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ORIGINAL PAPER

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COMPARISON OF THE EFFECTIVENESS OF FLAMING AND SPRAYING WITH GLUFOSINATE-AMMONIUM IN CONTROLLING WEEDS IN THYME (*Thymus vulgaris* L.) SOWING

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ABSTRACT

The purpose of this four-year study was to compare the effectiveness of flame weeding applied on two dates to that of spraying with glufosinate ammonium in controlling weeds in common thyme grown from sowing directly into the field. Flaming (90 kg propane·ha^{-1}) was applied immediately before thyme emergence or 6 days later, and glufosinate-ammonium (450 g·ha^{-1}) was applied on the same date as the first flaming. Emergence of thyme began 15–18 days after sowing, was very uneven and in some years it was extended up to 4 weeks. Thyme seedlings were very fine and their initial growth was very slow, which made them highly sensitive to the competition of weeds. The growth rate of thyme increased over time, reaching its greatest value in the last ten days prior to harvest, when the plants gained their average height, depending on the year, from 18.3 to 22.4 cm and developed from 17 to 21 first and second order branches. Weeds started to emerge 8–11 days after thyme was sown and about 3 weeks later their number in the control plots varied depending on the year from 175 to 541 pcs.·m^{-2}. All methods were very effective in controlling weeds immediately after treatment, but had no soil residual activity and soon new weeds emerged. Four weeks later, the most effective method was spraying with glufosinate-ammonium, which, depending on the year, reduced both the number and fresh weight of weeds by 43 to 85%. Flaming applied at the first or second dates controlled 33–59% and 37–68% of weeds, respectively. After first weeding, the differences between compared treatments disappeared. Essential oil content in the grated herb obtained from the control plants ranged from 2.5 to 3.4%. In the oil, a total of 39 compounds were identified, with the number ranging from 33 to 36 in individual years. More than half of the essential oil was thymol and two other important compounds were *γ*-terpinene and *p*-cymene

Key words: weed flora, thyme emergence and growth rate, herb yield, essential oil content and composition

INTRODUCTION

Common thyme (*Thymus vulgaris* L.) is a bushy, woody subshrub in the family Lamiaceae native to the Mediterranean basin and today grown in many countries all over the world [Kosakowska et al. 2021]. This species is known for its six genetically distinct chemotypes that can be distinguished on the basis of the dominant monoterpene produced in glandular trichomes on the surface of the leaves [Najar et al. 2021]. Thyme has been used as a flavoring agent, culinary herb and herbal medicine since ancient times and nowadays its oil is one of the most commonly used essential oils in the food and cosmetic industry [Almanea et al. 2019]. Also in Poland, thyme is an important herbal plant with an annual production of about 3000 tons

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of raw material, including 2000 tons from the Lublin region (south-eastern Poland) [http://polishherbs.com/thyme/]. It can be grown from seeding directly into the field or from planting transplants. The latter method is more labor-intensive and is recommended for crusted soils where plant emergence may be unreliable [Kołodziej 2009]. Under favorable weather conditions, the emergence of seeds sown in the field in spring begins 10–15 days after sowing, while the weeds emerge much earlier. However, under unfavorable conditions, the emergence can be uneven and stretched over time. Moreover, the initial growth of thyme plants is very slow, making them very sensitive to weed competition [Zawiślak 2018]. In this situation, weed control in thyme sowings is difficult and requires special care. Later, the plants close their canopy which prevents weeds from establishing [Fraser and Whish 1997]. In the studies conducted in Germany by Pank [1992], the number of working hours spent on weeding and hoeing 1 ha of thyme sown was 590 and was, just like in marjoram, the highest among several herbal plants studied. In an experiment carried out in Canada by Michaud et al. [1993], 383 weeds grew on 1 m^2 of thyme crop and the losses caused by them reached 95% of the herbal dry matter yield, while in Poland, the number of weeds growing in thyme crop was almost twice as high [Kucharski and Mordalski 2005]. In thyme grown by Kwiatkowski and Kołodziej [2005], Kucharski and Mordalski [2005] and Kwiatkowski [2007], the main species of weeds included barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), common chickweed (*Stellaria media* (L.) Vill.), common fumitory (*Fumaria officinalis* L.), common knotgrass (*Polygonum aviculare* L.), field pansy (*Viola arvensis* Murray), field pennycress (*Thlaspi arvense* L.), gallant soldier (*Galinsoga parviflora* Cav.), lamb's quarters (*Chenopodium album* L.), pale smartweed (*Polygonum lapathifolium* L.), redroot pigweed (*Amaranthus retroflexus* L.), and shepherd's purse (*Capsella bursa-pastoris* (L.) Medik.).

Initially, research on the protection of thyme crops from weeds focused on the chemical method [Czarnecki and Załęcki 1990, James et. al 1991, Pank 1991, Michaud et al. 1993, Kucharski and Mordalski 2005], but a vast majority of herbicides tested at that time have been withdrawn from use in the EU countries. Currently in Poland, it is allowed to use only fluazifop-P-butyl from the 2–4 leaf (12–14 BBCH) thyme stage against the species of the Poaceae family [Strażyński 2020]. In practice, it would be very beneficial to destroy all weeds just before the thyme emerges. Then its tiny seedlings would grow in a clean field with good conditions for further development. Such a treatment could be performed with the flame method [Carrubba and Militello 2013, Knežević 2016] or with the use of total foliar herbicides, e.g. glufosinate-ammonium, the timing of the treatment being of particular importance here [Borowy and Kapłan 2022a, b]. Both methods are contact and non-selective ones and they control young annual weeds, but they have a different mode of action. Glufosinate-ammonium is a phosphorus-containing amino acid derived from a natural toxin isolated from the species of Streptomyces fungi [Watts 2008], much less toxic to humans than diquat [Senseman 2007] used by Kwiatkowski and Kołodziej [2005] and Kwiatkowski [2007] for the same purpose. Flame weeding kills weeds with the help of a natural factor (high temperature), and therefore it can be used in organic farming [Council Regulation 2007]. This method can be applied even after the emergence of some crops, when conducted properly at the most tolerant growth stage [Knezevic 2017].

Habit, morphological structure and growth rate are important features that determine the competitive ability of cultivated plants against weeds [Zimdahl 2004]. In Iran, thyme plants, depending on the sowing date and planting density, by the time of the first harvest, developed from 13.3 to 26.1 branches and reached the height of 14.4 to 27.4 cm by the time of the first harvest [Moaveni et al. 2011]. Under Polish conditions (Lublin region), thyme sown directly onto the field by Król and Kiełtyka-Dadasiewicz [2015] in early April and harvested in late August was 23.4–28.2 cm heigh, depending on the weather conditions. According to Zawiślak [2018], in Poland, in the first year of cultivation from direct sowing in April and when harvested at the beginning of flowering in August, the yield of dry thyme herb varies from 0.8 to 1.2 $t \cdot ha^{-1}$. In an experiment carried out by Kołodziej [2009] thyme plants sown at the end of April and harvested in the first 10 days of August produced shoots 10.6 cm long and the dry herb yield of 1.44 $t \cdot ha^{-1}$, while the oil content of the herb was 2.0%. In the studies by Król and Kiełtyka-Dadasiewicz [2015], the yields of fresh and dry herb of two thyme cultivars ranged from 17.5 to 21.7 t·ha^{-1} and from 5.50 to 7.35 t·ha^{-1}, respectively, while dry herb constituted about 30% of fresh herb, essential oil content in air-dried leaves ranged from 3.32 to 3.61% and the content of thymol in the oil – from 53.2 to 59.2%. In an experiment conducted by Dzida et al. [2015], under the same natural conditions as for the above mentioned authors, thyme plants grown from planting seedlings after May 15th and harvested in mid-August reached a height of 13.8–16.6 cm, the yield of fresh and dry herb amounted to 5.4–6.9 t·ha^{-1} and 1.6–2.3 t·ha^{-1}, respectively, while essential oil content in the grated herb ranged from 1.45 to 2.04%. In an experiment by Kwiatkowski and Kołodziej [2005], herbicides used to control weeds in thyme sown in the last ten days of April and harvested in the middle of August did not have a negative effect on the dry herb yield (1.13–2.47 t·ha^{-1}), or the content of thymol in the herb (0.75–1.23%), however with clearly smaller content of this component in plants weeded with diquat and metamitron.

The most important component of the herb is essential oil, the content and composition of which depend, among others, on the thyme genetic characteristic, the stage of development, environmental conditions, agricultural practices and the method of extraction [Kosakowska et al. 2020, 2021, Najar et al. 2021]. Najar et al. [2021] identified 62 compounds in essential oils obtained by hydro- and steam distillation from thyme grown organically in central Italy. Its main compounds were thymol (49.9–51.3%) followed by *p*-cymene (7.2–17.1%), *γ*-terpinene (4.5–11.2%), carvacrol (4.3–11.7%) and linalool (2.0–2.6%). In Lithuania, Raal et al. [2005] identified 59 compounds, which constituted from 96.0 to 99.8% of oils obtained from dry herb from 9 countries with very different natural conditions. The main components were thymol (0.9–75.7%), carvacrol (1.5–83.5%), *p*-cymene (4.3–34.4%), *γ*-terpinene (0.9–19.7%), linalool (0.4–4.8%), (*E*)-β-caryophyllene (0.5–9.3%) and terpinen-4-ol (tr.–3.8%). In Poland, Zawiślak [2007] found the presence of 37 compounds, including one which was unidentified, in the oil obtained from the herb of thyme grown from planting seedlings and harvested in the first year of cultivation. The main compounds were thymol (49.9%), *p*-cymene (13.5%), γ-terpinene (12.1%), and carvacrol (6.3%). In the oil obtained in Iran by Moaveni et al. [2011], the main components were, like in case of the authors cited above, thymol (40.1–54.0%), linalool (3.1–4.8%) and carvacrol (0.4–1.3%), but also terpenol (1.6–2.7%). Nikolova et al. [2021] showed that the essential oil produced by plants of the genus *Thymus* exhibits herbicidal activity.

Considering the above, the first objective of this study was to compare the suitability of flame weeding applied in two terms and spraying with glufosinate-ammonium for weed control in thyme sowing. The second objective was to determine the content and composition of the essential oil obtained from the hand weeded thyme plants cultivated in the Lublin region.

MATERIAL AND METHODS

The experiment was carried out at the Felin Experimental Farm of the University of Life Sciences in Lublin in the years from 2016 to 2019. Thyme (*Thymus vulgaris* L.) was grown on haplic Luvisol soil developed from loess deposits, containing 1.7% of organic matter and with pH of 6.5. Various species of vegetables were the forecrop of thyme in the different years of the experiment. According to the recommendations [Zawiślak 2018], the field was fertilized with NPK mineral fertilizers and mixed with the soil by means of a cultivator two days before sowing the seeds. 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}. 1000 seed weight was 0.231–0.243 g. The exact dates of sowing and other important activities performed in the experiment are given in Table 1. After some of the weeds emerged and immediately before thyme emergence, flame weeding in the first term and spraying with glufosinate-ammonium were applied. At that time, the weeds were in the cotyledon and the first true leaves stage. After another 6 days, more emergence of weeds and emergence of the first thyme seedlings, flame weeding was applied for the second term. Glufosinate ammonium was sprayed at a dose of 450 g·ha^{-1} using 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 manually by means of a universal Italian

Table 1. Schedule of the most important works performed in the experiment

Work	2016	2017	2018	2019
Sowing thyme	April 23rd	April 25th	April 16th	April 27th
Spraying with glufosinate-ammonium and 1st term of flaming	May 7th	May 8th	May 2nd	May 13th
2nd term of flaming	May 13th	May 14th	May 8th	May 19th
1st assessment of weed infestation	May 28th	May 29th	May 23rd	June 1st
1st plant height measurement	June 7th	June 1st	June 9th	June 10th
2nd assessment of weed infestation	June 27th	June 24th	June 21st	June 30th
Counting thyme emergence	June 28th	June 26th	June 24th	June 30th
Harvesting of thyme herb	July 31st	July 26th	July 22nd	July 29th

KIT 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 20x50 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. 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. The plots were than weeded and kept weed-free until the harvest. 61–68 days after sowing, the thyme 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. Moreover, 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. This experiment was carried out parallelly and using the same method as the experiment in which sweet marjoram (*Origanum majorana* L.) was grown [Borowy and Kapłan 2022a].

At the end of October, the content of essential oil in grated herb obtained from dry hand weeded plants was determined by hydro-dstillation 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. 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 [2022a].

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 results obtained were statistically processed using the analysis of variance involving the model for orthogonal data, while the significance of differences between the means was determined using Tukey's test at the level of 0.05.

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

Name of the weed	Flaming 13–16 days after sowing					Flaming 18–21 days after sowing					Glufosinate-ammonium (450 g·ha^{-1})					Control				
	2016	2017	2018	2019	**av.**	2016	2017	2018	2019	**av.**	2016	2017	2018	2019	**av.**	2016	2017	2018	2019	**av.**
Amaranthus retroflexus L.	66	27	7	4	**26**	94	24	4	2	**31**	30	22	2	6	**15**	198	35	8	19	**65**
Capsella bursa-pastoris (L.) Medik.	7	29	122	14	**43**	5	26	98	11	**35**	2	27	51	12	**23**	4	60	171	37	**68**
Chenopodium album L.	48	2	22	4	**19**	41	0	18	1	**15**	21	0	28	7	**14**	153	11	69	23	**64**
Cirsium arvense (L.) Scop.	1	0	0	0	**1**	0	0	0	0	**0**	0	0	0	0	**0**	1	0	0	0	**1**
Echinochloa crus-galli (L.) P. Beauv.	67	86	37	30	**55**	54	81	31	26	**48**	15	69	29	19	**33**	140	99	41	36	**79**
Galinsoga ciliata (Raf.) S.F. Blake	1	9	2	3	**4**	0	7	2	2	**3**	2	13	0	4	**5**	3	20	4	9	**9**
Galinsoga parviflora Cav.	2	9	52	13	**19**	2	13	34	6	**14**	1	15	32	8	**14**	8	19	65	16	**27**
Gnaphalium uliginosum L.	0	6	0	1	**2**	0	8	0	3	**3**	0	6	0	2	**2**	0	13	0	3	**4**
Lamium amplexicaule L.	10	0	0	0	**3**	1	0	0	1	**1**	3	0	0	4	**2**	4	0	0	8	**3**
Matricaria chamomilla L.	2	7	0	0	**3**	1	3	0	1	**2**	0	2	0	1	**1**	3	9	0	3	**4**
Plantago major L.	1	0	0	0	**1**	0	0	0	0	**0**	0	0	0	1	**1**	1	0	0	2	**1**
Poa annua L.	6	1	0	3	**3**	3	1	0	2	**2**	1	0	1	3	**1**	4	1	0	3	**2**
Polygonum persicaria L.	0	0	2	0	**1**	0	0	1	0	**1**	0	0	1	1	**1**	1	0	3	1	**2**
Senecio vulgaris L.	1	0	0	0	**1**	0	0	0	0	**0**	0	0	0	0	**0**	2	0	1	0	**1**
Sonchus oleraceus L.	0	0	0	0	**0**	1	0	0	0	**1**	1	0	0	0	**1**	1	0	0	0	**1**
Stellaria media (L.) Vill.	7	1	1	1	**3**	8	4	0	1	**3**	4	1	0	7	**3**	15	3	1	14	**8**
Taraxacum officinale F.H. Wigg.	0	3	0	1	**1**	0	2	0	0	**1**	1	3	0	1	**1**	1	4	1	0	**2**
Urtica urens L.	2	0	4	0	**2**	2	5	4	0	**3**	0	1	1	3	**2**	2	2	3	1	**2**
Veronica persica Poir.	0	1	0	0	**1**	0	0	0	0	**0**	0	0	1	0	**1**	0	1	1	0	**1**
Vicia hirsuta (L.) Gray	0	0	0	0	**0**	0	0	1	0	**1**	0	0	1	0	**1**	0	0	1	0	**1**
Total number	221	181	249	74	**181**	212	174	193	56	**159**	81	159	147	79	**117**	541	277	369	175	**341**
Fresh weight	71.4	66.8	78.7	31.9	**62.2**	62.9	61.5	57.1	19.2	**50.2**	31.0	61.4	45.8	33.4	**42.9**	171.3	102.6	110.2	59.8	**111.0**

Averages for the years:
number of weeds: 263.8 (2016), 197.8 (2017), 239.5 (2018) and 96.0 (2019)
fresh weight of weeds: 84.2 (2016), 73.1 (2017), 73.0 (2018) and 36.1 (2019)

$LSD_{0.05}$:
number of weeds: for the weeding treatments (A): 63.18; for the years (B): 63.18; for the interaction A × B: n.s.
fresh weight of weeds: for the weeding treatments (A): 22.91; for the years (B): 22.91; for the interaction A × B: n.s.

av. – average

RESULTS AND DISCUSSION

Weeds started to emerge 8–10 days after thyme was sown. Approximately 3 weeks later, depending on the year, 175 to 541 weeds belonging to 13–17 species, with a total fresh weight of 59.8 to 171.3 g, grew per 1 m^{-2} of control plot, most frequently with significant differences between individual years (Tab. 2). These differences may have been partly the result of using different forecrops before setting up the experiment [Kwiatkowski and Kołodziej 2005, Kwiatkowski 2007]. The mean weed infestation density was similar to that found by Michaud et al. [1993] and lower than that reported by Kucharski and Mordalski [2005]. Annual weeds dominated, and the only sporadically occurring perennials were creeping thistle (*Cirsium arvense* (L.) Scop.), broadleaf plantain (*Plantago major* L.) and common dandelion (*Taraxacum officinale* F.H. Wigg.). Such a composition of weed infestation was conducive to the effectiveness of weed control methods tested in the experiment which were characterized by contact activity [Senseman 2007, Knežević 2016]. The most abundant species were (in pieces per 1 m^{-2} of control plot): barnyardgrass (36–140), shepherds' purse (4–171), redroot pigweed (8–198), lamb's quarter (11–153), gallant soldier (8–65), hairy galinsoga (3–20) and common chickweed (1–15). The remaining weeds occurred to a much lower intensity and not every year. This is largely consistent with the results obtained by Kwiatkowski and Kołodziej [2005], Kucharski and Mordalski [2005], and Kwiatkowski [2007]. It should be noted that in Poland in the middle of May the last frosts disappear, which favors the emergence of thermophilic weeds, such as barnyardgrass, redroot pigweed, gallant soldier and hairy galinsoga [Błażewicz-Woźniak et al. 2014].

As a result of flaming, a vast majority of the weed seedlings died during the treatment, while after the application of glufosinate-ammonium – 2–3 days later. All this created good conditions for the emergence and initial growth of thyme. The tested methods had no soil residual activity and therefore new weeds grew soon; however, their number and fresh weight measured 3 weeks later was significantly lower than in unweeded control plots (Tab. 2). In perennial weeds, only the above-ground parts were damaged, and new leaves grew from the permanent organs located in the soil. Therefore, the number of weeds was a better indicator of effectiveness than their fresh weight, because the weight of the above-ground part of the perennial weed was much greater than that of the short-lived weed seedling. The most effective method was spraying with glufosinate-ammonium, depending on the year, 13–16 days after sowing, which reduced both the number and fresh weight of weeds by about 43 to 85%. The effectiveness of this herbicide was significantly higher than that of flaming applied at the same time (33–59% weed control), but it did not differ significantly from that of flaming applied 6 days later (37–68% weed control), which also destroyed the weeds that emerged during this time (Tab. 2). Glufosinate-ammonium was more effective against barnyardgrass and shepherd's purse than flaming. According to Ascard [1995], the species with protected growth point such as shepherd's purse and grasses in the later stages of growth, show considerable resistance to flaming. Moreover, glufosinate-ammonium destroyed the leaves of perennial weeds better than flaming, which often only damaged the edges of the leaf blade. Application of the methods tested in the experiment in practice is associated with the difficulty of choosing the optimal time for their use [Borowy and Kapłan 2022a]. The timing of the emergence of thyme depends mainly on weather and soil conditions, and its uniformity – on soil preparation and sowing depth. Observations collected by the farmer in the earlier years of thyme cultivation may be useful here. It is worth noting that while flaming was less effective than spraying with glufosinate-ammonium, it is allowed in organic farming [Council Regulation 2007].

After 4 weeks from the first weeding, the number of weeds growing on the control plots was lower than in the first measurement of weed infestation and, similarly to this meaurement, it was significantly differentiated in individual years of the study (Tab. 3). The greatest number of weeds (582 pcs.·m^{-2}) also grew in 2016, and the least (129 pcs.·m^{-2}) – in 2019. Similar relationships were found in the case of fresh weight of weeds, although the weight of a single weed was much higher here, and the total weight was more dependent on perennial weeds than during the first measurement. These results are in line with those obtained in marjoram cultivation by Borowy and Kapłan [2022a].

Table 3. Effect of weed control method on the number (pcs.·m^{-2}) and fresh weight (g·m^{-2}) of weeds growing 4 weeks after first weeding (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 13–16 days after sowing	543	157	305	133	285	1281.4	465.3	619.4	357.4	680.9
Flaming 18–21 days after sowing	462	163	292	127	261	892.7	387.1	589.6	298.5	542.0
Glufosinate--ammonium (450 g·ha^{-1})	409	143	288	131	243	915.3	426.8	572.8	393.7	577.2
Control	582	161	311	129	296	1274.2	493.6	689.2	368.4	706.4
Average	499	156	299	130	271	1090.9	443.2	617.8	354.5	626.6
$LSD_{0.05}$	years: 67.5 methods of weeding: n.s. years × methods of weeding: n.s.					years: 175.1 methods of weeding: n.s. years × methods of weeding: n.s.				

Table 4. Effect of the weeding method on the number of thyme seedlings (pcs.·linear m^{-1}) growing 9 weeks after sowing in 2016–2019

Method of weeding	2016	2017	2018	2019	Average
Flaming 13–16 days after sowing	10	14	10	11	11.3
Flaming 18–21 days after sowing	9	13	8	9	9.8
Glufosinate-ammonium (450 g·ha^{-1})	11	15	11	12	12.3
Control	10	16	8	10	11.0
Average	10.0	14.5	9.3	10.5	11.1
$LSD_{0.05}$: method of weeding – 2.21, year – 2.21, method of weeding × year – n.s.					

In the experiment thyme was grown for approximately 14 weeks. Its emergence started 14–17 days after sowing, was very uneven and in some years it was extendend up to 4 weeks, which is generally similar to the data provided by Zawiślak [2018]. For this reason, thyme seedlings at very different growth stages were counted only about 9 weeks after sowing. Depending on the treatment, their number ranged from 8 to 16 pieces per linear meter (Tab. 4), which gives 16–32 seedlings per 1 m^2. A significantly higher number was recorded in 2017, with insignificant differences between the remaining years. The number of seedlings in control plots did not differ significantly from that in the plots treated with the tested weeding methods. Only the differences between the plots sprayed with glufosinate-ammonium and those flamed 17–20 days after sowing were significant. A visible tendency to decrease the number of seedlings on plots flamed on the second date indicates that a further delay in the treatment could lead to a significant reduction in seedlings, as was the case with sweet marjoram [Borowy and Kapłan 2022b].

Habit, height, growth rate, and plant density are important features that determine the ability of cultivated plants to compete with weeds [Zimdahl 2004]. In the experiment, very fine seedlings grew from very fine (0.23–0.24 g·1000 seeds^{-1}) thyme seeds. Moreover their initial growth was very slow. One month after from the beginning of emergence, the average plant height ranged from 3.4 to 3.7 cm, depending on the

Table 5. Average height and height increase of thyme plants (cm) in six 10-day periods in 2016–2019 (average for the treatments)

Year	10-day periods of June			10-day periods of July		
	1st	2nd	3rd	1st	2nd	3rd
2016	3.4	4.6	7.6	10.9	13.5	18.3
2017	3.6	5.2	7.9	11.4	13.6	19.0
2018	3.7	5.7	8.2	11.7	16.0	22.4
2019	3.6	5.9	8.1	12.3	15.4	21.9
Average	3.6	5.4	8.0	11.6	14.6	20.4
Average 10-day height increase	–	1.8	2.6	3.6	3.0	5.8
$LSD_{0.05}$: 10-day periods (A) – 2.64, plant height at harvest (3rd 10-day period) (B) – 2.17, A × B – n.s.						

Table 6. Yield of thyme fresh herb (kg·100 m^{-1}) in dependence on the method of weeding in 2016–2019

Method of weeding	2016	2017	2018	2019	Average
Flaming 13–16 days after sowing	28.6	36.5	27.1	32.9	31.3
Flaming 18–21 days after sowing	26.9	35.2	26.3	28.7	29.3
Glufosinate-ammonium 450 g·ha^{-1}	30.1	37.1	27.9	34.7	32.5
Control	29.7	38.9	26.8	31.9	31.8
Average	28.8	36.9	27.0	32.1	31.2
$LSD_{0.05}$: year – 5.26, method of weeding – n.s., year × method of weeding – n.s.					

year. The further growth rate increased over time, reaching its greatest average value of 5.8 cm in the last 10-day period (Tab. 5). Ultimately, at harvest, the mean plant height ranged from 18.3 to 22.9 cm which was similar to that found by Zawiślak [2006], greater than that found by Kołodziej [2009] and Dzida et al. [2015] but lower than found by Kosakowska et al. [2020]. This feature is highly variable [Kosakowska et al. 2020] and depends, among others, on the method of cultivation [Kołodziej 2009] and the date of sowing as well as planting density [Moaveni et al. 2011]. Thyme grown from direct sowing achieves lower height than that grown from planting seedlings [Kołodziej 2009], which reduces its competitiveness against weeds. In all studies cited above, the height of thyme was much lower than the height that could be achieved by the barnyardgrass, lambs' quarter or redroot pigweed [Błażewicz-Woźniak et al. 2014], which in the experiment emerged earlier and grew much more densely than thyme. It can be assumed that in the absence of control, these weeds would completely dominated the thyme, as it was stated by Kucharski and Mordalski [2007] for coriander (*Coriandrum sativum* L.), summer savory (*Satureja hortensis* L.) and sweet basil (*Ocimum basilicum* L.). Moreover, even a small number of weeds can create problems for mechanical harvest, and may alter the final quality of herb when mixed with the harvested product [Carrubba and Militello 2013]. All this allows common thyme grown from direct sowing to be classified as a plant very sensitive to weed competition. In the experiment, with proper weeding, thyme plants developed from 17 to 21 first and second order branches and were characterized by the suberect type of growth habit, which is in line with the results of Moaveni et al. [2011] and Kosakowska et al. [2020], respectively. By the time of harvest, they covered a considerable part of the interrow area, however, leaving some room for weeds to grow, in part in keeping with Fraser and Whish's [1997] observations.

Table 7. Composition of essential oil produced by thyme plants hand weeded (% share of total components) in the years 2016, 2018 and 2019

Name of the compound	IR	2016	2018	2019	Average
α-Thujene	924	0.96	1.33	1.13	1.14
α-Pinene	931	1.14	0.74	0.71	0.87
Camphene	947	0.38	0.31	0.28	0.32
Sabinene	970	–	0.05	tr.	0.02
β-Pinene	974	0.27	0.16	0.18	0.20
1-Octen-3-ol	980	0.39	0.28	0.08	0.25
Myrcene	989	1.28	1.15	1.32	1.25
α-Phellandrene	1003	0.96	0.25	0.22	0.48
α-Terpinene	1015	1.87	2.54	2.14	2.18
p-Cymene	1022	8.30	10.46	11.05	9.94
Limonene	1026	0.22	0.27	tr.	0.16
β-Phellandrene	1030	tr.	0.09	–	0.03
1,8-cineole	1031	0.41	0.26	0.32	0.33
Z-(β)-Ocimene	1037	–	tr.	tr.	tr.
E-(β)-Ocimene	1048	–	0.06	–	0.02
γ-Terpinene	1057	11.53	14.66	15.83	14.00
cis-Sabinene hydrate	1066	1.31	0.71	0.87	0.96
Linalool	1087	1.58	0.75	0.72	1.02
Camphor	1141	tr.	0.15	0.12	0.09
Terpinolene	1087	0.05	0.09	–	0.05
cis-Sabinene hydrate	1066	1.29	0.90	0.91	1.03
Trans-Sabinene hydrate	1099	0.48	0.71	0.47	0.55
Cis-p-Menth-2-en-1-ol	1141	–	–	tr.	tr.
Borneol	1169	0.70	0.58	0.55	0.61
Terpinen-4-ol	1178	0.55	0.35	0.13	0.34
α-Terpineol	1192	0.21	0.16	–	0.12
Methyl thymol ether	1232	0.07	0.43	0.17	0.22
Methyl carvacrol ether	1239	0.41	0.38	0.29	0.36
Bornyl acetate	1284	0.10	–	tr.	0.03
Thymol	1297	56.76	53.96	55.15	55.29
Carvacrol	1301	3.91	3.09	2.62	3.21
β-Caryophyllene	1426	2.85	2.15	2.12	2.37
α-Humulene	1456	0.10	–	0.05	0.05
γ-Muurolene	1476	–	0.06	–	0.02
γ-Cadinene	1515	0.18	0.22	0.14	0.18
δ-Cadinene	1525	0.31	0.19	0.23	0.24
Caryophyllene oxide	1587	0.26	0.30	0.20	0.25
γ-Eudesmol	1625	0.19	0.10	0.08	0.12
τ-Cadinol	1645	0.21	0.17	0.30	0.23
Total	–	99.03	98.06	98.38	98.49

IR – retention index [Van den Dool and Kratz 1963], tr. – traces (less than 0.05% or 0.001 $mg \cdot ml^{-1}$)

The yields of fresh herb harvested in the experiment were quite low and ranged, depending on the treatment, on average from 26.3 to 38.9 kg·100 m^{-2} (Tab. 6). The yields harvested in 2017, with weather conditions favorable for thyme, were significantly higher than in the other years, between which the differences were insignificant. The weather is an important factor in the yielding of thyme [Kołodziej 2009, Dzida et al. 2015]. Despite sometimes significant differences in the number of thyme seedlings (Tab. 4), ultimately the weeding methods did not affect the amount of the herb yield. According to Moaveni et al. [2011], even with large differences in planting density, the yield of thyme herb may differ insignificantly because at lower density individual plants produce more biomass. Taking into account the fact that dry herb constitutes approximately 30% of fresh herb [Król and Kiełtyka-Dadasiewicz 2015], the yields obtained in this experiment are generally consistent with the data relating to the first harvest of thyme grown from direct sowing provided by Zawiślak [2018], much higher than the yields harvested by Moaveni et al. [2011] and slightly lower than those collected by Kwiatkowski and Kołodziej [2005] and Kołodziej [2009]. However, they were much lower than the yields obtained by Kołodziej [2009], Dzida et al. [2015] and Król and Kiełtyka-Dadasiewicz [2015] in the same natural conditions but from seedling planting. The yielding of common thyme depends on many factors [Zawiślak 2018], and in the experiment the reason for its low yield could be greater than the recommended 30–40 cm row spacing, used to facilitate the observation and measurement of the changes in weed infestation. The relationships between the thyme and the weeds found in this experiment are similar to those observed by Borowy and Kapłan [2022a] in marjoram cultivated in the same natural conditions and characterized by similar biology.

The grated herb obtained in the experiment from hand weeded thyme plants contained, in the order of the research years, 3.1, 3.4, 2.4 and 2.5% of the essential oil. This content was slightly higher than that found by Dzida et al. [2015] in thyme grown from planting seedlings and slightly lower than that found by Król and Kiełtyka-Dadasiewicz [2015] in thyme grown from direct sowing under the same natural conditions. In the oil, a total 39 compounds were determined, with the number ranging from 33 to 36 in individual years of research (Tab. 7). In all the years, more than half of the oil was thymol (53.96–56.76%) and two other important compounds were γ-terpinene (11.53–15.83%) and *p*-cymene (8.30–11.05%), which makes it possible to classify the thyme cultivated in the experiment into the ‘thymol ’ chemotype [Kosakowska et al. 2020, Najar et al. 2021]. Carvacrol (2.62–3.91%), β-caryophyllene (2.12–2.85%) and *α*-terpinene (1.87–2.54%) were present in much smaller amounts. The average content of the remaining 32 components was equal to or less than 1.25%. The content of individual components was within the limits specified by Raal et al. [2005] and was similar to that found by Zawiślak [2007] under the same natural conditions. All components found in this experiment were also detected by at least one of the above mentioned authors.

CONCLUSIONS

1. In the natural conditions of central-eastern Poland, the emergence of thyme sown in the field in early spring began 14–17 days after sowing and lasted approximately 4 weeks. One month after the beginning of emergence, thyme height ranged from 3.4 to 3.7 cm. The further growth rate increased over time, reaching its greatest average value of 5.8 cm on the last 10 days before harvest. At harvest, the plants characterized by the suberect type of growth were 18.3 to 22.9 cm high and developed 17 to 21 first and second order branches.
2. Prolonged und uneven emergence as well as initially slow plant growth affected the very high sensitivity of thyme to the competition of weeds. The time of the greatest sensitivity to this competition was the period from the beginning of emergence, i.e. 2–3 weeks after sowing until the beginning of rapid growth after 4–5 consecutive weeks.
3. The most effective method of weed control was spraying with glufosinate-ammonium 13–16 days after sowing. The efficiency of flaming applied at the same date was significantly lower, while the efficiency of flaming applied 6 days later did not differ significantly, but it increased the probability of destroying some thyme seedlings. The influence of the tested methods on weed infestation disappeared after the first weeding.

4. The grated herb of thyme contained, depending on the year, from 2.5 to 3.4% of essential oil. In the oil, a total 39 compounds were identified, with the number ranging from 33 to 36 in individual years. More than half of the oil was thymol and two other important compouds were γ-terpinene and *p*-cymene. These compounds together ac-couted for 76.6 to 82.0% of the oil.

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