

Article

Sensor-Based Intrarow Mechanical Weed Control in Sugar Beets with Motorized Finger Weeders

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Abstract: The need for herbicide usage reduction and the increased interest in mechanical weed control has prompted greater attention to the development of agricultural robots for autonomous weeding in the past years. This also requires the development of suitable mechanical weeding tools. Therefore, we devised a new weeding tool for agricultural robots to perform intrarow mechanical weed control in sugar beets. A conventional finger weeder was modified and equipped with an electric motor. This allowed the rotational movement of the finger weeders independent of the forward travel speed of the tool carrier. The new tool was tested in combination with a bi-spectral camera in a two-year field trial. The camera was used to identify crop plants in the intrarow area. A controller regulated the speed of the motorized finger weeders, realizing two different setups. At the location of a sugar beet plant, the rotational speed was equal to the driving speed of the tractor. Between two sugar beet plants, the rotational speed was either increased by 40% or decreased by 40%. The intrarow weed control efficacy of this new system ranged from 87 to 91% in 2017 and from 91 to 94% in 2018. The sugar beet yields were not adversely affected by the mechanical treatments compared to the conventional herbicide application. The motorized finger weeders present an effective system for selective intrarow mechanical weeding. Certainly, mechanical weeding involves the risk of high weed infestations if the treatments are not applied properly and in a timely manner regardless of whether sensor technology is used or not. However, due to the increasing herbicide resistances and the continuing bans on herbicides, mechanical weeding strategies must be investigated further. The mechanical weeding system of the present study can contribute to the reduction of herbicide use in sugar beets and other wide row crops.



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1. Introduction

Herbicides have replaced the majority of weed control methods since their introduction in the middle of the 20th century [1,2]. However, due to a combination of legal constraints, public demand, herbicide resistance, and environmental concerns, along with the continuously arising interest from organic farming, mechanical weed control has re-emerged as an effective alternative to the application of synthetic herbicides [3]. New mechanical weeding tools and precise steering techniques have evolved rapidly during the past years [4].

In particular, combining already existing implements for mechanical weeding with a variety of sensor systems has increased their utilization in arable crops. For example, camera-guided hoes are readily available on the market from different manufacturers. Their guidance concept is based on a camera that tracks the crop rows and sends a signal to a hydraulic cylinder, which shifts the hoe left or right to stay aligned with the crop rows [5].

The benefits of such systems include: reduced driver fatigue, the possibility to work closer to the crop, which increases the area that is treated, and the potential to increase the working speed [6]. In weed densities from 15 to 150 weeds m^{-2} Kunz et al. [7] reported that, with camera-steered hoes, the weed densities could be reduced by up to 87% on *Beta vulgaris* L. (sugar beets) and 89% on *Glycine max* Merr. (soybean). This weed reduction was achieved even at application speeds of 7 to 10 $km\ h^{-1}$ while the crop yield was comparable to the herbicide application.

Depending on their targeted application area, mechanical weed control methods can be divided into intrarow and inter-row treatments. The intrarow area is the small strip of the crop rows themselves whereas the inter-row area is the space between two adjacent crop rows [8]. Today, post-emergent inter-row weeding can be performed reliably in wide row crops without excessive crop damage; however, the removal of intrarow weeds is still a challenging task [9,10]. Therefore, a variety of different tools have been developed to physically deal with intrarow weeds.

This includes finger weeders, torsion weeders, tactile hoeing, and weeding brushes [11,12]. Finger weeders have been quite successful [7], but are better used at later growth stages [11]. They require a much more advanced growth stage and root development of the crop compared to the weed. Although the intensity of conventional finger weeding can be increased by using finger weeders with more solid rubber and by increasing the overlap-area of the fingers in the crop row, only small weeds can selectively be controlled by these finger weeders.

Tactile hoeing can be performed inside the row. Many similar systems are currently being developed; however their cost and slow speed remain limiting factors [10]. Weed brushes are designed to uproot small weeds, yet they require optimum soil conditions as well as weed and crop growth stages [9,12].

In the course of automation, mechanical weed control in arable crops has also become of interest in combination with agricultural robots [13]. Bosch Deepfield Robotics developed the BoniRob, which eliminates individual weed plants with a stamp tool [14]. Robots have also been tested successfully to eradicate *Rumex obtusifolius* L. (broad leaved dock) in pastures [15]. The AgBotII combines mechanical and chemical weed control implements [16] and a combination of thermal and mechanical tools has been evaluated with robots of the RHEA fleet in Spain [17]. However, there is still room for improvement in the design and set-up of the tools for mechanical weed control with robots.

This study examined a novel approach to mechanical weeding in sugar beets (*Beta vulgaris* subsp. *vulgaris*, Altissima Group). Sugar beets are not very competitive with weeds, and they must be kept weed free until row-closure [18]. In Germany, two to three post-emergent herbicide applications are usually necessary for sufficient weed control in sugar beets. Mechanical weeding is not practised often due to the high risk of weed infestations if the treatments are not performed properly and timely. Intrarow weeds in particular are difficult to remove because sugar beets are sensitive plants and do not tolerate physical stress well.

Therefore, we developed an imaging system that determines the position of sugar beets to perform intrarow mechanical weed control with a motorized finger weeder. The motorized finger weeder is based on a conventional finger weeder, which was equipped with an electric motor. This enabled a rapid variation of the rotational movement of the finger weeder independent of the tractor driving speed. The system was integrated into a conventional camera-steered inter-row hoeing system for row crops. We tested this in a two-year field experiment with sugar beets and compared it to conventional mechanical and chemical weeding methods.

We hypothesized that (a) the motorized finger weeder increases the weed control efficacy compared to the conventional finger weeder, especially in the intrarow area and that (b) sugar beet yields are not negatively impacted by the motorized finger weeders compared to the conventional finger weeders. Furthermore, the combination of inter-row

and intrarow mechanical weed control provided equal weed control efficacies to herbicide applications across the whole plots.

2. Materials and Methods

2.1. Overview and Experimental Site

Field trials for intrarow mechanical weed control were carried out in sugar beets in 2017 and 2018. The experiment was located at the trial site Ihinger Hof (Renningen, south-west Germany) and consisted of eight different treatments and four replications. The Ihinger Hof trial site is 475 m above sea level with an average long-term rainfall of 738 mm. The total annual rainfall was 654 mm and 526 mm for the years 2017 and 2018, respectively.

The relevant precipitation of spring and summer can be seen in Table 1. Mechanical weed control methods with motorized finger weeders (MFW) were compared to an untreated control, a conventional herbicide application, and ground-driven conventional finger weeders (CFW). A detailed description of the treatments can be found in Table 2. The experimental design was a randomized complete block design in both trial years.

Table 1. Precipitation in mm for the months of March until September in the years 2017 and 2018 for the location Ihinger Hof.

	2017	2018
March	47.8	18.4
April	38.7	14.5
May	83.5	64.4
June	97.4	95.9
July	111.9	25.3
August	77.8	43.8
September	57.0	37.5
Sum	514.1	299.8

Table 2. Description of the treatments at Ihinger Hof in 2017 and 2018. The tractor driving speed was 1 km h⁻¹ for the motorized finger weeders (MFW) treatments and 6 km h⁻¹ for the conventional finger weeder (CFW) treatments. The nominal rotational speed (100%) of the MFW at the location of a sugar beet corresponded to a linear speed of 1 km h⁻¹.

Treatment	Treatment Acronyms	Description
Untreated control	UC	No weed control
Herbicide 2017	H2017	Herbicide spraying, see Table 3
Herbicide 2018	H2018	Herbicide spraying, see Table 3
Motorized finger weeder Fast speed	MFW (140)	3 × Motorized finger weeding with 40% higher rotational speed between two sugar beets than at the location of a sugar beet
Herbicide and motorized finger weeder Fast speed	H + MFW (140)	1 × Herbicide spraying 2 × Motorized finger weeding with 40% higher rotational speed between two sugar beets than at the location of a sugar beet
Motorized finger weeder Slow speed	MFW (60)	3 × Motorized finger weeding with 40% lower rotational speed between two sugar beets than at the location of a sugar beet
Herbicide and motorized finger weeder Slow speed	H + MFW (60)	1 × Herbicide spraying 2 × Motorized finger weeding with 40% lower rotational speed between two sugar beets than at the location of a sugar beet
Conventional finger weeder	CFW	3 × Conventional finger weeding
Herbicide and conventional finger weeder	H + CFW	1 × Herbicide spraying 2 × Conventional finger weeding

In both trial years, sugar beets cv. Hannibal were sown 3-cm deep with a 3-m wide seeder (Solitair 8, Lemken, Alpen, Germany) at a row distance of 0.5 m. The seeding density was 107,000 seeds ha⁻¹, which resulted in a distance of 18 to 22 cm between two beet plants. The plot size was 12 m × 3 m (length × width). Thus, each plot comprised six sugar beet rows and the sowing width (3 m) matched the hoeing width (3 m).

2.2. Herbicides and Application Details

Table 3 lists the herbicides that were used in the experiments in 2017 and 2018. The three chemical-mechanical treatments H + MFW (140), H + MFW (60), and H + CFW were sprayed once with the herbicides listed for BBCH 10 [19] of the sugar beets. Due to the high weed density in 2017, three herbicide applications (BBCH 10, 14, and 18) were applied in the H2017 treatment.

In 2018, only two herbicide applications (BBCH 10 and 14) were necessary to control the weeds. The herbicide application was performed with a battery-powered plot sprayer (Schachtner, Ludwigsburg, Germany). The spray boom of the sprayer was 3-m wide and equipped with flat spray nozzles (TWIN flat spray air-injector compact nozzles IDKT 120-05, Lechler, Metzingen, Germany). The herbicides were applied with 300 L water ha⁻¹ with a spray pressure of 200 kPa and 50 cm above ground level at a driving speed of 5 km h⁻¹.

Table 3. Herbicide type and application time (BBCH of the sugar beets) at Ihinger Hof in 2017 and 2018.

BBCH 2017	BBCH 2018	Active Ingredients	Product Name	FM *	Concentration	Application Rate	Supplier
10, 14, 18	10, 14	<i>desmedipham</i>	Betanal [®] maxxPro [®]	OD	47 g a.i. L ⁻¹	70.5 g ha ⁻¹	Bayer CropScience
10, 14, 18	10, 14	<i>phenmedipham</i>	Betanal [®] maxxPro [®]	OD	60 g a.i. L ⁻¹	90 g ha ⁻¹	Bayer CropScience
10, 14, 18	10, 14	<i>ethofumesate</i>	Betanal [®] maxxPro [®]	OD	75 g a.i. L ⁻¹	112.5 g ha ⁻¹	Bayer CropScience
10, 14, 18	10, 14	<i>lenacil</i>	Betanal [®] maxxPro [®]	OD	27 g a.i. L ⁻¹	40.5 g ha ⁻¹	Bayer CropScience
10, 14, 18	10, 14	<i>metamitron</i>	Goltix [®] Titan [®]	SC	525 g a.i. L ⁻¹	630 g ha ⁻¹	ADAMA Germany
10, 14, 18	10, 14	<i>quinmerac</i>	Goltix [®] Titan [®]	SC	40 g a.i. L ⁻¹	48 g ha ⁻¹	ADAMA Germany
14	14	<i>fluzifop-P-butyl</i>	Fusilade Max [®]	EC	107 g a.i. L ⁻¹	107 g ha ⁻¹	Nufarm Germany
14, 18	14	<i>clopyralid</i>	Lontrel [™] 720	SG	720 g a.i. kg ⁻¹	165 g ha ⁻¹	Dow AgroSciences

* FM—Formulation OD—oil dispersion; SG—water-soluble granules; SC—suspension concentrate; EC—emulsifiable concentrate; Spray volume: 300 l water ha⁻¹; Each herbicide application received 0.5 l ha⁻¹ of the additive Oleo FC (94% paraffin oils and 6% emulsifiers, ADAMA Germany).

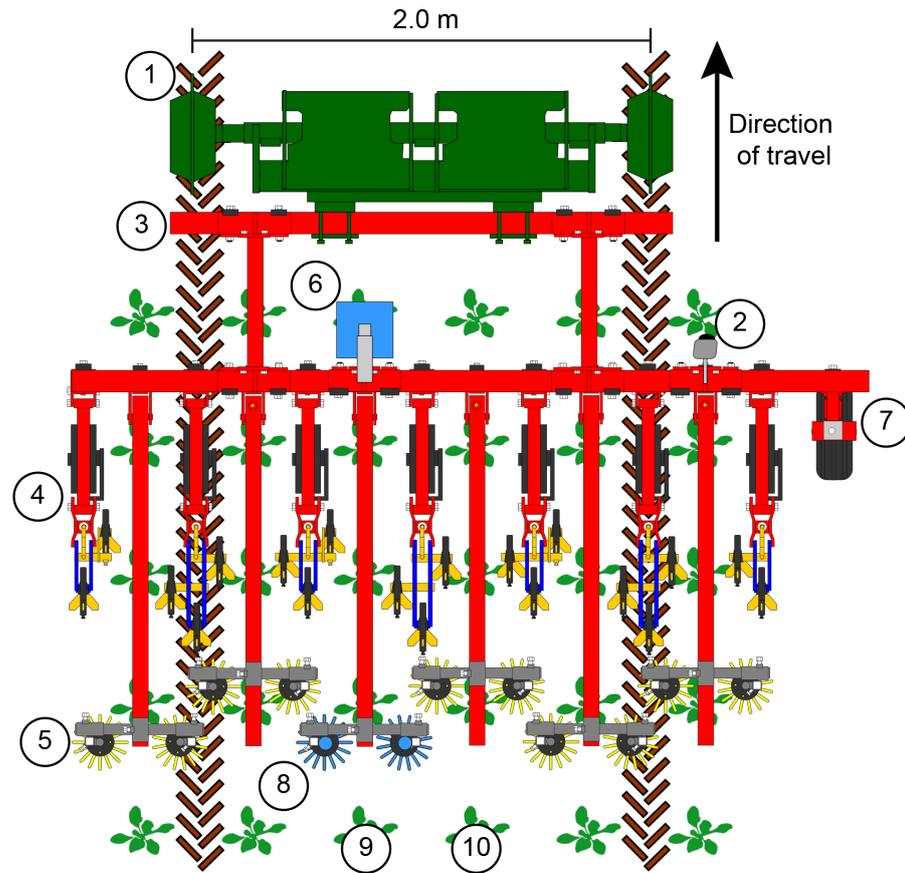
2.3. General Set-Up of the Hoe

The set-up of the mechanical weed control implement (Figure 1) was based on a 3-m wide hoeing frame (Argus, K.U.L.T., Vaihingen a. d. Enz, Germany) in combination with a Garford Robocrop Side Shift System (Garford Farm Machinery Ltd., Peterborough, England). The hoeing system had two cameras (Figure 1a). The first camera was the Garford camera for the general row alignment of the hoe to perform inter-row hoeing. The second camera was our bi-spectral camera, which was situated above a sugar beet row and responsible for the intrarow treatments with the motorized finger weeders (Figure 1b).

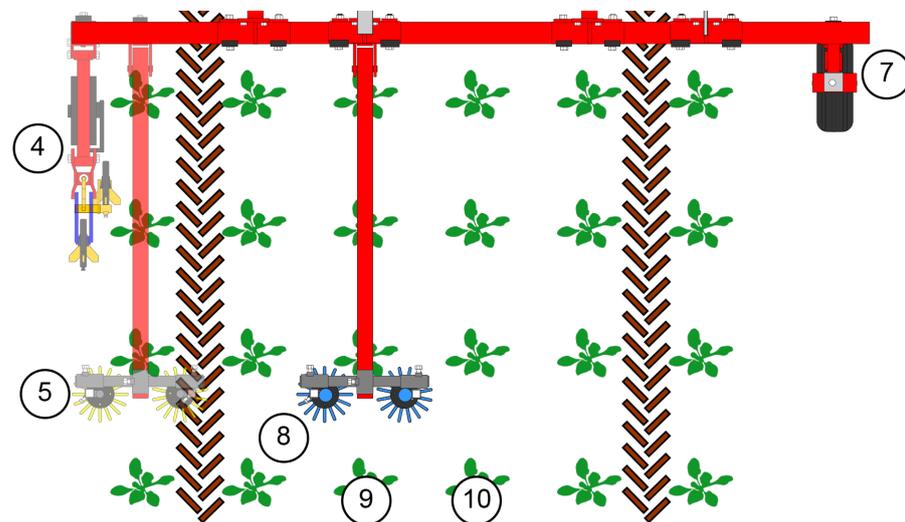
Hoeing between the sugar beet rows was performed with 20 cm wide goosefoot sweeps mounted on a parallelogram. Since each plot comprised six sugar beet rows, seven parallelograms were required to treat all inter-row spaces of one plot. The safety distance towards the sugar beet rows was set to 5 cm. For intrarow weeding, one pair of conventional finger weeders was used per sugar beet row. Prior to each application, the conventional and the motorized finger weeders were adjusted outside of the experiment to ensure an optimal weeding result.

2.4. Set-Up of the Motorized Finger Weeders

The idea behind the bi-spectral camera in combination with the MFW was to switch between two rotational speeds during the treatment. The distance between two sugar beets was supposed to be treated with a different rotational speed than the area at the location of a sugar beet. Two different treatment intensities (slow and fast) of the strip between two sugar beet plants were tested in this study (Figure 2a). On the one hand, this served to test whether the sensor system could reliably switch between different speeds and, on the other hand, whether there was a difference in the weed control performance between the two rotational speeds.

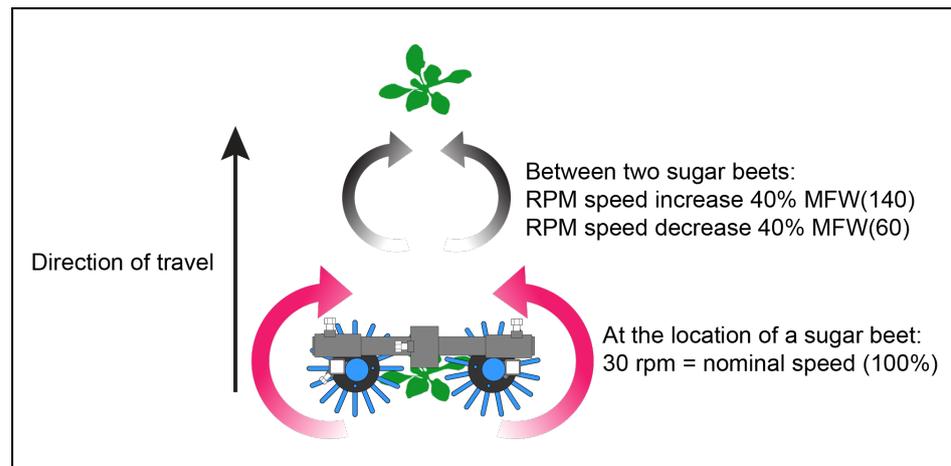


(a) Diagram of the complete implement used.

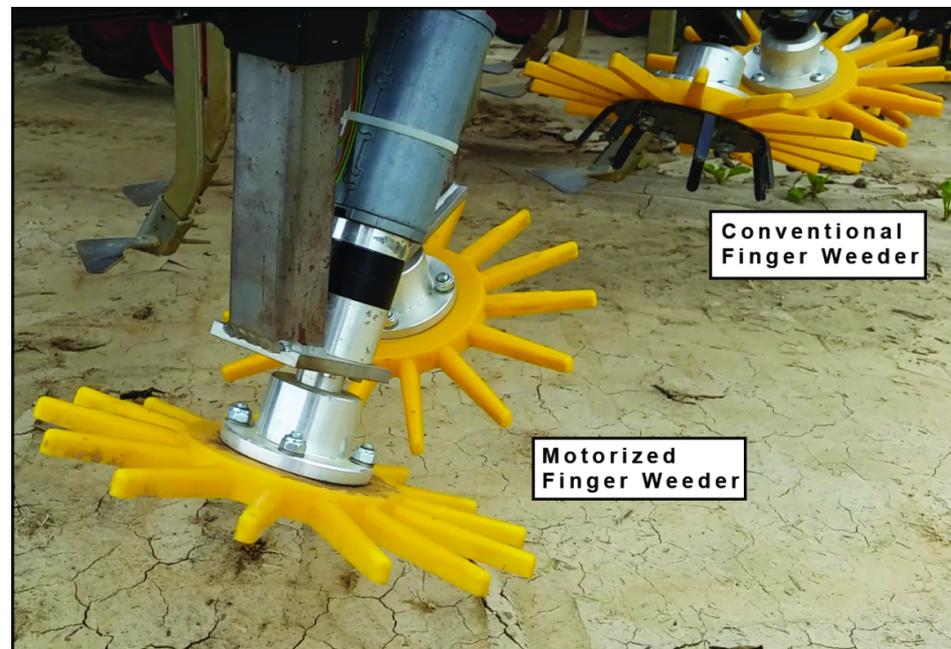


(b) Detail diagram focusing on two rows.

Figure 1. The set-up of the hoe used in the experiments at Ihinger Hof in 2017 and 2018. The image displays one plot width (six sugar beet rows). 1 = Garford Robocrop, 2 = Garford Robocrop camera for inter-row weeding, 3 = Argus hoe frame, 4 = parallelograms with goosefoot sweeps, 5 = conventional finger weeders, 6 = bi-spectral camera for intrarow weeding (colour blue), 7 = odometry wheel, 8 = motorized finger weeders (colour blue), 9 and 10 = the two center sugar beet rows of each plot that were treated with the MFW and used for harvesting. Design elements by K.U.L.T. Germany.



(a) Diagram showing the rotation direction and speed of the motorized finger weeders.



(b) The motorized finger weeders (front) and conventional finger weeders (back).

Figure 2. Normal and motorized finger weeders and their principles of use.

For the construction of the motorized finger weeders, one pair of conventional finger weeders was modified (Figure 2). The metal spines, typically mounted underneath the finger weeders, which pin on the ground, and normally propel the CFW as the tractor drives forward were dismantled (Figure 2b). Instead a flat metal disc was used for protection of the plastic finger weeder from the ground friction. Then, an electric motor (Bühler Motor GmbH, Germany) was mounted on each finger weeder.

The metal part above the finger weeder was connected to the motors, and, in combination with the flat metal disc, it created the holder to enforce the rotation of the plastic finger weeders (Figure 2b). The finger weeders had an external diameter (\varnothing) of 240 mm and an internal diameter of 120 mm. Since this prototype had never been tested in a field experiment, only one pair of motorized finger weeders was assembled and tested for its weed control performance. The motors used were PM12, which was a voltage-regulated DC gear motor. They were equipped with a two-stage gear giving a 19:1 speed reduction.

Therefore, each motor provided around $6 \text{ kg m}^2 \text{ s}^{-2}$ maximum rated torque. The maximum speed on the soil was 45 rpm when the motor was supplied with 24 V DC.

Since the motors were propelling the two finger weeders, they were placed in such a way that they were approaching in the left and right of the row. Therefore, the motors were configured to rotate clockwise and counterclockwise, respectively (Figure 2a). A dual-channel motor controller, namely the Robotec MDC2460 (Robotec Inc., Scottsdale, AZ, USA) was responsible for controlling the speed and the rotating motion of the two motors.

The typical speed of the motors at the location of a sugar beet plant was around 30 rpm when placed on the ground. Therefore, the middle of the finger weeder (\varnothing 180 mm) achieved a linear speed of 1 km h^{-1} , which was concurrent with the speed that the tractor was moving and is referred to as the nominal speed (100%) from here on. By rotating at the same speed as the tractor is moving forward, the MFW worked unhindered without causing any damage to the sugar beet plants.

The treatments MFW (140) and H + MFW (140) had the MFW rotate with a speed 40% faster than the driving speed of the tractor between two sugar beet plants. In this scenario, it was expected that the damage and the uprooting of the weeds was higher due to the more active and enforced collision of the MFW. A higher soil disturbance from the faster rotation was also expected.

In the treatments MFW (60) and H + MFW (60), the finger weeders rotated with a speed 40% slower between two sugar beet plants than that of the nominal speed applied at the location of a sugar beet. Thus, the rotational movement of the finger weeder was slower than the forward travel speed of the tractor (1 km h^{-1}). This forced the finger weeders to perform a small sliding motion in the direction of travel. Whether this caused changes in the weed control efficacy compared to MFW (140) and H + MFW (140) was part of this study.

2.4.1. Implementation of the Mechanical Treatments

One pair of CFW was replaced by the MFW for plots that received treatment with MFW. Only the two center sugar beet rows of each plot were treated with the MFW. Hoeing was performed either two or three times, depending on the treatment. Table 4 lists the mechanical treatments and their corresponding time of application as the BBCH growth stage and as the number of fully developed leaves of the sugar beets.

Table 4. Time of application of the mechanical treatments at Ihinger Hof according to the number of developed leaves and the BBCH stage [19].

Treatment	Acronym	Sugar Beet Growth Stage	BBCH Growth Stage
Motorized finger weeder Fast speed	MFW (140)	3 to 4 leaves	13–14
		4 to 5 leaves	14–15
		6 to 8 leaves	16–18
Herbicide and motorized finger weeder Fast speed	H + MFW (140)	4 to 5 leaves	14–15
		6 to 8 leaves	16–18
Motorized finger weeder Slow speed	MFW (60)	3 to 4 leaves	13–14
		4 to 5 leaves	14–15
		6 to 8 leaves	16–18
Herbicide and motorized finger weeder Slow speed	H + MFW (60)	4 to 5 leaves	14–15
		6 to 8 leaves	16–18
Conventional finger weeder	CFW	3 to 4 leaves	13–14
		4 to 5 leaves	14–15
		6 to 8 leaves	16–18
Herbicide and conventional finger weeder	H + CFW	4 to 5 leaves	14–15
		6 to 8 leaves	16–18

Since only one pair of MFW existed, two passes with the tractor were necessary to treat two sugar beet rows in each plot. The sowing pattern of the sugar beets was advantageous because both center rows were offset left and right from the actual center of the plot. Therefore, it was possible to perform hoeing with the bi-spectral camera and the MFW without having to change their position on the hoeing frame. The tractor simply had to turn

after the first pass with the hoe and drive through the plot again from the other direction. However, two consecutive passes with the goosefoot sweeps had to be avoided.

Otherwise, the plots receiving MFW-treatments would also receive double the amount of inter-row passes with the goosefoot sweeps, which would have distorted the weed control results. Therefore, the parallelograms with the goosefoot sweeps were lifted and locked into their floating position prior to driving through the plot a second time with the MFW. The treatments with CFW did not require two passes since enough conventional finger weeders were available for this weeding method. The harvest of the CFW-plots was also restricted to the two center rows in order to achieve comparable yield results.

2.4.2. Description of the Sensor System

In this experiment, a red-infrared camera was used for individual crop plant recognition. The sensor was a camera-based machine vision system with autonomous illumination in both the red and infrared, making the sensor usable even at night or low illumination conditions. A modified version of the software IMPASS was used for the image identification and plant species classification.

The bi-spectral camera took two pixel-congruent images in the red and near-infrared spectrum. Differential images (infrared-red) were calculated out of the two images. Thresholding was automatically performed, creating a binary image where the plant material was attributed as 1 (white) and the rest of the objects were attributed as background with a value of 0 (black). Due to the reflection characteristics of the different materials, the difference image did not contain any disturbances, like stones, straw, or other organic matter.

In addition, a strong contrast between the plants and background could be achieved [20]. For the weed classification, a data-based image analysis system was used. In the database, the parameters (shape features and morphological features) of the different weed species and sugar beets were stored. The features of the objects found in the images were compared with the features of the model plants stored in the database. They were classified in the appropriate class by a minimum distance classifier.

Each completely white object in the image was separated, and, based on the shape recognition attributes, it was classified as sugar beet or weed. Then, each image was separated into strips of around 40 mm for the direction of movement, and, for each strip, a decision was made as to whether it contained a sugar beet plant or a weed. The aforementioned system was used until the field mapping and spraying applications [21]. Modifications were made for continuous image acquisition and correlation with the positioning of the MFW.

Figures 1 and 3a describe the set-up of the sensor-system that was used in this study. The bi-spectral camera (Figure 3b) was mounted onto the hoe, facing downwards on one of the two center sugar beet rows. The principle of the setup was to separate the intrarow region into 40-mm strips. Since the space between the sugar beets was typically around 180 mm, this space had at least three and sometimes even four strips without the presence of a sugar beet and then a strip that contained a sugar beet.

At the strip with the sugar beet, the nominal speed was applied. At the rest of the strips, the speed was adjusted according to the treatment (faster or slower respectively). A wheel was mounted on the hoe, in order to measure the distance traveled by the hoe. If no movement was monitored from the wheel, the motors were halted to reduce the wear on the motors and the finger weeders and to avoid possible crop damage. A Raspberry Pi Model B coordinated the different tasks. Based on the input from the wheel encoder the Raspberry Pi triggered the sensor and activated IMPASS to process the image and make the necessary decisions.

These decisions were returned to the Raspberry Pi. In order to avoid untimely reactions, the image analysis was performed on another computer (ThinkPad Lenovo P50, Intel Core i7-6700HQ at 2.60 GHz, 32 GB of RAM & a Quadro M100M PCIe graphics card). An odometry measurement was necessary to measure the travel distance of the hoe in order to synchronize the movement of the MFW with the position of the crop plants. Based on

the odometry measurements and the image analysis, the Raspberry-Pi sent a signal to the Roboteq microcontroller to regulate the movement speed of the MFW.

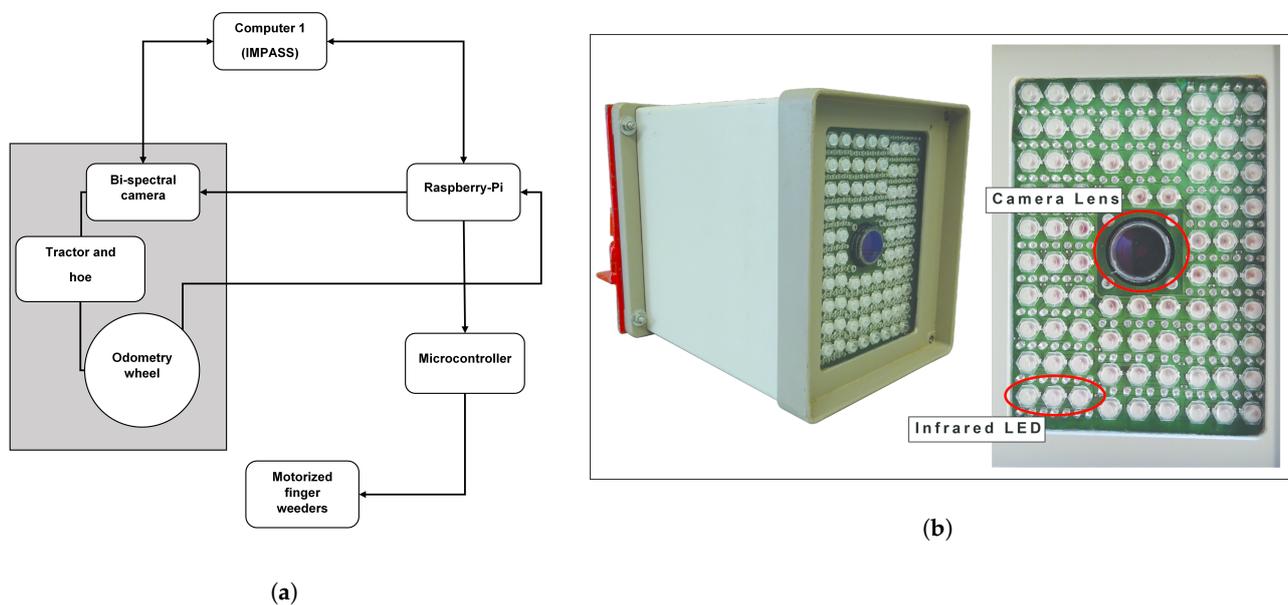


Figure 3. Sensor information. (a) Flowchart describing the sensor system. (b) The bi-spectral camera for intrarow weeding: the lens is surrounded by the infrared LEDs.

2.4.3. Data Acquisition

The weed density (plants m^{-2}) was measured using a 0.5×0.5 m frame. The frame was divided into an intrarow and inter-row section to differentiate between both areas (Figure 4). The frame was placed randomly at three locations inside the center of each plot three days after the final application of the mechanical treatments. The sugar beet harvest took place by the end of September in both trial years. A plot harvester uprooted and collected the sugar beets. All 12 m of the two center sugar beet rows of each plot were harvested. In order to evaluate the effect of the mechanical treatments in the crop the yield of those two rows was measured. Furthermore the number of sugar beet plants on the two center rows per treatment were counted prior to the treatments (crop emergence) and at the harvest time.

2.4.4. Data Analysis

The data were analyzed with RStudio (R Version 3.3.1) [22] as a randomized complete block design. Prior to the analysis of variance (ANOVA), the data were checked for homogeneity of variance and normal distribution of the residuals. The means of the observations were compared with the Tukey HSD-Test at $\alpha \leq 0.05$. The model used was the following:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + b_k + e_{ijk} \quad (1)$$

where Y_{ijk} is the result (e.g., the sugar beet yield) of treatment i at the driving speed j at block k . μ is the general mean, α_i is the yield attributed to treatment i , β_j is the effect of speed j , $(\alpha\beta)_{ij}$ is the effect of the interaction between treatment i and speed j , while b_k is the block effect of block k , while e_{ijk} is the residual error of that specific plot. The weed density (plants m^{-2}) in each plot was calculated according to Nkoa et al. [23] as:

$$Density = \frac{\sum \text{weed plants in each quadrat}}{\text{no. of quadrats} \times \text{quadrat area}} \quad (2)$$

The weed control efficacy (WCE in %) is a measure for the effectiveness of a treatment to reduce the weed density. For each treatment and plot, the WCE was calculated according to Rasmussen [24] as:

$$WCE(\%) = 100 - \frac{d_t}{0.01 \times d_u} \quad (3)$$

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



Figure 4. The frame (0.5 × 0.5 m) that was used for the measurements of the weed density in 2017 and 2018.

3. Results

3.1. Weed Density and Weed Control Efficacy

There was a high variation in the weed density between 2017 and 2018. In 2017, the weed densities in the untreated control plots reached on average 588 plants m^{-2} , whereas the mean weed density in 2018 was 38 plants m^{-2} . The divergence in weed density was due to a wet spring season in 2017 with almost 80% of the total annual rainfall dropped in spring and summer, compared to only 57% for 2018. We decided to analyze the data from 2017 and 2018 separately. However, the weed species found in both fields were typical for the local sugar beet production. The most frequent weed species were common lambsquarters (*Chenopodium album* L.), scentless false mayweed (*Matricaria inodora* L.), creeping thistle (*Cirsium arvense* L.), cleavers (*Galium aparine* L.), and black bindweed (*Polygonum convolvulus* L.) (Table 5).

Table 5. The weed composition of the major weed species for the trials of 2017 and 2018 at the research station Ihinger Hof.

Year 2017		Year 2018	
Species	Proportion (%)	Species	Proportion (%)
<i>M. inodora</i>	40	<i>G. aparine</i>	30
<i>C. album</i>	30	<i>P. convolvulus</i>	25
<i>C. arvense</i>	15	<i>C. album</i>	20
<i>G. aparine</i>	10	<i>M. inodora</i>	12
<i>P. convolvulus</i>	3	<i>C. arvense</i>	8
Others	2	Others	5

The results in Table 6 show that the herbicide treatments were the most effective method to reduce the weed density in both trial years. The highest weed densities were recorded in the untreated control plots, ranging from 588 plants m⁻² in 2017 to 43 plants m⁻² in 2018. The highest intrarow weed density was found in the untreated control in both trial years. However, the difference between the average weed density of the untreated control in 2017 and 2018 was 147.5 plants m⁻². All treatments were different than the control, yet no differences were obtained within the mechanical treatments. Conventional finger weeders with an average intrarow weed density of 37 plants m⁻² was the only difference from the herbicide application. The MFW (140) and MFW (60) led to lower weed densities of 15 and 19 plants m⁻², respectively, in 2017.

Table 6. The results obtained for the mean weed density (plants m⁻²) of the intrarow and inter-row area were measured three days after the final application of each treatment in 2017 and 2018. Additionally, the results for the intrarow weed control efficacy (%) are shown. Means with different letters within the same column indicate significant differences between the treatments according to the Tukey HSD-Test at $\alpha \leq 0.05$. WCE = weed control efficacy.

Treatment *	2017				2018			
	Weed Density (weeds m ⁻²)			Intrarow WCE (%)	Weed Density (weeds m ⁻²)			Intrarow WCE (%)
	Intrarow	Inter-Row	Sum		Intrarow	Inter-Row	Sum	
UC	177.0 ^a	411.0 ^a	588.0 ^a	-	29.5 ^a	13.5 ^a	43.0 ^a	-
H2017/18	0.0 ^c	0.0 ^b	0.0 ^e	100 ^a	0.0 ^d	0.0 ^b	0.0 ^c	100 ^a
MFW (140)	15.0 ^{bc}	3.3 ^b	18.3 ^c	92 ^{bc}	2.7 ^{bcd}	0.5 ^b	3.2 ^{bc}	91 ^{ab}
H + MFW (140)	1.7 ^c	0.0 ^b	1.7 ^{de}	99 ^{ab}	1.7 ^{cd}	0.3 ^b	2.0 ^{bc}	94 ^a
MFW (60)	19 ^{bc}	0.3 ^b	19.3 ^c	89 ^c	2.3 ^{bcd}	0.6 ^b	2.9 ^{bc}	92 ^{ab}
H + MFW (60)	1.3 ^c	0.0 ^b	1.3 ^{de}	99 ^{ab}	1.7 ^{cd}	0.1 ^b	1.8 ^{bc}	94 ^a
CFW	37 ^b	6.0 ^b	43 ^b	79 ^d	6.8 ^b	0.4 ^b	7.2 ^b	77 ^c
H + CFW	4.3 ^c	1.0 ^b	5.3 ^d	98 ^{ab}	6.5 ^{bc}	0.3 ^b	6.8 ^b	78 ^{bc}

* UC: Untreated Control, H: Herbicide spraying, MFW (140): Motorized finger weeder fast speed, MFW (60): Motorized finger weeder slow speed, CFW: Conventional finger weeder

Inter-row hoeing showed similar results as the intra-row with all treatments being different than the control; however, no differences were found between any of the treatments. The goosefoot sweeps eliminated most of the weed plants growing between the sugar beet rows. In 2017, weed densities of 1.7 and 1.3 plants m⁻² were recorded for the H + MFW (140) and the H + MFW (60) treatments, respectively. Slightly higher weed densities of 5.3 plants m⁻² were found in the H + CFW treatment, but the results were not different compared to the combined methods H + MFW (140) and H + MFW (60).

The mechanical treatments without an additional herbicide application (MFW (140), MFW (60), and CFW) showed significantly higher total weed densities than treatments that received a single herbicide application. In 2018, the differences between mechanical treatments in combination with an herbicide and without an herbicide were not as prominent as in 2017. The average intrarow weed densities after application of the treatments ranged from 1.7 to 6.8 plants m⁻².

Table 4 also shows the mean weed control efficacy (WCE) for the years 2017 and 2018 for each treatment. The lowest weed control efficacy was recorded for the conventional

finger weeders in 2017 (79%) and also in 2018 with a weed control efficacy of 77 to 78% for H + CFW and CFW. The highest weed control efficacy was achieved with the herbicide treatments H2017 and H2018. In 2017, the combination of mechanical and chemical treatments showed similarly high WCE levels to the herbicide application, while, in 2018, with the lower weed densities, only the conventional finger weeder applications were different from the herbicide applications.

3.2. Sugar Beet Yield

The lowest sugar beet yield (Figure 5) was found in the untreated control (2017) with an average yield of 6.9 t ha^{-1} . Higher yields of 57.2 t ha^{-1} for the untreated control were measured in 2018. The four treatments H2017, + MFW (140), H + MFW (60), and H + CFW achieved similarly high sugar beet yields between 75 and 77.9 t ha^{-1} . Among the purely mechanical weed control methods, MFW (140), and MFW (60) yielded between 48.5 and 52.4 t ha^{-1} , and CFW recorded 36.2 t ha^{-1} . No statistically significant differences were found between the average sugar beet yields of the mechanical and chemical-mechanical treatments in 2018.

Table 5 provides an overview of the number of sugar beets per hectare that were present prior to the treatments (crop emergence) and at harvest. As with all mechanical treatments, some crop plant losses were observed for all mechanical treatments (Table 5). As expected, the herbicide treatment had the minimum loss of sugar beet plants. In addition, even the use of one herbicide application almost halved the sugar beet losses compared with all types of mechanical treatments. However, the overall yields did not differ from the conventional herbicide treatment in 2017 and 2018.

The number of sugar beets for the untreated control in 2017 decreased by 40,000 until autumn because the weed competition was so high that only half of the sugar beets were in a harvestable condition (Table 7). Even though there was not a hand weeding treatment, the herbicide treatments did not interact with the establishment of the sugar beets. The sugar beet loss in the herbicide treatments of both years was less than 30 ha^{-1} . The data also shows that fewer sugar beets emerged in 2018 than in 2017. This was likely due to a lack of rainfall in the spring.

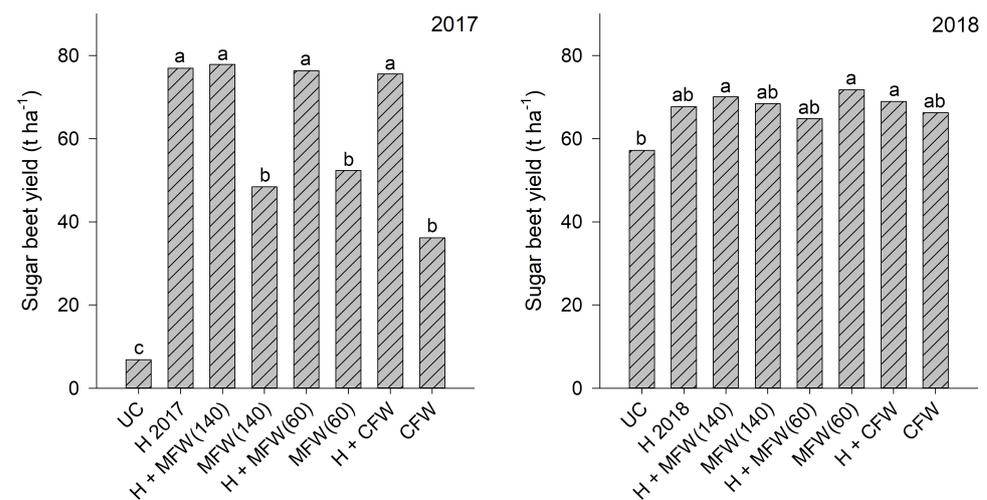


Figure 5. The bars represent the mean sugar beet yield (t ha^{-1}) recorded for each treatment in 2017 and 2018. Different letters above a bar and within the same graph (2017 or 2018) indicate significant differences between the treatments according to the Tukey HSD-Test at $\alpha \leq 0.05$. UC: Untreated Control, H: Herbicide spraying, MFW (140): Motorized finger weeder fast speed, MFW (60): Motorized finger weeder slow speed, and CFW: Conventional finger weeder.

Table 7. The number of sugar beets per hectare before the application of the treatments (crop emergence) and at the harvest date in 2017 and 2018.

Treatment *	Sugar Beets ha ⁻¹ before Treatments		Sugar Beets ha ⁻¹ at Harvest	
	2017	2018	2017	2018
UC	87,842	80,051	48,125	79,791
Herbicide	87,532	80,446	87,509	80,416
MFW (140)	86,546	79,258	86,455	78,333
H + MFW (140)	87,622	80,042	87,312	79,554
MFW (60)	87,331	80,427	86,959	78,103
H + MFW (60)	88,429	79,802	87,514	79,166
CFW	87,596	81,113	86,980	80,401
H + CFW	86,580	78,728	86,233	78,354

* UC: Untreated Control, H: Herbicide spraying, MFW (140): Motorized finger weeder fast speed, MFW (60): Motorized finger weeder slow speed, CFW: Conventional finger weeder

4. Discussion

Inter-row hoeing has been proven to be an effective post-emergent weed control method in wide row crops [25–27]. High weed control efficacy results can be obtained if the mechanical treatments are applied at the right stage of the weed development and under good weather conditions [28]. This could be confirmed in the present study. Furthermore, using the Garford steering-system provided a high guidance accuracy across all mechanical treatments. Post-emergent hoeing with goosefoot sweeps was very successful and recorded average inter-row weed control efficacies between 94% and 98% (Table 6).

Mechanical intrarow weeding with the motorized, and the conventional finger weeders also demonstrated weed control efficacies nearly as high as the conventional herbicide applications in both years. Only in the case of very high weed pressure, as observed in 2017, did the combination of a unique herbicide application with post-emergent finger weeding result in a higher weed control efficacy than mechanical weeding alone.

Like all post-emergent mechanical weeding operations, finger-weeding in sugar beets requires advanced crop development relative to weed development. The selectivity of finger weeding is low if weeds emerge earlier than the sugar beets [29]. Advanced crop development relative to weed growth can be achieved in different ways. Applying a pre-emergent herbicide is the most common method to suppress early emerging weeds in sugar beets. False seedbed preparation and shallow pre-emergent harrowing also prevent weeds from emerging before the crop [30].

It is interesting that using a herbicide treatment as the first application almost halved the losses in sugar beet plants for each treatment, and achieved similar, even slightly higher yield results as the multiple herbicide treatment. It can be concluded that later emerging weeds can then be removed with mechanical weeding tools at a higher intensity. In years with low weed densities, herbicide applications could be substituted partially or even completely by mechanical treatments as the results from 2018 demonstrate. Weeding with the MFW with and without spraying produced similarly high weed control efficacies as the conventional herbicide application in 2018.

Thus, in 2018, two out of three herbicide sprayings could have potentially been replaced with a mechanical treatment, without losses for the farmer. One other type or focused intrarow weeding technique—band spraying—was not performed in this study. Band spraying presents a viable option to reduce the herbicide input even further [12], saving the herbicide usage from 50% as stated in Perez-Ruiz et al. [31] to 65% as stated by Kunz et al. [32] when compared to overall spraying.

In 2018, the sugar beet yields were not adversely affected by the mechanical treatments compared to three times spraying. The low yield results of the MFW and the CFW in 2017 reflect the difficulties that come with high weed densities. Sugar beets simply do not tolerate weeds growing close-by due to their low competitiveness for resources [33]. Petersen [34] stated that yield losses in sugar beets could reach 95% if no plant protection measures were performed. This study confirmed these findings because the untreated control recorded a

yield decrease of 91% compared to the most successful treatment (herbicide + motorized finger weeder with 140 rpm) in 2017.

Not all intrarow weeds were removed from the sugar beet rows by the motorized finger weeders, and yield losses due to this crop-weed competition were inevitable even at high weed control levels of >90% in 2017. The reason for the lack of control was due to the unsuitable weather conditions at the time when the first hoeing was supposed to take place. Rainy conditions prevented timely mechanical control, and the treatments had to be postponed for 5 days. During this time the weeds grew vigorously and most of the larger intrarow weeds were impossible to remove without also damaging the sugar beets.

All weed species reaching an advanced developmental state are hard to remove mechanically if the crop plant is sensitive to physical damage. However, in this study, the particularly resilient species were *C. arvense*, *C. album*, *G. aparine*, and *M. inodora* due to their fast growth and, in the case of *C. arvense* also due to its fast vegetative proliferation via its roots. Figure 6 shows the ineffectiveness of the mechanical treatments and how these weed species established themselves inside the sugar beet rows in 2017.



Figure 6. Intrarow weeds *C. arvense* (left), *M. inodora* (right), and *G. aparine* (right).

Under ideal weather and soil conditions, finger weeders are highly effective and can reduce weed densities by up to 99% [35]. Therefore, this basic concept was adapted for the new autonomous weeding tool in the present study. Additionally, it was important to use a rotating tool similar to the cycloid hoe with metal tines used by [36]. However, finger weeders could be the better choice because they are made from rubber plastic. This makes them flexible yet tough and they are not as rigid as steel tools.

Other rotating tools like brushes can have trouble penetrating hard and heavy soils, thus, leading to insufficient weed control [12]. It must be stated that the motorized finger weeders had a slow working speed compared to conventional farming implements. This was due to the technological limitations of the system. However, the concept of the motorized finger weeders is not supposed to be used with a tractor but rather in conjunction with a robot to constantly perform autonomous weeding. Currently, agricultural robots work slowly compared to a tractor. This is an issue because conventional implements for mechanical weeding require a certain amount of speed to effectively cut, uproot or bury weed plants [37].

For example, inter-row hoeing is most effective at speeds of 4 to 12 km h⁻¹ [38]. Therefore, mechanical weeding tools that rotate independently of the tool carrier (robot) are the optimal solution for autonomous robotic weeding because the rotating movement compensates the slower forward travel speed. Hereby, the accurate guidance of the tool is essential to ensure alignment with the crop row to prevent crop damage. This was achieved successfully with the Garford steering-system in the present study.

The motorized finger weeders performed well in the loamy soils at Ihinger Hof. However, there were not any differences between the rotational speed and the weed control efficacy of the motorized finger weeders. The recognition of the sugar beets and adjusting the speed of the MFW was performed reliably by the data provided from the infrared camera and the IMPASS software. An image separation between weeds and crop suffices if only mechanical weeding is performed.

Our algorithm was based on shape-detection, and it was able to differentiate well between weeds and sugar beets. The motorized finger weeders require that the entire crop row is monitored so that the previously defined areas of a sugar beet and the space between two sugar beets can be targeted precisely with the implement. This is similar to the concept of using images (e.g., aerial data) that can be used to compute detailed herbicide application maps for specific weed species to perform site-specific spraying [39].

However, if more plant groups must be separated instead of just crop and weed plants, other deep learning algorithms are necessary. A promising alternative is convolutional neural networks that use raw pixel values instead of feature descriptors [40,41].

Even though the motorized finger weeders usually resulted in a higher weed control efficacy over the conventional finger weeders, no significant differences were found among the mechanical treatments concerning the sugar beet yield in 2017 and 2018. Furthermore, the system is not restricted to sugar beets alone and can be transferred to other crops in further studies. This may include vegetables (e.g., lettuce or cabbage) where the plant spacing of one crop plant to the other is large enough.

An improvement of the motorized finger weeders would be to use even smaller finger weeders with a diameter of less than 20 cm. This would increase their precision further because the space between two sugar beet plants is only about 18- to 22-cm wide. Higher and lower rotational speeds should also be tested in the future to determine if even better weed control results can be achieved. In general, robotic mechanical weeding is seen as a promising alternative to conventional herbicide applications and should be part of an integrated weed management concept. However, one prerequisite is that the robot should work continuously to compensate for its slow working speed. Additional benefits include that a robot is lightweight and causes less soil compaction than a tractor.

5. Conclusions

In the current paper, we devised a new weeding tool for agricultural robots to perform intrarow mechanical weed control in sugar beets. A conventional finger weeder was modified and equipped with an electric motor. A faster and a slower speed than the tractor speed was used in the motorized finger weeders to test their capabilities to control weeds. We concluded that the motorized finger weeders performed better than the conventional finger weeders and that they could be an ideal tool for mechanical weeding with an agricultural robot.

A combination of one herbicide application and the rest of the treatments as mechanical treatments reduced the sugar beet plant losses from the mechanical treatments. In years with low weed infestations, this combination achieved similar or even higher yields than the multiple herbicide application treatments. A robotic system with motorized finger weeders or other implements can easily compensate for the slow working speed, due to more robots working simultaneously (the concept of a swarm of robots). Overall, the motorized finger weeders proved to be an effective tool for intrarow mechanical weed control in sugar beets concerning the weed control efficacy.

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Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of Variance
BBCH	Biologische Bundesanstalt für Land- und Forstwirtschaft
CFW	Conventional finger weeder
H + ...	Herbicide + ...
LTZ	Landwirtschaftliche Technologiezentrum
MDPI	Multidisciplinary Digital Publishing Institute
MFW	Mechanical finger weeder
UC	Untreated control

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