



Sensor-Guided Mechanical Weed Control in Transplanted Lettuce and Cabbage

Roland Gerhards¹ · Michael Spaeth¹ · Alexandra Heyn¹ · Marcus Saile¹

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Abstract

Effective weed control is extremely important in vegetable production because weeds affect yield and quality of vegetable crops. Usually, only combinations of preventive and direct weed control methods can sufficiently suppress weeds. Therefore, costs for weeding are much higher in vegetables compared to most arable crops. Due to restrictions for herbicide use in vegetables, alternative and efficient direct weeding methods are urgently needed.

Six field experiments with transplanted cabbage and lettuce were conducted in Southwestern Germany to quantify the weed control efficacy (WCE) and crop response of sensor-guided mechanical weed control methods with different degrees of automation. A camera-guided inter-row hoe with automatic side-shift control alone and combined with intra-row finger weeders and a camera-guided intra-row hoeing (robot) were compared to standard mechanical weeding, a broadcast herbicide treatment and an untreated control.

Weed densities prior to treatment averaged 58 plants m⁻² in cabbage and 18 plants m⁻² in lettuce. *Chenopodium album*, *Amaranthus retroflexus*, *Thlaspi arvense*, *Solanum nigrum* and *Digitaria sanguinalis* were the dominating species. Until harvest, 80% weed coverage was measured in the untreated plots of cabbage and 28% in lettuce, which caused 56% yield loss in cabbage and 28% yield loss in lettuce. The highest WCE was achieved with the robot (87% inter-row and 84% intra-row). The broadcast herbicide treatment achieved 84% WCE for both inter-row and intra-row areas. Conventional inter-row hoeing had the lowest WCE of 73% inter-row and 35% intra-row. Camera-guided inter-row hoeing increased inter-row WCE to 80% and intra-row WCE to 56%. Finger weeding increased intra-row WCE in lettuce and cabbage to 54% with conventional hoeing and 62% with camera-guided hoeing. Camera-guidance reduced crop plant losses by 50% (from 9.1 to 4.5%) and increased crop yield by 13% compared to conventional hoeing.

This study highlights the benefits of camera-guidance, AI-based weed detection and robotic weeding in transplanted vegetable crops.

Keywords Conventional hoeing · Camera-guided hoeing · Robotic hoeing · Integrated Weed Management

Introduction

Weeds can be very problematic in vegetable crops not only by reducing yield due to competition (Oerke 2006), but also through affecting crop quality, such as size, colour and shape, as well as by contaminating the vegetables with toxins (Knott 2002). Vegetables that do not meet quality standards are not marketable. Therefore, effective weed management is extremely important in vegetable production

(Robinson 2014; Pannacci et al. 2017). In European vegetable fields, dicotyledonous weeds including *Amaranthus* spp., *Polygonum* spp., *Chenopodium album* L., *Convolvulus arvensis* L., *Solanum nigrum* L., *Datura stramonium* L., *Euphorbia* spp. and *Stellaria media* (L.) Vill. and some warm-season grasses including *Echinochloa crus-galli* L., *Setaria* spp. and *Digitaria sanguinalis* (L.) Scop. are very abundant (Tei et al. 1999, 2003). Acceptable weed suppression in vegetables can only be achieved by combinations of preventive and curative methods of weed control. Preventive methods include rotations of vegetables with cereals (Tei and Pannacci 2017) and intercropping of root (e.g., celery [*Apium graveolens* L.]) and shoot vegetables (e.g., leek [*Allium ampeloprasum* L.]) (Baumann et al. 2000). Transplanting is a common practice in vegetable production to

✉ Roland Gerhards
gerhards@uni-hohenheim.de

¹ Department of Weed Science, Institute for Phytomedicine, University of Hohenheim, 70593 Stuttgart, Germany

shorten the critical period of weed control and to allow growing several crops in one vegetation period. However, typical transplanted vegetables such as cabbage and lettuce still do not tolerate weed competition for 5–6 weeks after planting (Weaver 1984). The reasons for this relatively long period are the low crop densities, wide row spacings and low competitive ability of the crop plants, which allow early weed growth without competition (Tei and Pannacci 2017). Transplanting is often combined with the stale seedbed technique to reduce weed pressure. Weed densities in lettuce were 43–83% lower after employing stale seedbeds (Rasmussen 2004; Riemens et al. 2007). Cover cropping also represents a very effective preventive weed control method with up to 95% weed suppression through competition and allelopathy (Hartwig and Ammon 2002; Falquet et al. 2015; Gerhards and Schappert 2020). For direct weed control, herbicides, harrowing, hoeing and thermal weeding can be applied. Chemical weed control is not available for all vegetables, and it is mostly restricted to pre-emergence herbicides (Tei and Pannacci 2017). Mechanical weeding is widely used in vegetable production with high inter-row weed control efficacy (WCE) and positive effects on crop growth through soil loosening and aeration (Tei and Pannacci 2017). However, mechanical weeding usually provides lower intra-row WCE compared to inter-row weeding (Gerhards et al. 2020). Current weeding tools for intra-row weeding such as torsion weeders, finger weeders, rotor tillers and ridging tools have increased intra-row WCE (Van der Weide et al. 2008). However, they also caused higher crop damage (Gerhards et al. 2020). Mechanical weeding is also more dependent on suitable soil and weather conditions than chemical weeding. The soil should be relatively dry during and a few days after mechanical weeding so that weed plants will not recover from uprooting (Wiltshire et al. 2003; Fennimore et al. 2014).

Innovations in sensor technologies for weed/crop detection and machine guidance and autonomous weeding tools have started a new era in mechanical weeding. Several commercial row guiding systems have been developed for inter-row hoeing based on simple imaging algorithms for crop row detection or RTK-GPS position of the crop seeds/plants (Åstrand and Baerveldt 2005) and hydraulic side-shift control of the hoeing blades. This allowed moving hoeing blades faster and closer along the crop row, which increased WCE in sugar beet, soybean and maize to 85% compared to 70% WCE with conventional hoeing (Gerhards et al. 2020). Automatic intra-row control can be realized based on RTK-GPS position of the crop or by cameras and Artificial Intelligence (AI)-based imaging software for weed/crop detection (Zhang et al. 2022). In transplanted vegetable crops, simple features such as size, area and distance between plants allow crop/weed classification in digital images (e.g. K.U.L.T.i-Select®, Garford Robocrop InRow Weeder® and Steketee

IC®) (Lati et al. 2016; Gerhards et al. 2024b). However, only a few studies evaluated the benefits of sensor- and application technologies for mechanical weed control in vegetable crops.

The objectives of this study were to quantify the WCE and crop response of direct weeding systems with different degrees of automation in two transplanted lettuce and cabbage crops. We determined which benefits were achieved with technologies for weed/crop detection, camera-guidance and robotic weeding compared to standard mechanical and chemical weeding systems. The tested hypotheses were as follows: i) chemical weeding could be substituted by mechanical weeding without reducing WCE and increasing crop damage, ii) camera-guidance for inter-row weed hoeing resulted in equal WCE as standard inter-row hoeing and finger weeding, and iii) robotic inter-row and intra-row weeding resulted in highest WCE and crop yield.

Material and Methods

Experimental Sites

Six field experiments were conducted in Southwestern Germany near Stuttgart in 2021, 2022 and 2023, one in lettuce (*Lactuca sativa* L. var. *capitata* 'Iceberg') and one in cabbage (*Brassica oleracea* L. var. *capitata* f. *alba*) every year. Experiments were located at Hohenheim (48.71°N/9.19°E), Sielmingen (48.65°N/9.38°E), Bernhausen (48.42°N/8.88°E) and Wolfschlügen (Filderstadt) (48.39°N/9.17°E). Soil texture was similar in all experimental locations with 60–70% silt, 25–30% clay and 5–10% sand, which represents a loam originating from loess. Average yearly temperatures in 2021 (11.0°C) and 2022 (10.9°C) were approximately 1°C higher than the

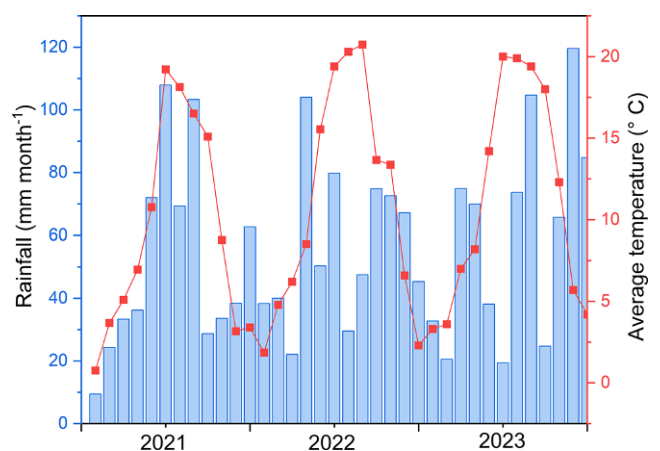


Fig. 1 Average monthly temperatures and precipitation in Hohenheim in 2021, 2022 and 2023; long-term average yearly temperature in Hohenheim is 10 °C and long-term average rainfall is 691 mm

Table 1 Weed control treatments tested in lettuce and cabbage 2021–2023

Treatment	Shortcut	Description
1	Untreated control	Untreated
2	Herbicide treatment	Herb
3	Conventional inter-row hoeing	Conv. Hoe
4	Conventional inter-row hoeing combined with intra-row finger weeding	Conv. Hoe + Finger
5	Camera-guided inter-row hoeing	Cam. Hoe
6	Camwra-guided inter-row hoeing combined with intra-row finger weeding	Cam. Hoe + Finger
7	Camera-guided inter-row and intra-row hoeing	Robot

long-term mean with 10.0°C. In 2023, mean temperature was 9.4°C, which was 0.6°C lower than the long-term mean. The fields received in total sufficient rainfall in all three years (between 655 and 750 mm). However, there were periods of drought during the growing period of lettuce and cabbage in all three years (Fig. 1). Vegetables were only irrigated directly after planting.

Experimental Design

Seven treatments were tested in a one-factorial randomized complete block design with four replications (Table 1). Plots were 15 m long and 3 m wide for cabbage and 15 m long and 2.4 m wide for lettuce. Plots in lettuce contained five crop rows and in cabbage four crop rows.

Before planting, all fields were mouldboard ploughed (25 cm deep). Seedbed preparation was performed with a ro-

tor tiller (Lembken, Zirkon, Germany). Cabbage and lettuce were planted with the semi-automated planter Trium (Checchi & Magli, Italy). Vegetables were irrigated only directly after planting. Cultivars, plant density, row spacing and dates of weeding and harvest are presented in Table 2.

In all mechanical weed control treatments, two passes of inter-row hoeing and one pass of intra-row hoeing were conducted. For conventional hoeing, the camera-guided row alignment was turned off. Goosefoot blades were mounted with a distance of 7.5 cm to the crop row. Working depth was 7 cm. For camera-guided inter-row hoeing, a K.U.L.T.iVision PV (K.U.L.T., Germany) with an RGB-camera and a hydraulic side-shift control was used. No-till sweeps were used for inter-row hoeing at a depth of 2 cm. Those tools were guided at a distance of 4 cm along the crop rows. Camera-guided hoeing was conducted at a speed of 8 km h⁻¹ compared to 5 km h⁻¹ for conventional

Fig. 2 Camera-guided intra-row hoeing using AI-based plant classification (left) and combination of camera-guided inter-row weeding with intra-row finger weeders (right)



Table 2 Dates and details of planting and weed control treatments in the lettuce and cabbage experiments

Location	Year	Crop/ cultivar	Plant den- sity m ⁻²	Planting date	Row dis- tance(m)	Herbicide treatment	Hoeing	Harvest
Sielmingen	2021	Lettuce/ Laibacher Eis	9	01-07-21	0.3	30-06-21	15-07-21, 29-07-21	20-08-21
Sielmingen	2021	Cabbage Sturidor	3.5	29-06-21	0.6	02-07-21	15-07-21, 29-07-21	28-09-21
Sielmingen	2022	Lettuce/ Laibacher Eis	9	04-07-22	0.3	03-07-22	20-07-22, 03-08-22	25-08-22
Bernhausen	2022	Cabbage/ Sturidor	3.5	22-05-22	0.6	– ¹	05-06-22, 21-06-22	20-09-22
Wolfschlugen	2023	Lettuce/ Laibacher Eis	9	29-06-23	0.3	28-06-22	13-07-23, 31-07-23	18-08-23
Hohenheim	2023	Cabbage/ Sturidor	3.5	17-05-23	0.6	20-05-23	31-05-23, 21-06-23	11-10-23

¹ Herbicide treatment was replaced by repeated hand-weeding (once per week) because the experiment was located on an organic farm

hoeing. Finger weeders with medium intensity were used for intra-row hoeing in combination with conventional and camera-guided hoeing (Fig. 1). For camera-guided intra-row and inter-row weeding (robot), in-row hoeing elements were mounted behind the inter-row hoe. Each in-row unit contained a multispectral camera (JAI, Japan), v-formed in-row blades with hydraulic opening and closing and a controller. The camera was mounted vertically above the crop rows (Fig. 2). Plants were segmented from the soil using an automatic grey level threshold. Image processing and AI-based classification was computed in real-time on the controller. Species were grouped into ‘crop’ and ‘weed’. If ‘weed’ exceeded a predefined threshold (0 plants m⁻²) and no ‘crop’ occurred, hoeing blades were moved into the crop row. The speed of the robot was 1 km h⁻¹. All mechanical weeders in this study were tractor-mounted.

Herbicides were sprayed before planting (lettuce) or directly after planting (cabbage) with a plot sprayer (Schachtner, Germany) calibrated for 200 l ha⁻¹ at a speed of 3.6 km h⁻¹ and a pressure of 2.3 bar.

Assessments

Crop and weed densities by species were counted four times in the experiments: (1) one day before weed management, (2) one day after the first hoeing (herbicide treatment was counted 14 days after treatment [DAT]), (3) one day after the second hoeing and (4) one day before harvest. Plants were counted in a 0.5 m² frame four times in each plot. The center of the frame was placed over the crop row. Weeds were counted separately in a 10 cm wide band over the crop row (intra-row) and 20 cm bands on both sides of the crop row (inter-row). RGB-images were taken of the counting frames to determine weed coverage by digital image analysis using a camera, model AD-130-GE (JAI Technology, China) from a height of 1 m above ground. Excessive Green Red Index (ExGR) was calculated out of

the three layers of the processed Red (R), Green (G) and Blue (B) to enhance the contrast between green vegetation and soil as described by Woebbecke et al. (1995) and Mink et al. (2018). A zero threshold was applied to create a binary image. Crops were removed from the ExGR image based on the size of plants. Weed control efficacy (WCE) was calculated according to Eq. 1, where d_a is the weed density after weed control application and d_b is the weed density in the same plot one day before the application.

$$WCE(\%) = 100\% - d_a (0.01 d_b)^{-1} \quad (1)$$

Crop density was counted four times per plot along a meter stick placed along the crop row. Crop loss (% uprooted) was calculated according to Eq. 2, where v_a is the crop density after weed control application and v_b is the crop density in the same plot one day before the application.

$$CL(\%) = 100\% - v_a (0.01 v_b)^{-1} \quad (2)$$

Fresh biomass yield was measured by harvesting the heads of lettuce and cabbage in two middle rows of each plot. The outer leaves were removed by hand and then the heads were weighed in the field.

Statistical Analysis

The data were analyzed with the statistical software RStudio (Version 3.4.1, R Foundation for Statistical Computing, Vienna, Austria). Figures were created with OriginPro 2022b (OriginLab Corporation, Northampton MA, United States). Homogeneity of variance and normal distribution of residuals were approved by utilizing residual plots and a quantile-quantile plot. An analysis of variance (ANOVA) was performed with treatment set as fixed effect and location/year set as random effects. The means of the fixed effects were compared with Tukey’s HSD test at $\alpha \leq 0.05$.

Table 3 Weed coverage (%) one day before harvest in lettuce and cabbage; data were pooled over three years (2021–2023). Means with the same letter were not significantly different according to the Tukey-HSD-Test at $\alpha \leq 0.05$

Treatment	Lettuce		Cabbage	
Untreated	28.3	A	80.4	A
Herbicide	3.2	B	8.7	C
Conv. Hoe	7.2	B	31.2	B
Conv. Hoe + Finger	5.8	B	23.7	B
Cam. Hoe	6.0	B	20.8	B
Cam. Hoe + Finger	4.6	B	18.5	B
Robot	6.1	B	22.5	B

Results

The statistical analysis showed no significant effects for year/location and no interactions between treatments and year/location. Treatments were significant (<0.01) for all parameters measured. The composition of weed species was similar in all experiments with *C. album*, *A. maranthus retroflexus* L., *Thlaspi arvense* L., *S. nigrum*, *D. sanguinalis*, *Galinsoga ciliata* (Raf.) Blake and *E. crus-galli* accounting for 89% of all weed plants observed.

Treatment Effects on Weed Density and Weed Coverage

Weed densities before treatment, 1 DAT (mechanical), 14 DAT (herbicide) and one day before harvest (Fig. 1) were higher in cabbage than in lettuce. Weed density in cabbage in the untreated control increased from 58 plants m^{-2} before treatment to 104 plants m^{-2} until one day before harvest, while weed densities in lettuce in the untreated control remained stable from one day before treatment until one day before harvest (18 and 19 plants m^{-2}). Weed coverage data in Table 3 highlight that weed infestations were much higher in the untreated plots of cabbage (80%) than in lettuce (28%). Weed control treatments suppressed weed coverage in lettuce to less than 10%. However, in cabbage only the herbicide treatment resulted in 9% weed coverage, whereas mechanical treatments had 19–31% weed coverage until one day before harvest.

Treatment effects on weed density were similar in both crops and at both times of assessment. The lowest weed densities were counted in the pre-emergence herbicide treatment and camera-guided inter-row and intra-row weeding with less than 5 weeds m^{-2} . Camera-guided hoeing with automatic side-shift control resulted in lower weed densities than conventional inter-row hoeing. The integration of finger weeding reduced weed densities in both inter-row weeding systems. Over all six experiments, weed density after conventional inter-row hoeing and finger weeding

Table 4 Crop loss (% uprooted plants) in lettuce and cabbage; data were pooled over three years (2021–2023). Means with the same letter were not significantly different according to the Tukey-HSD-Test at $\alpha \leq 0.05$

Treatment	Lettuce		Cabbage	
Untreated	0	A	0	A
Herb	0	A	0	A
Conv. Hoe	7.0	B	8.0	B
Conv. Hoe + Finger	17.5	C	4.5	B
Cam. Hoe	1.0	A	2.5	AB
Cam. Hoe + Finger	6.0	B	4.0	B
Robot	5.0	B	6.0	B

was similar to weed density after camera-guided inter-row weeding with automatic side-shift control (Fig. 3).

Inter-row and intra-row WCE were similar for the hoeing robot and the broadcast herbicide treatment. All other treatments showed much lower intra-row WCE than inter-row WCE regardless if finger weeders were applied or not. Inter-row hoeing with row detection and side-shift control resulted in higher WCE as conventional hoeing without sensor guidance even though goosefoot blades of the conventional hoe worked deeper and more aggressively than the no-till sweeps of the camera hoe. Camera-hoeing without finger weeders achieved equal WCE as conventional hoeing with finger weeders. Total WCE in lettuce was highest for the robotic hoeing treatment with 82%. In cabbage highest total WCE was measured for the herbicide treatment with 92% (Fig. 4).

Treatment Effects on Lettuce and Cabbage

No losses were observed for the herbicide treatment and the untreated control. All mechanical treatments except for camera-guided inter-row hoeing showed significantly higher losses. The maximum losses amounted 17.5% in lettuce after conventional inter-row hoeing plus finger weeding and 8% in cabbage after conventional inter-row hoeing. Robotic inter-row and intra-row hoeing caused 5% losses in lettuce and 6% in cabbage (Table 4).

In lettuce, robotic weeding resulted in highest yield. All other sensor-guided hoeing treatments and the combination of conventional hoeing plus finger weeding amounted a higher yield than conventional inter-row hoeing and the untreated control and equal to the herbicide treatment. In cabbage, all treatments achieved a significantly higher yield than the untreated control. Conventional hoeing had a significantly lower yield than all other mechanical treatments except for the robotic hoeing (Fig. 5).

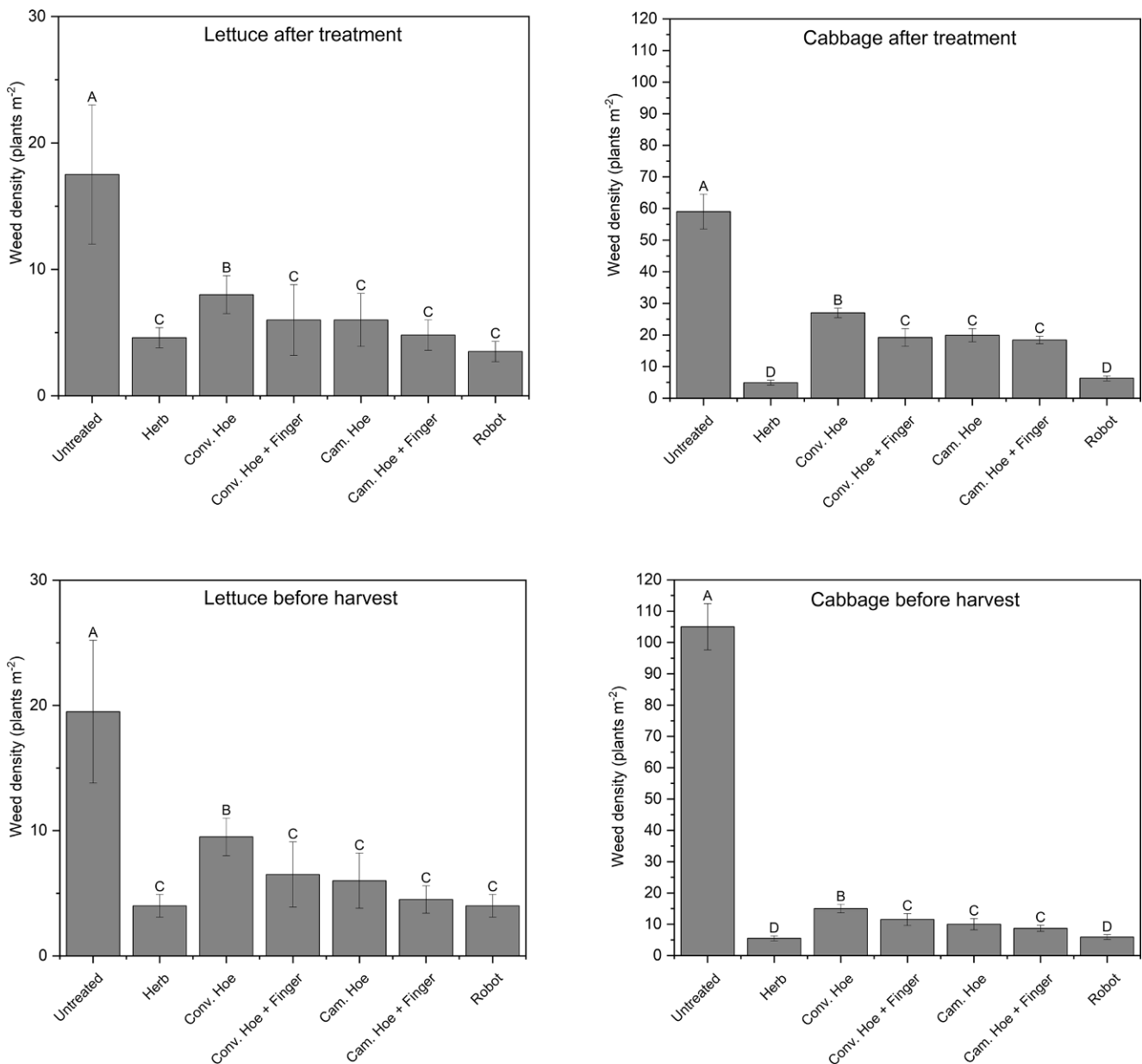


Fig. 3 Weed density (plants m⁻²) after treatment (one day after the second hoeing treatment and 14 days after herbicide application) and one day before harvest in lettuce and cabbage pooled over three years (2021–2023). Means with the same letter were not significantly different according to the Tukey-HSD-Test at $\alpha \leq 0.05$. Bars represent the standard errors of the mean

Discussion

This study emphasizes the benefits of sensor- and automation technology for mechanical weed control in transplanted vegetable crops. Camera-guided inter-row hoeing with automatic side-shift control increased inter-row WCE in lettuce and cabbage from 74 to 81% and intra-row WCE even from 35 to 56%, reduced crop damage from 9.1 to 4.5% and increased crop yield by 17% compared to conventional inter-row hoeing. This is in agreement with Tillett et al. (2002) for automatic inter-row hoeing in sugar beet and

Gerhards et al. (2020) for camera-guided hoeing in maize, sugar beet and soybean. Pérez-Ruiz et al. (2015) and Gerhards et al. (2024b) pointed out additional benefits of camera-guided inter-row weeding such as lower weeding costs, higher driving speed and easier machine handling. All those benefits were also realized in this study. The higher driving speed of 8 km h⁻¹ compared to 5 km h⁻¹ and the closer distance to the crop row is probably the reason for 21% higher intra-row WCE of camera-guided hoeing compared to conventional hoeing. Rasmussen et al. (2008) showed, that weed burial by soil increased with higher speed of

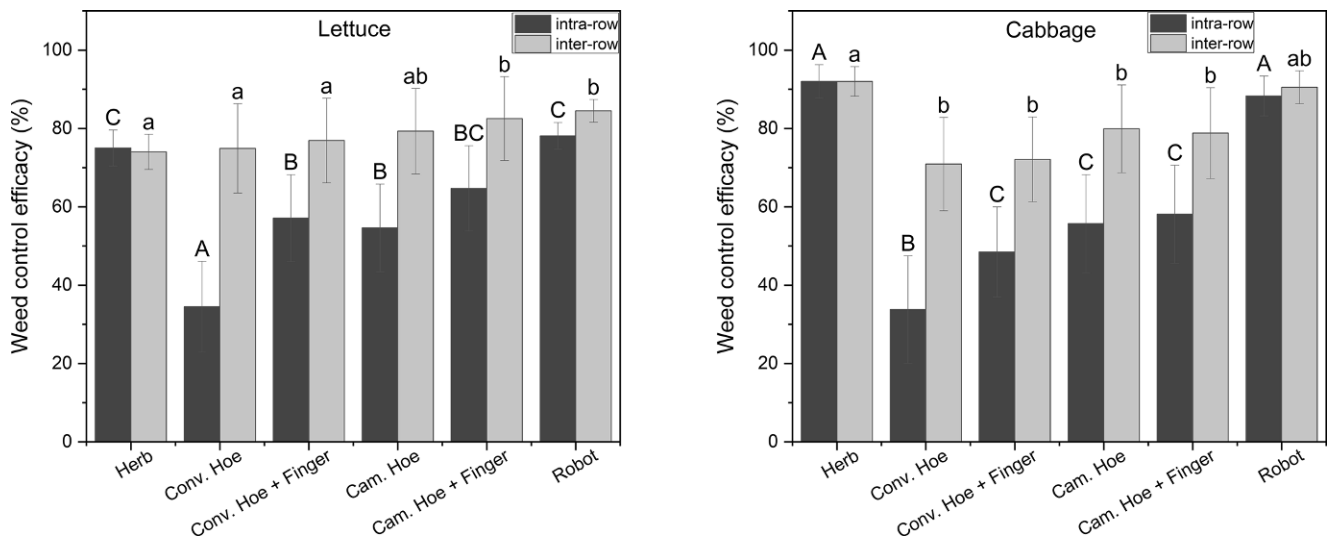


Fig. 4 Weed control efficacy (%) based on weed density data in and between rows of lettuce and cabbage averaged over three years (2021–2023) Means with the same letter were not significantly different according to the Tukey-HSD-Test at $\alpha \leq 0.05$. Capital letters represent differences among weed control treatments for intra-row WCE; small letters present significant differences for inter-row WCE. Bars represent standard errors of the mean

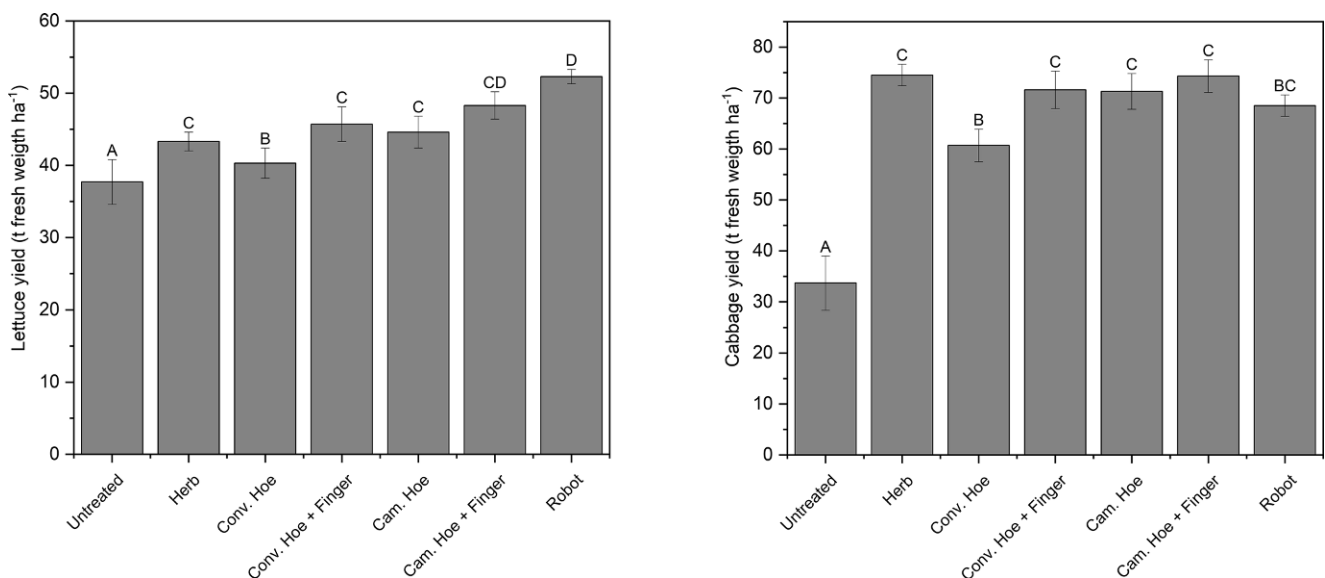


Fig. 5 Lettuce and cabbage yield (t fresh weight ha⁻¹) pooled over the experiments 2021, 2022 and 2023. Means with the same letter were not significantly different according to the Tukey-HSD-Test at $\alpha \leq 0.05$. Bars represent the standard errors of the mean

harrowing. Camera-guided intra-row and inter-row weed hoeing with the tractor-mounted robot further increased intra-row WCE by 18% compared to camera-guided inter-row hoeing with intra-row finger weeding. Total WCE of the robot was equal to the broadcast herbicide treatment. Camera-guided intra-row weeding in transplanted vegetables had already been developed by Pérez-Ruiz et al. (2012) and Raja et al. (2020). Those robots detect transplanted crops based on their size. Weeding tools operated around the crops. The system in the present study uses Artificial Intelligence to identify plant species. It differentiates between

several weed species and crops based on colour, shape and texture. It can be applied in transplanted and sown crops. If certain weed species were categorized as beneficial plants, those weed species also remain untreated similar to the crop plants (Gerhards et al. 2024b).

Even though 5% of the lettuce plants were uprooted by the robot, lettuce yield was still increased by robotic hoeing compared to the broadcast herbicide treatment. This indicates, that mechanical weeding provides other benefits to the crop besides weed control. Beiküfner et al. (2024) measured higher water infiltration into a sandy loam af-

ter several passes of hoeing in maize and barley and higher soil water contents. Steinmann (2002) observed higher mineral nitrogen contents in the soil after mechanical weeding. However, those effects were not measured in the present study. It is just speculated that mechanical weeding might have had positive effects on lettuce. Another reason for higher yield in the mechanical weeding treatments compared to the herbicide treatment could be herbicide phytotoxicity. In the cabbage experiments, yield of the herbicide treatment was similar to the mechanical treatments.

This study shows that selective intra-row weeding is still the biggest challenge for mechanical weed control in vegetable crops. Although finger weeding increased intra-row WCE in lettuce and cabbage on average from 46 to 59%, weed suppression was not sufficient. Surviving weeds may cause additional costs for hand-weeding or other weed control methods. Torsion weeders, rotary harrows and ridging elements are possible alternatives to finger weeders for intra-row weeding (Van der Weide et al. 2008). However, all in-row tools resulted in similar WCE as finger weeders. Asaf et al. (2023) observed that finger weeding in irrigated tomato, sweet corn, sunflower, cotton and beetroot did not cause crop plant losses and controlled 40–90% of the intra-row weeds. In our study, only camera-guided intra-row weeding tools resulted in acceptable weed control efficacies similar to herbicides. This was also reported by Gerhards et al. (2024b). Comparing camera-guided inter-row weeding with camera-guided intra-row and inter-row weeding (robot), this study highlights the benefits of robotic weeding due to the significantly higher intra-row WCE. Higher labour costs for camera-guided intra-row weeding due to the low driving speed can be compensated by fully autonomous weeders such as Farming GT®, Robovator® or Farmdroid FD20® (Gerhards et al. 2024b).

In cabbage, weed density in the untreated control significantly increased from time after weed control until harvest, whereas in lettuce, weed density remained almost constant from time after weed control until harvest. In the treated plots, weed densities did not increase. The increase of weed density in the untreated plots underlines the low competitive ability of cabbage in the early growth stage (Weaver 1984). If weed control was not applied in the critical period, cabbage plants were suppressed by weeds resulting in more than 56% yield loss (Pannacci et al. 2017).

Conclusion

Effective weed control in vegetable crops is extremely important mainly in the early growing period. New information and application technologies including camera guidance and automatic weed detection have improved mechanical weed control. In this three-year study, camera-guided

weed hoeing in lettuce and cabbage achieved equal WCE and yield as conventional broadcast herbicide applications. Although camera-guided weed hoeing can reduce the dependence on herbicide use in vegetable production and reduce the risks of herbicide residues in the food chain and selection of herbicide resistant weed populations, it should not be considered as the only weed control method. Weed hoeing may fail under wet soil conditions, and it can induce new weeds to emerge. Therefore, camera-guided weed hoeing in lettuce and cabbage should be part of an integrated weed management strategy including preventive weed control methods, such as mulches, rotations with winter cereals and false seedbeds and other curative methods including spot/band applications of herbicides.

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Conflict of interest R. Gerhards, M. Spaeth, A. Heyn and M. Saile declare that they have no competing interests.

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