





Sensor-based inter- and intra-row weed control methods in sugar beet, sunflower, and maize

Roland Gerhards  | Michael Spaeth  | Oyebanji O. Alagbo  | Marcus Saile 

Weed Science Department, University of Hohenheim, Stuttgart, Germany

Correspondence

Roland Gerhards, Weed Science Department, University of Hohenheim, 70593 Stuttgart, Germany.

Email: roland.gerhards@uni-hohenheim.de

Funding information

Bundesanstalt für Landwirtschaft und Ernährung

Subject Editor: Therese W. Berge, Norwegian Institute of Bioeconomy Research: Aas, Viken, NO

Abstract

Sensor-guidance and camera-based weed detection systems have improved weed control, resulting in higher weed control efficacy (WCE), less herbicide use, and less crop damage. In this study, four sensor-guided inter- and intra-row weeding systems were tested in sugar beet, maize, and sunflower. Those four systems included (1) camera-guided inter-row hoeing (HOE), (2) HOE + intra-row finger weeding (HOE+F), (3) HOE + camera-guided intra-row hoeing (HOE + InRow) and (4) HOE + intra-row band spraying (HOE + BS). A broadcast herbicide treatment and an untreated plot were included as control. Six experiments were conducted in 2022 and 2023 in Southwestern Germany. Inter-row and intra-row weed density and crop density were assessed before and after treatment. Yield was measured for each plot. The systems were evaluated based on WCE, crop losses (CL), yield, and herbicide savings. All sensor-based weeding systems controlled at least on average 77% of the weeds. HOE+BS achieved 91% WCE and was similar to the broadcast herbicide application (92% WCE). HOE on average controlled 90% of the inter-row weeds but only 69% of the in-row weeds. HOE and HOE+F had 14% less intra-row WCE than inter-row WCE. HOE+InRow resulted in 77% inter-row and intra-row WCE. Sensor-guided weed control did not cause significant CL or yield reduction compared to the broadcast herbicide application, except for HOE+InRow in maize 2023 because of wrong setting in the segmentation and weed/crop classification algorithm. This study underlines that sensor-guided hoeing and the combination of band spraying with inter-row hoeing provide effective and robust alternatives to conventional broadcast herbicide application in row crops.

KEYWORDS

band spraying, finger weeders, herbicide application, in-row hoeing, mechanical weed control, precision farming

1 | INTRODUCTION

Uncontrolled weeds can cause approximately 40% yield loss in maize and sunflower and up to 100% in sugar beet (Oerke, 2006; Gummert et al., 2012). Crops with wide row spacing such as maize, sunflower, and sugar beet are extremely sensitive to weed competition in the critical period of weed control, which is during the first 4–6 weeks

after sowing (Knezevic et al., 2002). Chemical weed control is a common practice in conventional farming systems. Herbicides often provide effective and cost-efficient weed control. However, the efficacy of herbicides has decreased due to the development of many herbicide-resistant weed populations (Moss et al., 2019). European policies aim to reduce herbicide use because of their potential negative side-effects on the environment including biodiversity (European

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2025 The Author(s). *Weed Research* published by John Wiley & Sons Ltd on behalf of European Weed Research Society.

Commission, 2020). The dependence on herbicide use can be reduced if preventive methods of weed management such as diverse crop rotations, stale seeding, ploughing, competitive crop cultivars, cover cropping, and living mulches are applied (Hillocks, 2012; Riemens et al., 2022).

Mechanical weed control including hoeing and harrowing can replace post-emergence herbicide applications as direct weed control method (Riemens et al., 2022). However, weed control efficacy (WCE) for mechanical weed control in row crops varied from 40% to 90%. Low WCE was observed, when the soil was relatively wet during mechanical weeding and when weed species emerged earlier than the crop and were taller at time of mechanical weed control (Melander et al., 2005; Pannacci & Tei, 2014; Van der Weide et al., 2008). Another disadvantage of mechanical weeding in row crops is the lower intra-row WCE compared to inter-row WCE, even when intra-row weeding elements such as finger weeders, torsion weeders or rotary harrows were used (Gerhards et al., 2020; Melander et al., 2005; Pannacci & Tei, 2014; Van der Weide et al., 2008). Combinations of inter-row hoeing with band spraying are promising alternatives to standard herbicide treatments resulting in high inter-row and intra-row WCE (Van der Weide et al., 2008).

Camera-guided inter-row hoeing with hydraulic side shift control increased WCE in sugar beet, maize and soybean from 70% to 85% (Kunz et al., 2015; Machleb et al., 2018). Recent field studies in cereals showed that camera-guided hoeing could achieve higher WCE and higher yield than conventional herbicide applications (Saile et al., 2022). Higher WCE of camera-guided inter-row hoeing was attributed to a closer distance of the hoeing blades to the crop row. Automatic guidance allowed increasing the driving speed from approximately 3–6 to 8–12 km⁻¹ without causing any crop damage. Higher driving speed resulted in a higher burial of weeds with soil and thus, increased WCE. Camera-guided hoeing systems can work with a maximum lateral offset from the crop row centre of 20 mm at a forward speed of up to 10 km h⁻¹ without causing crop losses (CL) (Gerhards et al., 2020; Griepentrog et al., 2007). This exact guidance system also facilitates intra-row weeding with finger weeders, torsion weeders and ridging tools (Gerhards et al., 2020). However, those intra-row tools failed when the weed plants were taller compared to the crop plants (Gerhards et al., 2020; Machleb et al., 2021). It needs more effective and selective tools for intra-row weed control. One such approach is robotic weeding using machine learning for classifying weeds and crop plants in digital images and targeting hoeing elements and spot sprayers only on weed plants (Gerhards et al., 2023).

Inter-row hoeing can also be combined with intra-row band spraying. This combination reduced herbicide use in sugar beet by 70% and 50% in maize (Mehrtens et al., 2005; Wiltshire et al., 2003). Inter-row hoeing plus band spraying resulted in equal WCE in maize and sugar beet as broadcast herbicide application (Kunz et al., 2018; Mehrtens et al., 2005). However, Gerhards et al. (2023) observed that band spraying had almost 30% (66% WCE) lower efficacy when it was applied simultaneously with inter-row hoeing. If band spraying and inter-row hoeing were carried out in two consecutive passes, band spraying had 95% WCE, which was equal to the broadcast herbicide.

The objective of this study was to combine camera-guided inter-row hoeing with the following weeding approaches: (1) in-row finger weeding, (2) band spraying, and (3) camera-controlled intra-row hoeing in maize, sunflower, and sugar beet. It was aimed to evaluate WCE, CL, and yield of those combined treatments in comparison to solely inter-row hoeing, broadcast herbicide application, and an untreated control. It was hypothesised that (i) WCE and yields of the combined inter-row and intra-row hoeing and inter-row hoeing plus band spraying treatments would be equal to the broadcast herbicide treatment, (ii) crop plant losses would be lower for camera-based intra-row hoeing compared to the conventional finger weeding treatment, and (iii) in-row WCE of band spraying would be equal to the in-row WCE of the broadcast herbicide treatment.

2 | MATERIALS AND METHODS

2.1 | Experimental sites and design

Six field experiments were conducted in sugar beet (*Beta vulgaris* L.), sunflower (*Helianthus annuus* L.), and maize (*Zea mays* L.) during 2022 and 2023. The experiments were located in different fields at the University of Hohenheim Research Station Ihinger Hof, Germany (48°44'32.5"N 8°55'31.1" E). Mean temperature during the growing season from April until September in 2022 was 1.3°C higher than the long-term average of 13.1°C. In 2003, temperatures were only 0.7°C above the long-term average. Ihinger Hof received sufficient precipitation in both years with 650 mm rainfall in total. Both years were characterised by drought periods in May/June 2022 and July/August 2023. However, fields were not irrigated during those dry periods. Experiments were established on a loamy soil at Ihinger Hof. Fertilisation and plant protection, besides weed control, were carried out in all trials according to common practice. Crops were sown at an inter-row distance of 50 cm in all experiments. Cultivars, seed rates and sowing dates are given in Table 1. All six experiments were realised as one factorial randomised complete block design with four replicate blocks. The plots in all experiments were 3 m wide and 20 m long, with the longer side in the sowing direction of the crop.

2.2 | Treatments

All experiments contained an untreated control (CON), a broadcast herbicide treatment (HERB) and four sensor-based weed control treatments:

1. Camera-guided inter-row hoeing with hydraulic side-shift control (HOE)
2. Treatment HOE combined with in-row finger weeding (HOE+F)
3. Treatment HOE combined with camera-based intra-row hoeing (HOE+InRow)
4. Treatment HOE combined with herbicide band spraying (HOE+BS)

TABLE 1 Experimental details of the six experiments including cultivar, code, year, seed rate, sowing date (DD-MM-YYYY), application time splitted in herbicide pre- and post-emergence and mechanical treatment in days after seeding (DAS).

Crop, cultivar	Code	Year	Seed rate (seeds ha ⁻¹)	Sowing date	Herbicide treatments (DAS)	Mechanical treatments (DAS)
Sugar beet, Advena	SB 22	2022	80 000	• 19-04-2022	21 Post	21
Sunflower, Delicio CLP	SF 22	2022	80 000	• 06-05-2022	5 Pre	18
Maize, Crosbey	M 22	2022	93 000	• 09-05-2022	5 Pre, 16 Post	16
Maize, Crosbey	M I 23	2023	90 000	• 16-05-2023	5 Pre, 18 Post	18
Maize, Crosbey	M II 23	2023	90 000	• 16-05-2023	5 Pre, 18 Post	18
Sunflower, Delicio CLP	SF 23	2023	80 000	• 15-05-2023	5 Pre	22



FIGURE 1 Broadcast herbicide application with Schachtner-plot sprayer in maize 2023.

The CON plots were left untreated for the entire growing season. However, it was ensured that the untreated control also received the same number of passes with the tractor wheels as the other treatments. Hoeing was conducted when sugar beet had two true leaves and sunflowers and maize four true leaves. Mechanical weeding was carried out when it was relatively dry and at least three consecutive days without rainfall were forecasted after the treatment. Weeds were in the seedling stage or had developed two true leaves at the time of hoeing. Inter-row hoeing and finger weeding were done at a driving speed of 5 km h⁻¹. Camera-based intra-row hoeing required a lower forward speed of 1 km h⁻¹ for image analysis and moving weeding elements in and out of the crop rows. Broadcast- and band spraying were applied with a plot sprayer (Schachtner-Fahrzeug- und Gerätetechnik, Ludwigsburg, Germany) equipped with flat jet nozzles (Lechler, AD 130-02) for broadcast application or band nozzles (Lechler, E 8002 (60 M)) for band spraying, at a pressure of 2.4 bar and a speed of 4.5 km h⁻¹. Band nozzles have a narrow spray angle (80°) and a uniform distribution over the spray width. Flat jet

nozzles have a wider spray angle (130°) that overlap with the spray angle of the neighbouring nozzles to guarantee a uniform droplet distribution.

2.2.1 | Broadcast herbicide application

Broadcast herbicide applications were realised with a 3 m wide boom with 7 nozzles at the recommended field rates, according to the crop (Figure 1). Nozzles had a distance of 50 cm to the ground. In sugar beet, a post-emergence tank-mix of 1.25 L ha⁻¹ Betasana® SC (160 g L⁻¹ phenmedipham, UPL) + 1.0 L ha⁻¹ Oblix® SC (500 g L⁻¹ ethofumesat, UPL) + 1.5 L ha⁻¹ Goltix Gold (700 g L⁻¹ metamitron, ADAMA) was applied 21 days after sowing (DAS). In sunflowers 2022, Bandur® SC (600 g L⁻¹ aclonifen, Bayer CropScience) was applied 5 DAS with 1.0 L ha⁻¹ as a pre-emergence herbicide. In Maize 2022, the pre-emergence herbicide Spectrum® plus EC (250 g L⁻¹ pendimethalin, 212.5 g L⁻¹ dimethenamid-P, BASF) was applied

5 DAS, with 2.5 L ha^{-1} . As a post-emergence herbicide, MaisTer® power OD (31.5 g L^{-1} foramsulfuron, 1.0 g L^{-1} iodosulfuron, 10 g L^{-1} thiencazazon, 15 g L^{-1} cyprosulfamide, Bayer CropScience) was applied 16 or 18 DAS, with 1.0 L ha^{-1} . In 2023, the same herbicide programme was used for maize and sunflower.

2.2.2 | Band spraying application

For band spraying, equal herbicide rates were applied as for the broadcast herbicide application. However, herbicides were only sprayed in a 20 cm wide band over the top of the crop row (Figure 2).

This resulted in 60% less herbicides compared to the broadcast herbicide treatment. Herbicides were sprayed in the morning and inter-row hoeing was done later in the afternoon on the same day. Herbicide mixtures and timings for band spraying were the same as for the broadcast application.

2.2.3 | Camera-guided inter-row hoeing

For all inter-row hoeing treatments, a 3 m wide hoe (K.U.L.T.-Vision control, KULT-Kress, Kürnberg, Germany) was used (see Figure 3). The hoe was equipped with a hydraulic side-shift control to guide the



FIGURE 2 Band spraying boom and nozzles mounted on a Schachter plot sprayer in maize in spring 2023.



FIGURE 3 Sensor-guided 3 m wide K.U.L.T.-Vision inter-row hoe in maize.

no-till sweeps in the centre between the crop rows with a distance of 5 cm to the crop rows. An RGB camera was used for real-time row detection, mounted on the flexible tool bar of the hoe scanning diagonally forward with four crop rows in the field of view. The images were segmented into green pixels of the plants and background of soil, stones, and dead plant residues. The areas of the highest green intensity were connected to the centre of the crop row (Tillett et al., 2002). This resulted in a robust and fast row detection even if the plant leaves overlapped in the inter-row area. The forward speed of camera-guided inter-row hoeing was 8 km h^{-1} . The no-till sweeps were guided 2 cm deep in the soil.

2.2.4 | Camera-guided intra-row hoeing and finger weeding

Pairs of finger weeders were mounted between the no-till sweeps on the flexible part of the hoeing frame. They were guided exactly above the crop rows with a 1 cm overlap of the fingers for the treatment HOE+F (Figure 4). Treatment HOE+InRow was realised with four camera-controlled intra-row weeding knives with hydraulic opening and closing mounted on the flexible part of the hoeing frame exactly above the crop row. A multispectral camera (AD-130 GE, Jai, Japan) was placed 10 cm in front and 30 cm above the crop row taking images of $30 \text{ cm} \times 20 \text{ cm}$ size with the longer side across the crop row. The camera was triggered by an encoder in the wheel of the hoe taking into account different forward speeds. Images were segmented into plants and soil and plants were classified into weed and crop. If no crop and weed were identified in the image, the in-row knives were closed and moved into the crop row. Otherwise, the knives were opened (Figure 4). Eleven images were analysed per second (Gerhards et al., 2023). Therefore, the maximum forward speed of this treatment was 1 m s^{-1} .

2.3 | Data collection

Weed density and crop density (plants m^{-2}) were measured 1 day before and after weed control treatment. The efficacy of the herbicide treatments was assessed 14 days after the application. The efficacy of mechanical weeding was measured 1–3 days after treatment before plants recovered from burial and before new weeds emerged. Weed density was counted using a 0.1 m^2 frame. Four random positions were selected per plot, both for intra- and inter-row area. For calculating total weed density, intra- and inter-row weed density was used in combination. Crop density was measured at four random positions per plot using a 1 m stick placed along the crop row. The sunflower experiment was harvested in an area of $2 \text{ m} \times 10 \text{ m}$ in the centre of each plot using a plot combine harvester (Zürn 150, Germany). Seed yield was recalculated for a dry matter content of 86%. The two centre rows of sugar beet were harvested by hand in each plot and fresh root biomass was determined. Silage maize yield was assessed in a $2 \text{ m} \times 10 \text{ m}$ area in the centre of each plot using the same harvester as for sunflower.

2.4 | Data analysis

The data were analysed 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, United States). Prior to analysis, the data were tested for homogeneity of variance and normal distribution of residuals by utilising residual plots and a quantile-quantile plot. Transformations of the response variables were not needed to fulfil requirements for ANOVA. An analysis of variance (ANOVA) was performed using the following linear one-factorial model.



FIGURE 4 University of Hohenheim InRow-Hoe in maize on the left side and finger weeders used in sunflowers on the right side.

$$Y_{ik} = \mu + a_i + b_k + e_{ik}, \quad (1)$$

where Y_{ik} is the observed value (yield, crop and weed density after weeding) of treatment a in block b , μ denotes the general mean and a_i represents the fixed effects of the i th treatment, while b_k and e_{ik} represent the random effects of the k th block and the residual error for each plot, respectively. The means of the fixed effects were compared with Tukey's HSD test at $p \leq 0.05$. The same test was also used for pairwise comparisons of inter-row and intra-row weed densities.

WCE was calculated according to Equation (2) separately for inter- and intra-row areas as suggested by Piepho et al. (2024).

$$\text{WCE} = 100\%(1 - w_a/w_b), \quad (2)$$

where w_a is the weed density after treatment and w_b is the weed density before the treatment in the same plot. CL were calculated according to Equation (3), with C_a representing the crop density after treatment and C_b showing the crop density before treatment in the same plot.

$$\text{CL} = 100\%(1 - C_a/C_b). \quad (3)$$

For ANOVA of WCE and CL, data from all experiments were combined with treatment as a fixed effect and crop/year as a random effect. The means of the treatments were compared with Tukey's HSD test at $p \leq 0.05$.

3 | RESULTS

Chenopodium album L., *Polygonum convolvulus* L., *Galium aparine* L., *Fumaria officinalis* L. and *Echinochloa crus-galli* (L.) Pal. Beauv. were the dominating weed species in all six experiments. Treatments significantly reduced weed density in all experiments. Crop density was significantly affected by treatment only in the maize experiment M 22. Treatment had a significant effect on yield in sugar beet SB 22 and maize M I 23 (Table 2).

TABLE 2 p -values from the analysis of variance (ANOVA) for the assessed parameters weed and crop density after weeding and yield of the factor treatment in all experiments separately.

Experiment/parameter	Inter-row weed density	Intra-row weed density	Crop density	Yield
M 22	<0.001	<0.001	0.039	0.734
M I 23	<0.001	<0.001	0.089	0.032
M II 23	<0.001	<0.001	0.711	0.823
SB 22	<0.001	<0.001	0.058	0.041
SF 22	0.029	0.021	0.061	0.052
SF 23	0.012	0.014	0.671	0.626

Note: p -values below $\alpha < 0.05$ are highlighted in bold.

3.1 | Maize trials

Weed density was highest in 2022, with an average of 80 weeds m^{-2} in the untreated control. The treatments HERB, HOE+F, and HOE+BS resulted in the lowest weed densities in all three maize experiments. Inter-row and intra-row weed densities did not differ in these three treatments. However, none of these treatments reduced weed density to less than 7 weeds m^{-2} in 2022. In 2023, less than three weeds m^{-2} were counted in these treatments. Inter-row hoeing (HOE) significantly reduced weed densities compared to the untreated control but resulted in higher weed densities compared to HERB, HOE+F, and HOE+BS in two maize experiments. In 2022, weed density after inter-row hoeing (HOE) still amounted to 30 weeds m^{-2} (Figures 5–7 left). In the maize M 22 trial, HERB, HOE+InRow, HOE+F, and HOE+BS significantly reduced weed density compared to HOE and CON. In two maize experiments, intra-row weed density in the HOE treatment was higher than inter-row weed density. Camera-guided inter-row and intra-row weed hoeing (HOE+InRow) performed well in 2022 but resulted in significantly higher weed density in both experiments in 2023. HOE+InRow was the only treatment that reduced maize density in one experiment (Figure 5 middle). Maize yield was equal in all treatments in 2022 and 2023 II. In 2023 I, maize yield was significantly higher in the treatments HERB and HOE+F compared to CON with only 30 $t\ ha^{-1}$ and HOE+InRow with 33 $t\ ha^{-1}$ (Figure 6 right).

3.2 | Sugar beet trial

All treatments resulted in a significant reduction of weed density (1–2 weeds m^{-2}) compared to the untreated control with 21 weeds m^{-2} . Intra-row weed density in the HOE treatment was significantly higher than inter-row weed density. In all other treatments, inter-row and intra-row weed densities were equal with less than 3 weeds m^{-2} (Figure 8 left). Crop density was not affected by treatments (Figure 8 middle). Inter-row hoeing combined with camera-guided in-row hoeing (HOE+InRow) resulted in significantly higher yield (89 $t\ ha^{-1}$) compared to the untreated control with only 62 $t\ ha^{-1}$ (Figure 8 right).

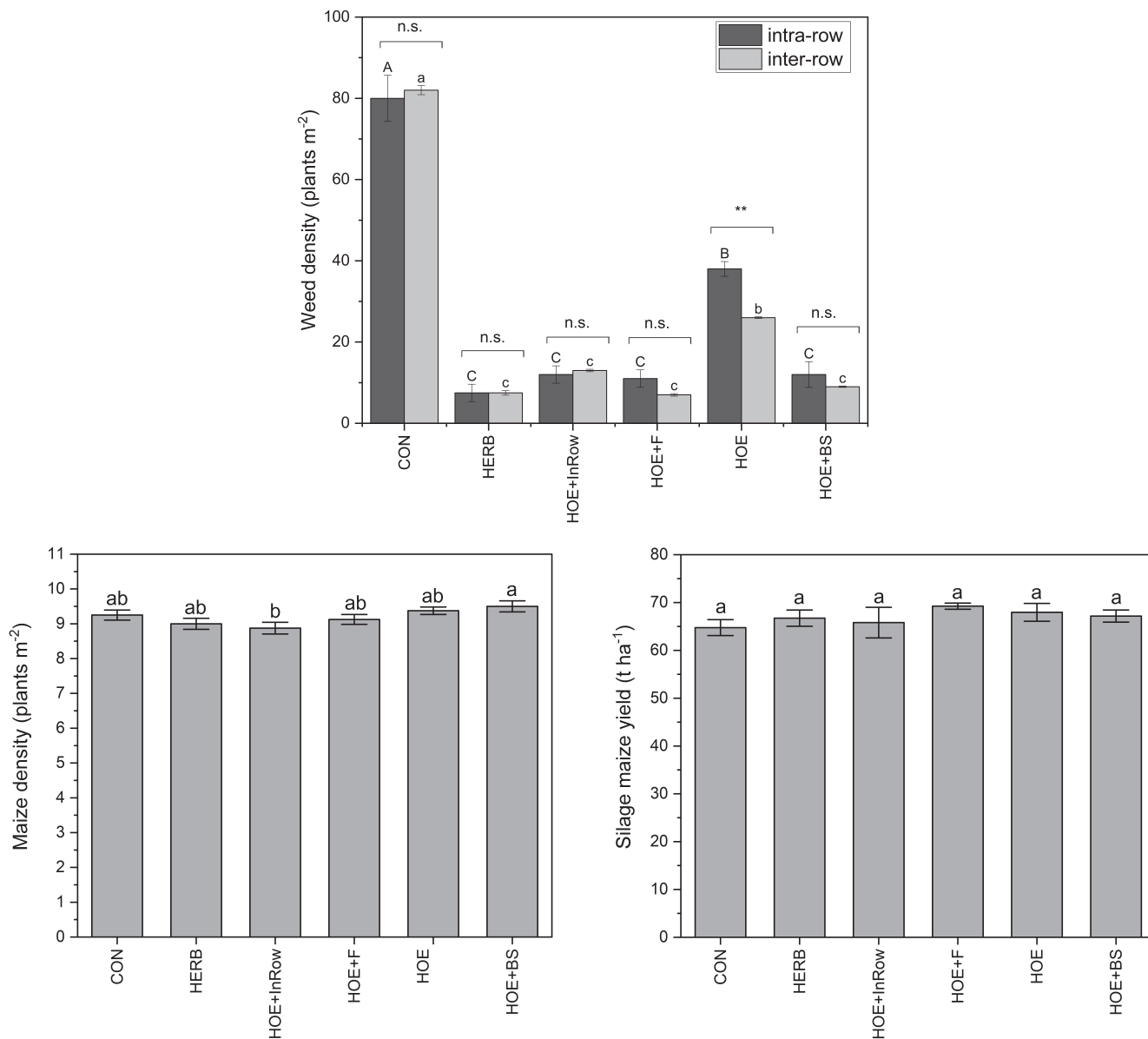


FIGURE 5 Intra-row and inter-row weed densities (plants m⁻²) after treatment, crop density after treatment (plants m⁻²) and yield (t ha⁻¹) in the maize experiment 2022 (M 22) at Ihinger Hof. Means with the same letter are not significantly different according to Tukey HSD test at $p \leq 0.05$. Bars represent the standard error of the mean.

3.3 | Sunflower trials

All treatments significantly reduced weed density compared to the untreated control with 16–30 weeds m⁻² (Figures 9 and 10 left). Hoeing and band spraying in 2023 showed the lowest inter-row weed density with only one weed m⁻² remaining after the treatment (Figure 10 left). Inter-row weed density in HOE and HOE+Inrow was significantly lower than in HOE+F and Herb. All other treatments resulted in weed densities with at least three weeds m⁻². Similar to the experiments in maize and sugar beet, intra-row weed density in the HOE treatment was significantly higher than inter-row weed density. In all other treatments, inter-row and intra-row

weed densities were equal (Figures 9 and 10 left). There was no significant difference in sunflower density across all treatments. Sunflower yield was equal across all treatments (Figures 9 and 10 middle and right).

3.4 | Average herbicide savings, WCE and CL across all trials

For inter-row hoeing plus band spraying (HOE+BS), 60% savings were realised. Crop stand losses were very low without significant difference between the treatments. HERB and HOE+BS resulted in higher

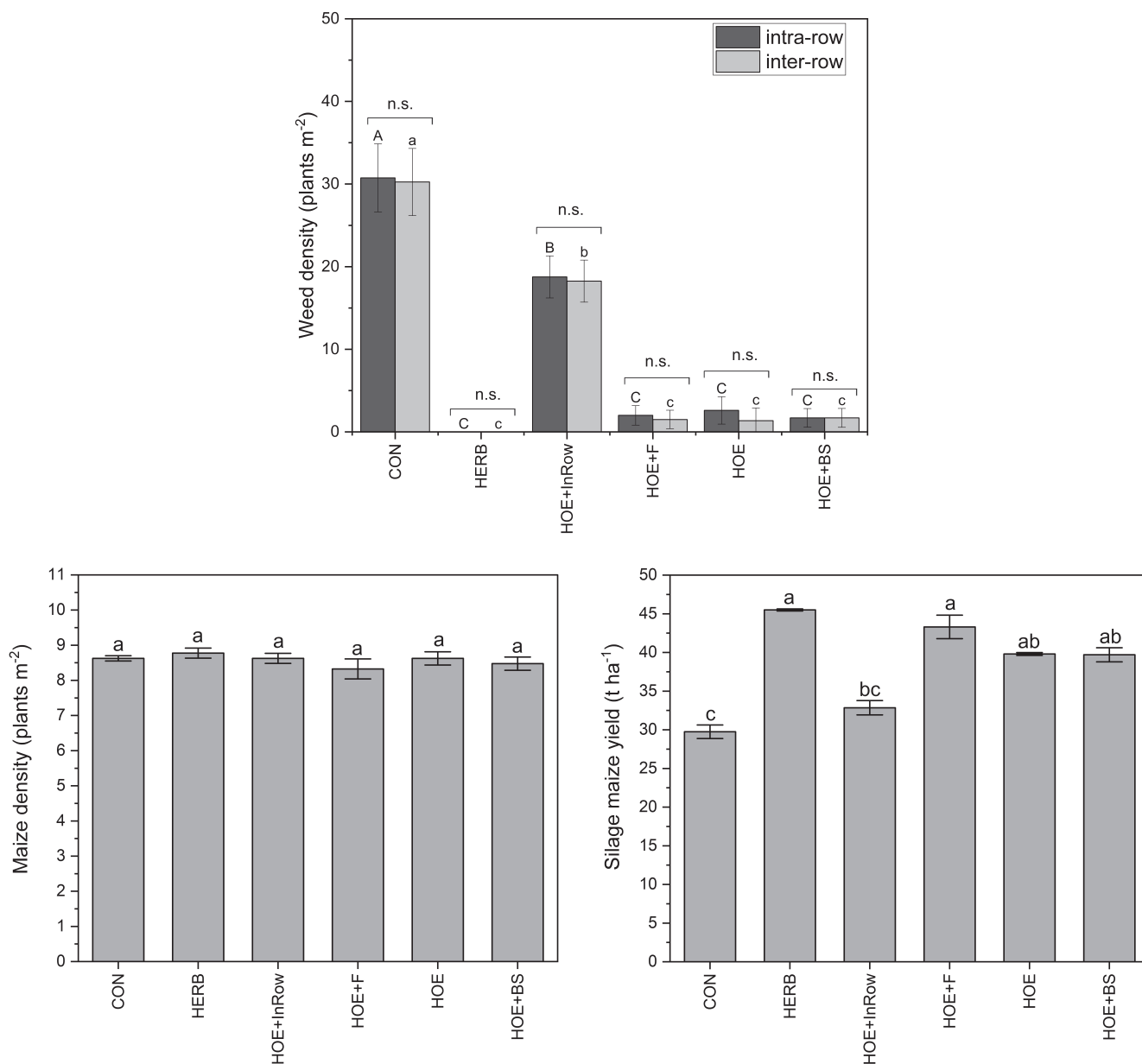


FIGURE 6 Intra-row and inter-row weed densities (plants m⁻²) after treatment, crop density after treatment (plants m⁻²) and yield (t ha⁻¹) in the maize experiment 2023 (M I 23) at Ihinger Hof. Means with the same letter are not significantly different according to Tukey HSD-test at $p \leq 0.05$. Bars represent the standard error of the mean.

total WCE and intra-row WCE than HOE, BOE + F and HOE+InRow. HOE had the lowest intra-row WCE. Inter-row WCE of HOE and HERB were higher than for the other treatments (Table 3).

4 | DISCUSSION

The data have proven the hypothesis that camera-guided inter-row hoeing in combination with band spraying in maize, sugar beet, and sunflower resulted in similar yield and WCE as the conventional broadcast herbicide treatment. Camera-guided inter-row hoeing and combinations of camera-guided inter-row hoeing with intra-row finger weeding and camera-guided intra-row hoeing achieved significantly

less WCE, with an average of 77%–82% WCE. Taking into account that only a single pass of mechanical weeding was applied, camera-guided hoeing has a great potential to replace broadcast herbicide applications. Usually, two to three passes of hoeing are applied in sugar beet, maize, and sunflower (Pannacci & Tei, 2014). Van der Weide et al. (2008) and Asaf et al. (2023) determined 60%–80% WCE with finger weeding and pointed out that finger weeders must be steered as close as possible to the crop rows. Otherwise, the risk of crop damage is high. With automatic steering in the present study, finger weeding did not cause any crop damage and achieved more than 80% WCE except for one study in sunflower.

It was expected that intra-row hoeing using machine vision control of hydraulic cutting knives would even increase WCE and

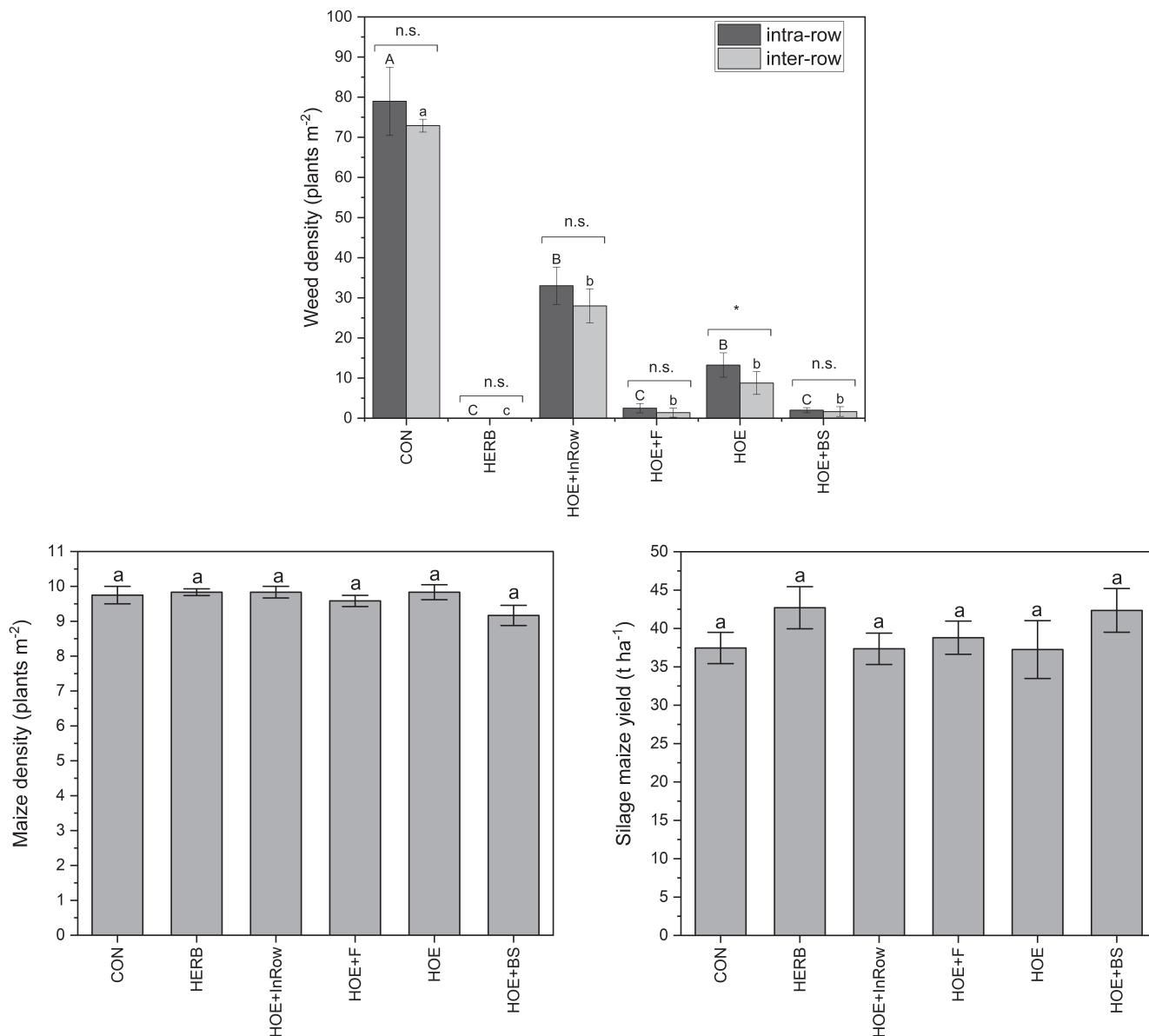


FIGURE 7 Intra-row and inter-row weed densities (plants m⁻²) after treatment, crop density after treatment (plants m⁻²) and yield (t ha⁻¹) in the maize experiment 2023 (MII 23) at Ihinger Hof. Means with the same letter are not significantly different according to Tukey HSD-test at $p \leq 0.05$. Bars represent the standard error of the mean.

selectivity compared to intra-row finger weeding. However, this treatment did not perform well in Maize 2023, because maize leaves shaded several intra-row weed seedlings in the images, so that they were not detected by the imaging system. In maize 2022, sugar beet and sunflower, the HOE+InRow treatment performed better than inter-row hoeing with finger weeding with higher WCE. This is in agreement with earlier studies in sugar beet using camera-guided inter-row and intra-row weeding (Gerhards et al., 2023). Camera-guided inter-row hoeing alone achieved an average WCE of 79.6% in the present study. This is higher than for conventional inter-row hoeing in earlier studies with 60%–70% WCE in arable crops (Kunz et al., 2018; Loddo

et al., 2020; Melander et al., 2005; van der Weide et al., 2008). Higher WCE of camera-guided hoeing can be explained by moving the hoeing elements closer to the crop row and by higher soil burial due to higher forward speed of camera-guided hoeing compared to conventional hoeing (Kunz et al., 2015; Kunz et al., 2018).

Crop stand losses of all mechanical weeding treatments were very low, with a maximum of 1.2% for HOE+InRow. This underlines that camera-guidance and machine vision systems have improved in the past 20 years (Gerhards et al., 2023; Tillett et al., 2002). Crop safety and robustness have also increased. This will probably promote the adoption of new sensor-guided weeding technologies into practical farming.

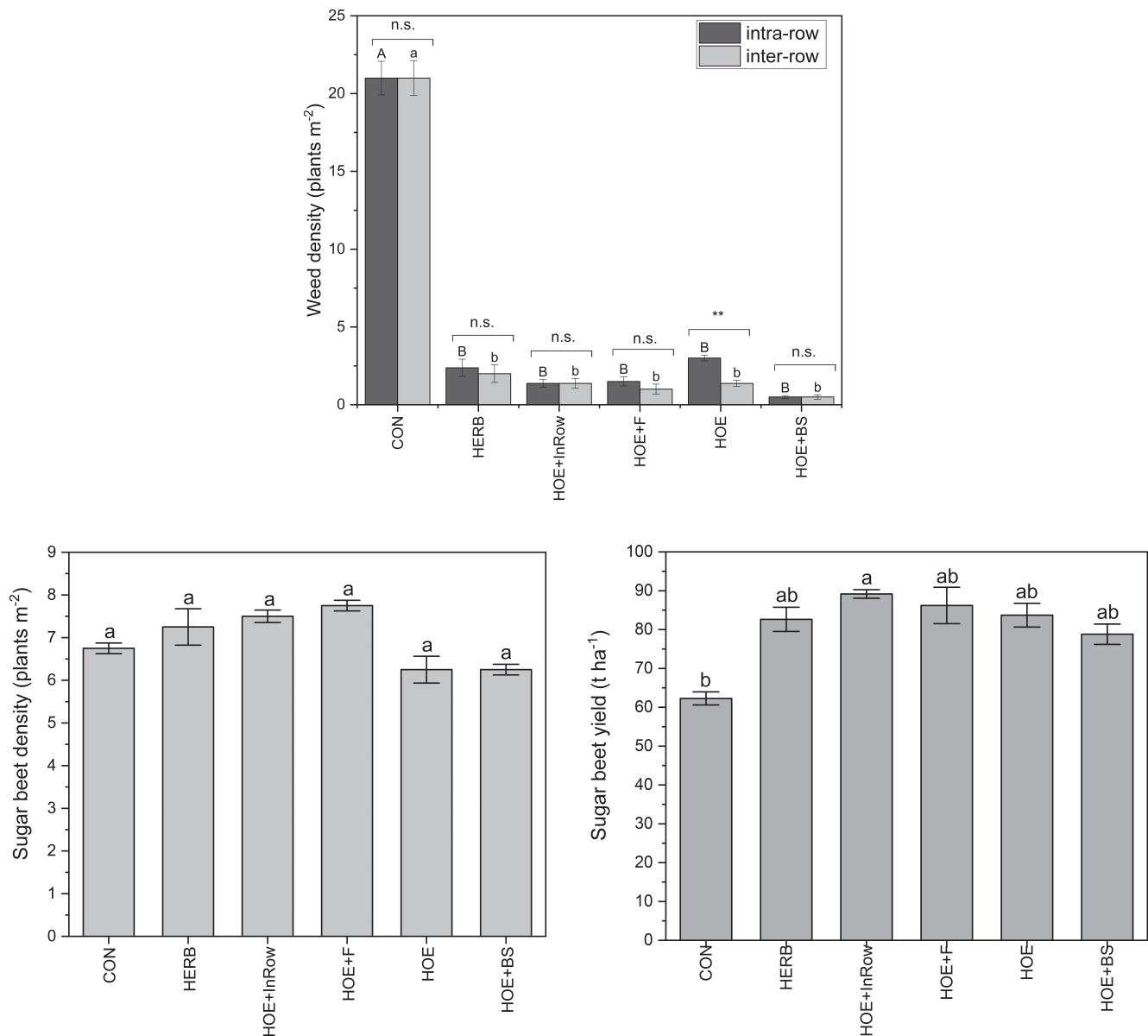


FIGURE 8 Intra-row and inter-row weed densities (plants m⁻²) after treatment, crop density after treatment (plants m⁻²) and yield (t ha⁻¹) in the sugar beet experiment 2022 (SB 22) at Ihinger Hof. Means with the same letter are not significantly different according to Tukey HSD-test at $p \leq 0.05$. Bars represent the standard error of the mean.

Combining camera-guided inter-row hoeing with intra-row band spraying (HOE+BS) was the most effective treatment in this study. This treatment achieved equal WCE as the broadcast herbicide application. On average, HOE+BS resulted in 91.2% WCE and 60% herbicide savings without causing any crop damage. Intra-row WCE was even higher for this treatment than for the conventional broadcast herbicide application. This might be explained by the fact that intra-row weeds in the combined treatment of inter-row hoeing and band spraying were controlled by herbicides and burial due to soil movement from the inter-row hoeing (Gerhards et al., 2020). Inter-row hoeing and band spraying

were realised at a forward speed of 4.5 km h⁻¹, which was much faster than camera-based intra-row hoeing, which requires low driving speeds of around 1 km h⁻¹ (Gerhards et al., 2023). Image processing and hydraulic opening and closing of the cutting knives are limiting the forward speed. Many of the commercial hoeing robots, regardless of whether tractor-mounted or fully autonomous, are facing the same problems with low forward speed (Gerhards et al., 2023; McCarthy et al., 2010; Pérez-Ortiz et al., 2016; Peteinatos et al., 2020). For autonomous robots, the disadvantage could be compensated by a fleet of many robots working simultaneously in the field.

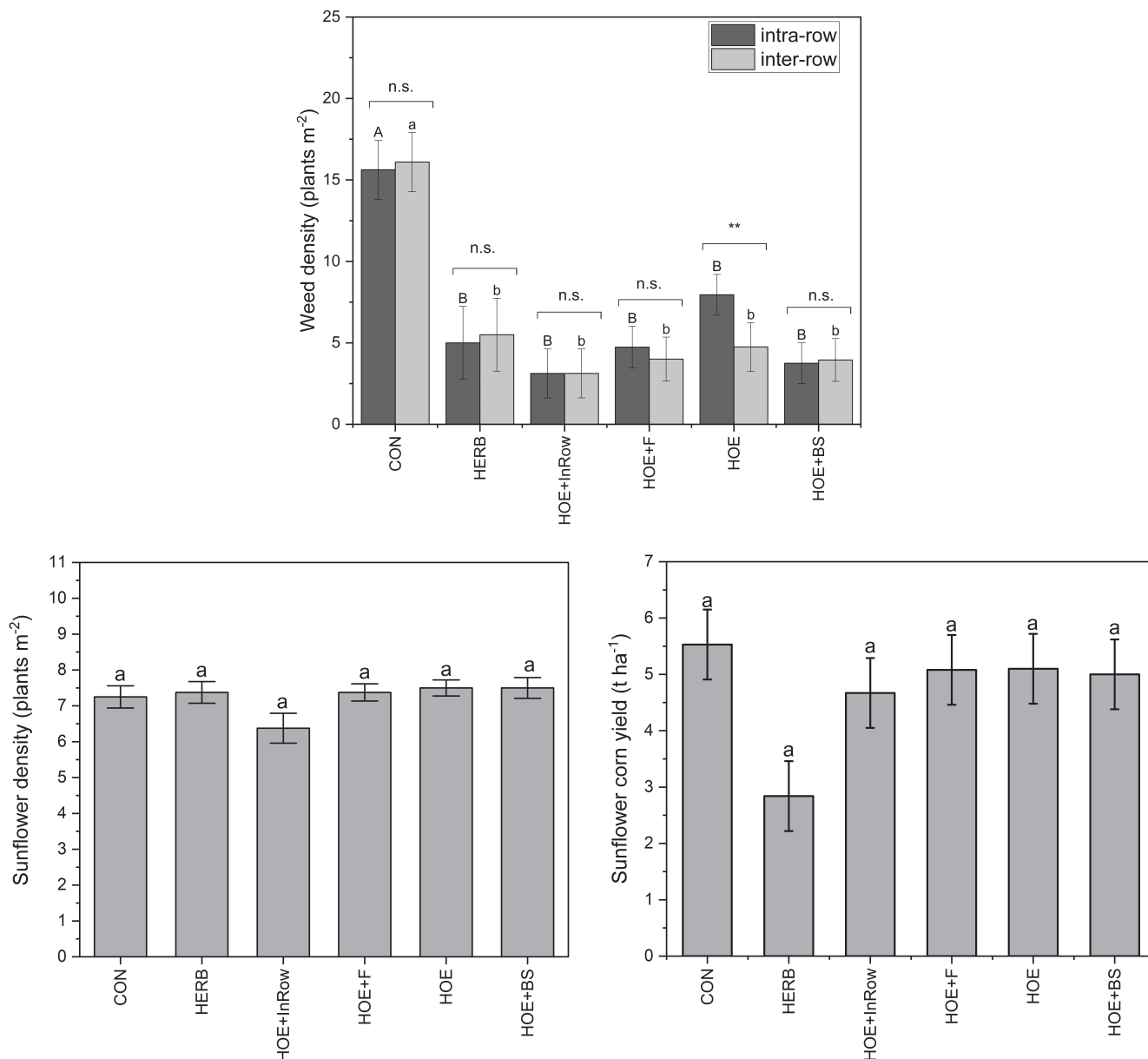


FIGURE 9 Intra-row and inter-row weed densities (plants m⁻²) after treatment, crop density after treatment (plants m⁻²) and yield (t ha⁻¹) in the sunflower experiment 2022 (SF 22) at Ihinger Hof. Means with the same letter are not significantly different according to Tukey HSD test at $p \leq 0.05$. Bars represent the standard error of the mean.

However, band spraying and inter-row hoeing might also have antagonistic effects. Warnecke-Busch (2022) observed that herbicide WCE was reduced if hoeing and band spraying were carried out simultaneously. The author explained this effect by a dust layer on the weed plants, which inhibits herbicide uptake. In the current study, inter-row hoeing was conducted after band spraying in two consecutive passes. Band spraying can also be realised with conventional boom sprayers if cameras for row detection or RTK-GNSS for seeding and spraying are used. This would even allow band spraying with pre-emergence herbicides (Griepentrog et al., 2005; Kunz et al., 2018).

Intra-row weeding robots based on weed/crop classification with artificial intelligence (AI) will probably gain more importance in the future. The results of this study with the camera-guided inter-row and intra-row hoe (HOE+InRow) show 77% WCE and only 1% crop stand losses, demonstrating the great potential of selective intra-row hoeing based on AI. Peteinatos et al. (2020) trained neural networks with 16 weed species and six crops that classified species with up to 99% accuracy when plants had developed the first true leaves. Once a weed has been identified in the intra-row area, various actuators can be used to target the weeds (Gerhards et al., 2022).

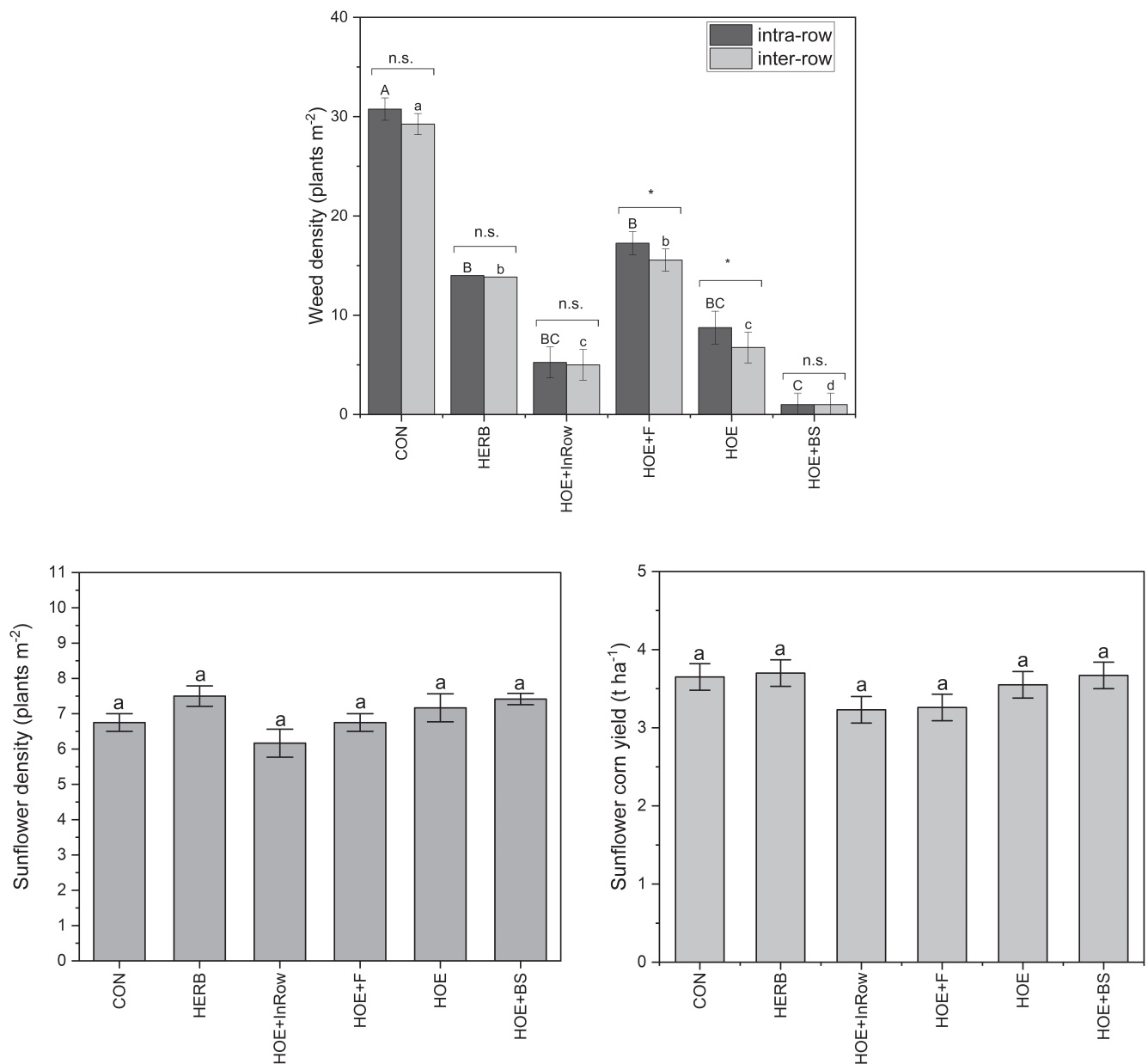


FIGURE 10 Intra-row and inter-row weed densities (plants m⁻²) after treatment, crop density after treatment (plants m⁻²) and yield (t ha⁻¹) in the sunflower experiment 2023 (SF 23) at Ihnger Hof. Means with the same letter are not significantly different according to Tukey HSD-test at $p \leq 0.05$. Bars represent the standard error of the mean.

TABLE 3 Average herbicide savings, total, inter-row and intra-row weed control efficacy (WCE) (according to Equation (2)), crops losses (CL) (according to Equation (3)) across all trials for each treatment applied. Means with the same letter are not significantly different according to Tukey HSD-test at $p \leq 0.05$. SE represents the standard error of the mean.

Treatment	Herbicide savings (%)	CL (%)	Total WCE (%)	Intra-row WCE (%)	Inter-row WCE (%)
CON	100	-	-	-	-
HERB	0	0.5 (0.4) a	91.6 (2.9) a	93.3 (2.0) a	89.8 (3.7) b
HOE+InRow	100	1.2 (0.8) a	77.2 (5.8) b	76.6 (5.9) b	77.6 (8.3) b
HOE+F	100	0 a	81.7 (7.1) b	74.5 (12.3) b	88.8 (3.4) b
HOE	100	0.8 (0.8) a	79.6 (3.3) b	68.8 (3.14) c	90.4 (3.8) a
HOE+BS	60	0.9 (0.8) a	91.1 (3.5) a	88.3 (5.2) a	93.8 (1.8) a

5 | CONCLUSIONS

It can be concluded from this study that camera-guided hoeing and combinations of camera-guided inter-row hoeing with band spraying provided similar WCE and crop yield as broadcast herbicide treatments. Herbicide WCE was similar within crop rows regardless of whether it was applied with a band sprayer or a conventional boom sprayer. Crop plant losses were very low in all treatments with a maximum of 1.2% without significant differences between the treatments.

ACKNOWLEDGEMENTS

We thank Jonas Frieß and Hauke Delfs for their support during weed control treatments and data collection in the field trials. We would also like to thank Dr. Adnan Nabout and the colleagues at Ihinger Hof Research Station for their technical support during the experiments. The project was funded by the Federal Ministry of Food and Agriculture (BMEL) with the grant number 28DK130A20 in the BLE-innovation fund. Open Access funding enabled and organized by Projekt DEAL.

FUNDING INFORMATION

The project is supported by funds from the Federal Ministry of Food and Agriculture (BMEL) based on a decision of the Parliament of the Federal Republic of Germany via the Federal Office for Agriculture and Food (BLE) under the innovation support programme. The Federal Office for Agriculture and Food (BLE) provides coordinating support of the grant number 28DK130A20.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/wre.70017>.

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon request.

ORCID

Roland Gerhards  <https://orcid.org/0000-0002-6720-5938>

Michael Spaeth  <https://orcid.org/0000-0003-4037-1650>

Oyebanji O. Alagbo  <https://orcid.org/0000-0002-6232-7282>

Marcus Saile  <https://orcid.org/0000-0001-7055-5026>

REFERENCES

Asaf, E., Rozenberg, G., Shulner, I., Eizenberg, H. & Lati, R.N. (2023) Evaluation of finger weeder safety and efficacy for intra-row weed removal in irrigated field crops. *Weed Research*, 63, 102–114.

European Commission. (2020) Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the Committee of the regions. In: *Biodiversity strategy for 2030 bringing nature back into our lives*. Brussels: European Commission.

Gerhards, R., Andújar Sanchez, D., Hamouz, P., Peteinatos, G.G., Christensen, S. & Fernandez-Quintanilla, C. (2022) Advances in site-specific weed management in agriculture—a review. *Weed Research*, 62, 123–133.

Gerhards, R., Kollenda, B., Machleb, J., Möller, K., Butz, A., Reiser, D. et al. (2020) Camera-guided weed hoeing in winter cereals with narrow row distance. *Gesunde Pflanzen*, 72, 403–411.

Gerhards, R., Risser, P., Spaeth, M., Saile, M. & Peteinatos, G. (2023) A comparison of seven innovative robotic weeding systems and reference herbicide strategies in sugar beet (*Beta vulgaris* subsp. *vulgaris* L.) and rapeseed (*Brassica napus* L.). *Weed Research*, 64, 42–53.

Griepentrog, H.W., Noerremark, M., Nielsen, J. & Ibarra, J.S. (2007) Autonomous inter-row hoeing using GPS-based side-shift control. *Agricultural Engineering International: the CIGR Ejournal*, IX.

Griepentrog, H.W., Nrremark, M., Nielsen, H. & Blackmore, B.S. (2005) Seed mapping of sugar beet. *Precision Agriculture*, 6, 157–165.

Gummert, A., Ladewig, E. & Märlander, B. (2012) Guidelines for integrated pest management in sugar beet cultivation—weed control. *Journal für Kulturpflanzen*, 64, 105–111.

Hillocks, R.J. (2012) Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture. *Crop Protection*, 31, 85–93.

Knezevic, S.Z., Evans, S.P., Blankenship, E.E., van Acker, R.C. & Lindquist, J.L. (2002) Critical period for weed control: the concept and data analysis. *Weed Science*, 50, 773–786.

Kunz, C., Weber, J. & Gerhards, R. (2015) Benefits of precision farming technologies for mechanical weed control in soybean and sugar beet—comparison of precision hoeing with conventional mechanical weed control. *Agronomy*, 5, 130–142.

Kunz, C., Weber, J.F., Peteinatos, G.G., Sökefeld, M. & Gerhards, R. (2018) Camera steered mechanical weed control in sugar beet, maize and soybean. *Precision Agriculture*, 19, 708–720.

Loddo, D., Scarabel, L., Sattin, M., Pederzoli, A., Morsiani, C., Canestrone, R. et al. (2020) Combination of herbicide band application and inter-row cultivation provides sustainable weed control in maize. *Agronomy*, 10, 20.

Machleb, J., Kollenda, B., Peteinatos, G. & Gerhards, R. (2018) Adjustment of weed hoeing to narrowly spaced cereals. *Agriculture*, 8, 54.

Machleb, J., Peteinatos, G.G., Sökefeld, M. & Gerhards, R. (2021) Sensor-based intrarow mechanical weed control in sugar beets with motorized finger weeders. *Agronomy*, 11, 1517.

McCarthy, C.L., Hancock, N.H. & Raine, S.R. (2010) Applied machine vision of plants: a review with implications for field deployment in automated farming operations. *Intelligent Service Robotics*, 3, 209–217.

Mehrtens, J., Schulte, M. & Hurlle, K. (2005) Unkrautflora in Mais. *Gesunde Pflanze*, 57, 206–218.

Melander, B., Rasmussen, I.A. & Barberi, P. (2005) Integrating physical and cultural methods of weed control—examples from European research. *Weed Science*, 53, 369–381.

Moss, S., Ulber, L. & den Hoed, I. (2019) A herbicide resistance risk matrix. *Crop Protection*, 115, 13–19. Available from: <https://doi.org/10.1016/j.cropro.2018.09.005>

Oerke, E.M. (2006) Crop losses to pests. *The Journal of Agricultural Science*, 144, 31–43.

Pannacci, E. & Tei, F. (2014) Effects of mechanical and chemical methods on weed control, weed seed rain and crop yield in maize, sunflower and soybean. *Crop Protection*, 64, 51–59.

Pérez-Ortiz, M., Peña, J.M., Gutiérrez, P.A., Torres-Sánchez, J., Hervás-Martínez, C. & López-Granados, F. (2016) Selecting patterns and features for between- and within- crop-row weed mapping using UAV-imagery. *Expert Systems with Applications*, 47, 85–94.

Peteinatos, G.G., Reichel, P., Karouta, J., Andújar, D. & Gerhards, R. (2020) Weed identification in maize, sunflower, and potatoes with the aid of convolutional neural networks. *Remote Sensing*, 12, 4185.

Piepho, H.-P., Malik, W.A., Bischoff, R., El-Hasan, A., Scheer, C., Sedmeier, J.E. et al. (2024) Efficacy assessment in crop protection: a tutorial on the use of Abbott's formula. *Journal of Plant Diseases and Protection*, 131, 2139–2160.

Riemens, M., Sønderkov, M., Moonen, A.-C., Storkey, J. & Kudsk, P. (2022) An integrated Weed Management framework: a pan-European

- perspective 1161-0301 133, 126443. *European Journal of Agronomy*, 133, 126443. Available from: <https://doi.org/10.1016/j.eja.2021.126443>
- Saile, M., Spaeth, M. & Gerhards, R. (2022) Evaluating sensor-based mechanical weeding combined with pre- and post-emergence herbicides for integrated Weed Management in cereals. *Agronomy*, 12, 1465.
- Tillett, N.D., Hague, T. & Miles, S.J. (2002) Inter-row vision guidance for mechanical weed control in sugar beet. *Computers and Electronics in Agriculture*, 33, 163–177.
- van der Weide, R.Y., Bleeker, P.O., Achten, D.C. et al. (2008) Innovation in mechanical weed control in crop rows. *Weed Research*, 48, 215–224.
- Warnecke-Busch, G. (2022) Mechanical-chemical weed control in sugar beets (*Beta vulgaris* subsp. *vulgaris*) and oil-seed rape (*Brassica napus*) with hoes in conjunction with a band spraying equipment. *Julius-Kühn Archiv*, 468, 385–399.
- Wiltshire, J.J.J., Tillett, N.D. & Hague, T. (2003) Agronomic evaluation of precise mechanical hoeing and chemical weed control in sugar beet. *Weed Research*, 43, 236–244.

How to cite this article: Gerhards, R., Spaeth, M., Alagbo, O.O. & Saile, M. (2025) Sensor-based inter- and intra-row weed control methods in sugar beet, sunflower, and maize. *Weed Research*, 65(3), e70017. Available from: <https://doi.org/10.1111/wre.70017>