°C, in order to obtain dry herb.

In the middle of October, content of essential oil in grated herb collected from control plots was determined by hydro-distillation in the Deryng' apparatus according to the method recommended by the European Pharmacopoeia 5 [2005]. In the years 2016, 2018 and 2019, the qualitative composition of the oil was determined by the Central Research Laboratory of the University of Life Sciences in Lublin accredited by the Polish Centre for Accreditation. The oil samples were analyzed with a gas chromatograph Varian Chrompack CP-3800 coupled with mass detector Varian 4000 GC/MS/MS and flame ionization detector (FID) using VF column – 5 ms (DB-5 equivalent) according to the procedure described by Borowy and Kapłan [2022b].

The field experiment was arranged in a randomized block design with two experimental factors (method of weeding and year of study) and four replications. The obtained results were analyzed statistically by means of the analysis of variance involving a model for orthogonal data, while the significance of differences between the means was determined using Tukey's test at the level of 0.05.

RESULTS

Depending on the weather conditions, and especially soil moisture, emergence of weeds started 8–11 days after sowing and about 4 weeks later, depending on the year, from 17 to 21 species of weeds, mainly annual dicotyledons grew in the experiment. Perennial weeds represented by creeping thistle (*Cirsium arvense* (L.) Scop.) and dandelion (*Taraxacum officinale* L.) occurred sporadically. The dominant species were barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) and lamb's quarter (*Chenopodium album* L.) constituting 22% each of the total weed population, shepherds' purse (*Capsella bursa-pastoris* (L.) Medik.) – 21%, and redroot pigweed (*Amaranthus retroflexus* L.) – 20%, whereas gallant soldier (*Galinsoga parviflora* Cav.) only accounted for 6%, hairy galinsoga (*Galinsoga ciliata* (Raf.) S. F. Blake) for 3%, and common chickweed (*Stellaria media* (L.) Vill.) for 2% of the weed population. The share of the remaining species (among others annual meadow grass (*Poa annua* (L.), annual nettle *Urtica urens* (L.), groundsel (*Senecio vulgaris* (L.), lady's thumb (*Polygonum persicaria* (L.)) was less than 1%.

After 34–39 days from the sowing of sweet marjoram, 1 m^2 of the control plot grew, depending on the year, from 177 to 616 weeds and their fresh weight ranged from 86.5 to 574.2 g on average for four replications. The differences between the average number of weeds growing in particular years, as well as between their fresh weight, were significant, except for 2016 and 2018 (Tab. 2). The tested methods of weed control were very effective in controlling annual weeds and young leaves of perennial species but a few days after treatment new weeds begun to emerge. By the time of measuring weed infestation, however, they grew significantly less and had significantly lower fresh weight than the weeds growing on the control plots from the day of marjoram sowing. The herbicide-treated plots had significantly fewer weeds than the flamed plots, although their fresh weight did not differ significantly. The time of flaming had no effect on the number or fresh weight of weeds. There was also no interaction between weed control methods and years of research. The tested methods of weeding significantly reduced the number of gallant soldier, lamb's quarter, redroot pigweed and shepherd's purse. In the case of barnyardgrass, only spraying with glufosinate-ammonium caused a significant reduction in its number. The amount of barnyardgrass growing in the plots sprayed with glufosinate-ammonium was smaller than in the flamed plots, but these differences were not significant (Tab. 3).

Immediately after the primary weed infestation was assessed, the plots were weeded. After another 26–30 days, the number and the fresh weight of weeds growing per 1 m^2 of the control plot differed significantly in the years and ranged from 59 to 337 individuals and 54.6 to 297.2 g, respectively (Tab. 4). Most of the weeds represented the same species that occurred at the time of the first measurement, but their species structure changed to some extent. The share of gallant soldier and hairy galinsoga increased to 13 and 18%,

Table 2. Effect of weed control method on the number (pcs. · m^{-2}) and fresh weight of weeds (g · m^{-2}) growing 5 weeks after sowing marjoram (on average, for 2016–2019)

Method of weeding	Number of weeds					Fresh weight of weeds				
	2016	2017	2018	2019	average	2016	2017	2018	2019	average
Flaming 13–17 days after sowing	252	224	312	58	212	43.6	39.6	86.2	14.2	45.9
Flaming 18–21 days after sowing	213	214	281	52	190	29.3	37.3	81.8	11.7	40.0
Glufosinate-ammonium 600 g · ha^{-1}	98	209	194	84	146	18.1	34.9	58.6	23.9	33.9
Control	616	247	368	175	352	574.2	233.7	408.2	86.5	325.7
Average	295	224	289	92	225	166.3	86.4	158.7	34.1	111.4
$LSD_{0.05}$	years – 42.6 methods of weeding – 42.6 years × methods of weeding – n. s.					years – 28.30 methods of weeding – 28.30 years × methods of weeding – n. s.				

Table 3. Effect of tested weed control methods on the number of weeds (pcs. · m^{-2}) of dominant species growing 5 weeks after sowing marjoram (on average, for 2016–2019)

Weed species	Flame weeding 13–17 days after sowing	Flame weeding 18–21 days after sowing	Glufosinate-ammonium 600 g · ha^{-1}	Control
Amaranthus retroflexus L.	22 b	19 b	12 b	51 a
Capsella bursa-pastoris (L.) Medik.	27 b	24 b	16 b	53 a
Chenopodium album L.	26 b	20 b	19 b	54 a
Echinochloa cruss-galli (L.) P. Beauv.	46 ab	39 ab	27 b	56 a
Galinsoga parviflora Cav.	9 b	8 b	7 b	14 a

Means followed with the same letter within a row do not differ significantly at $p = 0.05$

Table 4. Effect of weed control method on the number (pcs. · m^{-2}) and fresh weight of weeds (g · m^{-2}) growing 4 weeks after first weeding

Method of weeding	Number of weeds					Fresh weight of weeds				
	2016	2017	2018	2019	average	2016	2017	2018	2019	average
Flaming 13–17 days after sowing	325	181	119	52	169	289.5	174.8	109.1	56.1	157.4
Flaming 18–21 days after sowing	279	167	133	56	159	248.8	161.3	121.4	53.9	146.4
Glufosinate-ammonium 600 g · ha^{-1}	291	189	98	49	157	256.9	183.4	89.6	47.1	144.3
Control	337	215	122	59	183	297.2	205.5	112.7	54.6	167.5
Average	308	188	118	54	167	273.1	181.3	108.2	52.9	153.9
$LSD_{0.05}$	years – 44.2 methods of weeding – 44.2 years × methods of weeding – n.s.					years – 39.67 methods of weeding – 39.67 years × methods of weeding – n.s.				

Table 5. Worker hours spent on manual weeding of plots depending on the weed control methods used, in 2019 (worker hours · ha^{-1})

Term of hand weeding	Flame weeding 16 days after sowing	Flame weeding 21 days after sowing	Glufosinate-ammonium 600 g · ha^{-1}	Control
Primary weed infestation – weeding 24 days after sowing	142 b	130 b	125 b	329 a
Secondary weed infestation – weeding 57 days after sowing	109 a	115 a	116 a	118 a
Total	251 b	245 b	241 b	447 a

Means followed with the same letter within a row do not differ significantly at $p = 0.05$

respectively, the share of barnyardgrass (17%) and redroot pigweed (24%) remained at a similar level, while the share of lamb's quarter (9%) and shepherds' purse (9%) decreased. Moreover, the share of annual meadow grass increased to 6%, annual nettle – to 1.5% and the share of common chickweed decreased below 1%. There were no differences in the response of individual species to the weed control methods tested. Weeding methods also had no significant effect on the number or fresh weight of weeds (Tab. 4).

The labor input incurred for the first weeding of the control plots in 2019 amounted to 329 worker hours per ha and was significantly higher than the expenditure for weeding the flamed plots (130–142 worker hours · ha^{-1}) and those sprayed with glufosinate-ammonium (125 worker hours · ha^{-1}), while on the second date of weeding, these differences turned out to be insignificant (Tab. 5). The total expenditure on weeding the control plots amounted to 447 worker hours · · ha^{-1} and was significantly higher than the expenditure on weeding the plots of the other treatments. Labor expenditure on the weeding of plots flamed or sprayed with glufosinate-ammonium measured on the first and second dates, as well as the total expenditure on the weeding of plots of those treatments did not differ significantly.

Each year, marjoram cultivation lasted for approximately 13 weeks. Plant emergence began 13–17 days after sowing, was uneven and in some years it was extended up to 5 weeks. Depending on the treatment, the number of emergence varied from 9 to 19 pieces per linear meter and was significantly dependent on both the method of weeding and the year of research (Tab. 6). The highest average number of emergence was recorded in 2017 (17 pcs. · m^{-1}), and the lowest – in 2019 (12 pcs. · m^{-1}). The emergence in 2017 was much greater than in 2018 and 2019, and in 2016 it was greater than in 2019. Significantly less emergence was recorded on plots weeded with the flame method 18–21 days after sowing. In the remaining plots, the

Table 6. Effect of weeding method on the number of marjoram seedlings (pcs. · linear m^{-1}) growing 9 weeks after sowing in 2016–2019

Method of weeding	2016	2017	2018	2019	Average
Flaming 13–17 days after sowing	15	17	13	13	15
Flaming 18–21 days after sowing	13	15	9	10	12
Glufosinate-ammonium 600 g · ha^{-1}	14	16	14	12	14
Control	17	19	15	14	16
Average	15	17	13	12	14
$LSD_{0.05}$	year – 2.3; method of weeding – 2.3; year × method of weeding – n.s.				

Table 7. Average height of marjoram plants (cm) in five 10-days' periods and average 10-days' height increase in 2016–2019 (average for the weed control methods)

Year	10-days' periods of June			10 days' periods of July		
	first	second	third	first	second	third
2016	2.4	5.8	10.2	16.2	22.5	27.8
2017	2.5	8.1	10.0	15.2	22.0	22.9
2018	2.7	7.8	12.3	19.5	24.1	24.9
2019	2.8	4.8	10.5	16.7	23.6	30.1
Average	2.6	6.6	10.8	16.9	23.1	26.4
Average height increase	–	4.0	4.2	6.1	6.2	3.3
$LSD_{0.05}$	10-days' periods (A) – 3.42; plant height at harvest (third decade) (B) – 2.81; A × B – n.s.					

Table 8. Yield of marjoram fresh herb (kg · 100 m^{-2}) in dependence on the method of weeding in 2016–2019

Method of weeding	2016	2017	2018	2019	Average
Flaming 13–17 days after sowing	22.6	22.3	19.5	17.8	20.6
Flaming 18–21 days after sowing	21.4	21.1	17.4	15.8	18.9
Glufosinate-ammonium 600 g · ha^{-1}	20.2	21.8	18.1	16.4	19.1
Control	21.7	25.0	20.2	19.2	21.5
Average	22.7	21.6	18.8	17.3	20.1
$LSD_{0.05}$	year – 2.52; method of weeding – 2.52; year × method of weeding – n. s.				

Table 9. Composition of essential oil produced by marjoram plants hand weeded (% share of total components) in the years 2016, 2018 and 2019

Name of the compound	*IR	2016	2018	2019	Mean
α-Thujene	924	0.32	0.48	0.39	0.40
α-Pinene	931	0.38	0.71	0.54	0.54
Camphene	947	–	**tr	tr	tr
Sabinene	970	3.90	6.60	6.01	5.50
β-Pinene	974	0.41	0.35	0.28	0.35
Myrcene	989	1.63	1.56	1.06	1.42
α-Phellandrene	1003	0.17	0.21	0.13	0.17
α-Terpinene	1015	2.99	5.23	5.67	4.63
p-Cymene	1023	1.70	0.27	0.18	0.72
Limonene	1027	1.17	1.81	1.13	1.37
β-Phellandrene	1031	1.39	2.12	1.75	1.75
Z-(β)-Ocimene	1037	tr	0.06	tr	0.02
E-(β)-Ocimene	1048	0.06	0.11	0.14	0.10
γ-Terpinene	1057	5.59	7.18	9.14	7.30
trans-Sabinene hydrate	1066	34.30	29.85	28.01	30.72
Linalool	1085	0.69	0.78	1.04	0.84
Terpinolene	1087	1.17	1.99	1.94	1.70
cis-Sabinene hydrate	1098	4.88	5.01	5.54	5.14
tans-p-Menth-2-en-1-ol	1123	0.37	0.59	0.62	0.53
cis-p-Menth-2-en-1-ol	1141	0.76	1.13	1.40	1.10
Borneol	1170	–	tr	tr	tr
Terpinen-4-ol	1179	21.10	17.29	17.16	18.52
p-Cymene-8-ol	1188	0.11	–	–	0.04
α-Terpineol	1192	4.13	4.72	3.32	4.06
cis-Piperitol	1197	0.12	0.10	0.27	0.16
trans-Piperitol	1209	0.10	–	0.16	0.09
Thymol methyl ether	1232	–	tr	–	tr
Linalyl acetate	1254	6.30	4.21	5.03	5.18
Carvacrol	1286	tr	0.60	1.13	0.58
Thymol	1298	–	0.24	tr	0.08
Terpinen-4-ol acetate	1301	0.43	–	0.32	0.25
Neryl acetate	1370	0.12	tr	tr	0.04
Geranyl acetate	1383	–	tr	0.11	0.04
E-Caryophyllene	1428	3.23	4.46	3.03	3.57
α-Humulene	1456	0.20	0.16	0.11	0.16
Bicyclogermacrene	1499	2.11	1.74	0.98	1.61
γ- Cadinene	1511	–	tr	–	tr
Spathulenol	1591	tr	tr	0.10	0.03
Caryophyllene oxide	1594	0.10	–	0.08	0.06
Total		99.93	99.56	99.95	99.81

*IR – retention indices [Van den Dool and Kratz 1963]
**tr – content < 0.05% or 0.001 mg · ml^{-1}

emergence was slightly lower than in the control plots, but the differences were insignificant. The emergence on plots treated with glufosinate-ammonium did not differ significantly from the emergence on the control plots and those weeded with the flame method 18–21 days after sowing. There was no interaction between the weed control method and the year of research on marjoram emergence.

The tested methods of weeding had no effect on the height of marjoram plants and for this reason the averages for the study years are presented in Table 7. Plant growth was initially very slow: after about 5 weeks from the beginning of emergence, the plants had an average height of 2.4 to 2.8 cm depending on the year. The rate of further growth varied over time, and decade-long gains in height were significant until the third 10-days' period of July. During the second and third 10-days' periods of June, the average height gain was about 4 cm, and during the next 2 periods – about 6 cm. In the third 10-days' period of July, when marjoram began flowering, the height gain was almost twice as small and amounted to 3.3 cm. Finally, the average height of marjoram measured immediately before harvesting ranged from 22.9 to 30.1 cm and was significantly dependent on the year of study. Plants harvested in 2016 and 2019 were significantly higher than those harvested in 2017 and 2018. During growing season, the plants branched to form first and second order branches. At harvest, their total number was characterized by low variability, ranged on average from 17 to 21, and was independent of the year of study or the method of weeding.

Average yields of fresh herb ranged depending on the year of study and the method of weeding, from 15.8 to 25.0 kg · 100 m^{-2}, with the years having a greater impact than the methods. The differences between yields harvested in individual years were significant, apart from the differences between 2016 and 2017 and between 2018 and 2019 (Tab. 8). In the case of weed control methods, only the yields harvested from the control plots and those from plots flamed in the second term differed significantly.

The grated, air-dried marjoram herb of control plants contained, in the order of the research years, 2.34, 1.57, 1.84 and 1.35% of the essential oil. The differences between oil content in individual years were significant, except for the differences between 2017 and 2019 and 2018 and 2017. The oil was a thick liquid of pale yellow to greenish yellow color containing from 33 to 36 identified components, which constituted from 99.56 to 99.95% of the total (Tab. 9). It was dominated by *trans*-sabinene hydrate (28.01–34.30%) and terpinen-4-ol (17.16–21.10%), while the proportion of γ-terpinene (5.59–9.14%), sabinene (3.90–6.60%), linalyl acetate (4.21–6.30%), *cis*-sabinene hydrate (4.88–5.54%), α-terpinene (2.99–5.67%), α-terpineol (3.32–4.72%) and *E*-caryophyllene (3.03–3.23%) was much smaller. The average content of the remaining components was equal to or less than 1.70%.

DISCUSSION

There is very little information in the literature on the flora of weeds occurring in the cultivation of marjoram [El-Masry et a. 1996, Qasem and Foy 2006]. In the present study, the field in which the experiment was conducted had been used for many years for the growing of vegetable crops and the species of weeds found there were typical for these crops and the region [Dobrzański 1999]. Depending on the weather conditions, weeds started to emerge 8–10 days after sowing, that is 5–7 days before marjoram emergence. The observations made in this experiment are consistent with the earlier statements of Rumińska [1991] and Kucharski [2018] that until the marjoram emerges and the seed rows are marked in this way, it is difficult to use weeding tools, and after its emergence, there is a risk of covering marjoram seedlings with soil. The results of this experiment show that in this situation, like in the case of lemon balm and summer savory [Borowy and Kapłan 2022a, b], total methods, such as flame weeding or spraying with glufosinate-ammonium, applied within a short time determined by the emergence of weeds and marjoram, can be helpful. Such a treatment significantly reduces the primary weed infestation, thus reducing the amount of work needed to control weeds growing after this treatment. The observations made in this experiment also show a high sensitivity of marjoram to weed competition in the first half of the growing season, which is conditioned by slow emergence and initial plant growth. Only in the second half of this period, along with the increasing growth rate and plant branching, marjoram covers an increasing area of soil surface and competes better with weeds. The number of marjoram branches found in this experiment is similar to that reported by Nurzyńska-Wierdak and Dzida [2009]. It was characterized by low variability, which is in line with the results of Berbeć [1969] illustrating the share of stems with side branches in the total yield of marjoram herb. The height of marjoram grown from sowing, measured before harvesting the plants, was in this experiment very similar to the height of marjoram grown from seedlings by Zawiślak [2008], Nurzyńska-Wierdak and Dzida [2009], and Zawiślak and Dzida [2010] under the same natural conditions. Height, as well as the habit related to the number of branches, are important features that determine the ability of plants to compete with weeds [Dobrzański 1999].

The tested methods of weeding significantly reduced the number and fresh weight of weeds growing 3–4 weeks after the start of marjoram emergence, i.e. in the period of its greatest sensitivity to weed competition [Rumińska 1991, Kucharski 2018]. They were characterized by total action and immediately after application their effectiveness was even greater, but they had no soil residual activity and soon new weeds emerged. Only a few of the weeds that were covered with clods of soil survived the treatment. Ultimately, when the weed infestation was assessed, the weeds were significantly less numerous and smaller and therefore easier to remove than those growing in the control plots. The dominant dicotyledonous weed species such as gallant soldier, lamb's quarter, redroot pigweed and shepherd's purse were successfully controlled by the tested methods. In the case of barnyardgrass flaming was much less effective. This treatment was performed carefully and by observing its effect all weeds were destroyed, which was associated with high gas consumption. However, soon after flaming, barnyardgrass emergence appeared, which indicated, that despite the burning of the cotyledons and the first leaves, it was not completely destroyed. Like other annual grasses, barnyardgrass has a growth point located close to the soil surface and covered with leaf sheaths, which makes it quite resistant to flaming. Similarly, in the studies conducted by Ulloa et al. [2010a, b] leaves of grass species turned white shortly after flaming, leaving an appearance of a dead plant, but within a week or two plants began to recover with the growth of new leaves. The effect of flaming and glufosinate-ammonium on weeds observed in this experiment was similar to that stated by Borowy and Kapłan [2022a, b] in experiments carried out under the same natural conditions. The tested methods of weeding did not have soil residual activity and therefore their effect on weeds disappeared 4 weeks after first weeding. It should be noted that the number of weeds growing at that time was smaller but their fresh weight was greater than in the primary weed infestation, which is consistent with the results of the authors' previous research [Borowy and Kapłan 2022a].

The manual labor input for the first two weedings in 2019 was about 140 hours smaller than that given by Pank [1992], because it did not take into account the supplementary weedings performed as weeds appeared until the marjoram harvest. It fell within the lower range of inputs specified by Dobrzański [1999] for vegetables with a cultivation method similar to marjoram. The investigated methods of weeding significantly reduced the input of manual labor for the first weeding by about 60%, and the total input of this work – by about 45%. This was half of that reported by Pank [1992], as the tested weeding methods had no soil residual activity. In the second measurement of weed infestation, the number of weeds growing in the experiment was very small and therefore, despite significant differences in this number, the time spent on weeding plots of compared treatments did not differ significantly.

Flaming applied 18–21 days after sowing destroyed marjoram seedlings that had already emerged and therefore the final number of plants and yield of fresh herb in plots of this treatment was significantly smaller. The observations made in this experiment show that the small and delicate marjoram seedlings unlike the seedlings of large-seeded plants (corn, soybean, sunflower) [Knezevic 2017], are very sensitive to flaming. The negative effect of delayed flaming on emergence and herb yield could be prevented by applying a higher sowing rate. A slight reduction in the number of emergence may not affect the yield, as plants growing at a lower density can achieve higher weight [Nurzyńska-Wierdak and Dzida 2009]. The herbal yields harvested in this experiment were close to the lower yield limit for marjoram grown from seedlings by Zawiślak [2008] and much lower than those collected by Nurzyńska-Wierdak and Dzida [2009] and

Zawiślak and Dzida [2010] under the same cultivation system. This proves that marjoram grown from seedlings yields better than marjoram grown from sowing directly into the field. The lower yield could also be due to the use of a distance between the rows greater by 10–20 cm than recommended one in order to improve the weed infestation observation conditions.

In the experiment, marjoram emergence started depending on weather conditions, especially the amount of rainfall, 13–17 days after sowing and lasted up to 5 weeks, which is generally consistent with the literature data [Rumińska 1991, Kucharski 2018]. The emergence of weeds began 8–10 days after sowing, and therefore the application of marjoram-safe flaming or glufosinate-ammonium spraying ranged from 5 to 7 days. Under very favorable conditions, the emergence of marjoram can begin as early as 9 days after sowing [Gregorczyk 1997], which in practice would make it impossible to use both methods. In practice, usually 10 days after sowing, close observation of the field should be started and the treatment should be performed immediately after noticing the first marjoram emergence. Delaying the treatment by 5 days had no effect on the degree of weed control, but resulted in a significant reduction in the number of plants and marjoram herb yield.

The obtained results show that during the first 5 weeks from the beginning of emergence, marjoram growth was very slow. In the weeks that followed, the plants grew faster, produced numerous side shoots, and thus became more resistant to weed competition. The final height of marjoram was within the limits specified by Rumińska [1991] and Kucharski [2018] and was consistent with the results of Suchorska-Tropiło and Tołwiński [2001]. As in the case of garden savory and lemon balm [Borowy and Kapłan 2022a, b], it was significantly dependent on the year of research and independent of the short-acting weed control methods tested (Tab. 7). The dynamics of plant growth observed in this study was very similar to that described by Berbeć [1969] and Gregorczyk [1997], although in the pot experiments of these authors marjoram reached a much greater height.

The results obtained in this experiment prove that marjoram grown from sowing directly into the field has poor competitive ability against weeds. This was mainly due to quite late and uneven emergence and initially slow plant growth. Later on, marjoram grew faster, but finally reached the height of only about 20–30 cm, while the weeds dominant in the experiment may grow as high as 100–120 cm [Błażewicz-Woźniak et al. 2014]. Moreover, the weeds had a very great advantage in numbers over marjoram: on average, 320 weeds grew per m^2 of the field, compared to 32 marjoram plants. When planning the application of flaming or spraying with glufosinate-ammonium, the soil should be well tilled, the soil surface leveled and the seeds sown to the same depth, which will increase the uniformity of marjoram and weed emergence, as well as facilitate the treatment and increase its effectiveness.

The content and composition of the essential oil found in this experiment were similar to those found by Zawiślak [2008], Nurzyńska and Dzida [2009] and Nurzyńska et al. [2015] under cultivation from planting seedlings in the same natural conditions. The differences in the oil content in individual years of the study were due to the differences in the course of weather during the growing season, as it was also shown in the studies by Nurzyńska et al. [2015]. The obtained results confirm the results of the authors cited above that marjoram oil obtained in the Lublin region contains the most *trans*-sabinene hydrate and terpinen-4-ol, and that other important components are γ-terpinene, sabinene, linalyl acetate, *cis*-sabinene hydrate, α-terpinene and *E*-caryophyllene. A partially different and more diversified composition of the oil was stated by Lis [2007], who studied the raw material from various sources. However, the content and composition of the oil obtained in Brazil by de Souza et al. [2021] from marjoram grown in a greenhouse using the soilless method were very different. All compounds included in the oil were previously identified by authors cited in this work.

CONCLUSIONS

1. Marjoram cultivated from direct sowing into the field is a crop very sensitive to weed competition, requiring at least weeding three times. The period of the greatest sensitivity to this competition is the period from the beginning of marjoram emergence, i.e. approximately 2–3 weeks after sowing, until the beginning of rapid plant growth after 4–5 consecutive weeks.

2. Flaming the weeds using propane in the amount of 90 kg · ha^{-1} or spraying with glufosinate-ammonium at a dose of 600 g · ha^{-1} immediately after observing first marjoram emergence effectively limited weed infestation in the period of its greatest sensitivity to weed competition and had no effect on its growth and herb yield. Delaying the flaming by 5 days did not increase the effectiveness of weed control as compared to the first treatment date, but resulted in a significant reduction in the emergence and the yield of marjoram herb.

3. The grated herb of marjoram grown in central-eastern Poland contained, depending on the year, from 1.35 to 2.34% of essential oil. The oil contained 33 to 36 identified compounds, with *trans*-sabinene hydrate and terpinen-4-ol being the clearly dominant ones, accounting for between 45.17 to 55.40% of the total.

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