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Mechanical Weed Control: Sensor-Based Inter-Row Hoeing in Sugar Beet (*Beta vulgaris* L.) in the Transylvanian Depression

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Abstract: Precision agriculture is about applying solutions that serve to obtain a high yield from the optimization of resources and the development of technologies based on the collection and use of precise data. Precision agriculture, including camera-guided row detection and hydraulic steering, is often used as an alternative because crop damage can be decreased and driving speed can be increased, comparable to herbicide applications. The effects of different approaches, such as uncontrolled (UC), mechanical weed control (MWC), herbicide weed control (HWC), and mechanical + herbicide control (MWC + HWC), on weed density and yield of sugar beet were tested and evaluated in two trials (2021 and 2022) in South Transylvania Depression at the tested intervals BBCH 19 and 31. Weed control efficacy (WCE) depends on the emergence of the weeds and a good timing of weed controls in all the trials and methods, though the highest yield of sugar beet roots was recorded in the treatment MWC + HWC, with an increase up to 12–15% (56.48 t ha^{-1}) yield from HWC (50.22 t ha^{-1}) and a yield increase of more than 35–40% than MWC (42.34 t ha^{-1}). Our trials show that it is possible to increase yield and have fewer chemical applications with the introduction of new precision technologies in agriculture, including sensor-guided mechanical controls.

Keywords: herbicide reduction; sensor hoeing; weed management; precision farming; beta vulgaris

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1. Introduction

Weeds left in sugar beet (*Beta vulgaris* L.) cause problems during harvesting the beet roots for sugar production, decrease yield, and increase weed populations in future crops due to the mature weed seeds or rhizomes left in the soil [1]. Therefore, an Integrated Weed Management (IWM) strategy is very important, and practices need to be applied in sugar beet cultivation and in programs of pesticide reduction and environmental protection [2,3], such as the European Green Deal.

Economic, ecological, and social factors characterize modern and sustainable sugar beet production [4]. In this context, field cropping strategies should consider environmental aims while ensuring fair profits for farmers and the associated agricultural industry [5]. At the same time, after the elaboration of management factors such as pesticides, high-yielding and pest-tolerant cultivars, irrigation systems, and different synthetic fertilizers, the food quality must also be guaranteed [6]. The interaction of integrated methods of crop protection is mandatory for prospective and sustainable food production [7]. The European Union directives encourage farmers to meet stricter standards concerning pest management, and solutions are needed in this direction [8]. This leads to restrictions on herbicide applications and promotes the reduction of the total amounts of herbicides applied. The European Commission favors a reduced input of pesticides in the agricultural supply chain [9].

Chemical weed control still plays an important role in the weed management strategy in sugar beet [10]. Therefore, effective weed management is crucial. Chemical weed control has currently evolved into a required and unavoidable component of weed management in sugar beet production [11]. The most important herbicide mixtures contain the following active ingredients: metamitron, phenmedipham, and ethofumesate. Before being withdrawn from use in the European Union, the mixtures also included desmedipham [12]. For sugar beet, the common weed control practice is the implementation of 3–5 postemergence herbicide applications in the cotyledoneous stage of the weeds [13]. Nevertheless, high environmental risks and crop damage may be the consequences of the herbicide application [14].

A part of IWM is mechanical weed control, with new perspectives today [15,16]. The implementation of mechanical weed control tools in sugar beet production can substitute herbicide treatments and therefore reduce the amount of different herbicides in the environment [17–19]. Due to the slow driving speeds and limited working width of the implements, labor efficiency is relatively low compared to chemical weed control [11]. Even more, hoeing in the intra-row area and operating as closely as possible to the crop area are the requirements for a successful mechanical weed control management strategy [20]. The use of precision agriculture (PA) is an expedient way of steering the hoe close to the crop row and offers new research perspectives. Gerhards et al., 2021 [20] showed that 3 m camera-guided hoeing in cereals was possible with only a lateral offset of 19 mm from the crop row. Furthermore, driving speed could be increased up to 8 km h^{-1} with a weed control efficacy of nearly 80% and no crop losses [21]. The use of PA in agriculture is gaining more and more importance due to the commercialization of new developments like the Global Positioning System (GPS) [22–24]. The operation with PA can reduce labor costs and is able to increase the speed of the applications [25]. The use of Global Navigation Satellite System (GNSS) technologies or digital image progression is needed for accurate guidance [26,27]. Guidance systems within the field identify the position of the crop rows, and a hydraulic side shift system steers the hoe close to the crop area (5 cm on each side) and provides higher driving speeds by reducing the farmer's work time [28–31].

Weed control in sugar beet cultivation is increasingly difficult because the physiological stage of the crop is small and strict, and technical rules are imposed with low and precisely fractionated doses [1,32]. Thus, it is interesting to investigate the differences between chemical and mechanical controls on weeds in the sugar beet crop [18,33].

Mechanical weed control in agriculture has advanced in terms of precision and working rate over recent years [34]. The real-time communication of implements with sensor systems further increased the potential of mechanical weeding [35]. There is a wide array of available sensors, including image analysis using cameras, the GNSS, lasers, and ultrasonic systems, that can improve weed control efficacy in combination with mechanical systems [36,37]. Every sensor type has its advantages and disadvantages [38]. Camera-steered hoes with a hydraulic side shifting control for row crops are robust and reliable, and they are now widely available from different manufacturers [33].

The advantages as we anticipate during the experiment is that in the region of study the farmers cultivate sugar beet on 100–200 ha maximum in the culture rotation at a normal farm of 1000 ha arable land, so the hoeing can be undertaken easily in a couple of days because of the high speed advantage from the row guard steering and the recognition of the sugar beet row, and the crop damage is very low.

Therefore, the objectives of this study were to combine chemical (pre- and post-emergence herbicides) and sensor-based mechanical treatments (sensor-guided hoeing) to evaluate these combinations to reduce the amount of herbicide use while maintaining high yield, equal weed control, and adequate crop selectivity.

The hypotheses of this study were as follows: (i) reduce the chemical treatments (pre-emergence and post-emergence herbicides) and reduce the stress of the plant; (ii) increase weed control efficacy up to 98%, including precision technologies, and maximize the yield

up to 60 t ha^{-1} due to mechanical weed control included in the conditions and weed abundance from the South Transylvanian Depression, Romania.

2. Materials and Methods

2.1. Experimental Site and Design

This study investigated sugar beet during the years 2021–2022, in the hilly Depression of Transylvania. This depression relief unit inside the Carpathian arc has a predominantly hilly relief, and the representative agricultural crops are cereals and technical plants, especially sugar beet. The experiments were located at the conventional farm fields "Vinţana SA" in the village of Vinţu de Jos (45.99° N, 23.48° E), country Alba. The field trials are in the intra-Carpathian chain of mountains and at the plateau of the river Mureș, which has a good environment for agriculture and sugar beet cultivation, at an elevation of 284 m above sea level and an average rainfall of 520–550 mm annual^{-1}. The precipitations that are relevant for our climate and included in the zone of study can be found in Table 1 from spring and summer. The precipitation recorded during the sugar beet vegetation period was 281.67 mm for the year 2021 and 268.17 mm for the year 2022. The multiannual average temperature is, in general, between 8 and 9 °C. During the experimentation period, the annual temperature was 9.1 °C in 2021 and 9.0 °C in 2022, respectively.

Table 1. Precipitations in mm for the months of March until September in the years 2021 and 2022 for the location Vinţu de Jos.

Month/Year	2021	2022
	mm	
March	50.21	17.10
April	36.12	69.42
May	82.04	48.67
June	28.41	8.71
July	49.32	18.63
August	27.51	35.22
September	8.06	70.42
Total	281.67	268.17

Data source: meteoblue.com (accessed 15 November 2023).

The type of soil in the experimental field is Fluviosol, which is one of the most fertile in the area, easily mechanized, and usually completely arable. The soil texture was classified as loam soil with a balanced percentage of clay, dust, and sand, a weak acidic pH of around 6.3, and a humus content of around 2%.

Tillage before sowing was identical across all experimental variants. First, the soil was ploughed in autumn at a 25–30 cm depth with Kuhn Huard plough MM 150 with 4 corps (Saverne, France), followed by a seedbed preparation in early March with a Horsch Finer 7 SL combinator (Ronneburg, Germany), both performed with the tractor New Holland T7.190 (New Holland, PA, USA). Sugar beets were sown in the middle of March at conventional densities of 110,000 seeds ha^{-1}, at a depth of 4–5 cm and a row distance of 45 cm; the distance between plants within a row was 18 cm in all experimental variants.

The experiment was set up as a polyfactorial randomized complete block design with four repetitions and three treatments. The plot size in all trials was 3 × 24 m^2, with the longer side of the plots in the sowing direction of the crop.

The experimental variants were represented by the following treatments:

- V_1: Untreated control (UC);
- V_2: Conventional herbicide application (HWC);
- V_3: Mixture of 2× hoeing plus 3× chemical weed control method (HWC + MWC).

The treatment descriptions can be found in Table 2.

Table 2. Detailed description of the variants at Vinţana farm in 2021 and 2022.

No.	Variants	Description
V_1	Untreated control (UC)	No weed control
V_2	Conventional herbicide application (HWC)	3× Chemical weed control only; spraying 3 times with a mix of 3 herbicides and 5 different substances
V_3	Mixture of 2× hoeing plus 3× chemical weed control method (HWC + MWC)	3× Chemical weed control only; spraying 3 times with a mix of 3 herbicides and 5 different substances + 2× mechanical weed control with goose feet at the stages of 6 leaves (BBCH 19) and 9 leaves (BBCH 3) of sugar beet

Notes: In 2022, we also tested the MWC (mechanical only weed control) variant separately.

The UC variant was left untreated for the entire growing season. However, it was ensured that the UC also received the same number of passes with the tractor wheels as the mechanical and herbicide treatments.

The hoeing system of the experiment had one camera to recognize 3 rows from the experiment field of the sugar beet rows and a hydraulic side shift system (Figure 1). Hoeing was performed parallel to the crop rows with a driving speed of 8 km h^{-1}. Hoeing the sugar beet row was performed with two goosefeet sweeps (20 cm), two side-knives, and two protection disks. Figure 2 shows an image 2 plots wide, with a total of six sugar beet rows; the picture was from the manufacturer Einbock, Austria.



Figure 1. Camera sensor-based row hoeing using Chopstar.

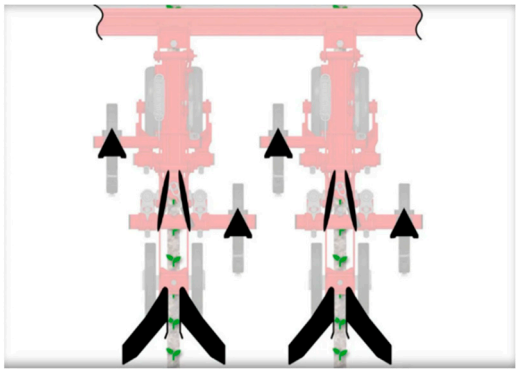

Figure 2. The set-up for the hoe used in the experiments at Vinţana farm in 2021–2022.

2.2. Implementation of the Herbicide Treatments

The herbicide application in both years was carried out with a mounted sprayer, the Amazone UF2002, from the company Amazone Hasbergen Dreyer GmbH & Co from Hasbergen, Germany, equipped with Lechler IDN 120–025 nozzles from the company Lecher GmbH from Metzingen, Germany, at a pressure of 8 bar and a speed of up to 8 to 10 km h^{-1}. Due to the high weed density in Transylvania Depression and the slow emergence of the crop until row closure, up to 60 days, a minimum of three herbicide mix sprayings must be applied over the whole field post-emergence with the low dosage technique for the broad leaf weeds (Table 3). Also, it is common for farmers to spray pre-emergence herbicides on sugar beet with a mix of three herbicides. The weed control experiment conducted in sugar beet in the year 2021 involved chemical spraying the whole field 6 times, including the substances glyphosate and metamitron pre-emergence, and in 2022, we reduced two chemical pre-emergence herbicides and left only 4 sprayings as post-emergence control only.

Table 3. Application time (BBCH of the sugar beet), active ingredients, and herbicide product at both experimental fields in 2021 and 2022.

BBCH 2021	BBCH 2022	Active Ingredients	Product Name	FM	CT g L^{-1}	AR, g ha^{-1}	Supplier
10, 14, 19	10, 14, 19	ethofumesate	Betanal tandem	SC	190	285	Bayer Crop Science
10, 14, 19	10, 14, 19	phenmedipham	Betanal Tandem	SC	200	300	Bayer Crop Science
03, 10, 14	10, 14, 19	metamitron	Goltix	SC	700	630	Adama
03		glyphopsate	Clean up	SL	360	1080	Nufarm
	10, 14, 19	lenacil	Venzar 500	SC	500	125	FMC Corporation
14, 19		clopyralid	Lontrel 300	SL	300	225	Corteva Agriscience
19	19	quizalofop-p-tefuril	Pantera 40	EC	40	40	Arysta Life science

Notes: FM—formulation; CT—concentration; AR—application rate; SC—suspension concentrate; SL—soluble liquid; EC—emulsifiable concentrate; spray volume 200 water L ha^{-1}; BBCH—Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie.

2.3. Description of the Camera-Based Row-Detection System Used in the Chopstar, Einböck

Images were taken continuously by a 2D RGB camera, scanning diagonally forward on 4 rows of sugar beets (Figure 3). The camera was mounted on a separate bracket at a height of 1,8 m on the left side of the hoe. The camera setting could be adjusted to suit the color or height of the crop. We could choose between green/yellow (e.g., corn), green/blue (e.g., soybeans and vegetables), or red (vegetables, e.g., beetroot) in 2D mode. The 3D mode can be used for corn, soybeans, sunflowers, etc., if the plant rows have a clear growth advance (approx. 10 cm/3.90″) over the weed. Correct adjustment to the crop further increases the accuracy of row guidance (Figure 4).

If there is too much weed pressure and crop leaves overlap with weed leaves and the crop line cannot be recognized clearly anymore, there is an additional 3D mode. The camera automatically recognizes the height of the plants and allows for differences between the row structure of the high crops and the small weeds. This guarantees fast row detection even if the crop leaves partly overlap in the inter-row area. The camera provides robust row detection under most lightning conditions. External artificial light improves the quality of row detection. The automatic camera steering can be conveniently set from the tractor via an operating terminal. With the help of different setting parameters adapted to the crop (row spacing, number of rows in the camera's field of view, and plant width and height), an appropriate grid is laid over the image. Based on this data, the hoe is centered exactly along the row with the help of the side-shift frame. This ensures a narrow hoeing belt, which guarantees maximum weed control.

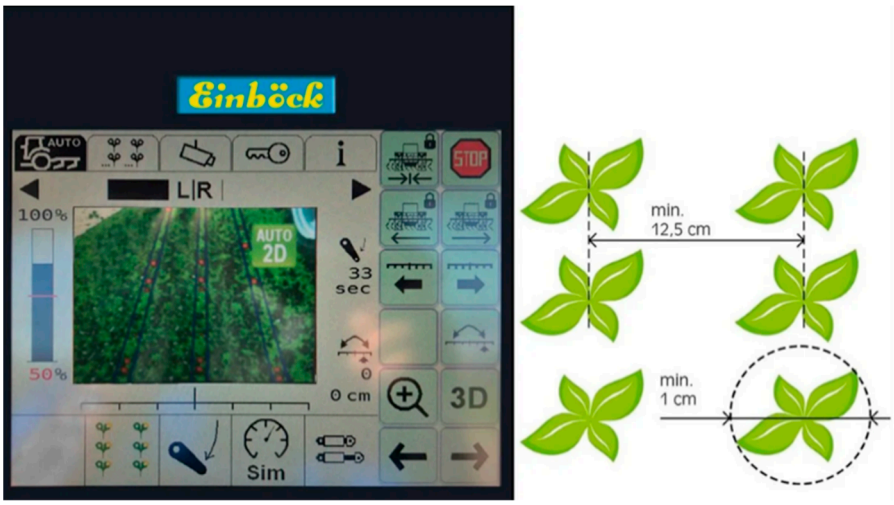

Figure 3. The software recognizes the plant rows even in cases of heavy weed infestations and/or small plants. The settings can be adjusted depending on the conditions (Einbock GmbH, Schatzdorf, Austria).

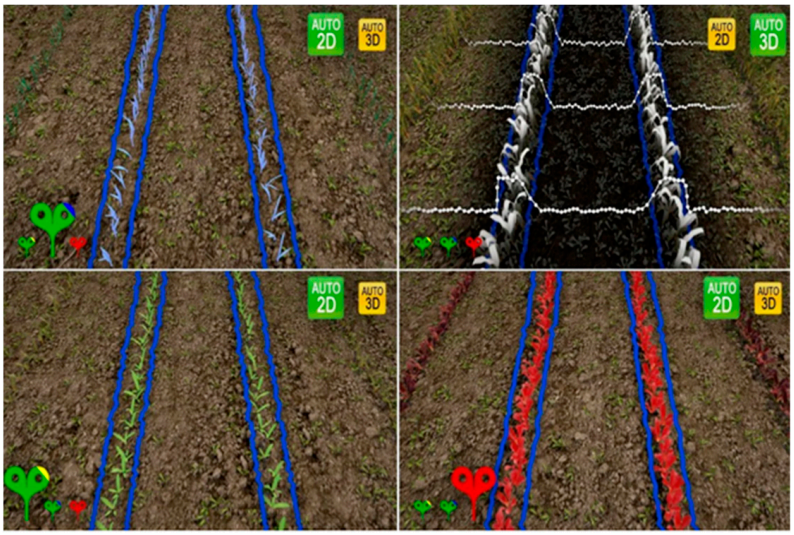

Figure 4. Adaptation of the camera application to the culture.

2.4. Implementation of the Mechanical Treatments

Hoeing was performed with the 3 m wide camera-guided hoeing system Chopstar from Einböck Gmbh, Schatzdorf 7, 4751 Dorf an der Pram, Austria. Camera-based row detection was implemented in a real-time system for automatic guidance of the goosefoot sweeps in the inter-row at a distance of 50 mm from the crop rows. Since only one model of goosefoot swipes existed, two passes with the tractor New Holland (Figure 5) were necessary to treat two sugar beet rows in each plot that had mechanical weed control with the hoe. So, it was performed on the two different plots, MWC and HWC + MWC, with the goosefoot swipes twice after the chemical treatments, in the two different stages of the sugar beet growth, the six-leaf stage and the nine-leaf stage, meaning the two different BBCHs, 19 and 31. The set-up of the mechanical sensor hoe was made on the farm adjusted to the culture of the sugar beet, meaning the width between the rows aligned with the width of the tillage controlling wheels.

Since each plot comprised six sugar beet rows, seven implements were required to control all inter-row spaces of one 3 m plot. The safety distance towards the sugar beet rows was set up to a 5 cm wide range. For intra-row control of the weeds, the finger weeders

were set up above the ground, and the protection shield elements were left on the soil to prevent sugar beet crop damage.



Figure 5. The New Holland tractor used and the sensor-based hoe Chopstar from Einbock.

2.5. Data Acquisition

Weed density (weeds m^{-2}) and weed species were measured using a 0.5 m × 0.5 m frame (Figure 6). The frame was placed in a random way three times per plot, three days after the application of the mechanical treatments and after 14 days of chemical treatments, as well as after three days on the uncontrolled plot. Sugar beet harvest (t ha^{-1}) took place in the middle of September or at the start of October in both trial years, depending on the sugar content and the weather conditions, particularly from each other every year in agriculture. The harvest of the sugar beet was performed with a plot combine harvester Agrifac, Kleine tip K62, Netherlands, and after that, washing and weight measurement were performed at the farm.



(**a**) (**b**)

Figure 6. The frame (0.5 × 0.5 m^2) used for the measurement of the weed density (**a**) and the effect on the sugar beet crop after the hoeing (**b**).

2.6. Data Analysis

The data were analyzed with the statistical software Anova Polifact Soft (ANOVA 2020, Cluj Napoca, Romania) [39]. Prior to analysis, the data were tested for homogeneity of variance and normal distribution. An analysis of variance was performed. The results of the trials were compared by the Duncan test at $p = 0.05$.

The weed control efficacy (WCE) in % was calculated with the weed density for each plot and for two different growth stages of BBCH, according to Rasmussen [40]:

$$WCE\% = 100 - d_t/(0.01 \times d_u)$$

where d_t is the weed density (weeds m^{-2}) after application of the treatments, and d_u is the weed density (weeds m^{-2}) in the untreated control plots.

3. Results

3.1. The Five Most Abundant Weed Species at Each Trial Site

Average weed densities for BBCH 19 at treatment time ranged from 12 plants m^{-2} to 49 plants m^{-2} in sugar beet. For BBCH 31, the average weed densities at treatment time ranged from 8 plants m^{-2} to 24 plants m^{-2}. The most abundant weed species, with their dominance, are listed in Table 4.

Chamomile (29%, *Matricaria chamomilla* L.), the perennial creeping thistle (21%, *Cirsium arvense* L.), lamb's quarters (19%, *Chenopodium album* L.), cocklebur (15%, *Xanthium italicum* L.), and green foxtail (12%, *Setaria viridis* (L.) P. Beauv.) were most abundant in 2021. Common knotgrass (23%, *Polygonum aviculare* L.), cleavers (21%, *Galium aparine* L.), shepherd's purse (18%, *Capsella bursa-pastoris* L.), cockspur grass (16%, *Echinochloa crus-galli*), and birdeye speedwell (12%, *Veronica persica* L.) occurred in 2022.

Both of the trial years were different concerning the emergence of the weeds and the precipiation date of arrival in the field after the seeding of the sugar beet, but we can see in Figure 7 the composition of the weed species, concluding the groups for dictoyledonates and monocotyledonates in the area of the experiment.

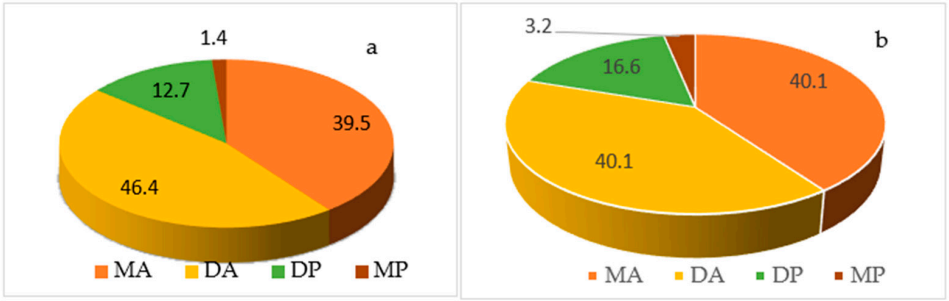

Figure 7. Composition groups of the weed species (%) in two different years, 2021 (**a**) and 2022 (**b**). MA—annual monocotyledonates; DA—annual dicotyledonates; DP—perennial dicotyledonates; MP—perenial monocotyledonates.

Table 4. The five most abundant species of weeds in both trial years 2021–2022 (average of each species participation).

No.	2021		2022	
	Weed Species	**%**	**Weed Species**	**%**
1	*Matricaria chamomilla*	29	*Polygonum aviculare*	23
2	*Cirsium arvense*	21	*Galium aparine*	21
3	*Chenopodium album*	19	*Capsella bursa-pastoris*	18
4	*Xanthium italicum*	15	*Echinochloa crus-galli*	16
5	*Setaria viridis*	12	*Veronica persica*	12
6	Other species	4	Other species	10

3.2. Weed Control Efficacy in 2021

In the year 2021, the weed control efficacy was up to 97.3–100% until the crop rows were closed (up to 60 days after crop emerge) for the 2021 chemical control, as shown in Figure 8.

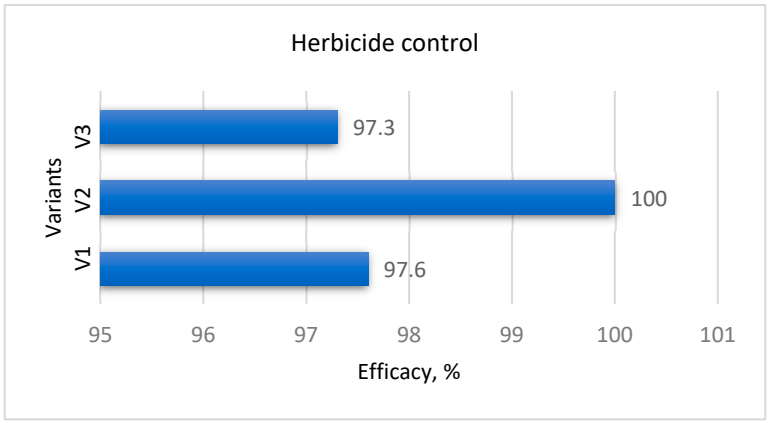

Figure 8. Chemical weed control efficacy in 2021, depending on the experimental variants.

3.3. Weed Control Efficacy in 2022

The highest WCE for the first weed control pass at BBCH 19 could be achieved in the MWC + HWC treatment with 75.20%, followed by the pure herbicide control HWC with 56.37% WCE (Table 5 and Figure 9).

Table 5. The results obtained for the mean weed density (plant m^{-2}) at BBCH 19 at 14 days after the first application of each treatment in 2022.

Treatment BBCH 19	Weed Density (Plants m^{-2})	WCE, %
UC	49.67 ^{a}	100 (Ct.) ^{a}
MWC	31.33 ^{b}	36.93 ^{c}
HWC	21.67 ^{ab}	56.37 ^{ab}
MWC + HWC	12.33 ^{c}	75.20 ^{ab}

Notes: UC—untreated control; MWC—only mechanical weed control; HWC—herbicide control of weeds; MWC + HWC—mechanical and herbicide weed control; ^{a,ab,b,c}—classification according to the Duncan test, where letters further along the alphabet indicate a better experimental variant.

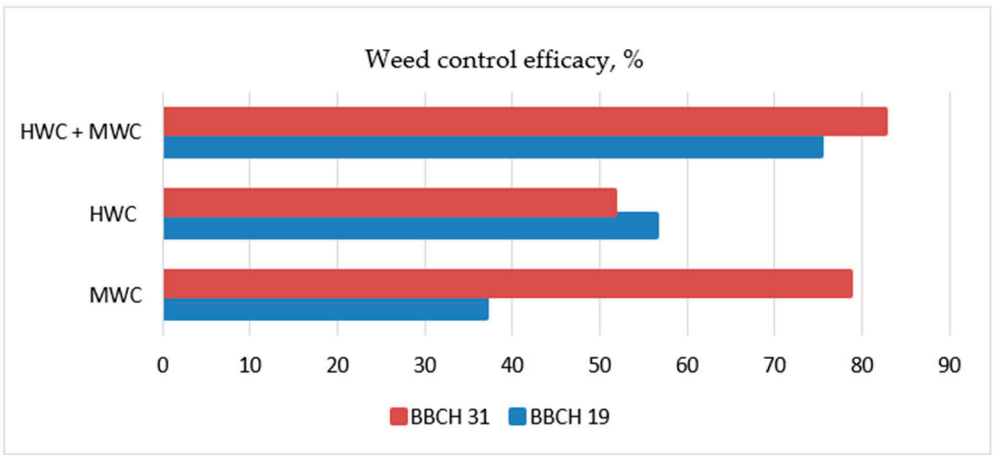

Figure 9. Bar chart of WCE for both stages in 2022.

Weed control efficacy was undertaken in 2022 at BBCH 31 with three repetitions in all experimental variants like control (UC), mechanical only weed control (MWC), herbicide

only weed control (HWC), and mechanical + herbicide weed control (MWC + HWC) (Table 6).

Table 6. Results obtained for the mean weed density (plants m^{-2}) at BBCH 31 at 14 days after the final application of each treatment in 2022.

Treatment BBCH 31	Weed Density (Plants m^{-2})	WCE, %
UC	108.33 [a]	100 (Ct.) [a]
MWC	10.67 [c]	78.52 [b]
HWC	24.0 [b]	51.68 [c]
MWC + HWC	8.67 [c]	82.55 [b]

Notes: UC—untreated control; MWC—only mechanical weed control; HWC—herbicide control of weeds; MWC + HWC—mechanical and herbicide weed control; Ct—control; [a,b,c]—classification according to the Duncan test, where letters further along the alphabet indicate a better experimental variant.

The hoeing treatment MWC performed only 36.93% WCE (Table 5). The MWC treatment achieved the significantly lowest weed control in total.

For the second application time, MWC + HWC could again achieve the significantly highest WCE of 82.55%, followed by the pure mechanical treatment MWC with 78.52% WCE. The conventional herbicide application HWC could only achieve 51.68% WCE but did not differ from the MWC treatment.

3.4. Sugar Beet Yield

The maximum production of sugar beet in 2021 was 48.57 t ha^{-1}, against the background of a dry summer, and it is almost 10 tons higher in 2022 (56.48 t ha^{-1}), against the background of a better distribution of precipitation.

In 2021, no crop losses were recorded, and in the second year, the crop losses were up to 2% due to the sensor-based mechanical control. In 2022, combined treatment of mechanical and herbicide weed control methods (HWC + MWC) showed a significant increase in sugar beet yield of nearly 28.36 t ha^{-1} compared to the UC (28.12 t ha^{-1}) (Table 7). Followed by HWC with 50.22 t ha^{-1} and MWC with 42.34 t ha^{-1}. There was a significant difference between UC and MWC and between MWC and HWC and HWC + MWC.

Table 7. Yield in sugar beet from Vințu de Jos, years 2021–2022.

Treatment/ Year	Indicatory	UC	MWC	HWC	HWC + MWC
2021	Yield, t ha^{-1}	24.18 [a]	36.41 [b]	-	48.57 [c]
	Differences, ±	Ct.	+12.23 **	-	+24.39 ***
	%	100 (Ct.)	150.58	-	200.87
2022	Yield, t ha^{-1}	28.12 [a]	42.34 [b]	50.22 [c]	56.48 [c]
	Differences, ±	Ct.	+14.22 **	+22.10 ***	+28.36 ***
	%	100 (Ct.)	150.57	178.59	200.86
2021: LSD p 5% = 5.41 t ha^{-1}; LSD p 1% = 12.13 t ha^{-1}; LSD p 0.1% = 14.41 t ha^{-1}					
2022: LSD p 5% = 6.21 t ha^{-1}; LSD p 1% = 10.51 t ha^{-1}; LSD p 0.1% = 16.31 t ha^{-1}					

Notes: Ct—control; [a,b,c]—classification according to the Duncan test, where letters further along the alphabet indicate a better experimental variant; **—significantly positive difference; ***—very significantly positive; LSD—least significant difference.

Sugar beet yield can be increased by introducing sensor-based mechanical control with hoes in Transylvanian Depression up to 56.48 t ha^{-1} for a performant farm, in the conditions proper to the usage of the hoeing at the period of BBCH 19 and 31 of sugar beet, and with good quantities of water in the soil in the spring and mid-summer. At present, the yield is at the level of 34.20 to 40.61 t ha^{-1} (Table 8) in almost all the farms with the chemical control.

Table 8. Yield of sugar beet crop from Romania.

Year	UM	2015	2016	2017	2018	2019	2020
Surface	1000 × ha	26.59	24.92	28.20	25.72	22.73	22.76
Medium yield	t ha^{-1}	39.14	40.61	41.64	38.03	40.35	34.20
Total yield	1000 × t	1040.65	1012.19	1174.50	978.27	917.16	778.30

Analyzing the yield results from the experiment and comparing them with the medium yields at country level from the period 2015–2020 [41], we can say that except for the UC trial, in all other trials the yields are above average for the country. The yield from HWC and HWC + MWC trials is higher than the highest medium yield from Romania.

4. Discussion

Weed management by using novel hoeing devices ensures profitable yields and an acceptable residual weed infestation. Post-emergent hoeing with goosefoot sweeps was very successful and recorded average inter-row weed control efficacies between 94% and 98% [33]. Mechanical weed control is a complex part of agriculture. It requires considerable experience of the farmer to develop a long-term concept to keep the weed pressure as low as possible [30].

In our experiment, there was a high weed density on the intra-row section, especially with the grass weed, which is needed in further research to have better control over the intra-row area between the plants and, of course, to have low crop damage because the intra-row practices are very close to the cultivated crop. The inter-row sensor-based hoe is effective for large parcels of sugar beets because of the higher speed at which the tractor can be driven and the very low crop damage. Also, farm parcels cultivated with sugar beets have a medium–large size of 30–40 ha and the entire hectares cultivated for sugar beets are between 120 and 140 ha, each year, which leads to a few days' work on the fields with the sensor-based hoe with hydraulic steering.

Weed control efficacy is better for herbicide control at the early stages of the sugar beet undergoing spraying with herbicides, which, in most cases, is performed weekly, and we can lose considerable yield of the sugar beet if it is undertaken after the six-leaf stages of the crop (BBCH 19). Mechanical weed control can be undertaken at the late stages of the crop after BBCH 19 and until the sugar beet leaves cover the soil between the rows [1,35].

In our experiment, WCE is lower at BBCH 19 because of the slower growth of the weeds, and it is higher at BBCH 31 for the MWC control when the weeds are more developed and the hoe ripped them off from the ground. Also, at the HWC, we realize better control in the early stage of the crop and when the weeds are in the 2–3-leaf stage.

Herbicides should be applied more in the early stages of crop development, and mechanical control can be performed after the six-leaf stage of the sugar beets [42].

Weed control in sugar beet cultivation is increasingly difficult because the physiological stage of the crop is small and strict, and technical rules are imposed with low and precisely fractionated doses of herbicides [43,44]. It is interesting to investigate the differences between chemical and mechanical controls on weeds in the mentioned crop, first of all on the products and physiology of the crop plant as well as on the finished product, like sugar percentage (obtained from the roots), the animal consumer (packages and leaves), or after industrialization on humans in different foods [45].

Concern about herbicides polluting ground and surface water, human health risks from herbicide exposure or residues, effects on the flora and fauna, the development of herbicide resistance, and the lack of approved and effective herbicides for minor crops such as vegetables are the major factors driving the present and increasing interest in non-chemical weed control [46,47].

Trials have shown that it is possible to control weeds in integrated systems combining mechanical weeding and phytosanitary treatment, even for beet growing, which is highly demanding in terms of weed competition [18]. Questions may be legitimately asked about

the cost of implementing these practices. The available studies show variable results depending on whether direct costs and/or some indirect impacts are taken into account.

Thus, we consider that our research hypothesis is confirmed and that the best practice of the IWM will enhance overall productivity in the long term. It will reduce the spread of serious weed species, e.g., herbicide-resistant biotypes and other weed species that are hard to control by herbicides. Continuing research in this direction helps to maintain the long-term efficiency of herbicides by reducing the selection pressure for certain weed species.

5. Conclusions

The methods of integrated control management of weeds used in this study include post-emergence herbicides and sensor-based mechanical control replacing pre-emergence herbicides. The results show that by optimizing the integration of control methods, it is possible to reduce pre-emergence herbicides but not completely replace post-emergence herbicides in the sugar beet weed control scheme. This situation is due to the high weed density and species abundance on most farms in the Transylvanian Depression area. However, the results show that a better yield can be obtained by including integrated weed control strategies. We must also specify that weed abundance is much higher in Romania than in west European countries that cultivate sugar beet; species of weeds that grow in agricultural lands are up to 5–6 times higher than in Germany, for example. The number of chemical herbicides in sugar beets is becoming smaller and is continuing to be banned. Also, the herbicide resistance of weeds is increasing, so the present study can contribute to the reduction of herbicides and lower weed density testing, whereby the growing stage of the sugar beet can be the most suitable for sensor-based mechanical control.

The results of the study show that it is possible to obtain increased production of beet roots with a significant reduction of chemical products in the farms from the Transylvania Depression. The mechanical shifting precision weed control methods could also achieve less stress for the plants and better aeration of the soil, and these facts can, of course, increase the target yield. The growing stages experimented with in this study were the six-leaf and nine-leaf stages of sugar beet, i.e., BBCH 19 and 31, respectively, which are suitable for the control of weeds and low crop losses. Results show that in a dry summer, as it was for sugar beet in the year 2022, mechanical and chemical weed control (HWC + MWC) can offer a sustainable and accepted yield while controlling significant weed densities.

Similar recent studies from Germany showed that the sensor-based mechanical control inter-row had fewer crop losses of sugar beet and that the uprooted plants were not significant according to the number of plants per hectare. Weeds close to the crop, however, will remain a major constraint of mechanical weeding, making it necessary to continue research in this direction for the Transylvanian Depression area.

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