

Article

Evaluation of Chemical Weed-Control Strategies for Common Vetch (*Vicia sativa* L.) and Sweet White Lupine (*Lupinus albus* L.) Under Field Conditions

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Abstract: Seed production of common vetch (*Vicia sativa* L.) and sweet white lupine (*Lupinus albus* L.) is risky due to weed infestation as few herbicides are permitted for use in crops. Our aim was to test herbicides in these crops in order to expand the list of available herbicides. Various pre- and post-emergence herbicides were tested for their phytotoxicity and weed-control activity in field cultures of the common vetch (cv. Emma) and sweet white lupine (cv. Nelly). After the application of herbicides, phytotoxicity was monitored visually. Data collection involved the Normalized Difference Vegetation Index (NDVI), the plant height, the number of weeds, yield, and its contamination. Additionally, 1000-seed-weight measurements were taken for lupine. Summarizing the phytotoxicity and efficacy results in common vetch, the agents S-metolachlor, flumioxazin, and clomazone can be recommended for further pre-emergence testing, while metazachlor + quinmerac, chlorotoluron, and flumioxazin can be recommended for further post-emergence testing. In sweet white lupine, pre-emergence applications of flumioxazin, pendimethalin, dimethenamid-P, pethoxamid, clomazone, metobromuron, and diflufenican were found to be effective without any significant phytotoxicity. Further post-emergence testing of flumioxazin, chlorotoluron, carfentrazone-ethyl, and diflufenican can also be recommended, as well as the application of halauxifen-methyl and sulfosulfuron at low doses (0.4 L ha⁻¹; 13.0 g ha⁻¹). Additional evaluations of these treatments are recommended, including in different soil and weather conditions.

Keywords: crop yield; herbicides; legumes; NDVI; phytotoxicity; weed management; yield contamination



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1. Introduction

The common vetch (*Vicia sativa* L.; Fabaceae) and sweet white lupine (*Lupinus albus* L.; Fabaceae) are minor crops that are often lacking effective weed-control practices, which could be important to many farmers for seed production. Incorporating legumes into crop rotations has many benefits, including increasing soil fertility in an effective and environmentally friendly way [1,2].

The common vetch (*Vicia sativa* L.), native to the Middle East, was cultivated as early as 3800 BC in Egypt [3,4]. The common vetch can be used as a main crop and cover crop, or in rotation with cereals, to improve soil health and reduce chemical use [5–7]. Lupine is native

to the Mediterranean region, North Africa, and the Middle East [8], and it was cultivated in ancient civilizations. The root system of lupine allows for the efficient exploration of essential nutrients such as phosphates in the soil [9]. In Hungary, sweet white lupine (*Lupinus albus* L.) is primarily grown for soil improvement [10], although it is well-adapted to acidic soils, can produce over 3000 kg/ha of grain yield, and more than 1000 kg/ha of protein [1]. White lupine has significant nutritional value of up to 44% protein content, a favorable fatty acid profile, and bioactive compounds [11–13]. However, the production of high-quality, clean seeds is often difficult due to plot weed infestation.

Weeds compete with crops for nutrients, water, and light, as well as for the soil that provides habitat [14,15]. Soil type, climate, and farming practices can significantly impact the growth, distribution, and number of weeds, leading to different weed compositions in different regions [16]. The presence of weeds can significantly reduce the yield [17,18] and cause greater economic damage than any other pests [19–21]. Climate change is expected to exacerbate weed problems, particularly in drought-prone regions, through competition for water. Weeds significantly hinder legume food production globally [22]. The slow initial growth of many legumes and their limited leaf development make them less competitive against weeds [23,24]. Weeds serve also as hosts for pest vectors [22], e.g., a phytoplasma disease was transmitted to several legume crops, such as lupines [25,26]. Since weed invasion has a detrimental effect on the environment, biodiversity, and ecosystem balance [27] and mechanical weed control is not always possible, the use of herbicides is necessary in legume crops to increase crop yield [28]. In order to increase the effectiveness of weed control, experiments have been conducted in several countries, including active substances with different mechanisms of action focused on phytotoxicity and weed-control activity.

Flumioxazin and carfentrazone-ethyl, the inhibitors of the protoporphyrinogen oxidase enzyme, cause damage to cell membranes and cellular components [29]. Flumioxazin inhibits germination when applied pre-emergence, while post-emergence application results in the necrosis and death of susceptible weed species [29]. In a field experiment, flumioxazin was applied pre-emergence at a dose of 150 g·ha⁻¹ in common vetch, pea (*Pisum sativum* L.), faba bean (*Vicia faba* L.), and white lupine [30]. In the white lupine (cv. Detn 20), carfentrazone-ethyl was tested pre-emergently at 20 g·ha⁻¹ [31]. The carfentrazone-ethyl has already been approved for application in lupine in the state of Kansas [32].

In addition, bentazon, metribuzin, metobromuron, and chlorotoluron, which are the inhibitor of photosynthesis in the Ps II system, are also under field study. [33,34]. Several legume crops, including common vetch and Narbonne vetch (*Vicia narbonensis* L.), were tested for the post-emergence application of bentazon (1 and 1.2 kg·ha⁻¹ + 1.5% oil) [35]. Bentazon was also tested post-emergence at a dose of 2 L·ha⁻¹ in the common vetch cv. Emma [36]. Metribuzin has been tested pre-emergence in sweet white lupine at three different doses (500, 750, and 1000 g·ha⁻¹) at two experimental sites (Charlottetown and Cornhill) over several years [37]. Metobromuron is a phenylurea active substance that controls dicotyledonous weeds in various crops [38,39], which was also applied pre-emergence at rates of 1.0 and 1.5 kg·ha⁻¹ and in combination with S-metolachlor [37]. Chlorotoluron is frequently used to control monocotyledonous weeds [40], and it was applied at a dose of 1.5 kg·ha⁻¹ pre-emergently in white and yellow lupine (*Lupinus luteus* L.) plots [41]. Recently, it was tested via post-emergence application in sweet white lupine at a dose of 2.8 L·ha⁻¹ [42].

Other active ingredients such as clopyralid, 2 methyl-4-chlorophenoxybutyric acid (MCPB), and picloram enhance respiratory metabolism, causing auxin-like symptoms in susceptible plants. Clopyralid acts in plants in a dose-dependent manner: at low concentrations it can cause abnormal growth, whereas at higher doses it reduces cell growth and division, which ultimately damages the plant [43–46]. MCPB disrupts ATP synthesis,

which is essential for energy production in plant cells [47]. The post-emergence application of MCPB is permitted on faba beans (*Vicia faba* L.) under the specific authorized rate of 2–4 L·ha⁻¹ [48]. The symptoms caused by halauxifen-methyl are similar to those caused by other auxin-like herbicides [49]. In field trials of soybean (*Glycine max* L. Merr.), halauxifen-methyl was applied at the stages of pre-sowing, pre-emergence, and post-emergence with 5 g·ha⁻¹ and 10 g·ha⁻¹ doses [50]. Quinmerac is generally used in combination with other active substances as a pre-emergence and post-emergence herbicide against dicotyledonous weeds [51].

Germination and growth inhibitors hinder the development of weeds by exerting different mechanisms of action. The fatty acid elongation pathway is the main target of chloroacetamides (metazachlor, S-metolachlor, pethoxamid, and dimethenamid-P) [52]. Pethoxamid is a pre-emergence herbicide that disrupts the development and emergence of weed seedlings [53]. Pethoxamid was applied pre-emergence at a dose of 0.84 kg·ha⁻¹ in white navy beans (*Phaseolus vulgaris*) alone and in combination with other herbicides against monocotyledonous and dicotyledonous weeds [54].

Dimethenamid-P is a pre-emergence or early post-emergence herbicide with activity against many annual grasses and certain broadleaf weeds. It is absorbed through the coleoptiles or the roots and inhibits cell division and plant growth in the initial stage of development [55]. Dimethenamid-P was tested with a pre-emergence dose (1.4 L·ha⁻¹) in sweet white lupine on humic sandy soil [56]. S-metolachlor is an active substance with a smaller spectrum of activity that was approved in lupins in Hungary and internationally and has been tested in vetch species in Greece and Argentina [57–59]. Pendimethalin has been used experimentally in several legumes (lupine, common vetch, and hairy vetch (*Vicia villosa* Roth.)) at different doses before emergence [41,58,60].

Acetolactate synthase (ALS) inhibitors target the ALS enzyme, resulting in the termination of cell growth and ultimately plant death [61]. Sulfosulfuron and thifensulfuron-methyl act similarly on weed growth [62,63]. Sulfosulfuron's potential as a less-harmful herbicide option for green gram (*Vigna radiata* L.) promotes improved root nodulation and higher grain protein content compared to other tested herbicides [64]. Additionally, trials were conducted on sweet white lupine to assess the phytotoxic effects and herbicide activity of thifensulfuron-methyl and other active substances [63]. Triflurosulfuron-methyl has a similar mechanism of action [65] but it has not yet been tested in legumes. Imazamox is an approved herbicide for several leguminous crops. In Hungary, it is specifically registered for post-emergence use in Hungarian vetch (*Vicia pannonica* Crantz.), and its potential use was tested in lupine and other vetch species in field experiments [30,58,66].

Several classes of herbicides have been developed that disrupt different stages of carotenoid synthesis [67], such as clomazone and diflufenican. The active substance clomazone was applied pre-emergence at a dose of 0.2 L·ha⁻¹ in sweet white lupine [56]. The pendimethalin + clomazone (412.5 + 82.5 g·ha⁻¹) and metribuzin + clomazone (349.5 + 90 g·ha⁻¹) were applied pre-emergence in vetch, white lupine, faba bean, and pea (*Pisum sativum* L.) [30]. Diflufenican targets the enzyme phytoene desaturase, which plays a role in the carotenoid biosynthesis pathway [68]. Diflufenican has been used in several research studies, such as in lupins at 50 g·ha⁻¹ pre-emergence and post-emergence [41] and in hairy vetch at 0.25 L·ha⁻¹ [69]. Also, prosulfocarb—in a pre-emergence application on white- and yellow-flowered lupine (*Lupinus luteus* L.) at the dose of 2.4 kg·ha⁻¹—exhibited inhibition of lipid biosynthesis as the mechanism of action [41].

Despite many field trials, the list of herbicides that can be used on these crops (lupine and common vetch) without harming them is still limited. In addition, more and more chemicals are being phased out to protect the environment, and so the list of herbicide options is narrowing further. Based on the above overview, the aim of this study was to

investigate the herbicidal activity and phytotoxicity of several active ingredients on lupine and common vetch under field conditions with the aim of providing valuable field results to expand the list of usable herbicides. In the long term, the results will help the cultivation of these crops by improving weed-control technology and contributing to the more efficient production of them.

2. Materials and Methods

2.1. Experimental Site, Plant Materials, and Experimental Design

The experiments were carried out at the Nyíregyháza Research Institute (Hungary: 47.976727, 21.695890 in 2023; 47.973865, 21.699876 in 2024) on sandy loam soils with adequate humus content (2023, 2024) (Table 1).

Table 1. Soil characteristics (sampling depths 0–25, 25–50 cm).

Characteristics of Soil	Indicators	
	2023	2024
pH (KCl)	7.66	7.4
Plasticity Index by Arany ³	34	30
Water-soluble salt % ¹	0.03	0.02
Carbonated lime content % ¹	5.84	2.42
Humus content (SOM) ² % ¹	1.63	1.53
Phosphorus pentoxide mg kg ⁻¹	347	231
Potassium oxide mg kg ⁻¹	340	263

¹ mass/mass %: g 100 g⁻¹ soil; ² Soil Organic Matter; ³ this index characterizes the fine particle content of soils—this means that the clay content of soil can be about 25% and 30% in the case of the index scores 30 and 34, respectively.

For the common vetch experiments, the variety ‘Emma’ was used (registered in 2005), which is characterized by fast initial growth, high fresh green biomass production, and resistance to several diseases [70]. In the case of the sweet white lupine, the ‘Nelly’ variety developed at the Nyíregyháza Research Institute (registered in 1985) was used. ‘Nelly’ is characterized as a branching stem of between 70 and 100 cm in height with good tolerance to water deficit [56].

Before the experiments, sunflower (*Helianthus annuus* L.) and corn (*Zea mays* L.) were cultivated in 2022 and in 2023, respectively. The agro-technical implementation of crop production was carried out according to a widely practiced cultivation technique. All experiments were set up in a randomized complete block design (RCBD) with four replicates. Seeds were sown in plots sized 2 × 10 m in 2023 and 1.7 × 5 m in 2024. The plot size had to be changed due to changes in technical and soil conditions. However, the results were not influenced by the size of the plot: all observations and measurements were made at the center of the plots. In 2023, the common vetch was sown on 24 April, whereas in 2024, sweet white lupine and common vetch were sown on 18 March. No fertilizers or soil conditioners were used in the experiments.

2.2. Herbicide Treatments Applied

In the first year of common vetch experiments, fifteen post-emergence treatments with several active substances were applied in different doses (Table 2). The active substances were applied on 1 June 2023 in the growth stage of BBCH 36. On this day, the weather was calm, there was no precipitation, and the mean temperature was 18.7 °C. Precipitation was received on 6 June (16 mm). To minimize spray drift, the active substances were sprayed using a Szolnok PP01HT machine designed for small-plot experimental applications. It has a sprayer frame length of 2.0 m with 4 spray heads (spacing 0.5 m), working with compressed air as propellant gas and with 2-bar spraying pressure. An application rate

of 275 L·ha⁻¹ water was used in the experiments to deliver herbicides. In the common vetch experiment, pre-emergence treatments were also included but due to a lack of rainfall in the two weeks following application, these treatments were excluded from this study. Rainfall is essential for the activation of pre-emergence herbicides and, consequently, their effectiveness.

Table 2. The active substances contained in the herbicide treatments in the common vetch experiment (2023).

Active Substances	Time of Application	Herbicide Application Rate	Doses of Active Ingredient	Treatment Codes	Mechanism of Action
Flumioxazin	Post-emergence	0.06 kg·ha ⁻¹	30 g ai·ha ⁻¹	T1	Protoporphyrinogen oxidase inhibition
Flumioxazin	Post-emergence	0.08 kg·ha ⁻¹	40 g ai·ha ⁻¹	T2	Protoporphyrinogen oxidase inhibition
Chlorotoluron	Post-emergence	2.8 L·ha ⁻¹	1400 g ai·ha ⁻¹	T3	Photosynthesis inhibition in the Ps II
Chlorotoluron	Post-emergence	3.0 L·ha ⁻¹	1500 g ai·ha ⁻¹	T4	Photosynthesis inhibition in the Ps II
Clopyralid + picloram	Post-emergence	0.3 L·ha ⁻¹	80 + 20 g ai·ha ⁻¹	T5	Respiratory metabolism stimulant (synthetic auxin)
Metazachlor + quinmerac	Post-emergence	2.0 L·ha ⁻¹	666 + 166 g ai·ha ⁻¹	T6	Germination and growth inhibition
Metazachlor + quinmerac	Post-emergence	2.25 L·ha ⁻¹	749 + 187 g ai·ha ⁻¹	T7	Germination and growth inhibition
MCPB	Post-emergence	2.0 L·ha ⁻¹	876 g ai·ha ⁻¹	T8	Respiratory metabolism stimulant (synthetic auxin)
MCPB	Post-emergence	3.0 L·ha ⁻¹	1314 g ai·ha ⁻¹	T9	Respiratory metabolism stimulant (synthetic auxin)
Triflusaluron-methyl	Post-emergence	20.0 g·ha ⁻¹	10 g ai ha ⁻¹	T10	Acetolactate synthase inhibitors
Triflusaluron-methyl + ethoxylated isodecyl alcohol (adjuvant)	Post-emergence	20.0 g ha ⁻¹	10 g ai·ha ⁻¹	T11	Acetolactate synthase inhibitors
Sulfosulfuron	Post-emergence	10.0 g·ha ⁻¹	7.5 g ai·ha ⁻¹	T12	Acetolactate synthase inhibitors
Thifensulfuron-methyl	Post-emergence	15.0 g ha ⁻¹	7.5 g ai·ha ⁻¹	T13	Acetolactate synthase inhibitors
Thifensulfuron-methyl + ethoxylated isodecyl alcohol (adjuvant)	Post-emergence	15.0 g·ha ⁻¹	7.5 g ai ha ⁻¹	T14	Acetolactate synthase inhibitors
Bentazon	Post-emergence	1.5 L·ha ⁻¹	720 g ai·ha ⁻¹	T15	Photosynthesis inhibition in the Ps II
Control	-	-	-	T16	-

ai: active ingredient.

In the second year of common vetch trials, five treatments (T1–T5) were applied pre-emergence three days after sowing (21 March) (Table 3). Other active substances were applied post-emergence on 29 April 2024 in the growth stage of BBCH 36. This day, the weather was calm, there was no precipitation, and the mean temperature was 17.3 °C. Flumioxazin was applied both pre- (T3) and post-emergence (T6, T7). In 2023, we cooperated with the Plant and Soil Protection Department of the Szabolcs-Szatmár-Bereg County Government Office so we had the Szolnok PP01HT plot sprayer (Hungary, Jász-Nagykun-Szolnok county, Szolnok) at our disposal. However, this cooperation ended so the Szolnok PP01HT plot sprayer was no longer available to us. This is why we had to change the sprayer machine in 2024. The active substance was delivered in 300 L·ha⁻¹ water using an Sg 71 back sprayer (Andreas Stihl AG & Co. KG in Waiblingen, Germany). The professional backpack sprayer features an 18-liter tank, and a built-in shut-off valve with a pressure gauge ensures precise spraying.

Table 3. The active substances contained in the herbicide treatments in the common vetch experiment (2024).

Active Substances	Time of Application	Herbicide Application Rate	Doses of Active Ingredients	Treatment Codes	Mechanism of Action
Pendimethalin	Pre-emergence	5.0 L·ha ⁻¹	2275 g ai·ha ⁻¹	T1	Germination and growth inhibition
S-metolachlor	Pre-emergence	1.4 L·ha ⁻¹	1344 g ai·ha ⁻¹	T2	Germination and growth inhibition
Flumioxazin	Pre-emergence	0.06 kg·ha ⁻¹	30 g ai·ha ⁻¹	T3	Protoporphyrinogen oxidase inhibition
Clomazone	Pre-emergence	0.2 L·ha ⁻¹	96 g ai·ha ⁻¹	T4	Inhibition of carotenoid biosynthesis
Metribuzin	Pre-emergence	0.55 L·ha ⁻¹	330 g ai·ha ⁻¹	T5	Photosynthesis inhibition in the Ps II
Flumioxazin	Post-emergence	0.06 kg·ha ⁻¹	30 g ai·ha ⁻¹	T6	Protoporphyrinogen oxidase inhibition
Flumioxazin	Post-emergence	0.08 kg·ha ⁻¹	40 g ai·ha ⁻¹	T7	Protoporphyrinogen oxidase inhibition
Chlorotoluron	Post-emergence	2.8 L·ha ⁻¹	1400 g ai·ha ⁻¹	T8	Photosynthesis inhibition in the Ps II
Chlorotoluron	Post-emergence	3.0 L·ha ⁻¹	1500 g ai·ha ⁻¹	T9	Photosynthesis inhibition in the Ps II
Clopyralid + picloram	Post-emergence	0.3 L·ha ⁻¹	80 + 20 g ai·ha ⁻¹	T10	Respiratory metabolism stimulant (synthetic auxin)
Metazachlor + quinmerac	Post-emergence	2.0 L·ha ⁻¹	666 + 166 g ai·ha ⁻¹	T11	Germination and growth inhibition
Metazachlor + quinmerac	Post-emergence	2.25 L·ha ⁻¹	749 + 187 g ai·ha ⁻¹	T12	Germination and growth inhibition
MCPB	Post-emergence	2.0 L·ha ⁻¹	876 g ai·ha ⁻¹	T13	Respiratory metabolism stimulant (synthetic auxin)
MCPB	Post-emergence	3.0 L·ha ⁻¹	1314 g ai·ha ⁻¹	T14	Respiratory metabolism stimulant (synthetic auxin)
Sulfosulfuron	Post-emergence	10.0 g·ha ⁻¹	7.5 g ai·ha ⁻¹	T15	Acetolactate synthase inhibitors
Thifensulfuron-methyl	Post-emergence	15.0 g·ha ⁻¹	7.5 g ai·ha ⁻¹	T16	Acetolactate synthase inhibitors
Thifensulfuron-methyl + ethoxylated isodecyl alcohol	Post-emergence	15.0 g·ha ⁻¹	7.5 g ai·ha ⁻¹	T17	Acetolactate synthase inhibitors
Bentazon	Post-emergence	1.5 l·ha ⁻¹	720 g ai·ha ⁻¹	T18	Photosynthesis inhibition in the Ps II
Imazamox	Post-emergence	0.8 l·ha ⁻¹	32 g ai·ha ⁻¹	T19	Acetolactate synthase inhibitors
Control	-	-	-	T20	-

ai: active ingredients.

In the sweet white lupine experiment (2024), the active substances were applied pre-emergence, post-emergence, and late post-emergence—3, 30, and 42 days after sowing, respectively (Table 4). The growth stage of lupine was BBCH 25 at post-emergence application (17 April), whereas it was BBCH 37 at late post-emergence application (29 April). The weather was calm each day, the mean temperatures were 7.2 °C, 9.6 °C, and 17.3 °C, respectively. There was precipitation in the relevant period on 28 March (4.4 mm), on 2 April (5.1 mm), 19 April (6.0 mm), and 7 May (1.4 mm). The method for herbicide spraying was the same as described for common vetch (2024).

Table 4. The active substances contained in the herbicide treatments in the sweet white lupine experiment (2024).

Active Substances	Time of Application	Herbicide Application Rate	Doses of Active Ingredients	Treatment Codes	Mechanism of Action
Flumioxazin	Pre-emergence	0.06 kg·ha ⁻¹	30 g ai·ha ⁻¹	T1	Protoporphyrinogen oxidase inhibition
Pendimethalin	Pre-emergence	5.0 L·ha ⁻¹	2275 g ai·ha ⁻¹	T2	Germination and growth inhibition
Dimethenamid-P	Pre-emergence	1.4 L·ha ⁻¹	1008 g ai·ha ⁻¹	T3	Germination and growth inhibition
Pethoxamid	Pre-emergence	2.0 L·ha ⁻¹	1200 g ai·ha ⁻¹	T4	Germination and growth inhibition
Clomazone	Pre-emergence	0.2 L·ha ⁻¹	96 g ai·ha ⁻¹	T5	Inhibition of carotenoid biosynthesis
Metobromuron	Pre-emergence	3.0 L·ha ⁻¹	1500 g ai·ha ⁻¹	T6	Photosynthesis inhibition
Metribuzin	Pre-emergence	0.55 L·ha ⁻¹	330 g ai·ha ⁻¹	T7	Photosynthesis inhibition in the Ps II
Diflufenican	Pre-emergence	0.25 L·ha ⁻¹	125 g ai·ha ⁻¹	T8	Phytoene desaturase inhibition
Flumioxazin	Post-emergence	0.06 kg·ha ⁻¹	30 g ai·ha ⁻¹	T9	Protoporphyrinogen oxidase inhibition
Chlorotoluron	Post-emergence	2.8 L·ha ⁻¹	1400 g ai·ha ⁻¹	T10	Photosynthesis inhibition in the Ps II
Halauxifen-methyl	Late post-emergence	0.4 L·ha ⁻¹	1.3 g ai·ha ⁻¹	T11	Auxin effect
Halauxifen-methyl	Late post-emergence	0.5 L·ha ⁻¹	1.6 g ai·ha ⁻¹	T12	Auxin effect
Halauxifen-methyl	Late post-emergence	0.6 L·ha ⁻¹	1.9 g ai·ha ⁻¹	T13	Auxin effect
Halauxifen-methyl + picloram	Late post-emergence	0.25 L·ha ⁻¹	2.5 + 12 g ai·ha ⁻¹	T14	Respiratory metabolism stimulant (synthetic auxin)
Halauxifen-methyl + picloram	Late post-emergence	0.5 L·ha ⁻¹	5 + 24 g ai·ha ⁻¹	T15	Respiratory metabolism stimulant (synthetic auxin)
Prosulfocarb	Post-emergence	2.5 L·ha ⁻¹	2000 g ai·ha ⁻¹	T16	Lipid biosynthesis inhibition
Carfentrazone-ethyl	Post-emergence	35.0 g·ha ⁻¹	14 g ai·ha ⁻¹	T17	Protoporphyrinogen oxidase inhibition
Sulfosulfuron	Post-emergence	13.0 g·ha ⁻¹	9.8 g ai·ha ⁻¹	T18	Acetolactate synthase inhibitors
Sulfosulfuron	Post-emergence	17.0 g·ha ⁻¹	12.8 g ai·ha ⁻¹	T19	Acetolactate synthase inhibitors
Imazamox	Post-emergence	1.0 L·ha ⁻¹	40 g ai·ha ⁻¹	T20	Acetolactate synthase inhibitors
Diflufenican	Post-emergence	0.25 L·ha ⁻¹	125 g ai·ha ⁻¹	T21	Phytoene desaturase inhibition
Control	-	-	-	T22	-

ai: active ingredients.

2.3. Normalized Difference Vegetation Index (NDVI)

In the experiments, the Trimble GreenSeeker HCS-100 (Trimble Inc., Sunnyvale, CA, USA) hand-held meter was used to monitor the development of crops and changes caused by the phytotoxicity of herbicides. The vegetation values may vary from 0 to 1, with different phenological states exhibiting distinct characteristic values [71]. In the 2023 growing season, the NDVI recording was made only once due to late sowing and rainy weather (on 15 June; BBCH 49). In the 2024 growing season, NDVI data for both legumes were recorded 6 times (8, 15, 21, and 28 May and 5 and 20 June). The growth stages were for common vetch BBCH 39, 42, 46, 49, 64, and 75, whereas the growth stages of lupine were BBCH 39, 63, 65, 67, 71, and 79. The growth stages were detected by BBCH scale [72,73].

During the measurement, we recorded 2 data points from the plots, always at the same height. We passed along the left side of the plots once and then again along the right side. The device performs the averaging automatically. In general, as plant development progresses, and biomass increases, the NDVI values may vary between 0.6 and 0.9. For example, in the case of Andean lupine (*Lupinus mutabilis* Sweet.), the 0.82 NDVI value

obtained in the control plots indicated the good health status of the plants [74]. In the case of common vetch, the highest NDVI value (0.68) was detected in the control plots when flowering began [36].

2.4. Visual Assessment of Phytotoxicity

Observations of phytotoxicity symptoms were started 8–10 days after the treatments as the effects of all types of herbicides should have appeared by then (contact herbicides: within a few hours; systemic herbicides: after 3–10 days; hormonal herbicides: after 3–7 days). Accordingly, in the 2023 growing season, phytotoxicity monitoring was conducted on 13 June (BBCH 49) and 27 July (BBCH 87) in common vetch. For the 2024 growing season, 4 phytotoxicity evaluations were conducted in the common vetch experiment on 7 May (BBCH 39), 15 May (BBCH 42), 21 May (BBCH 46), and 5 June (BBCH 64). Three phytotoxicity observations were conducted on sweet white lupine: on 7 May (BBCH 39), on 14 May (BBCH 63), and on 21 May (BBCH 65). The phytotoxicity symptoms were recorded using a method already proven in a previous study [36]. According to the individual scale method, the plants were symptom-free (1) or showed symptoms ranging from very mild (2), mild (3), medium (4), damaged (5), strongly damaged (6), serious damage (7), and very serious damage (8) to extinction (9) [36].

2.5. Plant Height

In the 2024 experiments, the plant height was measured with a ruler from the soil surface to the shoot tip on three plants selected randomly in the center of the plots. The measurement was made on 28 May 2024 at the growth stage of BBCH 49 for common vetch and BBCH 67 for lupine.

2.6. Weed Counts

The number of weeds per plot was observed on 13 June 2023 and 7 May 2024 in common vetch plots. We documented the number of weeds in sweet white lupine on 7 and 16 May 2024. We used a 0.5×0.5 m sampling frame, which is suitable for obtaining the distribution of weeds in a research area [75]. The number of weeds is given per 0.25 m^{-2} . It is important to note that weed counts can be taken at the time after post-emergence application and before the crop has fully covered the soil, which can be a short period depending on the season. The results of the number of weeds are only an addition to the research as manufacturers provide information on the efficacy of herbicides against specific weeds in their product specifications.

2.7. Harvesting and Crop Cleaning Process

In 2023, diquat dibromide was applied ($1.5 \text{ L}\cdot\text{ha}^{-1}$) to desiccate common vetch on 10 August, which was harvested on 21 August. In 2024, both crops were desiccated on 16 July and harvested on 22 July. In both years, the harvest was performed with a small-plot combine (Zürn 130 SE, Zürn Harvesting GmbH & Co. KG, Waldenburg, Germany). After drying the yield until 13% (lupine) and 11% (vetch) water contents, the seed yield was cleaned using the Westrup Kamas laboratory seed cleaner (type: LA LS, No. 78110182146634, Industry AB, Malmö, Sweden) to remove weed seeds and dry the green plant debris. The top sieve used for cleaning common vetch seeds was 3.75 mm round, and the bottom sieve was 3.5 mm round. In the sweet white lupine, the top sieve was 12 mm round, and the bottom one was 3.75 mm oval. The quantity of contamination of the crop was documented and their ratio to the whole yield was calculated.

2.8. Precipitation and Average Monthly Temperature for the Growing Seasons

In the 2023 growing season, there was a gradual increase in temperature until August. For precipitation, June had the highest (99 mm), which corresponded to the period when biomass accumulation took place in the common vetch stands (Figure 1).

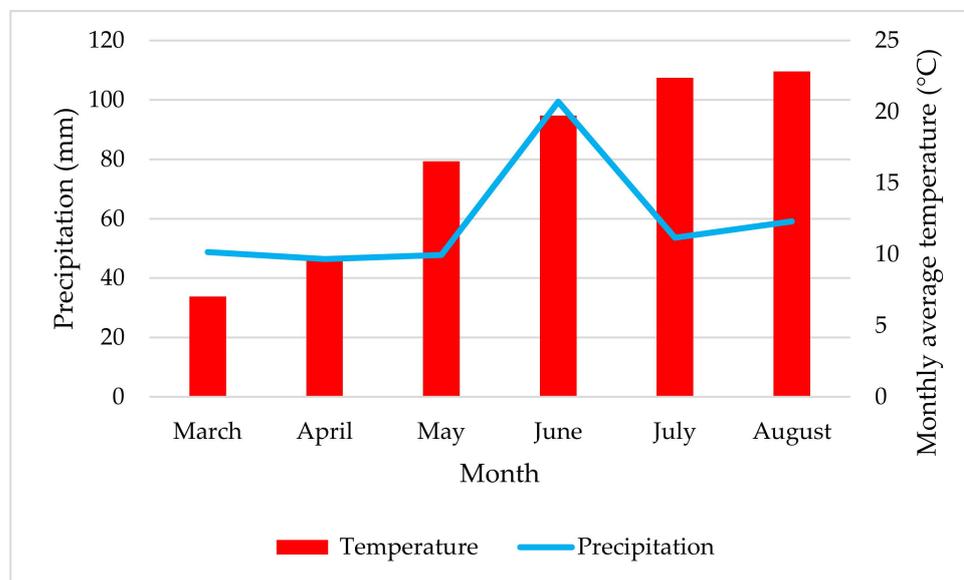


Figure 1. The precipitation and the average monthly temperature in the common vetch experiment in the 2023 growing season (Nyíregyháza, Hungary).

The growing season of 2024 also exhibited a gradual increase in temperature from February to July. The highest rainfall (130 mm) was in June, when the pods were ripening in the common vetch and the seeds were ripening in the sweet white lupine (Figure 2).

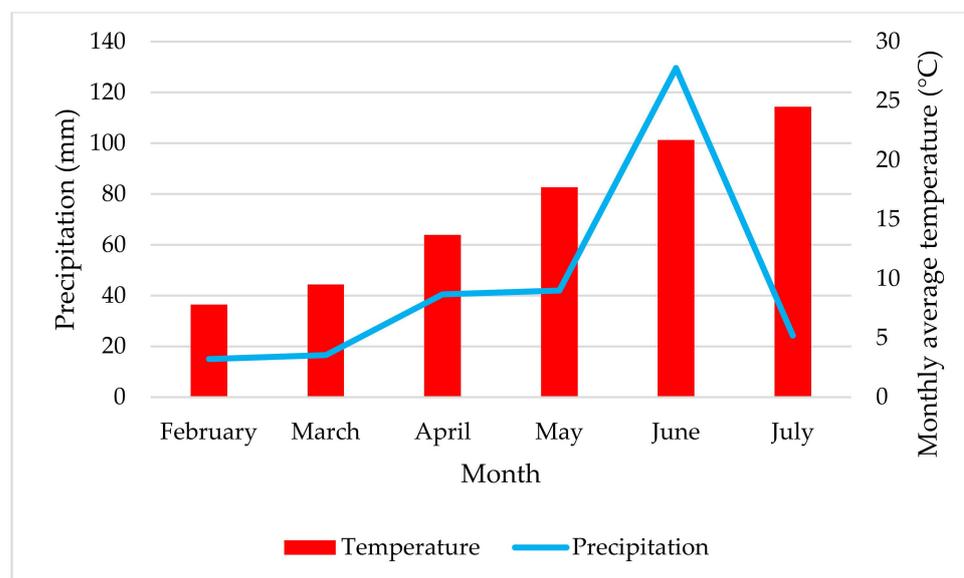


Figure 2. The precipitation and the average monthly temperature in the common vetch and sweet white lupine experiment in the 2024 growing season (Nyíregyháza, Hungary).

2.9. Statistical Analyses of Data Collected

All treated and control plots were set in four replications in both years. One datum per plot was collected for the phytotoxicity and number of weeds, whereas three data points per plot were measured for plant height. In addition, one NDVI datum per plot was used

for statistical evaluation but this was the average of two measurements per plot calculated by the instrument. The seed yield, the yield contamination, and 1000-seed-weight data were collected from each plot, which means four repetitions per treatment. The data on the effect of herbicides on the observed variables (NDVI, phytotoxicity, number of weeds, height of plants, seed yield, and 1000-seed weight) were subjected to a One-Way Analysis of Variance (ANOVA), and post hoc comparisons were performed using Duncan's test ($p < 0.05$). Additionally, the validity of the study methods and the relationships between variables (NDVI, phytotoxicity, number of weeds, plant height, seed yield, seed yield contamination, and 1000-seed weight) were determined using Spearman's rho correlation test (2-tailed). All statistical analyses were conducted using SPSS® software (version 22.0 for Windows).

3. Results

3.1. The Effect of Treatments on Common Vetch in the First-Year Experiment (2023)

3.1.1. The Effect of Treatments on the NDVI Values of Common Vetch

NDVI data measured before flowering (BBCH 49) showed that the NDVI values of plots treated with clopyralid + picloram (T5) were significantly lower than the other treatments and the control (T16) plots (Figure 3). Plots treated with triflurosulfuron-methyl + adjuvant (T11) and sulfosulfuron (T12) also showed significantly lower NDVI values than the control plots and the majority of the treated plots. Similarly, both thifensulfuron-methyl treatments with or without adjuvant (T13 and T14, respectively) resulted in significantly lower NDVI values compared to the others. The NDVI values of the plots treated post-emergence with the other active substances such as flumioxazin (T1, T2), chlorotoluron (T3, T4), metazachlor + quinmerac (T6, T7), MCPB (T8, T9), triflurosulfuron-methyl without adjuvant (T10), and bentazon (T15) were similar to those measured in the control plots (T16).

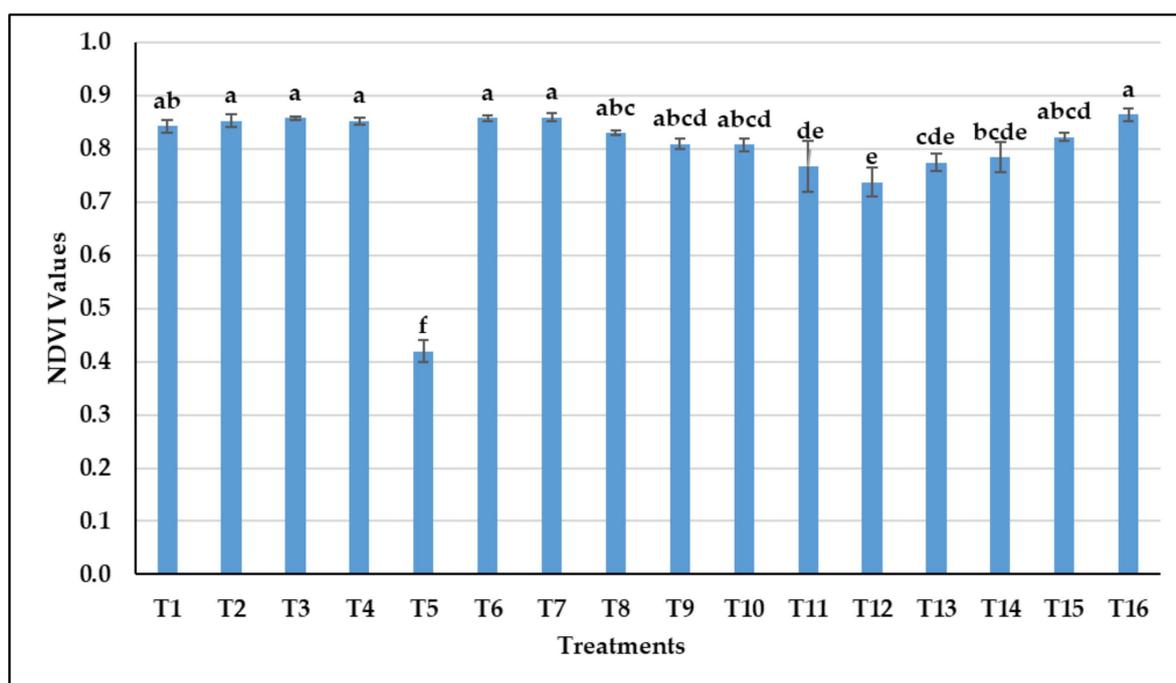


Figure 3. Influence of different herbicides on NDVI values of common vetch at growth stage of BBCH 49. Each bar illustrates the mean with the standard error of the respective datasets. Letters indicate significant differences between treatments (Duncan's post hoc test: $p < 0.05$).

3.1.2. Phytotoxicity of Treatments on Common Vetch

Treatment with clopyralid + picloram (T5) caused very severe symptoms (Table 5). In addition, the active substance sulfosulfuron (T12) also caused severe damage (yellowish leaf with smaller mass) on common vetch. Several treatments caused different symptoms, with the mildest symptoms observed on plots treated post-emergence with the higher dose of chlorotoluron (T4), followed by the higher dose of metazachlor + quinmerac (T7).

Table 5. Effect of post-emergence application of herbicides on phytotoxicity score, on the number of seeds, and on the seed yield in the case of common vetch (2023). Letters indicate significant differences between treatments (Duncan's post hoc test: $p < 0.05$).

Active Substances	Treatment Codes	Phytotoxicity Score ¹	Number of Weeds 0.25 m ⁻²	Yield kg ha ⁻¹
Flumioxazin	T1	3.88 ef	0.5 b	511abc
Flumioxazin	T2	4.0 ef	0.8 b	560 abc
Chlorotoluron	T3	3.75 ef	4.0 ab	647 a
Chlorotoluron	T4	2.38 g	1.3 b	467 a–d
Clopyralid + picloram	T5	8.5 a	7.0 a	307 cde
Metazachlor + quinmerac	T6	4.63 def	0.8 b	633 ab
Metazachlor + quinmerac	T7	3.38 fg	1.5 b	567 abc
MCPB	T8	4.13 ef	1.8 b	413 a–d
MCPB	T9	4.0 ef	1.3 b	427 a–d
Triflusulfuron-methyl	T10	5.88 cd	3.5 ab	117 e
Triflusulfuron-methyl + adjuvant	T11	5.63 cd	2.8 b	350 b–e
Sulfosulfuron	T12	7.75 ab	2.3 b	180 de
Thifensulfuron-methyl	T13	6.63 bc	2.0 b	177 de
Thifensulfuron-methyl + adjuvant	T14	5.88 cd	1.0 b	283 cde
Bentazon	T15	5.13 de	4.0 ab	652 a
Control	T16	1.0 h	1.0 b	520 abc

¹ Phytotoxicity score is the average of the results obtained during vegetation period.

The common vetch plants showed recovery ability to some degree after the majority of the herbicide treatments, although the condition of the plants recorded the second time (27 July) was only significantly better in the case of treatments T2, T6, T8, and T9. In contrast, the phytotoxic symptoms became significantly more serious by the second observation date in the case of T12 and T13 (Figure 4).

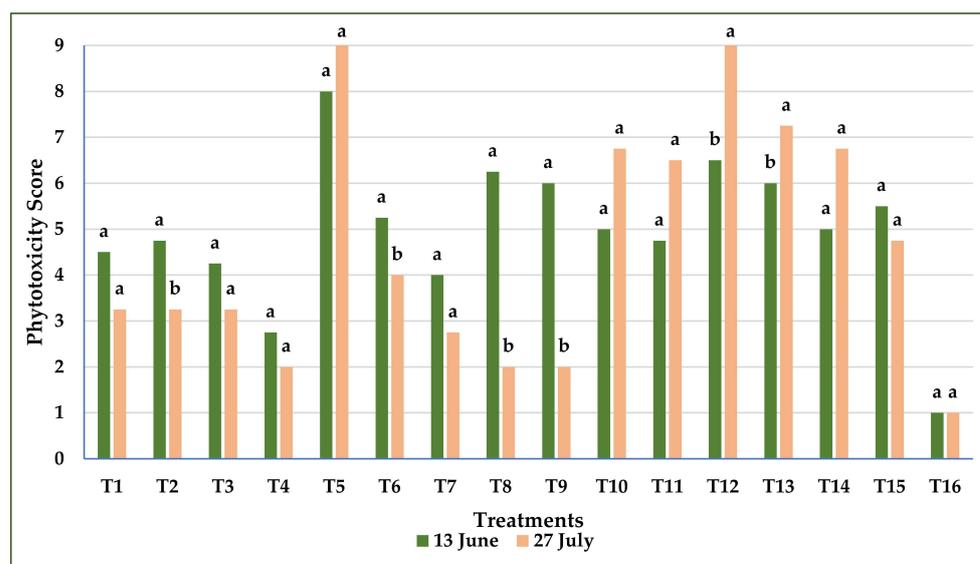


Figure 4. The results of visual phytotoxicity assessments of common vetch observed at BBCH 49 (13 June) and BBCH 70 (27 July) for herbicide treatments. Letters indicate significant differences between results of different observation times within a treatment (Duncan's post hoc test: $p < 0.05$).

As shown in Figure 5A, the clopyralid + picloram (T5) treatment caused almost complete desiccation of the common vetch plants with irreversible damage, while redroot pigweed (*Amaranthus retroflexus* L.) and white goosefoot (*Chenopodium album* L.) weeds were not damaged. In contrast, common vetch treated with the higher dose of metazachlor + quinmerac (T7) grew well and produced sufficient green mass (Figure 5B). The common vetch in the control plot (T16) grew a large green biomass that completely covered the soil (Figure 5C).



Figure 5. The common vetch plot treated with clopyralid + picloram (A), the plot treated with higher dose of metazachlor + quinmerac (B), and the control plot (C). The photodocumentation was taken 57 days after sowing (2023).

3.1.3. Herbicide Efficacy on the Number of Weeds of Common Vetch

As detailed above, the clopyralid + picloram (T5) had low efficacy on several common weeds and, consequently, registered the highest number of weeds, which significantly differed from the control and other treatments (Table 5). Partly due to the favorable weather conditions, common vetch developed well during the growing season and only a minimal number of weeds were documented in the control (T16) plots. The most abundant weed species in the experimental area were redroot amaranth (*Amaranthus retroflexus* L.), green foxtail (*Setaria viridis* L.), and white goosefoot (*Chenopodium album* L.).

3.1.4. The Effect of Herbicides on the Seed Yield of Common Vetch

Although the clopyralid + picloram treatment (T5) resulted in the worst outcomes of all other measured indicators, it did not show a statistically significant reduction in seed yield compared to the control (T16) (Table 5). The triflurosulfuron-methyl without adjuvant (T10), sulfosulfuron (T12), and thifensulfuron-methyl without adjuvant (T13) treatments resulted in significantly lower mean seed yields compared to the control (T16). The lowest seed yield ($117 \text{ kg} \cdot \text{ha}^{-1}$) was obtained in the plots treated with triflurosulfuron-methyl without adjuvant (T10). The seed yield of some post-emergence treated plots (higher dose of flumioxazin (T2), lower dose of chlorotoluron (T3), both doses of metazachlor + quinmerac (T6, T7), and bentazon (T15)) exceeded the seed yield of the control plots but not significantly different. The bentazon-treated plots (T15) produced the highest seed yield that exceeded the control by $132 \text{ kg} \cdot \text{ha}^{-1}$. A significant outlier was observed in the bentazon treatment, with one plot yielding substantially more than the rest.

3.1.5. Seed Yield Contamination in Treated and Control Plots of Common Vetch

The thifensulfuron-methyl applied without adjuvant (T13) exhibited the highest (49%) level of seed yield contamination (Figure 6). The lowest (29%) seed yield contamination was recorded in both the triflurosulfuron-methyl + adjuvant treated plots (T11) and the control

(T16) plots. However, it should be noted that high levels of seed yield contamination (more than 40%) were also observed in the plots treated with triflurosulfuron-methyl without adjuvant (T10), clopyralid + picloram (T5), and sulfosulfuron (T12). The average seed yield contamination of the treated plots and control plots was 36%.

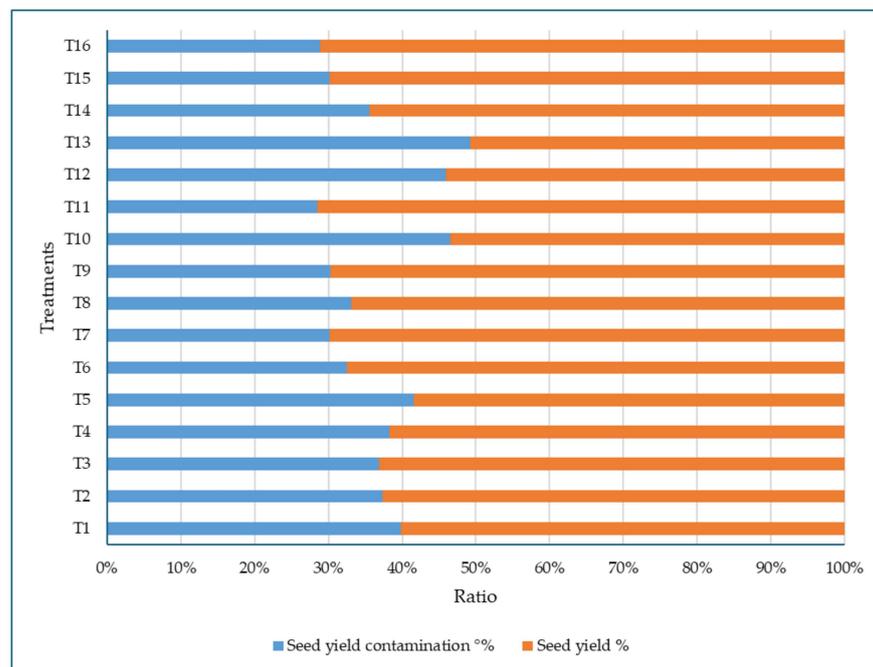


Figure 6. The ratio between seed yield contamination (%) and total seed yield (%) in common vetch (2023).

3.1.6. Relationship Between Variables Obtained from the First-Year Common Vetch Experiment (2023)

The strongest negative correlation was detected by Spearman’s rho test at the 0.01 level, ($r = -0.783$), between the NDVI values and phytotoxicity scores (Table 6). There was also a negative correlation between the NDVI values and weed abundance (at the 0.01 level). However, the NDVI values were positively correlated with the quantity of seed yield contamination (0.01 level). The second-strongest positive correlation was achieved between the NDVI values and seed yield (0.01 level). Phytotoxicity scores were negatively correlated with seed yield contamination (0.05 level) and seed yield (0.01 level), respectively. Accordingly, the strongest positive correlation was obtained between seed yield contamination and the seed yield ($r = 0.656$; $p \leq 0.01$).

Table 6. Spearman’s rho correlation test results obtained at two levels in the common vetch (2023 experiment).

	NDVI Data	Phytotoxicity	Number of Weeds	Contamination	Seed Yield
NDVI data	1				
Phytotoxicity	-0.783 **	1			
Number of weeds	-0.344 **	0.295 *	1		
Contamination	0.368 **	-0.316 *	0.017	1	
Seed yield	0.618 **	-0.493 **	-0.14	0.656 **	1

Note. * $p < 0.05$, ** $p < 0.01$ Spearman’s rho. The color of the cells shows the direction of the correlation (positive direction: green color; negative direction: red color), as well as the strength of the correlation: the darker the color shade, the stronger the correlation.

3.2. Results Obtained in the Second Year of the Common Vetch Experiment (2024)

3.2.1. The Effect of Treatments on the NDVI Values of Common Vetch

Post-emergence applications of clopyralid + picloram (T10), MCPB (T13, T14), sulfosulfuron (T15), thifensulfuron-methyl with and without adjuvant (T16, T17), bentazon (T18), and imazamox (T19) negatively impacted plant health, as indicated by significantly lower NDVI values compared to the control (T20) (Figure 7, Table S1). The plots treated with clopyralid + picloram (T10) had the lowest NDVI values. Of the post-emergence treatments, both doses of flumioxazin (T6, T7), both doses of chlorotoluron (T8, T9), and metazachlor + quinmerac active substances (T11, T12) resulted in NDVI values similar to the control. Similarly, none of the pre-emergence treatments (pendimethalin (T1), S-metolachlor (T2), flumioxazin (T3), clomazone (T4), or metribuzin (T5)) differed from the control.

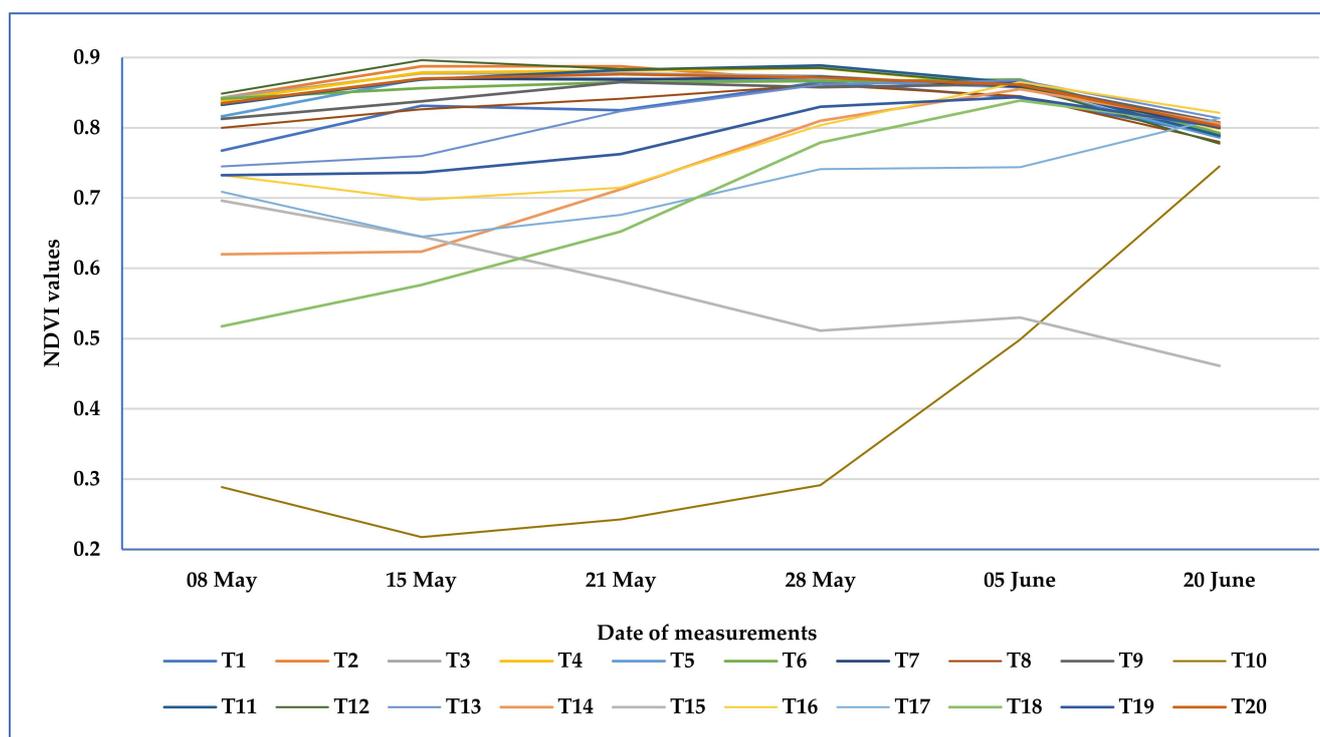


Figure 7. Influence of herbicides on NDVI values during vegetation period in common vetch (2024). Details including means and homogenous groups are in Table S1.

3.2.2. The Phytotoxicity Effect of Treatments on Common Vetch

The post-emergence treatment with clopyralid + picloram (T10) completely destroyed the common vetch plants during the growing season and was significantly more phytotoxic than the other treatments (Table 7). Out of the post-emergence treatments, different doses of metazachlor + quinmerac (T11, T12) did not cause symptoms, and the different doses of flumioxazin (T6, T7) also did not differ from the control in terms of mean phytotoxicity values. Similarly, the pre-emergence-applied T2, T3, T4, and T5 treatments also did not result in significant damage. In contrast, the phytotoxicity of post-emergence treatments ((chlorotoluron treatments (T8, T9), MCPB treatments (T13, T14), sulfosulfuron (T15), thifensulfuron with and without adjuvant (T16, T17), bentazon (T18), and imazamox (T19)) all differed from the control plots. Despite the medium phytotoxic effects of post-emergence applied chlorotoluron (T8, T9) (phytotoxic scores were 3.6 and 2.4, respectively), some individual plots exhibited complete regeneration as the growing season progressed. Among the pre-emergence treatments, only pendimethalin (T1) resulted in significant phytotoxicity

compared to the control. However, plants treated with pendimethalin eventually recovered from the initial mild symptoms.

Table 7. Effect of herbicide treatments on phytotoxicity, number of weeds, and plant height in common vetch plots (2024). Letters indicate significant differences between treatments (Duncan's post hoc test: $p < 0.05$).

Active Substances	Treatment Codes	Phytotoxicity Score ¹	Number of Weeds 0.25 m ⁻²	Plant Height cm
Pendimethalin (pre-emergence)	T1	1.94 ef	0.8 ab	39.9 ab
S-metolachlor (pre-emergence)	T2	1.13 fg	0.5 ab	44.4 a
Flumioxazin (pre-emergence)	T3	1.06 g	0.0 b	44.8 a
Clomazone (pre-emergence)	T4	1.00 g	0.5 ab	47.4 a
Metribuzin (pre-emergence)	T5	1.94 ef	0.0 b	46.8 a
Flumioxazin (post-emergence)	T6	1.81 efg	0.0 b	44.0 a
Flumioxazin (post-emergence)	T7	1.50 fg	0.0 b	41.5 a
Chlorotoluron (post-emergence)	T8	3.63 d	0.8 ab	42.9 a
Chlorotoluron (post-emergence)	T9	2.38 e	0.0 b	40.3 ab
Clopyralid + picloram (post-emergence)	T10	8.75 a	0.5 ab	0.0 e
Metazachlor + quinmerac (post-emergence)	T11	1.00 g	0.0 b	44.3 a
Metazachlor + quinmerac (post-emergence)	T12	1.00 g	0.3 ab	45.3 a
MCPB (post-emergence)	T13	4.19 d	0.3 ab	46.2 a
MCPB (post-emergence)	T14	5.63 c	0.3 ab	39.4 ab
Sulfosulfuron (post-emergence)	T15	6.63 b	0.0 b	15.6 d
Thifensulfuron-methyl (post-emergence)	T16	5.31 c	0.5 ab	31.8 bc
Thifensulfuron-methyl + ethoxylated isodecyl alcohol (post-emergence)	T17	5.88 bc	0.3 ab	24.6 c
Bentazon (post-emergence)	T18	5.88 bc	0.0 b	41.0 ab
Imazamox (post-emergence)	T19	4.38 d	1.0 a	38.8 ab
Control	T20	1.00 g	0.3 ab	45.9 a

¹ Phytotoxicity score is the average of the results obtained during vegetation period.

The common vetch plants showed significantly lower phytotoxicity results by the last observation date in the cases of T7, T13, T14, T16, and T18 (Figure 8). In contrast, the phytotoxic symptoms became significantly more serious by the last observation date in the cases of T15 and T19.

Plants in plots treated with clomazone (T4) showed no symptoms during the growing season (Figure 9A). The lower leaves of chlorotoluron-treated plants (post-emergence application: T8, T9) showed drying symptoms at the time of photodocumentation (Figure 9B). Figure 9C shows the effect of the sulfosulfuron treatment (T15) where it has caused severe symptoms with more yellowish small leaves than the plants in the control plots (T20) (Figure 9D).

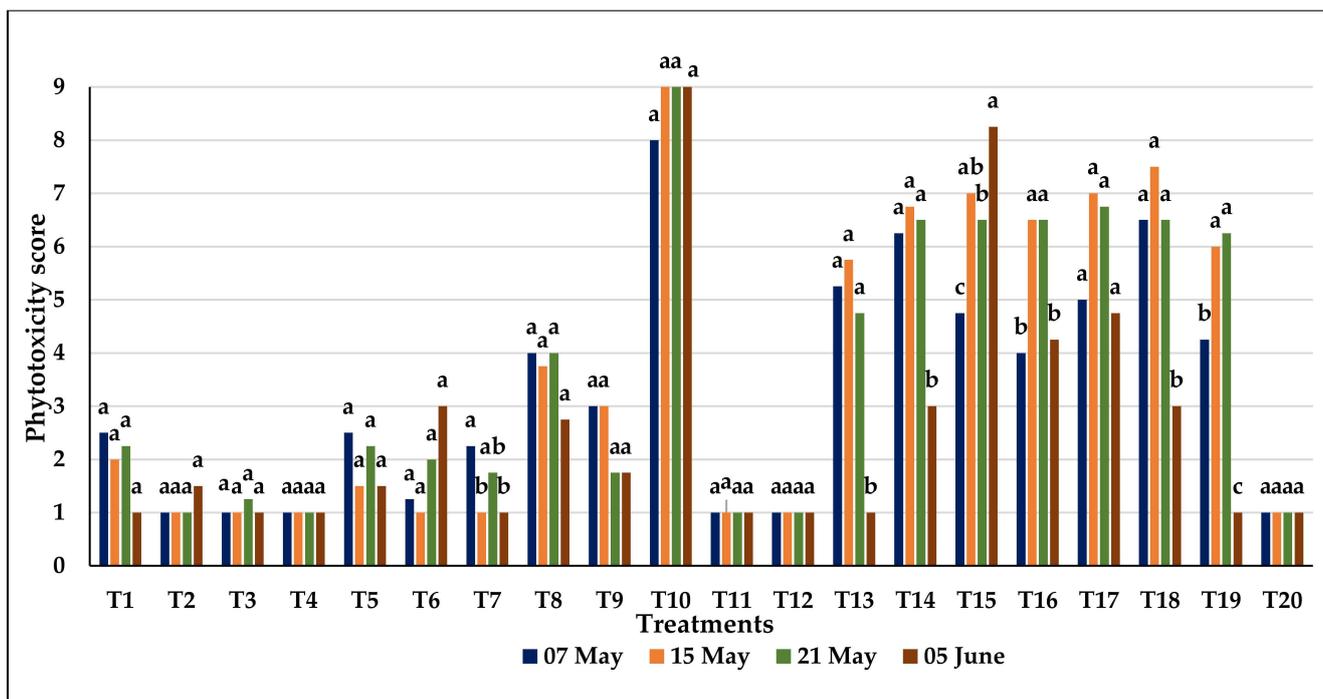


Figure 8. The results of visual phytotoxicity assessments of common vetch observed at BBCH 39 (7 May), BBCH 42 (15 May), BBCH 46 (15 May), and BBCH 64 (5 June) for herbicide treatments (2024). Letters indicate significant differences between results of different observation times within a treatment (Duncan's post hoc test: $p < 0.05$).



Figure 9. The common vetch plot treated with clomazone (A); the plot treated with the higher dose of chlorotoluron post-emergence (B); the plot treated with sulfosulfuron (C); and the control plot (D). The photodocumentation was taken 56 days after sowing (2024).

3.2.3. Herbicide Efficacy in Reducing the Number of Weeds in Common Vetch Plots

Due to the late application of the active substances, ideal weather conditions, and the rapid development of common vetch, weed infestation was not prevalent in the area, including in the control plots (Table 7). There was no significant difference in the number of weeds between the control and any of the treatment plots. Wild radish (*Raphanus raphanistrum* L.), common ragweed (*Ambrosia artemisiifolia* L.), and Lady's-thumb (*Persicaria maculosa* Gray.) were the most abundant in the plots.

3.2.4. Effect of Herbicides on Plant Height of Common Vetch

The clopyralid + picloram (T10) treatment caused complete plant death, hence, no plant height could be measured (Table 7). The growth of plants treated with sulfosulfuron (T15) was significantly lower than that of plants in other treated and control plots (T20). Also, the height of plants treated with the active substances thifensulfuron-methyl (T16, T17) was significantly lower than those in other treated and control plots. Other pre- and post-emergence treatments did not significantly affect the plant height, though clomazone (T4) had the tallest plants on average.

3.2.5. Relationships Between Variables Detected by Spearman's Rho Correlation Test at Two Levels in Common Vetch

According to Spearman's correlation test, the strongest negative correlation was obtained between the NDVI and phytotoxicity ($r = -0.936$; $p \leq 0.01$). On the contrary, the strongest positive correlation was achieved between the NDVI and plant height ($r = 0.530$; $p \leq 0.01$). In addition, phytotoxicity was negatively correlated with plant height ($r = 0.558$, $p \leq 0.01$). The number of weeds did not correlate with other variables (Table 8).

Table 8. Spearman's rho correlation test results obtained at two levels in the common vetch (2024 experiment).

	NDVI	Phytotoxicity Scores	Number of Weeds	Height of Plants
NDVI	1			
Phytotoxicity scores	-0.936 **	1		
Number of weeds	-0.049	0.087	1	
Height of plants	0.53 **	-0.558 **	-0.094	1

Note. ** $p < 0.01$ Spearman's rho. The color of the cells shows the direction of the correlation (positive direction: green color; negative direction: red color), as well as the strength of the correlation: the darker the color shade, the stronger the correlation.

3.3. Results of the Herbicide Test in Sweet White Lupine (2024)

3.3.1. Effect of Herbicide Treatments on the NDVI Values of Sweet White Lupine

NDVI values of plots were significantly affected by herbicide treatments, especially those applied post-emergence. NDVI values were significantly lower measured in plants treated with the highest dose of halauxifen-methyl (T13), halauxifen-methyl + picloram treatments (T14, T15), prosulfocarb (T16), the higher dose of sulfosulfuron (T19), and imazamox (T20) compared to the control (T22) (Figure 10, Table S2). The higher dose of halauxifen-methyl + picloram (T15) was the most harmful to the plants, resulting in the lowest NDVI values in these plots, which were significantly lower than all other treatments. The NDVI values on plots treated with the lower doses of halauxifen-methyl + picloram (T14) and imazamox (T20) were also significantly lower than those obtained in the other plots. The NDVI values of plants in the plots treated with the other active substances were similar to the control plots. Among all treatments, flumioxazin applied pre-emergence (T1) resulted in the highest NDVI values.

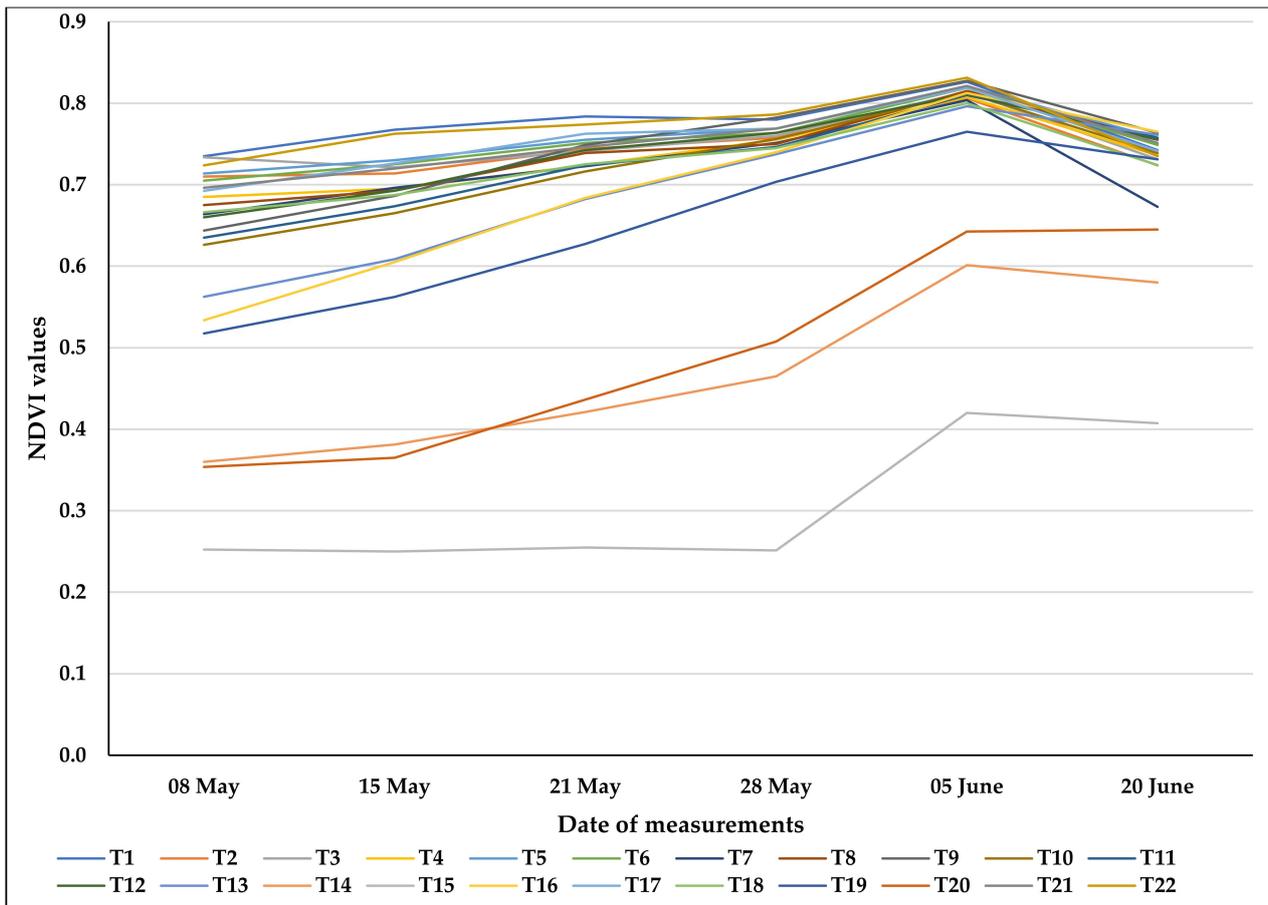


Figure 10. Effect of different herbicides on NDVI values during vegetation period in sweet white lupine (2024). Details including means and homogenous groups are in Table S2.

3.3.2. Phytotoxicity of Herbicides on Sweet White Lupine

The phytotoxicity score of plots treated with different doses of halauxifen-methyl + picloram (T14, T15) and with the imazamox (T20) were significantly higher than that of the control (T22) and the other treatments (Table 9). Among the post-emergent treatments, the medium and high doses of halauxifen-methyl (T12, T13), prosulfocarb (T16), and the higher dose of sulfosulfuron (T19) also resulted in significantly higher phytotoxicity to varying degrees as compared to the control. Among the pre-emergence treatments, only metribuzin (T7) caused damage symptoms, which varied from plot to plot—resulting in high standard error values. The other pre-emergence treatments were completely symptom-free or caused only very mild symptoms but it should be noted that in the case of diflufenican (T8), although some color change was observed after application, the plants recovered from this over time. No phytotoxicity was detected in any of the flumioxazin-treated plots, either applied pre-emergence or post-emergence.

The sweet white lupine plants showed some recovery ability as time went on after several treatments, although this regeneration was significant only after treatment T11 and T21 (Figure 11). In contrast, the symptoms became significantly more severe after their first observation in treatments T14 and T19 (Figure 11).

Table 9. Effect of herbicides on the phytotoxicity score, number of weeds, plant height, yield, and 1000-seed weight in sweet white lupine (2024). Letters indicate significant differences between treatments (Duncan's post hoc test: $p < 0.05$).

Active Substances	Treatment Codes	Phytotoxicity Score ¹	Number of Weeds 0.25 m ⁻²	Plant Height cm	Yield kg ha ⁻¹	1000-Seed Weight g
Flumioxazin (pre-emergence)	T1	1.00 f	0.9 a	52.4 a	1847 ab	290 a
Pendimethalin (pre-emergence)	T2	1.42 f	1.1 a	47.1 a–d	1374 abc	284 a
Dimethenamid-P (pre-emergence)	T3	1.17 f	0.6 a	46.9 a–d	1506 abc	305 a
Pethoxamid (pre-emergence)	T4	1.42 f	0.4 a	45.2 a–d	1416 abc	299 a
Clomazone (pre-emergence)	T5	1.33 f	0.5 a	49.4 ab	1906 a	311 a
Metobromuron (pre-emergence)	T6	1.08 f	1.1 a	48.0 abc	1834 ab	304 a
Metribuzin (pre-emergence)	T7	3.25 de	0.5 a	48.3 abc	1248 bc	304 a
Diflufenican (pre-emergence)	T8	1.83 f	0.5 a	47.8 abc	1540 abc	300 a
Flumioxazin (post-emergence)	T9	2.08 ef	0.9 a	46.6 a–d	1537 abc	294 a
Chlorotoluron (post-emergence)	T10	1.92 f	0.3 a	41.1 b–e	1597 abc	302 a
Halauxifen-methyl (post-emergence)	T11	2.25 ef	0.5 a	48.8 abc	1691 ab	330 a
Halauxifen-methyl (post-emergence)	T12	3.25 de	0.4 a	52.2 a	1500 abc	320 a
Halauxifen-methyl (post-emergence)	T13	4.75 c	0.4 a	41.5 b–e	988 c	330 a
Halauxifen-methyl + picloram (post-emergence)	T14	7.50 a	0.3 a	31.5 fg	88 d	269 ab
Halauxifen-methyl + picloram (post-emergence)	T15	8.08 a	0.1 a	0.0 h	0 d	0 c
Prosulfocarb (post-emergence)	T16	3.92 cd	0.1 a	39.8 de	1397 abc	312 a
Carfentrazone-ethyl (post-emergence)	T17	1.17 f	1.3 a	47.8 abc	1672 ab	295 a
Sulfosulfuron (post-emergence)	T18	1.33 f	0.5 a	44.8 a–d	1447 abc	306 a
Sulfosulfuron (post-emergence)	T19	6.00 b	0.5 a	35.1 ef	381 d	292 a
Imazamox (post-emergence)	T20	7.50 a	0.3 a	28.1 g	157 d	224 b
Diflufenican (post-emergence)	T21	1.50 f	0.8 a	45.2 a–d	1775 ab	306 a
Control	T22	1.00 f	0.5 a	51.3 a	1431 abc	284 a

¹ Phytotoxicity score is the average of the results obtained during vegetation period.

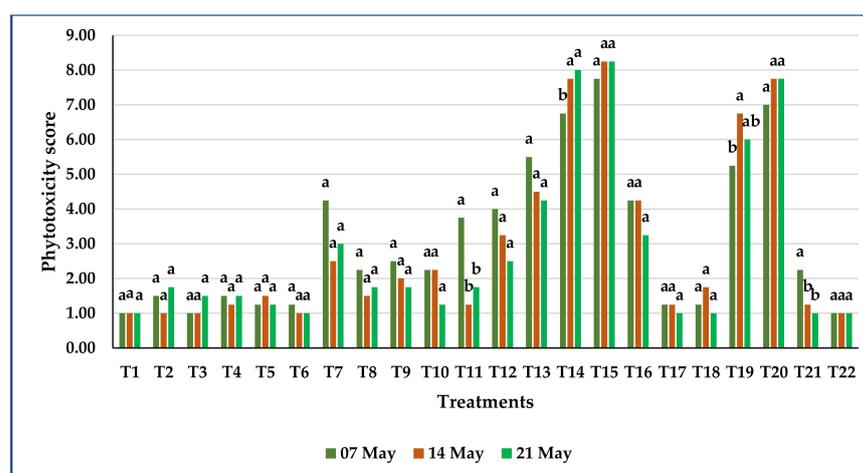


Figure 11. The results of visual phytotoxicity assessments of sweet white lupine observed at BBCH 39 (7 May), BBCH 63 (15 May), and BBCH 65 (21 May) for herbicide treatments. Letters indicate significant differences between results of different observation times within a treatment (Duncan's post hoc test: $p < 0.05$).

Figure 12A shows a healthy stand of plants treated pre-emergence with flumioxazin (T1). Although the plants treated with the highest dose of halauxifen-methyl (T13) were slightly closer to healthy stands at the time of observation after phytotoxicity monitoring, they were still lagging behind the control in size and developmental stage, as shown by the lower flowering rate in Figure 12B. Figure 12C shows severe damage, stunted plant growth, uneven stand development, and low plant population caused by the lower dose of halauxifen-methyl + picloram (T14). In contrast, Figure 12D shows the control plot with uniformly developed and flowering plants.



Figure 12. The plot treated by flumioxazin applied pre-emergence (A); the plot treated by the highest dose of halauxifen-methyl (B); the plot treated by a lower dose of halauxifen-methyl + picloram (C); and the control plot without any herbicide treatment (D). The photodocumentation was taken 70 days after sowing (2024).

3.3.3. Herbicide Efficacy on the Number of Weeds in Sweet White Lupine

During the experimental season, no serious weed infestation occurred, hence, there was no significant difference between the most and least effective treatments (Table 9). This was validated by the absence of weed infestation in the control (T22) plots. However, the common ragweed, white goosefoot, and redroot pigweed were the most common weeds in the plots.

3.3.4. Effect of Herbicides on Plant Height of Sweet White Lupine

The plant height was measured 71 days after sowing. The higher dose of halauxifen-methyl + picloram (T15) caused complete plant death by the time of measurement, thus the plant height data was 0 cm (Table 9). Significantly lower heights were recorded in the case of post-emergence applied chlorotoluron (T10), the highest dose of halauxifen-methyl (T13), lower dose of halauxifen-methyl + picloram (T14), prosulfocarb (T16), sulfosulfuron (T19), and imazamox (T20) compared to the control (T22). The height values for the other treatments were similar to the control.

3.3.5. The Effect of Herbicides on the Seed Yield of Sweet White Lupine

The seed yield of plants from plots treated with different doses of halauxifen-methyl + picloram (T14, T15), higher doses of sulfosulfuron (T19), and imazamox (T20) were significantly lower than the control (T22) plots and the other treatments (Table 9). There was an extremely large difference in the seed yield between plants treated with lower doses of sulfosulfuron (T18) and plants treated with higher doses (T19). The seed yield of plants in plots treated with the highest dose of halauxifen-methyl (T13) also differed significantly from the control. The seed yield of lupines in the other treated plots was not significantly different from the control plots. The seed yield of plants in plots treated pre-emergence with flumioxazin (T1), clomazone (T5), metobromuron (T6), and diflufenican (T21) tended to exceed the yield of plants in the control plots, although these differences were not significant. The clomazone (T5) treatment resulted in the highest seed yield, with the seed yield from plots treated with this active substance exceeding (not significantly), the seed yield from control plots by 181·kg/ha.

3.3.6. Seed Yield Contamination in Treated and Control Plots of Sweet White Lupine

Plots treated with higher doses of halauxifen-methyl + picloram (T15) yielded essentially only damaged seeds, weed seeds, and dry and green parts of the plants, thus, the crop contamination increased significantly to 100% (Figure 13). This was followed by a 17% crop contamination rate from plots treated with lower doses of halauxifen-methyl + picloram (T14). The lowest seed yield contamination of 2% was recorded in plots treated with dimethenamid-P (T3) and clomazone (T5). The contamination rate of the crop from the control (T22) plots was 9%.

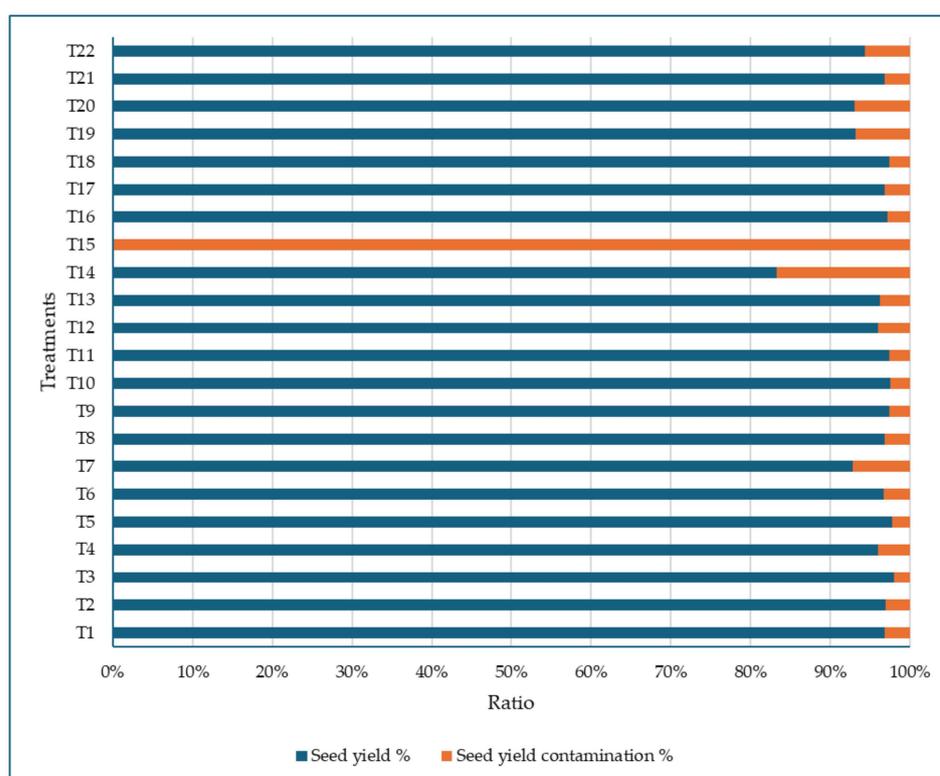


Figure 13. The ratio of seed yield contamination to the total seed yield (%) in sweet white lupine (2024).

3.3.7. Effect of Herbicides on 1000-Seed Weight in Sweet White Lupine

The plants in the plot (T15) treated with the higher dose of halauxifen-methyl + picloram did not set seeds so we could not measure 1000 seeds' weight (Table 9). The

imazamox (T19) treatment resulted in a significantly lower 1000-seed weight compared to the control (T22) and the other treatments (except halauxifen-methyl + picloram lower-dose treatment (T14)). The imazamox treatment significantly reduced the seed yield of plots, with one plot failing to produce any seeds at all. This outlier contributed substantially to the large standard error observed in the data. The 1000-seed weights of seeds from the other treated plots were similar to those of the control.

3.3.8. Relationship Between Parameters Assessed in Sweet White Lupine Experimental Plots

Spearman's rho correlation two-test analysis showed a significant inverse relationship between the NDVI values and phytotoxicity scores ($r = -0.880$; $p = 0.01$). There was a positive correlation between NDVI and the number of weeds. The strongest positive correlation was observed between NDVI and the height of plants with a correlation coefficient of $r = 0.843$ at the 0.01 level. There was also a positive relationship between NDVI and crop contamination. For the measured data, the second strongest positive correlation between NDVI values and seed yield was at the 0.01 level. However, the phytotoxicity scores were negatively correlated with all measured values at the 0.01 level (weed number, plant height, crop contamination, and net seed yield), except for the 1000-seed weight where the negative correlation was not significant. The number of weeds was positively correlated with the height of the cultivated plant at the 0.01 level and with the crop contamination and seed yield at the 0.05 level. Lupine height was positively correlated with crop contamination data. Plant height value was positively correlated even with seed yield and 1000-seed weight at the 0.01 level. Seed yield contamination was positively correlated with seed yield and 1000-seed weight at the 0.01 level (Table 10).

Table 10. Relationships between observed parameters of experimental plots.

	NDVI	Phytotoxicity Scores	Number of Weeds	Height of Plants	Seed Yield Contamination	Seed Yield	1000-Seed Weight
NDVI	1						
Phytotoxicity scores	-0.88 **	1					
Number of weeds	0.381 **	-0.325 **	1				
Height of plants	0.843 **	-0.712 **	0.316 **	1			
Seed yield contamination	0.586 **	-0.568 **	0.227 *	0.544 **	1		
Seed yield	0.779 **	-0.748 **	0.257 *	0.737 **	0.593 **	1	
1000-seed weight	0.192	-0.132	0.026	0.305 **	0.285 **	0.485 **	1

Note. * $p < 0.05$, ** $p < 0.01$ Spearman's rho. The color of the cells shows the direction of the correlation (positive direction: green color; negative direction: red color), as well as the strength of the correlation: the darker the color shade, the stronger the correlation.

4. Discussion

Effective herbicide management strategies are critical components of modern crop production. However, cultivated crops are sensitive to herbicides in different ways, thus experiments should be conducted to test their phytotoxicity. We tested several active substances applied pre- and post-emergence in sweet lupine and common vetch in the 2023 and 2024 crop years.

Weed species in the field can significantly impact both the quantity and quality of the seed yield. Besides an evaluation of the phytotoxicity of herbicides, we studied their effectiveness in weed control. The number of weeds per unit of soil surface and the contamination of yield are the parameters, which are direct indicators of the effectiveness of herbicides.

Contamination of the harvested crop primarily refers to unwanted weed seeds, along with empty and damaged seeds [76]. Weeds can contribute to the formation of smaller and flatter seeds of cultivated crops as they shade the soil, compete for water and nutrients, and thus retard the development of the main crop [77]. Moreover, green and dry plant parts harvested with the crops are also considered as contamination. In our study, the control plots did not receive herbicide treatment so they showed the natural weed flora growing in the crop. In this case, the crops harvested from the control plots may contain a large amount of contamination in the event of heavy weed infestation.

We found a positive correlation between NDVI values and seed yield contamination. This relationship can probably be explained by the fact that there was also a positive correlation between contamination and the number of weeds. Since NDVI values measure the total above-ground biomass on the plot including crops and weeds, this may contribute to the positive correlation between NDVI values and yield contamination. Accordingly, where there are more and well-growing weeds, the NDVI value will be higher, as will the yield contamination. During this study, the most significant negative correlation was observed between NDVI values and phytotoxicity ($r = -0.880$, $p < 0.01$). This correlation indicates that herbicide damage resulted in measurable differences in the biomass growth in the treated plots. Based on this, NDVI measurement proves to be an effective tool for accurately detecting the extent of herbicide damage [78]. A positive correlation was also obtained between NDVI values and the number of weeds in the lupine experiment, whereas in the case of common vetch, the relationship was negative in both years, although the correlation was only significant in the first year. The reason for this may have been that weeds in the common vetch culture primarily emerged in those plots where the vetch was heavily damaged by the herbicide, thus, overall lower biomass was produced in these plots. We also measured a significant positive correlation between NDVI values and the plant height for both crops ($r = 0.843$ in lupine, $r = 0.53$ in common vetch). Since higher plant height may be associated with more nodes and therefore larger foliage, the higher biomass associated with higher plant height may result in higher NDVI values [79]. However, it is likely that higher plant height is associated with a more advanced age, which is the key factor for the quantity of biomass [80]. We also found a strong positive correlation between NDVI values and seed yield, as well as between NDVI values and crop contamination. Higher biomass (resulting in higher NDVI values) is generally associated with a larger photosynthetically active surface area, promoting higher crop yield [81], which explains the strong relationship between the two variables. Higher crop contamination can be attributed to the presence of higher weed mass, which also leads to higher biomass and thus higher NDVI values [82], as mentioned above. The strong positive correlation between plant height and seed yield—and in the case of lupine, between plant height and 1000-seed weight—was also demonstrated in our experiments. The same relationships may explain the negative correlation of phytotoxicity values with plant height, yield, and crop contamination. Additionally, the NDVI values could predict forage quality parameters with 49–85% accuracy, making it a valuable method for the non-destructive assessment of vetch species' nutritive value [83].

Pendimethalin did not significantly reduce the height of common vetch, which was similar to other results [58]. The NDVI values measured for pendimethalin-treated plants were also not significantly different from the control results, similar to our 2022 findings where we did not find any difference between pendimethalin-treated and control plants using different vegetation index datasets (NDVI, GNDVI, and ENDVI) by unmanned aerial vehicle (UAV) [56].

In the year 2024, there were also no negative effects of S-metolachlor on common vetch. Other results showed that S-metolachlor applied in lower doses could be a good

choice due to a minimal risk of phytotoxicity. However, when applied with other substances it may have negative effects [58]. The flumioxazin applied pre-emergence exhibited minor phytotoxic effects during the initial stages of hairy vetch development [69], although it had no negative effect on plant height and did not negatively affect seed yield in common vetch [58]. These results are consistent with our findings since we also found flumioxazin to be among the more promising active substances in both pre-emergence and post-emergence applications.

Although MCPB has not been previously evaluated for its effects on common vetch, it was reported that it may affect negatively the growth, yield, and nitrogen fixation of lentil (*Lens culinaris* 'Eston') [84]. Similarly, we observed in both experimental years that the herbicide caused notable symptoms.

The imazamox resulted in chlorosis and growth inhibition, which aligns with previous findings. The herbicide also caused mild injury on common vetch, manifesting as chlorosis of the stems and leaves, particularly at the growing apex. At 12 weeks after sowing, injury levels ranged from 5% to 16.3% [58]. Post-emergence application of imazamox, triflurosulfuron-methyl, sulfosulfuron, and thifensulfuron-methyl in hairy vetch (*Vicia villosa* Roth.)—a species closely related to common vetch—induced chlorosis and inhibited plant growth [85]. Our results showed that these ALS inhibitors resulted in high phytotoxicity and seed yield reduction in common vetch.

In our herbicide trial in 2022, the seed yield of common vetch plots treated with bentazon was lower than the control plots [36]. In 2024, it caused severe damage, which could have resulted in a poor seed yield. In our 2023 experiment, bentazon resulted in the highest seed yield. However, an earlier study reported complete crop failure under bentazon application. This contrast highlights the variability in bentazon's effects. Our findings align with an earlier study [86], which concluded that while bentazon does not always inhibit plant growth, its use is limited under certain conditions [86]. In the first growing season, flumioxazin applied pre-emergence was one of the herbicide treatments that resulted in greater plant dry biomass of lupines compared to untreated plots. Kousta et al. [30] explained that pre-emergence-applied flumioxazin not only lacks phytotoxic effects but also has the potential to improve the growth of lupine plants. Our results suggested that pre-emergence applications of flumioxazin provide a better approach to weed management in lupines, whereas post-emergence use may cause some plant stress. Its effect on the seed yield is uncertain and may vary depending on factors such as application timing and environmental conditions [42,56].

Pethoxamid and clomazone have been reported as being effective across two years, with clomazone-treated sweet white lupine plots consistently yielding more than control plots in two growing seasons [56]. Likewise, another experiment found that while pethoxamid caused phytotoxicity in several bean genotypes, it did not negatively affect their seed yield [87]. In our 2022 experiment, the highest seed yield was recorded under pendimethalin-treated plots in sweet white lupine. However, in this current study, the seed yield from pendimethalin-treated plots was lower than in control plots, although the differences were insignificant. Thus, we can confirm the results of several studies that no significant phytotoxicity is expected when pendimethalin is applied pre-emergence in sweet white lupine [41,56,88,89]. For example, earlier reported results suggested that dimethenamid-P can be used alone or in combination with pendimethalin in white lupines [41,56,90]. Our findings also supported this, showing no significant phytotoxic effects of dimethenamid-P applied alone on sweet white lupine. Additionally, metobromuron, whether used alone or in combination with other herbicides, did not exhibit significant phytotoxic effects on sweet white lupine [37]. Therefore, based on our 2022 and current results, we con-

firm the applicability of metobromuron in white sweet lupine, just as the earlier author suggested [56].

Metribuzin, when applied pre-emergence, can cause injury to faba beans, particularly when used at higher dosages [91]. The extent of this damage is influenced by the timing and method of application, as well as environmental conditions such as soil moisture and temperature. We also observed the highest phytotoxicity and the lowest NDVI values in the metribuzin-treated plots in our sweet white lupine experiment conducted in 2022 [56], whereas in the present study, we found that the active substance also caused symptoms in lupines but not to the same extent. Diflufenican was tested in our experiments in lupine culture for one year and we found that although pre-emergence applications of diflufenican showed slightly more phytotoxic effects than post-emergence applications, neither method resulted in significant phytotoxicity to the crop, similar to other results [41]. In the growing season of 2023, the plants treated post-emergence with chlorotoluron showed significantly lower NDVI values and exhibited phytotoxic symptoms in sweet white lupine [42]. However, in the next season (2024), test results showed no significant difference compared to the control plants. This suggests that the active ingredient may work differently in different areas and under different seasonal conditions.

Halauxifen-methyl applied post-emergence caused significant visible symptoms in soybeans, and reduced biomass, population, heights of the plants, and seed yield [50] but it was the least phytotoxic active substance in sweet white lupines [42]. In this study, the halauxifen-methyl applied in sweet white lupine at a lower dose ($0.4 \text{ L}\cdot\text{ha}^{-1}$) showed better phytotoxicity results than higher doses ($0.5 \text{ L}\cdot\text{ha}^{-1}$ and $0.6 \text{ L}\cdot\text{ha}^{-1}$). Further tests should evaluate the efficacy of a lower dose ($0.4 \text{ L}\cdot\text{ha}^{-1}$) of the active substance against weeds. In an experiment where prosulfocarb was applied at $2400 \text{ g}\cdot\text{ha}^{-1}$ to yellow and white lupines pre-emergence, no phytotoxic symptoms were observed [41]. In contrast, prosulfocarb caused symptoms in post-emergence applications in two growing seasons, and the seed yields of treated plots were lower than those of control plots, even if the differences were not significant [42].

Pre-emergence application of $20 \text{ g}\cdot\text{ha}^{-1}$ carfentrazone-ethyl resulted in greater plant mortality than rimsulfuron in sweet white lupine without affecting the vigor of the survivor plants [31]. Based on our results published earlier, the active substances carfentrazone-ethyl sulfosulfuron and halauxifen-methyl were found to be worthy of further testing [42]. The seed yield of lupine plots treated with carfentrazone-ethyl and lower doses of sulfosulfuron were not significantly lower than those of control plots, and no phytotoxicity was observed. However, the use of higher doses of sulfosulfuron caused severe damage and significantly reduced seed yield.

Post-emergence application of imazamox caused only 16% damage in soybeans [92]. In one study, imazamox did not cause significant symptoms and resulted in higher dry matter accumulation in the first growing season of sweet white lupine [30]. In contrast, we observed damage in the 2022 growing season and imazamox resulted in the lowest seed yield [56]. Similarly, in this study, the use of imazamox caused severe damage and the affected plants produced almost no seeds.

To our knowledge, the herbicide combination of metazachlor + quinmerac is primarily used in oilseed rape (*Brassica napus* L.). While it has not been extensively tested in legume crops, our two-year study suggests its potential efficacy in common vetch and other legumes, though further studies are needed.

Our study did not examine the long-term effects of the active substances on soil and crop rotation. Several of the active substances proposed for further testing may have negative effects on soil and crop rotation in the longer term, according to the literature sources. Clomazone and chlortoluron impact microbial diversity and nutrient cycling,

with clomazone persisting for years and potentially harming subsequent crops [93,94]. Carfentrazone-ethyl disrupts the soil microbial balance and reduces wheat yields at high doses [95]. Sulfosulfuron's persistence in soil varies, lasting less than five months in sandy loam and approximately one hundred and fifty days in silty clay loam [96]. Metribuzin application in potatoes (*Solanum tuberosum* L.) did not reduce the following spring's yields of winter rye (*Secale cereale* L.) and red clover (*Trifolium pratense* L.) but significantly reduced those of barley (*Hordeum vulgare* L.) and timothy (*Phleum pratense* L.) [97].

Although different doses have been tested, further detailed studies are needed to determine the optimal application rates that minimize phytotoxicity while providing effective weed control.

5. Conclusions

In our experiments, several herbicide-active substances were tested in leguminous crops like sweet white lupine and common vetch for the first time. The phytotoxicity results obtained in common vetch—including the NDVI, phytotoxicity scores, and plant height data—indicated that S-metolachlor, flumioxazin, and clomazone applied pre-emergence showed no phytotoxic effects on the studied crops. Thus, we recommend further testing them. The effect of crop year could be detected considering the post-emergence treatments. Slightly higher phytotoxicity values were obtained in the year 2023 in common vetch compared to the year 2024. Similarly, flumioxazin and metazachlor + quinmerac post-emergence treatments had conspicuous symptoms only in the 2023 crop year. In addition, chlorotoluron applied post-emergence has also exhibited promising results. Accordingly, we recommend further evaluation of flumioxazin, metazachlor + quinmerac, and chlorotoluron in post-emergence applications.

In sweet white lupine, out of the pre-emergence treatments, the application of flumioxazin, pendimethalin, dimethenamid-P, pethoxamid, clomazone, metobromuron, and diflufenican showed no phytotoxicity, thus it would be worthwhile to be tested them further. Results obtained from lupine plots treated with post-emergence application of the active substances flumioxazin, chlorotoluron, carfentrazone-ethyl, and diflufenican were not statistically different from the control plots. Moreover, the lowest doses of halauxifen-methyl and sulfosulfuron ($0.4 \text{ L}\cdot\text{ha}^{-1}$ and $13 \text{ g}\cdot\text{ha}^{-1}$, respectively) are also suggested to be evaluated further in field experiments.

Based on Spearman's correlation test, the results of the NDVI, phytotoxicity test, and plant height datasets can be used as good predictors for estimating the seed yield of treated plots.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/agronomy15040916/s1>, Table S1: Effect of herbicide treatments on the NDVI values of common vetch. Table S2: Effect of herbicide treatments on the NDVI values of sweet white lupine.

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