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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.)

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Abstract

More than 40 weeding robots have become commercially available, with most restricted to use in crops or fallow applications. The machines differ in their sensor systems for navigation and weed/crop detection, weeding tools and degree of automation. We tested seven robotic weeding systems in sugar beet and winter oil-seed rape in 2021 and 2022 at two locations in Southwestern Germany. Weed and crop density and working rate were measured. Robots were evaluated based on weed control efficacy (WCE), crop stand loss (CL), herbicide savings and treatment costs. All robots reduced weed density at least equal to the standard herbicide treatment. Band-spraying and inter-row hoeing with RTK-GPS guidance achieved 75%–83% herbicide savings. When hoeing and band spraying were applied simultaneously in one pass, WCE was much lower (66%) compared to the same treatments in two separate passes with 95% WCE. Hoeing robots Farmdroid-FD20®, Farming Revolution-W4® and KULTi-Select® (+finger weeder) controlled 92%–94% of the weeds. The integration of Amazone spot spraying® into the FD20 inter-row and intra-row hoeing system did not further increase WCE. All treatments caused less than 5% CL except for the W4-robot with 40% CL and the combination of conventional inter-row hoeing and harrowing (21% CL). KULT-Vision Control® inter-row hoeing with the automatic hydraulic side-shift control resulted in 80% WCE with only 2% CL. Due to the low driving speed of maximum 1 km h^{-1} of hoeing robots with in-row elements, treatment costs were high at 555–804 € ha^{-1} compared to camera-guided inter-row hoeing at 221 € ha^{-1} and broadcast herbicide application at 307–383 € ha^{-1}. Even though the costs of robotic weed management are still high, this study shows that robotic weeding has become a robust, and effective weed control method with great potential to save herbicides in arable and vegetable crops.

KEYWORDS
artificial intelligence, in-row hoeing, precision farming, sensor technologies, spot-spraying

1 | INTRODUCTION

Advances in sensor, information and application technologies enabled a new era in weed management with autonomous robots. Since 2015, more than 40 commercial weeding robots have been commercialized (Gerhards et al., 2022; Zhang et al., 2022). Systems vary in their degree of automation, weed/crop detection, guidance and tools for weeding. Most robotic weeding systems are restricted to certain crops, to the inter-row area or to fallow applications (Longchamps et al., 2014). Some systems can be considered as completely autonomous (e.g., Farmdroid FD20®, Kilter AS AX-1®, Naio Oz®, Dino® and Orion®, Farming Revolution W4® and GT®, because crop/weed detection, guidance and weeding occurs automatically and unmanned. Other systems are tractor mounted (e.g., Ecorobotix ARA®, KULTi-Select®, Steketee IC®, Blue River See&Spray® and Trimble Weed Seeker®) and partly require human operation (Zhang et al., 2022). For automatic guidance of inter-row hoeing, simple imaging algorithms for crop row detection or RTK-GPS-based steering are sufficient (Åstrand & Baerveldt, 2005; Gerhards et al., 2020). Camera-based intra-row weeding and spot spraying can also be realized with RTK-GPS guidance based on the exact position of each crop seed/plant. Commercial systems like the Kverneland OptimaV® precise seeder is an example for such sowing technology. Most systems use 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 simple crop/weed classification (e.g., KULTi-Select®, Garford Robocrop InRow Weeder® and Steketee IC®) (Lati et al., 2016). Robots can be grouped into hoeing and spraying robots (Slaughter et al., 2008). Few robots use other physical weed control methods such as sensor-based electrical weed control (Reiser et al., 2019) (Zasso xpower®), laser-weeding (LaserWeeder®) (Zhang et al., 2022). Robotic weeders can be separated into online-applications when the sensor simultaneously controls an actuator and offline-applications when mapping/decision and weeding occur in two separate operations (Gerhards et al., 2022). For site-specific weed control, unmanned aerial vehicle (UAV)-based weed mapping can be an efficient approach to create application maps for the hoe or sprayer (Rasmussen et al., 2013).

Few studies have been conducted to evaluate the performance and selectivity of robotic weeding in comparison to herbicides. Therefore, it is difficult to decide how profitable robotic weeding is for farmers and how it can be included into a strategy for integrated weed management (IWM). This study was conducted to find out if robotic weeding can help to meet the European Union directives and reduce the use of herbicides (European Parliament, 2009). Sugar beet and oil-seed rape were selected for this study because they are very sensitive to weed competition in the early growth stages. Effective weed control is essential in both crops until crop canopy has closed to prevent yield losses (Ali et al., 2013; Wahmhoff, 1994). Treatment frequency index (TFI) for chemical plant protection is also very high in both crops (Rossberg, 2013). The objective of this study was to evaluate seven automatic weeding systems in comparison to standard herbicide and mechanical weed control treatments. Weed control efficacy (WCE) and crop stand loss (CL), working rate and treatment costs were the criteria for the evaluation. The hypotheses were that (i) robotic weeding would result in equal WCE compared to the conventional herbicide treatment; (ii) robotic in-row hoeing would cause higher CL than spot spraying and (iii) treatment costs would be lowest for camera-based inter-row hoeing.

2 | MATERIALS AND METHODS

2.1 | Experimental sites

Five field experiments were set up in sugar beet 2021–2022 and oil-seed rape 2021 at Südzucker AG Research Station in Kirschgartshausen, Germany (49°62′85.5″ N 08°45′85.0″ E) and in sugar beet and oil-seed rape 2022 at University of Hohenheim Research Station Ihinger Hof, Germany (48°44′32.5″ N 8°55′31.1″ E). Ihinger Hof received 120 mm more rainfall in 2021 than the long-term mean of 690 mm. In 2022, precipitation at Ihinger Hof was 157 mm lower than average. Similar conditions were recorded at Kirschgartshausen with 40 mm more precipitation than the long-term average of 569 nm in 2021 and almost 160 mm less rainfall in 2022. Experimental fields did not receive any rainfall 0–3 days after treatment except for one pass of inter-row hoeing in oil-seed rape at Ihinger Hof in autumn 2021. Mean annual temperatures were approximately 1.0°C higher than the long-term average of 7.9°C at Ihinger Hof and 9.9°C in Kirschgartshausen in 2021 and 2.0°C higher in 2022 at both locations. Experiments were established on a loamy soil at Ihinger Hof and a sandy loam in Kirschgartshausen.

2.2 | Experimental design and weed control treatments

All five experiments were established as a one-factorial randomized complete block design with four replicates. Plots in Kirschgartshausen were 50 m long and 5.4 m wide. At Ihinger Hof, plots were 12 m long and 3 m wide. Sugar beet and oil-seed rape were sown after conservation tillage with a row distance of 45 cm in Kirschgartshausen and 50 cm at Ihinger Hof. Seed density was 110.000 seeds ha^{-1} for sugar beet and 180.000–350.000 seeds ha^{-1} for oil-seed rape resulting in 18 cm distance of sugar beet plants in the row and 7–12 cm in-row distance for oil-seed rape. Oil-seed rape was sown in the first week of September and sugar beet in mid-March.

An untreated control and a broadcast herbicide treatment were included in all five experiments (Table 1). Mechanical weeding started when sugar beet and winter oil-seed rape had two true leaves. Sugar beets were weeded until 8-leaf stage. In winter oil-seed rape, the last pass of hoeing was done before shoot elongation.

TABLE 1 Experimental sites and robotic weeding treatments.

Crop/cultivar	Year	Location	Soil texture/type	Treatments
Sugar beet, BTS 7300 N	2021	Kirschgarts-hausen	Loamy sand (gleysol)	Band herbicide + hoe Hoe + harrow Hoeing robot in-row and inter-row (*FR W4®*)
Sugar beet, Fitis	2022	Kirschgarts-hausen	Loamy sand (gleysol)	FD20 band spraying and inter-row hoe Hoeing robot in-row and inter-row (*FD20®*) Hoeing robot inter-row and in-row and spot spraying on top of each sugar beet (*FD20* + *Amazone Spot spray®*)
Winter oil-seed rape, Ludger	2021	Kirschgarts-hausen	Loamy sand (gleysol)	Hoeing robot in-row and inter-row (*FD20®*) Hoeing robot inter-row and in-row and spot spraying (*FD20 + Amazone Spot spray*)
Winter oil-seed rape, Ludger	2022	Ihinger Hof, Renningen	Loam (Luvisol)	Inter-row hoeing (*KULT-Vision*)
Sugar beet, Hannibal	2022	Ihinger Hof, Renningen	Loam (Luvisol)	Inter-row hoeing (*KULT-Vision*) *KULT-Vision* + band spraying *KULT-Vision* + in-row finger weeding Hoeing robot in-row and inter-row (KULT-iSelect®)

2.2.1 | Broadcast herbicide treatment

Broadcast herbicides were applied with an 18 m wide boom sprayer (Gaspardo, Italy) with 200 L ha^{-1} water and air-injector flat jet nozzles (Lechler, IDKN 120-03, Germany) at a speed of 8 km h^{-1}. In sugar beet, a tank-mix of 4.25 L ha^{-1} Betasana® SC (160 g L^{-1} phenmedipham, UPL) + 1.5 L ha^{-1} Oblix® SC (500 g L^{-1} ethofumesat, UPL) + 5.0 L ha^{-1} Metafol® SC (696 g L^{-1} metamitron, UPL) and 50 g ha^{-1} Debut® WG (50 g kg^{-1} triflusulfuron, UPL) was split into four applications. In 2021, 1.2 L ha^{-1} Vivendi® SC (100 g L^{-1} clopyralid, UPL) was added to the third application to control *Cirsium arvense* L. In 2022, 1.25 L ha^{-1} Trepach® EC (50 g L^{-1} quizalofop-p-ethyl, AGRIA SA) was added to the fourth treatment to control grass-weeds. Herbicides were applied 30, 45, 52 and 64 days after sowing (DAS) in 2021 and 29, 39, 52 and 64 DAS in 2022. In oil-seed rape, 2.5 L ha^{-1} Butisan® Gold SE (200 g L^{-1} dimethenamid-P + 100 g L^{-1} quinmerac + 200 g L^{-1} metazachlor, BASF) was applied 5–8 DAS, 1.3 L ha^{-1} Leopard EC (46.3 g L^{-1} quizalofop-P, Syngenta) was sprayed 22–35 DAS against grass-weeds and volunteer cereals. In Kirschgartshausen, also 0.2 L ha^{-1} Runway™ SC (240 g L^{-1} clopyralid + 80 g L^{-1} Picloram + 40 g L^{-1} aminopyralid, Corteva) was applied 20 DAS. At Ihinger Hof, 1.88 L ha^{-1} Kerb™ Flo SC (400 g L^{-1} propyzamid, Corteva) was sprayed 78 DAS to control herbicide-resistant *Alopecurus myosuroides* Huds.

2.2.2 | Band-spraying

In sugar beet 2021 at Kirschgartshausen and in sugar beet 2022 at Ihinger Hof, band spraying and hoeing were realized in two consecutive passes. First, herbicides were sprayed over each crop row in a 20 cm band with a band sprayer (Schmotzer, Germany) with band nozzles (AirMix OC 80-012®, Agrotop, Germany) and a 1500 L front tank (FT-P 1502, Amazone Werke, Germany) at a speed of 8 km h^{-1}. A few hours later, inter-row hoeing was done at a speed of 3–8 km h^{-1}. In sugar beet 2022 at Kirschgartshausen, band-spraying and hoeing was executed simultaneously in one pass with the Farmdroid FD20® robot and the Amazone spot spraying® in the band application mode at a speed of 0.7 km h^{-1}. Herbicides and timings for band-spraying were the same as for the broadcast application.

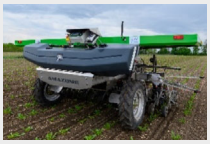
2.2.3 | Inter-row hoeing and harrowing

Inter-row hoeing was done with 25 cm wide goosefoot blades mounted on a Fobro Mobil D49® (Baertschi Agrartechnik AG, Switzerland) at a speed of 2 km h^{-1} for the first pass (29 DAS) and 4–5 km h^{-1} for the second and third pass (48 and 66 DAS). The Fobro mobile used the RTK-GNSS data of the seeder to guide the hoes through the inter-row area. Harrowing (Treffler, Germany) was applied uniformly across the whole plot directly after inter-row hoeing at the second and third date (48 and 66 DAS) at a speed of 4–5 km h^{-1}.

2.2.4 | Farming revolution W4® hoeing robot

The W4 robot is a completely autonomous system for inter-row and in-row hoeing in sugar beet. The robot is 2 m wide. It can simultaneously weed four sugar beet rows with side-cut knifes in the inter-row area and small rotary hoes within sugar beet rows. Small circles of approximately 3 cm diameter around each sugar beet plant remained untreated. The in-row hoeing elements and the front wheels are driven by electric motors. The robot uses RTK-GNSS for guidance. Bi-spectral (red and infrared) cameras (JAI, Japan) are mounted above

TABLE 2 Technical details of the sensors, actuators and degree of automation of the weeding robots used in this study.

Robot	Photo	Sensor system/controller	Actuator	Grade of automation
Farming Revolution W4®		Multispectral cameras (R/IR), artificial illumination, CNN-based plant species classification with NVIDIA Jetson on-board computer	Side-cut knifes inter-row, rotary hoes in-row	Completely autonomous
Farmdroid FD20®		RTK-GPS records exact position of each crop seed	Hoeing wires inter-row, cutting knifes in-row	Completely autonomous
Amazone spot spraying® and precise band-spraying		Can be combined with other weeding robots	Front tank and PWM-controlled nozzles	Completely autonomous
KULT-Vision Control®		RGB-camera for crop row detection	Hydraulic side-shift control of hoeing frame, no-till inter-row sweeps	Tractor mounted
KULT- Vision Control® + in-row finger weeding		RGB-camera for crop row detection	Hydraulic side-shift control of hoeing frame, no-till inter-row sweeps	Tractor mounted
KULT-Hohenheim i-Select®		Camera for row detection and AI based plant species recognition (crop, problematic weed, beneficial/rare weed)	Inter-row and in-row hoeing	Tractor mounted

each crop row. Plant species (sugar beet and weed species) in the images were classified with a Deep Neural Network on the board computer (NVIDIA Jetson®, USA) (Table 2). If crop row identification failed, the robot only performed inter-row weeding based on the RTK-GNSS seeding lines. The maximum speed was 1 km h^{-1}. The Farming Revolution W4® was used three times in sugar beet 30, 45 and 60 DAS.

2.2.5 | Farmdroid FD20® robot

The FD20® is a completely autonomous system for RTK-GNSS controlled sowing, hoeing and spraying in sugar beet and oil-seed rape. The robot is 2.7 m wide. The position of each crop seed was recorded by RTK-GNSS and a safety area of 3 cm diameter was computed around each crop plant. Inter-row hoeing, in-row-hoeing, band spraying and spot spraying (Amazone spot sprayer®, Germany) was guided based on the RTK-GNSS position (Table 2). Hoeing was applied four times in sugar beet (29, 39, 46 and 52 DAS) and oil-seed rape (14, 21, 32, 43 DAS) at a speed of 0.7 km h^{-1}.

2.2.6 | Amazone spot spraying®

The Amazone spot sprayer® was used based on seeding data from the FD20® robot. The spots had a size of 8 × 10 cm and were applied on top of each crop plant, resulting in 90% herbicide savings. The crop position was derived from the RTK-GPS coordinates of the seeds. For spot spraying, magnetic valves and spot spraying nozzles (Agrotop RowFan 40-01E®, Germany) were used (Table 2). Timing and herbicide mixtures was the same as for broadcast- and band-spraying.

2.2.7 | KULT-Vision Control®

The 3 m wide tractor-mounted hoe was equipped with a hydraulic side-shift control to guide the no-till sweeps in the inter-row area with a distance of 25 mm to the crop rows. Real-time row detection was performed with an RGB-camera connected to a controller. The camera was mounted at the tool bar of the hoe scanning diagonally forward on 4–6 crop rows. Images were segmented into green plants and background consisting of soil and mulch. In the regions of highest green pixel densities tracking of crop row is done by an extended

Kalman filter (Tillet et al., 2002). This enables a fast row detection even if the crop leaves partly overlap in the inter-row space. The camera provides robust row detection under most lightning conditions. Artificial light and shading above the camera improved the quality of row detection (Gerhards et al., 2020) (Table 2). In one treatment, in-row finger weeding was combined with camera-guided inter-row hoeing.

2.2.8 | KULT.-iSelect® + University of Hohenheim in-row hoe

KULT-iSelect® + University of Hohenheim in-row hoe is an extension of the KULT-Vision Control Hoe®. Four in-row hoeing elements were mounted behind the inter-row hoe in a distance of 50 cm above the crop row. Multispectral cameras (JAI, Japan) were placed in front of v-formed in-row blades with hydraulic opening and closing. Cameras were mounted vertically above the crop rows taking 30 × 20 cm pictures. Image processing and AI-based classification was computed in real-time on a controller mounted on the tractor (Table 2). Plants were segmented from the soil based on the captured image using a grey-level threshold. Species were grouped into 'crop' and 'beneficial/rare weed' and 'problematic weed'. The group of beneficial/rare weeds included *Centauria cyanus* L., *Papaver rhoeas* L., *Delphinium consolida* L., *Agrostemma githago* L., *Legousia speculum-veneris* (L.) Chaix., *Anchusa officinalis* L. and *Scandix pecten-veneris* L. At low densities (<1 plant m^{-2}), those plants were not controlled. Hoeing blades were moved into the crop row, where more wanted plants and where problematic weeds were present (e.g., *Chenopodium album* L., *Polygonum convolvulus* L., *Galium aparine* L. and *Fumaria officinalis* L.). The speed was 1 km h^{-1}.

2.3 | Assessments and data analysis

Crop density and weed density by species (plants m^{-2}) were assessed before and after each weed control treatment. Before hoeing, weed densities were equal for all mechanical weeding treatments in the same experiment. Only the data of the final sampling are presented after all weed control treatments had been completed, which was 70 days after sowing (DAS) in sugar beet 2021, 63 DAS in sugar beet 2022, 48 DAS in oil-seed rape 2021 and 189 DAS in oil-seed rape 2022. Weeds were counted in four quadrats with a 0.1 m^2 frame randomly placed in each plot. Crops were counted four times with a meter stick placed along the crop row.

Weed control efficacy (WCE) was calculated according to Equation (1).

$$\mathrm{WCE} = 100\,(1 - w_t/w_u) \tag{1}$$

with w_t representing the weed density in the treated plots and w_u showing the density of weeds in untreated plots. Crop stand loss (CL) were calculated according to Equation (2).

$$\mathrm{CL} = 100\,(1 - L_t/L_u) \tag{2}$$

with L_t representing the crop density of treated plots and L_u showing the crop density of the untreated plots.

At Ihinger Hof, 2 m × 12 m plots of winter oil-seed rape were harvested with a plot harvester (Zürn 150, Germany). Seed yield was recalculated for a dry matter content of 86%. Two rows of sugar beets were harvested by hand in each plot at Ihinger Hof and fresh beet biomass was calculated.

Working rates (ha h^{-1}) of each weed control treatment was calculated based on the working width, driving speed, number of passes and time for turning, filling and operation according to KTBL (2022a). Treatment costs (€ ha^{-1}) were calculated according to KTBL (2022b) including expenditures for herbicides, fuel, depreciation, labour, interests and maintenance. Even in the case of autonomous vehicles, the current EU regulations enforce a human supervision. Therefore, for the autonomous weeding operations, 20% of the labour cost was calculated assuming that the operator could easily control five robots simultaneously.

2.4 | Statistical analysis

Counts of weed and crop density showed non-normality of residuals and heterogeneity of variance. Therefore, data were modelled assuming a negative binomial distribution with a log-link using a generalized linear model (GLM) with software R (version 4.3.0) (R Core Team, 2018).

The linear predictor for the block design can be written as:

$$\eta_{jh} = \theta + b_h + \tau_j \tag{3}$$

Here, η_{jh} denotes the linear predictor of the treatment j and block h, θ is the intercept, τ_j is the jth weed control treatment effect and b_h is the hth block effect.

Weed control treatment was considered as fixed effect, block effects as random. Multiple mean comparisons were performed using the Tukey test with $p < 0.05$. Afterwards and for presentation purposes only, means and their standard errors were re-scaled to the original scale using the inverse link function. Note that the difference in weed count between a treatment and the control on the link-scale corresponds to the ratio on the original scale and therefore is denoted as WCE. Analogously, the difference in crop number on the link-scale corresponds to CL on the original scale.

3 | RESULTS

3.1 | Weed species composition

In sugar beet, *C. album* and *P. convolvulus* were the most dominant weed species. *Cirsium arvense* L. was the only perennial among the major weeds. In the chemical weed control treatment, herbicides containing clopyralid were needed to control *C. arvense*. In the mechanical weeding treatments, one additional pass of hoeing was necessary to suppress this weed species. *C. album* was also predominant in oil-seed rape in Kirschgartshausen 2021 probably because mostly summer annual crops are grown at that location. The major weed species in oil-seed rape at Ihinger Hof in 2022 were volunteer barley, *Stellaria media* (L.) Vill., *Veronica persica* Poir., *Lamium purpureum* L., *G. aparine* and *Alopecurus myosuroides* Huds. Those species are characteristic of crop rotations with mostly winter annual crops. Almost two third of the weeds were volunteers of the previous winter barley. They emerged in oil-seed rape because of minimum tillage and short time between harvest of winter barley and sowing of oil-seed rape (Table 3).

TABLE 3 Composition and frequency of the predominant weed species in the field experiments.

Experiment	Frequency of the most dominant weed species
Sugar beet 2021 Kirschgartshausen	*Chenopodium album* 44%, *Cirsium arvense* 24%, *Polygonum convolvulus* 18%, *Brassica napus* 8%, *Polygonum aviculare* 3%
Sugar beet 2022 Kirschgartshausen	*C. album* 41%, *Amaranthus retroflexus* 31%, *B. napus* 15%, *Mercurialis annuus* 12%, *P. aviculare* 1%
Oil-seed rape 2021 Kirschgartshausen	*C. album* 64%, *Papaver rhoeas* 17%, *C. arvense* 13%, *Thlaspi arvense* 4%, *P. convolvulus* 2%
Oil-seed rape 2022 Ihinger Hof	*Hordeum vulgare* (volunteer barley) 63%, *Stellaria media* (15%), *Veronica persica* (7%), *Lamium amplexicaule* (4%), *Galium aparine* (4%), *Alopecurus myosuroides* (4%)
Sugar beet 2022 Ihinger Hof	*C. album* 24%, *P. convolvulus* 23%, *G. aparine* 16%, *Fumaria officinalis* 11%, *Atriplex patula* 8%, *Echinochloa crus-galli* 7%, *C. arvense* 6%

3.2 | Experiment in sugar beet 2021 at Kirschgartshausen

Broadcast herbicide treatment, the combination of band herbicide application and inter-row hoeing and robotic inter-row and intra-row hoeing (FR-W4) resulted in 93%–97% WCE and significantly lower weed density (1–2 weeds m^{-2}) than the conventional mechanical treatment with hoe and harrow (9 weeds m^{-2} and 74% WCE). All treatments significantly reduced weed density ($p < 0.001$) compared to the untreated control with an average density of 35 weeds m^{-2}. Sugar beet density was relatively low in all treatments due to a frost period from 26 to 28 DAS. That reduced crop density in all plots from 10 to 5.6 plants m^{-2}. Robotic inter-row and intra-row hoeing (FR-W4) significantly reduced sugar beet density ($p = 0.0351$) compared to all other treatments to 3.4 plants m^{-2} (39.5% CL) (Table 5, Figure 1).

3.3 | Experiment in sugar beet 2022 at Kirschgartshausen

In average, 54 weeds m^{-2} were counted in the untreated control plots. All treatments significantly reduced the weed density ($p < 0.001$) compared to the untreated control. The broadcast herbicide treatment

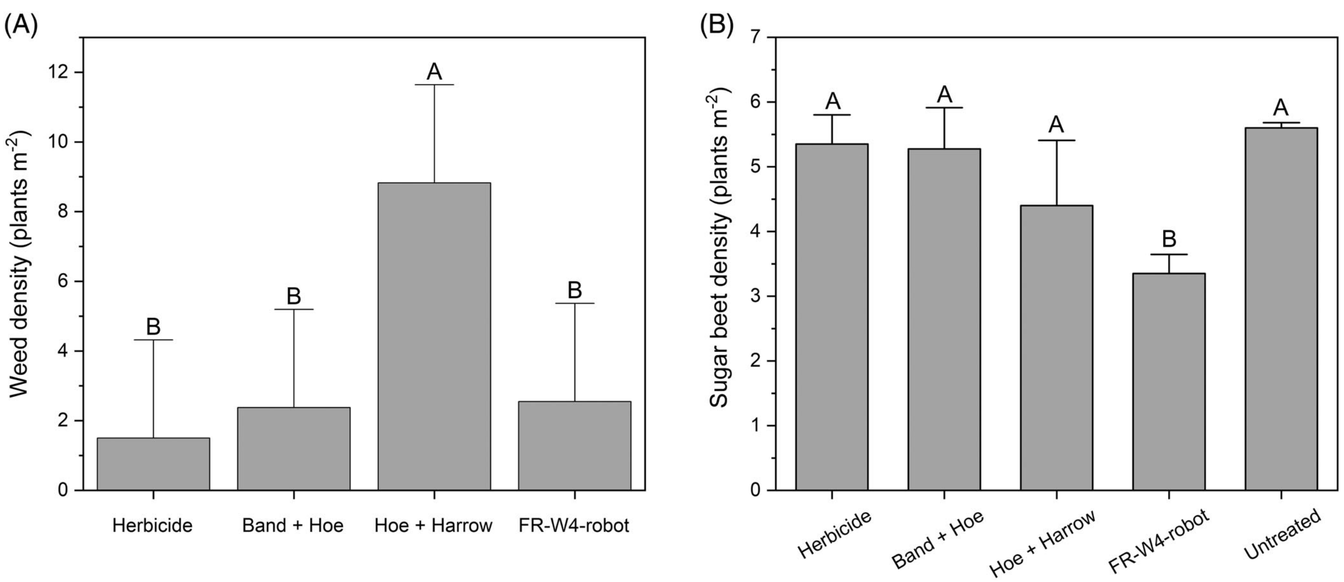


FIGURE 1 Weed and sugar beet densities (plants m^{-2}) 70 DAS at Kirschgartshausen in 2021 after all weed control methods had been completed; Herbicide = broadcast herbicide treatment splitted into three applications, Band + Hoe = three passes of conventional inter-row hoeing and herbicide band spraying splitted into three applications, Hoe + harrow = three passes of conventional inter-row hoeing and harrowing, FD-W4®-robot = Farming Revolution inter-row and in-row hoeing. Means with the same letter are not significantly different according to Tukey HSD-test at $p \le 0.05$. Bars represent the standard error of the mean.

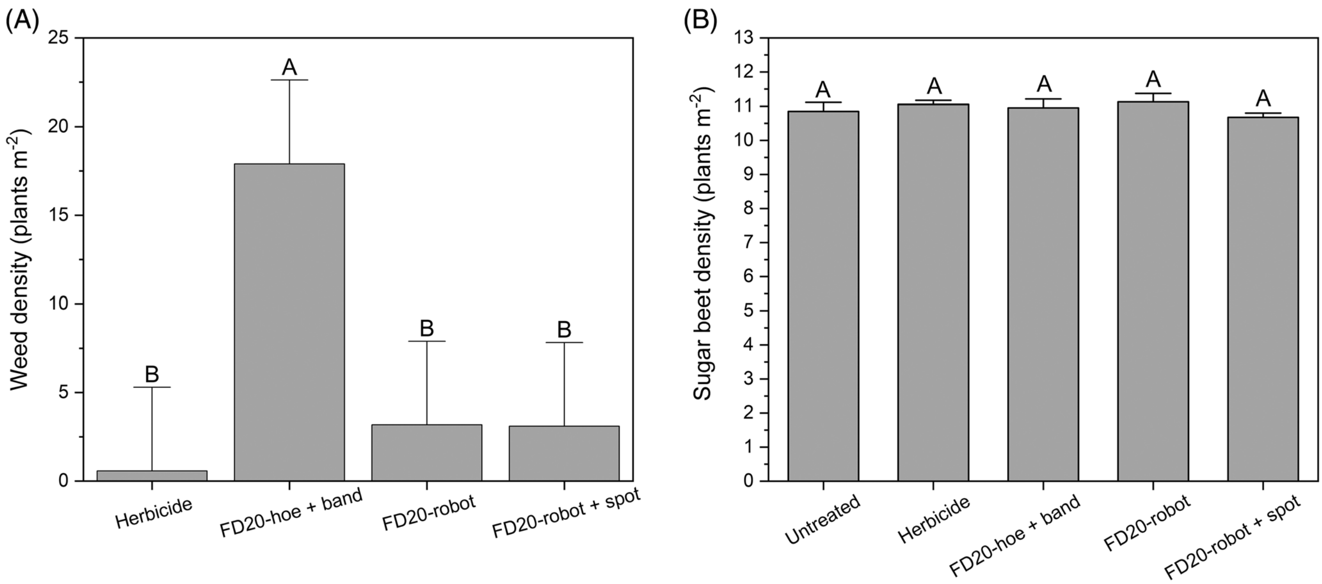


FIGURE 2 Weed and sugar beet densities (plants m^{-2}) 63 DAS at Kirschgartshausen in 2022 after all weed control methods had been completed; Herbicide = broadcast herbicide treatment splitted into three applications, Band + Hoe = three passes of FD20®-inter-row hoeing and herbicide band spraying splitted into three applications, FD20®-robot = three passes of Farmdroid inter-row and in-row hoeing, FD20® + spot = three passes of Farmdroid inter-row and in-row hoeing combined with Amazone spot spraying® on top of sugar beets. 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.

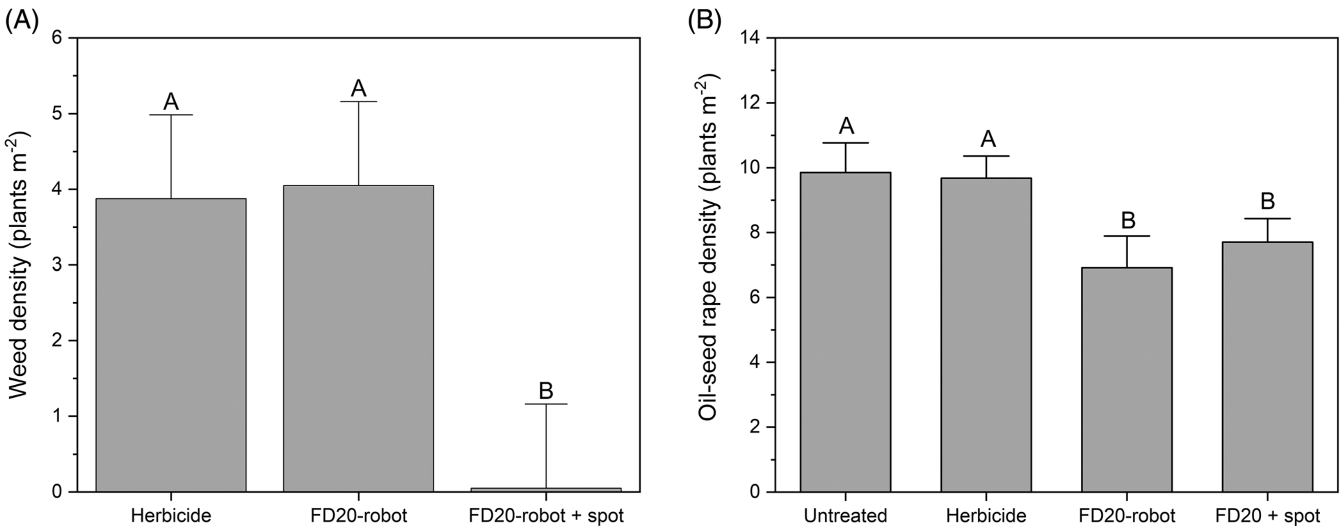


FIGURE 3 Weed and oil-seed rape densities (plants m^{-2}) 48 DAS at Kirschgartshausen in 2021 after all weed control methods had been completed; Herbicide = broadcast herbicide treatment splitted into three applications, FD20®-robot = four passes of Farmdroid inter-row and in-row hoeing, FD20® + spot = four passes of Farmdroid inter-row and in-row hoeing combined with Amazone spot spraying® where oil-seed rape seeds were placed. 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.

resulted in the highest WCE of 98%, which was not significantly different from the FD20® hoeing robot with 94%. The integration of the Amazone spot spraying did not provide any additional benefit to the robotic mechanical weeding. Weed density after inter-row hoeing with simultaneous band-spraying was significantly higher and provided only 66% WCE. No significant crop stand losses were observed in this experiment. Sugar beet density was around 11 plants m^{-2} for all treatments (Table 5, Figure 2).

3.4 | Experiment in oil-seed rape 2021 at Kirschgartshausen

The combination of robotic hoeing and spot spraying on top of the oil-seed rape plants achieved higher WCE (98%) than the broadcast herbicide application and the hoeing robot. Still, both treatments reduced weed density from 39 weeds m^{-2} in the untreated control to 4 weeds m^{-2} (90% WCE). Only 35% of the oil-seed rape seeds

TABLE 4 Yield of winter oil-seed rape (seed weight 86% dry biomass) and sugar beet (fresh beet biomass) and the field experiments at Ihinger Hof.

Treatment	Oil-seed rape (t ha^{-1})	Sugar beet (t ha^{-1})
Untreated	23.5 A	63.2 A
Herbicide	44.1 B	84.7 B
KULT-Vision Control® inter-row hoeing	44.9 B	85.8 B
KULT-Vision Control® inter-row hoeing with Hohenheim in-row hoeing		90.6 B
KULT-Vision Control® inter-row hoeing with in-row finger weeding		87.1 B
KULT-Vision Control® inter-row hoeing and herbicide band spraying		82.4 B

emerged due to dry soil conditions after sowing. Crop density before robotic weeding was equal in all treatments with 10 plants m^{-2}. The two robotic treatments including inter- and intra-row hoeing and the combination of robotic hoeing with spot spraying on top of each oil-seed rape caused significant CL ($p = 0.0371$). Crop losses amounted 31% for the hoeing robot and 24% for the combination of robotic hoeing with spot spraying on top of each oil-seed rape (Table 5, Figure 3).

3.5 | Experiment in oil-seed rape 2022 at Ihinger Hof

Weed density was higher than in Kirschgarthausen with an average of 98 weeds m^{-2} in the untreated control plots. Two third of those plants were volunteer barley, which was taller than oil-seed rape at

TABLE 5 Average herbicide savings, weed control efficacy (WCE) and crop stand loss (CL) of all treatments applied.

Treatment	Savings (%) (mean/min/max)	WCE (%) (mean/min/max)	CL (%) (mean/min/max)
Herbicide broadcast	0	82.7 (61.5–98.9)	2.2 (0–8.8)
Conventional hoeing + harrowing	100	74.0	21.4
Band spraying + inter-row hoeing (offline)	75	95.3 (93–97.6)	4.7 (2.0–7.4)
FD20®-band spraying + inter-row hoeing (online)	83.1	66.5	1.8
FR-W4® inter-row + in-row hoeing	100	93.0	39.5
FD20® inter-row + in-row hoeing	100	92.0 (89.7–94.2)	20.7 (0.9–40.4)
FD20® inter-row+ in-row hoeing + Amazone spot spraying®	92.2	94.2	2.3
KULT-Vision Control® inter-row hoe	100	80.2 (69.9–90.5)	2.5 (0–7.4)
KULT-Vision Control® inter-row hoe + finger weeding	100	92.9	0
KULT-iSelect® with Hohenheim camera	100	93.5	0

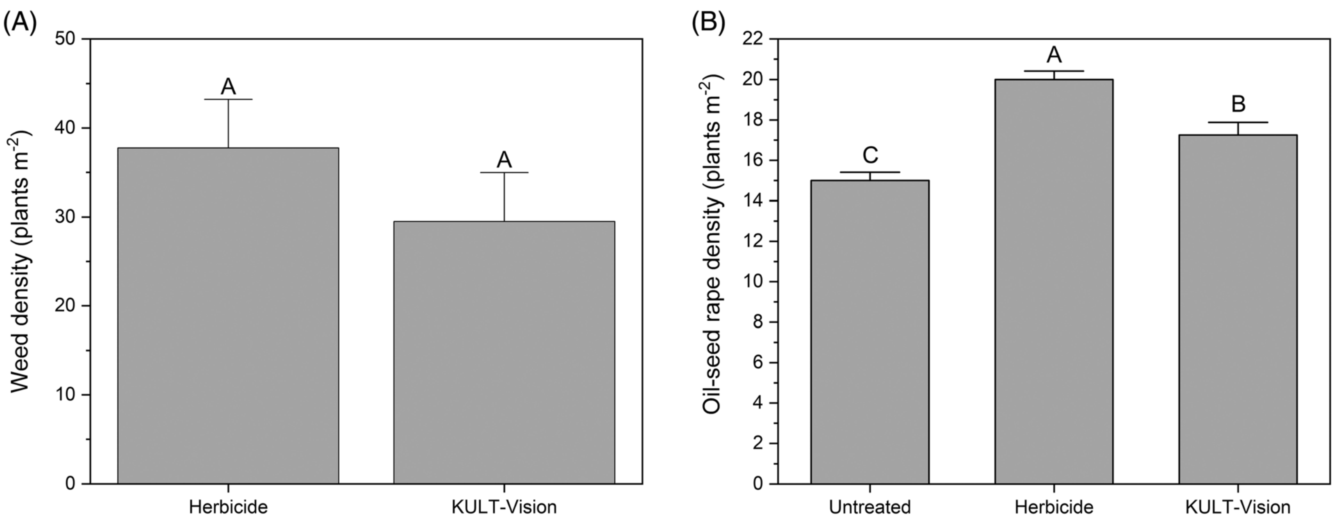


FIGURE 4 Weed and oil-seed rape densities (plants m^{-2}) 189 DAS at Ihinger Hof in 2022 after all weed control methods had been completed; Herbicide = broadcast herbicide treatment splitted into two applications, KULT-Vision Control® = four passes of camera-guided inter-row hoeing. Means with the same letter are not significantly different according to Tukey HSD-test at $p \leq 0.05$. Bars represent the standard error of the mean.

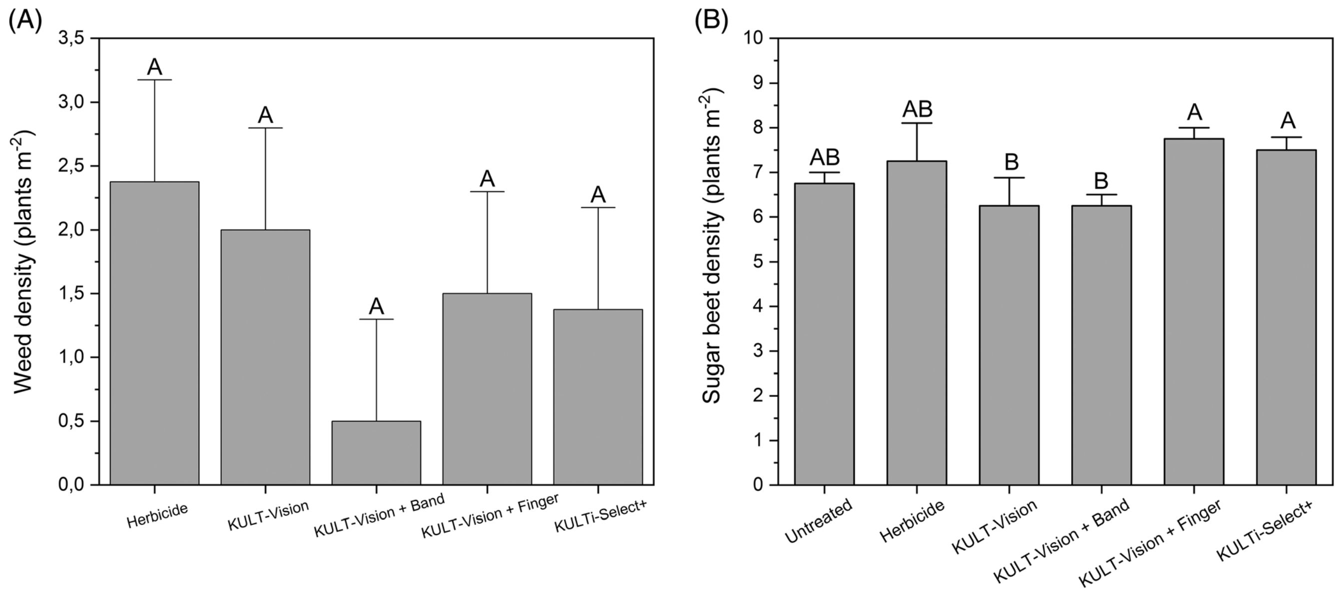


FIGURE 5 Weed and sugar beet densities (plants m^{-2}) 39 DAS at Ihinger Hof in 2022 after all weed control methods had been completed; Herbicide = broadcast herbicide treatment splitted into two applications, KULT-Vision = camera-guided inter-row hoeing with KULT-Vision Control®, KULT-Vision + Band = two passes of KULT-Vision Control® inter-row hoeing and herbicide band spraying splitted into two applications, KULT-Vision + Finger = two passes of KULT-Vision Control® inter-row hoeing with in-row finger weeding, KULTiSelect+ = two passes of KULT-Vision Control® inter-row hoeing with Hohenheim in-row hoeing. 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 6 Area performance and treatment costs of conventional and robotic weed control applications.

Treatment	Working width (m)	Speed (km h^{-1})	Working rate (ha h^{-1})[a]	Treatment costs (min/max) (€ ha^{-1})[b]
Herbicide broadcast application	18	8	6.2	308.6 (oil-seed rape), 307.4 (sugar beet Ihinger Hof), 383.4 (sugar beet Kirschgartshausen)
Conventional hoeing + harrowing	5.4 (12)	4 (8)	1.0	230.6
Band spraying + inter-row hoeing (offline)	12 (5.4)	8 (4)	1.0	298.7
FD20®-band spraying + inter-row hoeing (online)	2.7	(2.5)[c] 5	0.95	804.2
FR-W4® inter-row + in-row hoeing	2.7	1	0.42	804.2[d]
FD20® inter-row + in-row hoeing	2.7	1	0.42	733.4
FD20® inter-row and in-row hoeing + Amazone spot spraying®	2.7	1	0.42	804.2
KULT-Vision Control® inter-row hoe	3	(3)[c] 8	1.3	102.5 (sugar beet) 205 (oil-seed rape)
KULT-Vision Control® inter-row hoe + finger weeding	3	(2.5)[c] 5	1.0	220.8
KULT-iSelect® with Hohenheim camera	3	1	0.4	554.7

[a]Data are based on KTBL (2022a) and Jungwirth and Handler (2022).
[b]Treatment costs were calculated based on KTBL (2022b); costs include herbicides, fuel, depreciation, labour, interests and maintenance. For autonomous weeding operation, only 20% of the labour cost were calculated assuming that the operator could control five robots simultaneously.
[c]First pass of hoeing was realized at lower speed to prevent crop damage and burying.
[d]Depreciation, fuel consumption and maintenance were estimated.

the time of treatment. Camera-guided inter-row hoeing with automatic side-shift control provided 70% WCE, which was equal to the broadcast herbicide application. Mainly, volunteer barley survived herbicide treatments and mechanical weeding. Weed competition probably reduced crop density in the untreated control compared to both weed control treatments ($p = 0.0018$). Crop density was higher after broadcast herbicide treatment (20 plants m^{-2}) than after inter-row hoeing (17 plants m^{-2}). Herbicide application and camera-guided inter-row hoeing almost doubled the seed yield of oil-seed rape from 23.5 to 44 t ha^{-1} and 45 t ha^{-1} (Tables 4 and 5, Figure 4).

3.6 | Experiment in sugar beet 2022 at Ihinger Hof

All treatments significantly reduced weed density ($p < 0.001$) compared to the untreated control with an average density of 21 weeds m^{-2}. WCE ranged from 89% to 98%. A maximum CL of 7% was recorded for the inter-row hoeing treatment and the combination of inter-row hoeing and herbicide band-spraying. All treatments significantly increased fresh sugar beet biomass compared to the untreated control. Highest yield with 91 t ha^{-1} was recorded for the KULT-Vision Control® inter-row hoeing with Hohenheim in-row hoeing (Tables 4 and 5, Figure 5).

3.7 | Comparison of all automatic weeding systems

In average over all five experiments, WCE of robotic weeding with in average of 87% was not different from the broadcast herbicide application (83% WCE). Fully automated robots achieved equal WCE as semi-automated systems mounted on the tractor. All robots caused less than 3% CL except for the Farming Revolution W4® robot with 40% CL and one application of the Farmdroid FD20® robot with 21% CL (Table 5).

Working rates of the broadcast herbicide treatment was considerably higher than for the robotic weeding because of higher speed and wider working width. Robotic hoeing had a lower working rate than robotic spraying due to the low speed of maximum 1 km h^{-1} for the in-row hoes (Table 6). Treatments costs with in-row hoeing robots were approximately twice as high as for broadcast herbicide applications. Treatment costs for tractor-mounted hoeing and harrowing were lower than for conventional herbicide spraying. Because labour still remains one of the most significant cost factors, the most profitable weed control treatment was inter-row hoeing with a camera-based row detection and automatic side-shift control (KULT-Vision Control®), because it allowed higher driving speed and therefore caused less expenses for labour (Table 5).

4 | DISCUSSION

This study demonstrated that robotic weeding resulted in equal WCE as broadcast herbicide applications. Five robots had an average WCE of 93%, which was even higher than the average of the broadcast herbicide applications (83% WCE). Camera-guided inter-row hoeing without any in-row weed control method provided 80% WCE. This so-called first generation weeding robot improved mechanical weeding from 60%–70% WCE to 80%–85% WCE (Kunz et al., 2015, 2018; Pérez-Ruíz et al., 2014; Tillett et al., 2008). Higher WCE of camera-guided inter-row hoeing was explained by guiding hoeing blades closer along crop rows and by increasing weed burial due to higher driving speed (Gerhards et al., 2020). However, the problem of in-row weed competition still remained with camera-guided inter-row hoeing. In crops such as sugar beet and oil-seed rape inter-row weeding alone can often not prevent significant yield losses due to a higher weed competition (Gummert et al., 2011). Therefore, the combination of sensor-guided inter-row hoeing with selective in-row weeders is necessary. This combination resulted in approximately 10% additional WCE regardless if intra-row weeding was applied by band-spraying, finger weeding or selective hoeing. Larger sampling units than the 0.1 m^{-2} frames, which were used in the present study, would probably provide more confident WCE estimates and better differentiation between the treatments, especially if the weed densities in the untreated plots were relatively low.

Only direct weeding with herbicides or mechanical tools can often not provide sufficient WCE, especially under high weed pressure (Riemens et al., 2022). Combinations of preventive weed control with direct weeding tactics resulted in higher weed suppression (Riemens et al., 2022). Preventive methods such as diverse crop rotations of spring crops and autumn-sown crops, rotational ploughing and false-seedbed preparation are key elements of an IWM (Gummert et al., 2011). Winter-kill cover cropping can provide additional weed suppression in sugar beet (Gummert et al., 2011; Teasdale, 1996). Repeated stubble tillage before sowing of winter oil-seed rape can effectively control weeds and volunteers in winter oil-seed rape (Blackshaw et al., 2005; Lemerle et al., 2017).

In seven applications, robotic weeding did not cause more than 2.5% crop stand loss. However, in two experiments unacceptable crop losses of in-row hoeing were observed for the Farming Revolution W4® robot in sugar beet with 40% and for the Farmdroid FD20® robot in oil-seed rape with 21%. Losses were observed already after the first pass of intra-row hoeing. Crop plants can be damaged during in-row hoeing if they were misclassified with a weed, by unprecise guidance of the hoeing tool, displacement of the crop seed or by soil burial (Machleb et al., 2020; Melander, 2006; Rasmussen et al., 2012; Rasmussen & Svenningsen, 1995). It has often been reported that CNN-based classifiers have difficulties to identify weeds in the early cotyledon growth stage. In later growth stages, when plants have developed the first true leaves, classification accuracies ranged between 94% and 99% depending on the neural network selected, the number of species trained and the quality of training (dos Santos Ferreira et al., 2017; Peteinatos et al., 2020). Therefore, it is assumed that crop losses of the Farming Revolution W4® could have been caused by misclassifications of the Neural Network classifier.

Herbicide savings of the combination of band-spraying and inter-row hoeing increased from 75% to 83% when an RTK-GPS controlled guidance system was used. This allowed a smaller spray-band of only 10 cm width on the top of the crop rows. If the position of crop seeds or crop row is recorded with RTK-GPS, band-spraying can also be realized with pre-emergence herbicides (Kunz et al., 2018). WCE was considerably low (67% WCE) if band-spraying and inter-row hoeing were conducted simultaneously. Much higher WCE of 95% was achieved when band-spraying and inter-row hoeing were realized in two consecutive passes. The offline-approach may also provide benefits when pre-emergence band-spraying is combined with several passes of post-emergence hoeing. Warnecke-Busch (2022) explained lower WCE of online band-spraying and hoeing by dust covering the leaves and by unsuitable timing of the combined treatment. If it is conducted in the morning or evening, herbicide efficacy may be high but weeds in the inter-row area may regrow after hoeing. If both treatments are applied in the afternoon, hoeing may achieve better WCE, but herbicides may be less effective or even drifted in the atmosphere (Warnecke-Busch, 2022).

Band spraying in combination with hoeing can achieve 75% reductions in herbicide usage with high WCE and an acceptable CL. This technology can be easily adapted from the current conventional farming with minimum investment in machinery and know-how. Even though the cost reduction is minimal compared to the broadcast herbicide application, the current environmental directives can encourage that technology. Furthermore, there are plenty of systems (e.g., FD20 + Amazone Spot spray®, KULTi-Select®), which could achieve similar WCE as a broadcast herbicide application with minimal or no crop loss.

Robotic weeding represents an efficient and based on reduced herbicide demand, an environmentally friendly alternative to conventional chemical weeding strategies (Bručienė et al., 2021; Gerhards et al., 2022). The KULTi-Select® robot with the University of Hohenheim is the first robot that can differentiate between problematic and beneficial weeds, which allows to protect endangered weed species during weeding operations. Hoeing robots with in-row technologies are needed for an increasing market of organic food production as it is targeted in the EU until 2030 (European Commission, 2020). In organic farming, robotic weeding will increase productivity, because robots can replace manual weeding (Pérez-Ruíz et al., 2014; Sørensen et al., 2005). High WCE and robustness under field conditions as it was found in this study will encourage farmers to invest in weeding robots. However, organic farmers also need to consider working rate, overall life-time, additional data handling, safety and maintenance under long-term operation before they decide to invest in robotic weeding (Balafoutis et al., 2020). The present study showed that working rate of in-row hoeing robots was very low. Treatment costs for in-row hoeing robots were almost twice as high as the broadcast herbicide treatment. Therefore, in-row hoeing robots will have difficulties to replace herbicides in conventional farming unless other reasons force farmers to replace chemical weed control, for example, herbicide-resistant weed populations (Gerhards et al., 2020). Standard herbicide treatments have proved itself effective under a wide range of soil and weather conditions (Gummert et al., 2011). This is not the case for mechanical weeding operations, which require ideal conditions for high WCE (Machleb et al., 2020).

In conclusion, this study underlines the great potential of robotic weeding in arable crops. Besides their high WCE and mostly low crop losses, weeding robots offer a huge potential for herbicide savings. Camera-guided inter-how hoeing in combination with finger weeding was the most promising treatment in this study. It had low treatment costs, low crop losses, 93% WCE and an acceptable working rate due to the higher working speed compared to other in-row robots.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interests.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Data of all experiments will be made availabe to the reader upon request.

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