

A comparative applied analysis of six robotic-assisted weeding systems in sugar beets

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Abstract: Effective weed management is crucial in the critical period of sugar beet production, but often lacks sustainability and environmental protection. Recent advancements in sensor-based weed control systems have rendered the latter a realistic prospect, which demands detailed analyses, especially under suboptimal field conditions. The present study analysed six robotic-assisted weed control systems (RAWS) in three experiments on sugar beets in 2024, conducted under dry soil and high weed pressure. The experiments included sensor-based inter-row and intra-row hoeing, spot- and band-spraying and were compared to a broadcast herbicide treatment and an untreated control. Weed control efficacy (WCE) in the intra- and inter-row areas, as well as weed species composition and crop plant damage, were assessed after treatment. The data show that intra-row WCE of two hoeing robots (Farming GT® and Robovator®) equipped with

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selective intra-row blades achieved up to 80%, which was higher than the broadcast herbicide control with 67% WCE. In the inter-row area, Farming GT® robotic hoeing and ARA® spot-spraying resulted in more than 90% WCE, which was equal to the broadcast herbicide application. Weed species composition was not affected by the different RAWS. Crop plants were affected by all hoeing treatments with maximum non-lethal burial rates of 33%. The highest lethal uprooting of crop plants occurred after Farming GT® robotic hoeing, at 5.5% overall. The results demonstrate the great potential of robotic weeding to replace broadcast herbicide applications.

Keywords: weeding robots; plant detection; sensor technologies; artificial intelligence; precision farming

Effective weed control is essential in sugar beet (*Beta vulgaris* subsp. *vulgaris* L.), particularly during the critical period from emergence to the 6–8 leaf stage. Uncontrolled weed competition during this phase may result in yield losses of up to 90% (Kropff and Spitters 1991, Jursík et al. 2008). The ban on several herbicides in the European Union, such as triflusaluron and desmedipham, poses major challenges for conventional sugar beet production (Heap 2023, Federal Office of Consumer Protection and Food Safety 2024). Simultaneously, we face the increasing problem of herbicide-resistant weeds, such as *Chenopodium album* L., *Matricaria chamomilla* L., or *Amaranthus retroflexus* L. (Bhattacharya et al. 2025). Furthermore, perennial species, including *Convolvulus arvensis* L. and *Rumex crispus* L., remain particularly difficult to manage with herbicides (Petersen 2004). As a result, there is an increasing demand for sustainable yet profitable weed control solutions.

The development of robotic-assisted weeding systems (RAWS) has made significant progress recently. Camera-guided, AI-based robotic systems allow for precise, site-specific weeding in both inter-row and intra-row areas. These technologies are often implemented on autonomous or tractor-mounted systems and can operate with a cultivar of tools including finger-weeders, torsion weeders, or sensor-guided spot-sprayers (van der Weide et al. 2008, Zhang et al. 2022). In field trials, Gerhards et al. (2024) demonstrated weed control efficacies (WCE) of up to 94% using AI-supported hoeing robotics, while minimising crop damage compared to unguided mechanical weeding systems. Spaeth et al. (2024) demonstrated that Smart Spraying® can reduce herbicide use by more than 60% while maintaining similar WCE to broadcast herbicide applications. Even though recent reviews by Shamshiri et al. (2024) and Uehleke et al. (2024) underline the technological maturity of precision weeding technologies, they also emphasise the lack of robust data from on-farm trials conducted

under agronomically challenging conditions. These findings highlight a research gap: while RAWS show high efficacy under idealised circumstances, their performance under realistic field conditions – such as compact soil or advanced weed stages – remains poorly understood.

This study specifically addresses the following research questions to close this research gap: (i) How does the intra-row and inter-row WCE of six RAWS compare to that of a conventional broadcast herbicide application in terms of robustness and agronomic performance of the systems beyond idealised scenarios? (ii) How do the different robotic systems affect field ecology, specifically weed community composition and crop plant responses to the treatments?

MATERIAL AND METHODS

Experimental location. Three experiments in sugar beets, cv. Fitis were conducted simultaneously at three sites in 2024 at the research station Ihinger Hof, Germany (48°44'32.5"N, 8°55'31.1"E, 450 m a.s.l.). During spring 2024 (March–June), Ihinger Hof received 379 mm of precipitation with a mean temperature of 12 °C. No rainfall was recorded two days before and three days after application of the treatments. Soil conditions at Ihinger Hof were classified as Luvisol; the soil texture was loamy-clay, and the pH was 7.08.

The three sites differed in crop rotations of previous years. At experiment 1 in 2023 winter barley (*Hordeum vulgare* f. *distichon* (L.) Körn., cv. Bordeaux) was followed by the cover crop mixture Biomaxx by DSV-Saaten (Deutsche Saatveredelung AG, Lippstadt, Germany) (crop rotation WB-CCM), at experiment 2 maize (*Zea mays* subsp. *mays*) was followed by winter wheat (*Triticum aestivum* subsp. *aestivum*, cv. Cevignon) (crop rotation MZ-WW) and at experiment 3 winter wheat (cv. Cevignon) was followed by winter barley (cv. Bordeaux) (crop rotation

WW-WB). Before sowing, the fields were ploughed (2024-01-09) and the seedbed was prepared by a spring tine harrow (2024-04-02). Sugar beets were sown on 2024-05-13 with a seed density of 106 000 seeds/ha, a row distance of 50 cm and a crop plant distance within the row of 18 cm at a depth of 2 cm.

Experimental design and weed control treatments. Each experiment included the same eight RAWS treatments, each with four replicates. A row-column design was laid out across all three experiments to minimise spatial effects (Figure 1). The plot size was 6 m (width) × 20 m (length). Six of the eight treatments comprised different innovative weeding systems (Tables 1 and 2); Orio® (Naïo Technologies, Escalquens, France) (Orio),

Farming GT® (Farming Revolution GMBH, Model 2022, Bömenkirch, Germany) (F-GT), Robovator® (F. Poulsen Engineering ApS., Hvalsø, Denmark) (Robo), K.U.L.T.-iVision Control® for inter-row hoeing + finger weeder (K.U.L.T.-Kress, Kürnbach, Germany) (Finger), K.U.L.T.- iVision Control® for inter-row hoeing + band sprayer (K.U.L.T.-Kress, Kürnbach, Germany + University of Hohenheim, Stuttgart, Germany) (Band) and ARA® (Model 2022, Ecorobotix SA, Yverdon-les-Bains, Switzerland) (ARA). Additionally, an untreated control (Con) and a broadcast herbicide treatment (Herb) were included. The broadcast herbicide spraying was split into three applications, 0, 21 and 30 days after sowing (DAS). It was performed using a plot

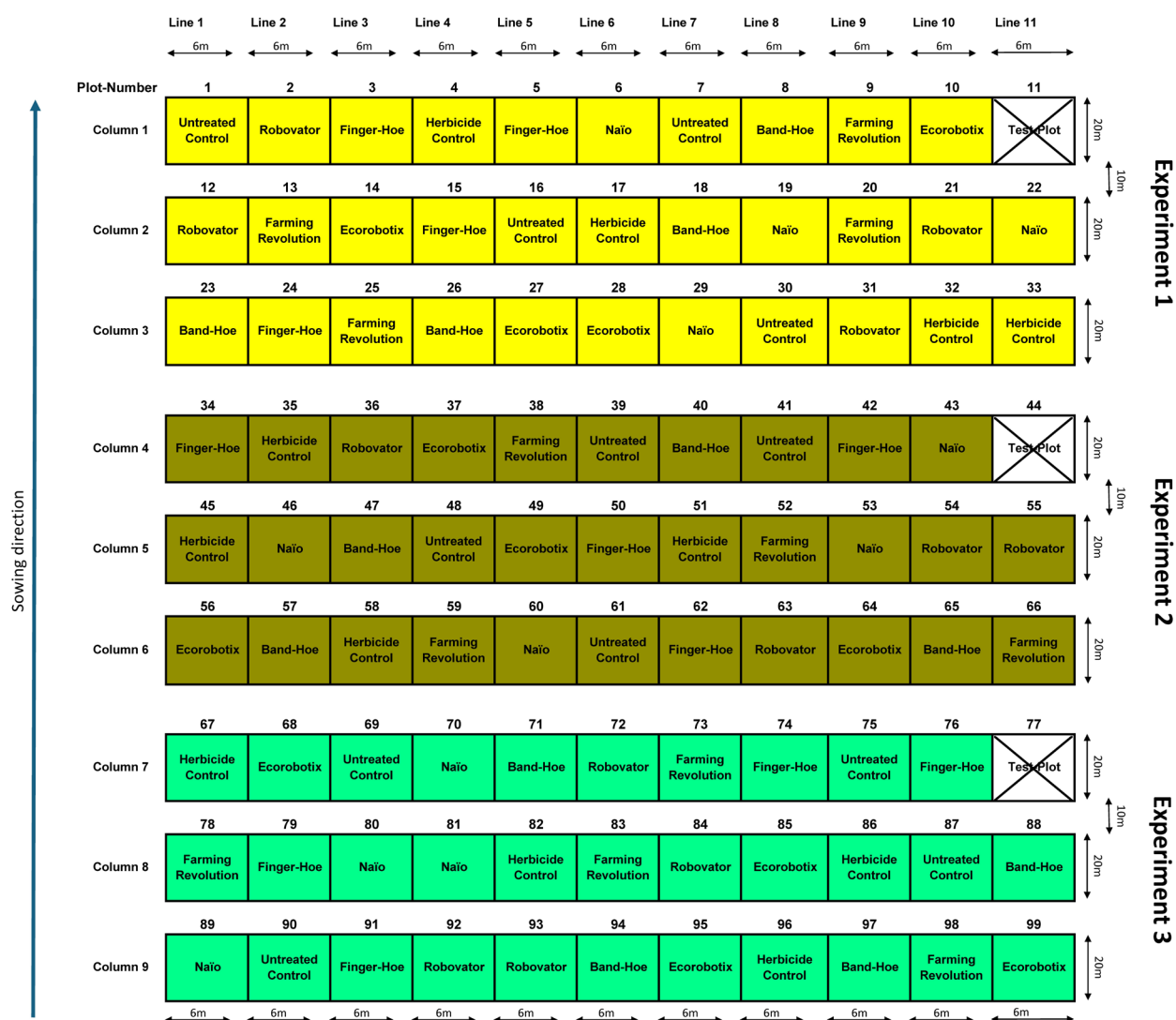
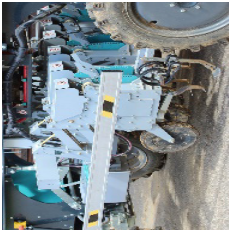
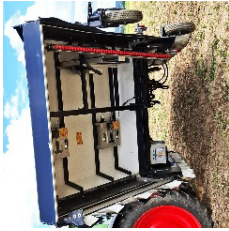


Figure 1. Experimental plan over the three experiments at Ihinger Hof in 2024

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Table 1. Overview of the relevant details from the utilised six robotic-assisted weeding systems (RAWS) at Ihinger Hof in 2024

Robot (treatment name)	Orio® (Orio)	Farming GT® (F-GT)	Robovator® (Robo)	K.U.L.T.-iVision Control® for inter-row hoeing + finger-weeder (Finger)	K.U.L.T.-iVision Control® for inter-row hoeing + band sprayer (Band)	ARA® (ARA)
Photo						
Grade of autonomy	autonomous mobile	autonomous mobile	tractor-mounted	tractor-mounted	tractor-mounted	tractor-mounted
Weeding system	Tools exchangeable; (sensor-based) inter-row hoeing (here 15 cm goosefoot-blades + side cutting blades)	15 cm inter-row goosefoot-blades; camera-guided selective intra-row blades;	Inter-row goosefoot- blades (15 for small and 30 cm for large shares); side cutting blades; camera-guided selective intra-row blades	30 cm inter-row goosefoot-blades; intra-row finger- weeder (medium-hard, ø 31 cm); camera- guided hydraulic side-shift control	Two 9 cm hoeing blades inter-row were followed by one 13 cm hoeing blade per parallelogram; intra-row spray band of 15 cm (30° spray angle); camera-guided hydraulic side-shift control	Spot-spraying; 156 nozzles (0.1 mm, IC1X502, Euspray®, Sant Joan Despi (Barcelona), Spain), 4 cm distance; 6 × 6 cm spot

sprayer (Schachtner-Fahrzeug- und Gerätetechnik, Ludwigsburg, Germany) equipped with flat fan nozzles (Lechler, AD 120-02, Metzingen, Germany) at a speed of 3.6 km/h, with a volume of 200 L/ha, and a spraying pressure of 280 kPa. For the pre-emergence application, 2 L/ha metamitron (Goltix® Gold 700 SC, 700 g a.i./L, SC, ADAMA) was used. For both post-emergence applications, 1.5 L/ha phenmedipham (Betasana® SC, 160 g a.i./L, SC, UPL) was used. The two spraying robots, i.e. band-sprayer and ARA® spot-spraying, used the combination of metamitron and phenmedipham in their treatment applications. Detailed information on the RAWS is listed in Table 1; further technical and economic details are provided in the supporting information (Table 2). All RAWS treatments were conducted on June 11, 2024, when sugar beets had four to six true leaves (BBCH 14–16; Lancashire et al. 1991).

Assessments in the field

Weed and crop assessments. Weed and crop assessments took place one day after treatment (DAT; 2024-06-12) for hoeing treatments and 14 DAT (2024-06-25) for herbicide treatments to record the actual effects of the treatments on the weeds. For weed measurements, each plot was assessed three times by three sampling teams, each consisting of three persons, resulting in nine samples per plot. Separately, crop measurements were assessed by one team, and soil compaction was assessed by another team. Weed density by species (plants/m²) was assessed separately for inter- and intra-row areas. The counting frame was divided into two inter-row parts, each measuring 20 × 50 cm, and an intra-row part measuring 10 × 50 cm. The counting frame was

Table 2. Continuation of Table 1 about the technical and economical details of the robotic assisted weeding systems (RAWS) at Ihinger Hof in 2024

Robot (treatment name)	Orio® (Orio)	Farming GT® (F-GT)	Robovator® (Robo)	K.U.L.T.-iVision Control® for inter-row hoeing + finger-weeder (Finger)	K.U.L.T.-iVision Control® for inter-row hoeing + band sprayer (Band)	ARA® (ARA)
Working width	3 m	3–6 rows (1.35–3 m)	3–12 rows (here 6 rows/ 3 m)	6 m	3 m	6 m
Working speed (km/h)	7	0.5–2.5	4	5	4–6	7.2
Camera/ sensor system	NIR, LIDAR; Crop row detection by GNSS RTK receiver	RGB, NIR; real-time weed identification by AI	RGB; real-time crop identification using AI	RGB; camera connected to a controller, scanning diagonally forward on four to six crop rows; real-time crop row detection	RGB camera connected to a controller, scanning diagonally forward on four to six crop rows; real-time crop row detection	Multi-spectral 2D & 3D Cameras, located 1 m before the nozzles, and 60 cm distance above the crop; real-time weed identification by AI
External illumination	–	pulsating flashes of red light	–	–	–	High-frequency pulsating flashes of light
Frames per second (fps); reaction time	–	10 fps; 0.3–0.4 s	5 fps; < 1 s	5 fps; < 1 s	5–10 fps; < 0.225 s	1 fps; 0.5 s
Costs (€ per given working width)	200 000	150 000	150 000 for 12 rows	100 000	60 000	110 000

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randomly placed three times in each plot, with the intra-row area adjusted over the crop line.

Weed density was used to calculate the WCE, adapted from Rasmussen (1991) as Eq. (1):

$$\text{WCE} = 100\% - d_s / (0.01 \times d_u) \quad (1)$$

With d_s as the weed density in the treated plots and d_u as the weed density in the untreated control plots.

Crop density (plants/m) was assessed by counting crop plants along a meter stick three times per plot. Additionally, crop damage (%) after each treatment was estimated manually for the whole plots. The types of damage were categorised as follows: per cent crop soil burial, crop uprooted, and leaves damaged. Topsoil structure was visually classified after application (fine, medium, coarse, untreated).

Statistical analysis

Data was analysed by using R and RStudio (version: 4.4.1, R Core Team (2024)). A generalised linear mixed model was fit to the data using the package "glmmTMB" (Brooks et al. 2017) to account for the complex experimental design and variable field conditions. The model was the following:

$$y_{(ijkl)} = \mu + a_i + b_j + (a \times b)_{ij} + (c)_k + (d)_l + (b:f)_{jm} + e_{(ijkl)} \quad (2)$$

Where: $y_{(ijkl)}$ – observation; μ – general mean; a_i and b_j – fixed effects of the i^{th} treatment in the j^{th} experiment. The interaction of the i^{th} treatment with the j^{th} experi-

ment is denoted as $(a \times b)^{ij}$ and is treated as a random effect. Additional random effects are c_k and d_l , denoting the k^{th} row and l^{th} column, as well as the m^{th} group nested within the j^{th} experiment, indicated as $(b:f)_{jm}$. The error term $e_{(ijkl)}$ was taken as a normal distribution with zero mean and homogeneous variance σ^2 .

Normal distribution and homogeneity of variance were checked visually by utilising residual plots before performing an analysis of variance (ANOVA). Significance of factors was analysed using ANOVA, and pairwise comparisons of treatment means were tested with least-square means using the package "emmeans". Square-root transformations were necessary for variables of crop damage to achieve normality and homogeneity of variance before further analysis. Displayed results in graphs show back-transformed values. Results were combined for all three experiments, as the factor experiment was non-significant.

RESULTS AND DISCUSSION

The most abundant weed species and post-treatment weed species composition

Although *Veronica persica* Poir. It is not typically described as a dominant weed in sugar beet, but it was the most abundant species in the untreated control at all three experiments (Tables 3 and 4). This indicates that even with differing former crop

Table 3. Average weed density (plants/m²) in the untreated control treatment for the intra- and inter-row area as well as the frequency of the ten most abundant weed species (%) at the three experiments at Ihinger Hof 2024

Experiment	Weed numbers (plants/m ²)	Frequency of the most abundant weed species
WB-CCM	intra-row: 17	<i>Veronica persica</i> Poir. (birdeye speedwell) 15%, <i>Poa annua</i> L. (annual meadow grass) 14%, <i>Galium aparine</i> L. (cleavers) 11%, <i>Chenopodium album</i> L. (lamb's quarters) 9%, <i>Lamium purpureum</i> L. (red dead-nettle) 9%, <i>Stellaria media</i> (L.) Vill. (chickweed) 7%,
	inter-row: 19	<i>Polygonum aviculare</i> L. (common knotgrass) 6%, <i>Cirsium arvense</i> (L.) Scop. (creeping thistle) 4%, <i>Sonchus arvensis</i> L. (perennial sow thistle) 3%, <i>Papaver rhoeas</i> L. (common poppy) 2%
MZ-WW	intra-row: 30	<i>V. persica</i> 61%, <i>C. album</i> 8%, <i>P. aviculare</i> 8%, <i>G. aparine</i> 5%, <i>L. purpureum</i> 4%, <i>Fallopia convolvulus</i> (L.) Á.Löve (black-bindweed) 3%, <i>Persicaria maculosa</i> Gray (lady's thumb) 2%, <i>Fumaria officinalis</i> L. (common fumitory) 1%, <i>P. annua</i> 1%,
	inter-row: 32	<i>Rumex obtusifolius</i> L. (bitter dock) 1%
WW-WB	intra-row: 22	<i>V. persica</i> 41%, <i>P. aviculare</i> 16%, <i>L. purpureum</i> 10%, <i>G. aparine</i> 7%, <i>C. arvense</i> 4%, <i>C. album</i> 4%, <i>Sonchus asper</i> (L.) Hill (rough milk thistle) 4%, <i>P. maculosa</i> 3%,
	inter-row: 20	<i>Atriplex patula</i> L. (spear saltbush) 2%, <i>Echinochloa crus-galli</i> (L.) P. Beauv. (cockspur) 1%

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Table 4. List of all observed species and numbers of individuals observed during the counting in the counting frames (in each experiment, average and total one day after treatment application on 2024-06-12) at the research station Ihinger Hof

Species	WB-CCM	MZ-WW	WW-WB	Average	Total
<i>Veronica persica</i> Poir.	62	361	206	210	629
<i>Polygonum aviculare</i> L.	23	46	83	51	152
<i>Lamium purpureum</i> L.	38	28	51	39	117
<i>Galium aparine</i> L.	46	32	37	38	115
<i>Chenopodium album</i> L.	38	46	18	34	102
<i>Poa annua</i> L.	54	5	0	20	59
<i>Cirsium arvense</i> (L.) Scop.	16	3	19	13	38
<i>Stellaria media</i> (L.) Vill.	28	5	4	12	37
<i>Sonchus asper</i> (L.) Hill	11	1	19	10	30
<i>Persicaria maculosa</i> Gray	0	11	17	9	28
<i>Fallopia convolvulus</i> (L.) Á.Löve	5	15	5	8	25
<i>Echinochloa crus-galli</i> (L.) P.Beauv.	9	4	7	7	20
<i>Fumaria officinalis</i> L.	5	5	7	6	17
<i>Taraxacum</i> Sect. <i>Ruderalis</i> F.H.Wigg.	5	3	5	4	13
<i>Sonchus arvensis</i> L.	4	5	3	4	12
<i>Atriplex patula</i> L.	0	0	10	3	10
<i>Papaver rhoeas</i> L.	10	0	0	3	10
<i>Capsella bursa-pastoris</i> (L.) Medik.	7	2	0	3	9
<i>Alopecurus myosuroides</i> Huds.	6	1	0	2	7
<i>Brassica napus</i> L.	5	0	1	2	6
<i>Euphorbia helioscopia</i> L.	0	1	5	2	6
<i>Sonchus oleraceus</i> L.	5	0	1	2	6
<i>Lamium amplexicaule</i> L.	1	0	4	2	5
<i>Rumex obtusifolius</i> L.	0	5	0	2	5
<i>Anagallis arvensis</i> (L.) U.Manns & Anderb.	0	3	1	1	4
<i>Equisetum arvense</i> L.	2	2	0	1	4
<i>Matricaria discoidea</i> DC.	4	0	0	1	4
<i>Silene noctiflora</i> L.	3	0	1	1	4
<i>Convolvulus arvensis</i> L.	0	3	0	1	3
<i>Hordeum vulgare</i> L.	1	2	0	1	3
<i>Thlaspi arvense</i> L.	3	0	0	1	3
<i>Descurainia sophia</i> (L.) Webb ex Prantl	2	0	0	1	2
<i>Tripleurospermum inodorum</i> (L.) Sch.Bip.	2	0	0	1	2
<i>Rumex crispus</i> L.	0	2	0	1	2
<i>Sinapis arvensis</i> (L.) D.A.German	0	2	0	1	2
<i>Triticum aestivum</i> L.	0	2	0	1	2
<i>Beta vulgaris</i> L.	1	0	0	0	1
<i>Camelina microcarpa</i> Andr. ex DC.	1	0	0	0	1
<i>Fagopyrum esculentum</i> Moench	1	0	0	0	1
<i>Fagopyrum tataricum</i> (L.) Gaertn.	1	0	0	0	1
<i>Geranium dissectum</i> L.	1	0	0	0	1
<i>Matricaria chamomilla</i> L.	1	0	0	0	1
Total	401	595	504	500	1 500

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rotation, *V. persica* is ecologically best adapted to the loamy-clay at Ihinger Hof (Cioni and Maines 2010). In the second and third experimental fields, which had a history of MZ-WW and WW-WB rotations, approximately 60% of the ten most frequent weed species were accounted for, suggesting a substantial impact of winter cereals on winter-annual weed species. In the first experiment with a WB-CCM rotation preceded by a diverse cover crop mixture, weed composition was more evenly distributed with a higher number of weed species. *Veronica persica* only accounted for 15% of the ten most frequent weed species. Cover crops may have prevented the dominance of particular weed species and encouraged a more balanced and biodiverse community of weed species (Restuccia et al. 2020). Common annuals such as *Galium aparine* L., *C. album*, *Lamium purpureum* L., and *Polygonum aviculare* L. were present at all sites, consistent with the typical Central European weed flora in sugar beet (Petersen 2004, Cioni and Maines 2010). Hence, it can be concluded that in former years, mainly shallow tillage was conducted at all sites. *Cirsium arvense* (L.) Scop. was also present

across all sites. This perennial weed is very tolerant to non-chemical weeding and very competitive in arable crops (Brandsæter et al. 2020). These results demonstrate that, in addition to crop rotation and former tillage, RAWS must equip farmers with practical tools to manage the diverse weed control demands.

Intra- and inter-row weed control efficacy

All results are based on mean weed densities of 15–20 plants/m² in the untreated control. As can be seen in Figure 2, both mechanical weeding robots with selective intra-row blades achieved higher intra-row WCE (Farming GT® and Robovator®) than the broadcast herbicide application. These results support previous findings by Gerhards et al. (2024) and Berg et al. (2025), who also demonstrated an intra-row efficacy of more than 76% with sensor-guided mechanical intra-row tools. A significant advantage of the intra-row blades over broadcast, band, or spot-spraying is that the blades move close to the sugar beet plant and below the leaf surface. The much lower intra-row WCE in

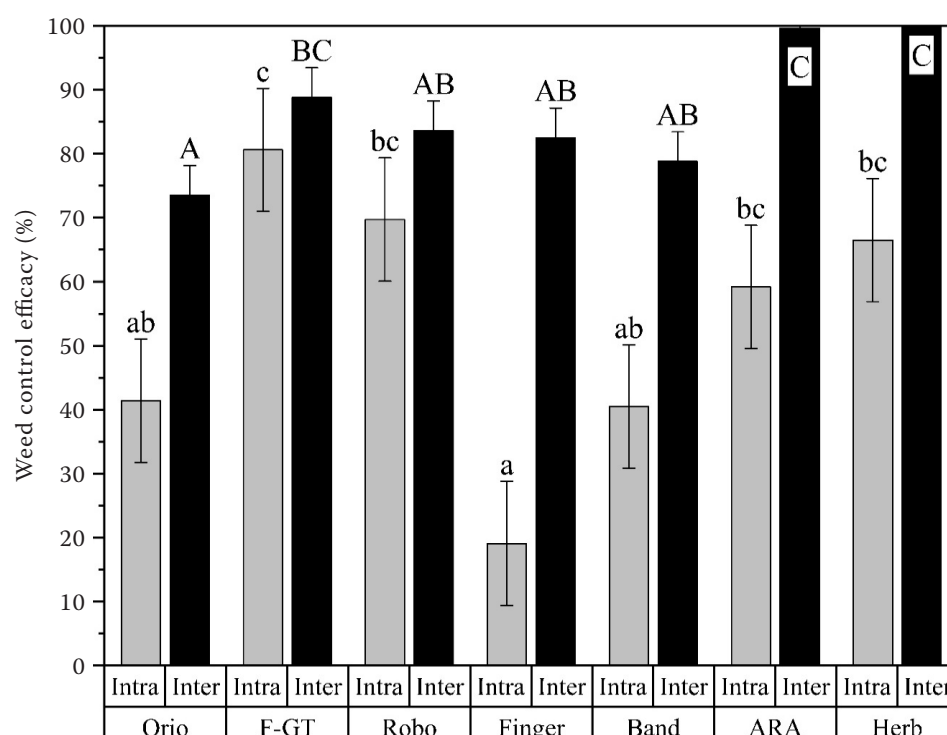


Figure 2. Average intra-row and inter-row weed control efficacies (WCE; equation (1)) one day after treatment (DAT; 2024-06-12) for hoeing and 14 DAT (2024-06-25) for herbicide treatments. Data were pooled over the three experiments at Ihinger Hof 2024. Results of least-square means comparison: Same small letters – no significant differences between the treatments in the intra-row area; same capital letters – no significant differences between the treatments in the inter-row area; $\alpha = 0.05$; error bars – standard errors of the mean

spraying treatments is most likely due to small weeds remaining below the sugar beet plants, as they did not receive the recommended herbicide dose. Inter-row WCE for broadcast and ARA[®] spot-spraying, on the other hand, achieved nearly 100%, even better than what was found in the literature by Vijayakumar et al. (2023) and Spaeth et al. (2024), who reported inter-row WCEs with herbicides between 70% and 99% for similar spot-spraying systems under less challenging conditions.

The compacted topsoil and the enormous weeds in advanced growth stages at the time of treatment surely had no impact on the WCE of spraying treatments; however, it has long been known as a limiting factor in mechanical weed control (Kurstjens and Kropff 2001). Inter-row WCE did not significantly differ between hoeing robots in this study, since all of them used similar inter-row goosefoot-blades. The soil and growth stages of weeds can be solely responsible for not achieving 100% WCE in the inter-row area. No intra-row weeding (Orio[®], 45% WCE) and intra-row hoeing with finger-weeders (19% WCE) achieved significantly lower WCEs than in earlier studies (Kunz et al. 2015, Gerhards et al. 2024). These results suggest that mechanical intra-row weed control remains a key challenge under challenging field conditions. However, systems such as Farming GT[®] and Robovator[®] present solid working tools, further expandable in preciseness of tools and AI-technology.

Crop damage

Crop response to weeding operations must be considered when evaluating the success of weed control (Rasmussen 1991). In all three experiments, crop density ranged from 5.1 to 5.6 plants/m, with no significant differences observed among experiments and treatments. This density is relatively low for sugar beet fields in that area. Due to heavy rainfall after sowing and subsequent topsoil compaction, approximately half of the seeds could not emerge. Crop damage caused by the RAWS, as shown in Figure 3, remained within acceptable limits. Crop soil burial one day after treatment was highest after intra-row hoeing with finger-weeders, with 33%, which was not surprising given the constantly rigid rotating fingers of the weeder. Unexpected was the low crop soil burial rate, with only 4% by the Farming GT[®], which resulted in hardly any burial despite the moving intra-row blades. This is most likely attributable to the robot's low speed of only 0.5 km/h, resulting in

a gentle movement of the soil. However, most crop plants recovered from soil burial and only a maximum of 5.5% of sugar beet plants were lethally uprooted in the Farming GT[®] plots. These losses, caused by the Farming GT, were most likely due to topsoil crusting, which dammed the plants, rather than being caused by the misclassification of the AI-based classification system. Nevertheless, this is within economically acceptable ranges, provided that standing room for the crop plants and subsequent loss are not amplified. Crop plant losses in the present study were considerably lower than those reported in earlier studies with camera-guided mechanical intra-row weeding (Gerhards et al. 2024). They partly used earlier versions of the same robots as in our study, indicating the technical progress of those robots.

Interestingly, robots with selective intra-row blades caused medium to coarse topsoil fragmentation, while non-selective systems created finer soil particles. This may influence soil moisture and water retention, as well as further weed emergence dynamics (Kunz et al. 2016), since coarse topsoil fragments may shorten the window for further weed germination.

In conclusion, based on the presented results, selective intra-row robotic hoeing systems such as Farming GT[®] and Robovator[®] should be prioritised for commercial use, as they achieved the highest WCE (up to 81% intra-row, 89% inter-row) with minimal crop damage (< 5.5%). Their performance demonstrated that effective non-chemical weed control is already feasible under realistic field conditions, including soil compaction and advanced weed stages. The ARA[®] spot-spraying system achieved excellent inter-row efficacy (up to 99%) but showed reduced intra-row performance under advanced weed growth stages (Gerhards et al. 2024). Combining both approaches, an inter-row spot-sprayer/intra-row mechanical weeding robot would theoretically achieve the highest WCEs based on the results of this study. This should be tested in future RAWS experiments.

Systems like finger-weeders and band-sprayers demonstrated insufficient intra-row efficacy (< 45%), especially in dry or crusted soils. Therefore, the use of these systems should be restricted to favourable soil conditions or complemented by chemical measures. Additionally, perennials such as *C. arvensis* and dominant species like *V. persica* in certain rotations require integrated control strategies. Preventive methods, such as crop rotation (e.g., with 2 years of clover-grass mixtures) and the timing of crop sowing, can already reduce the growth of weeds. Further

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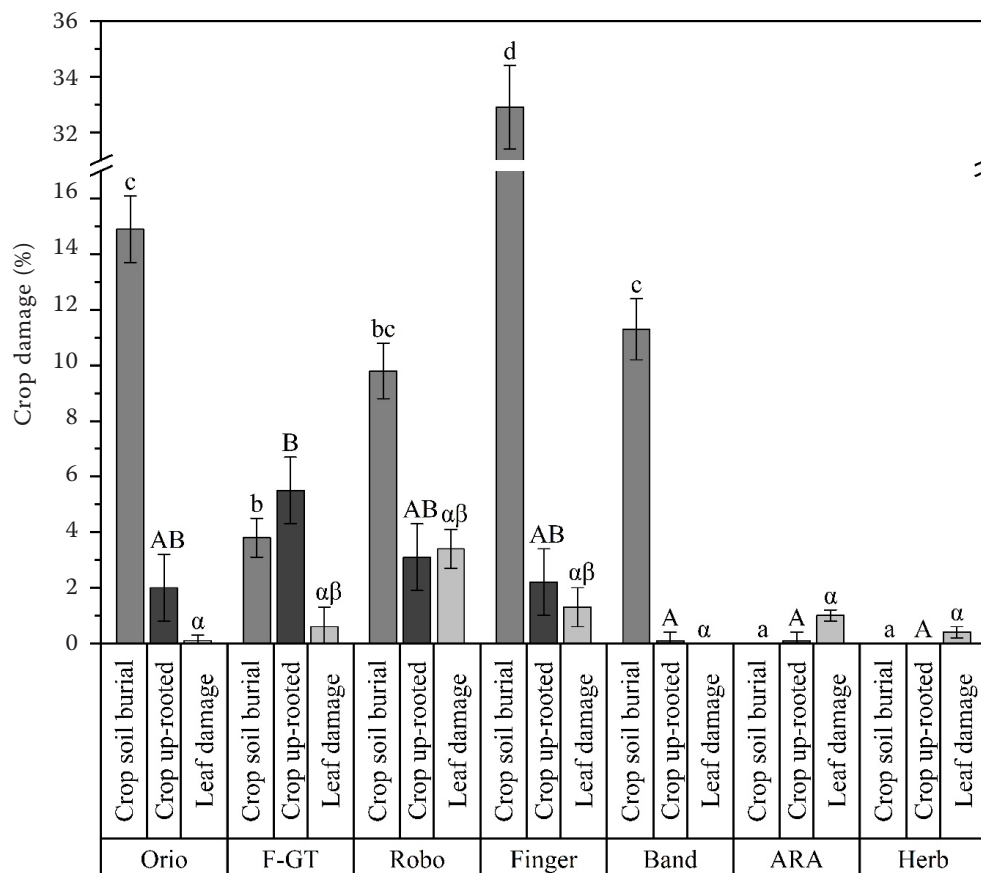


Figure 3. Average crop damage one day after treatment (DAT; 2024-06-12) for the respective treatment pooled across three experiments. Estimated crop damage of each treatment subdivided in crop soil burial (%), crop up-rooted (%) and leaf damage of crop plant (%). Results of least-square means comparison: Same small letters – no significant differences between the treatments for crop soil burial; same capital letters – no significant differences between the treatments for crop up-rooted; same greek letters – no significant differences between the treatments for leaf damage; $\alpha = 0.05$. Error bars indicate standard errors of the mean

indirect methods are repeated shallow tillage against *C. arvensis* or ploughing against annual weeds. The utilisation of RAWS can then cover direct plant protection during the season.

Looking forward, the full potential of robotic weeding will depend on further developments in plant detection, AI-optimisation, adaptive tool actuation, and real-time soil condition sensing. Future systems will then enable both ecological and economic resilience, protecting beneficial weed species. For this, close cooperation between technology developers, agronomists, and farmers is essential.

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