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Control of *Sorghum halepense* in soybean using the ATAR smart sprayer system

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SUMMARY

The ATAR smart sprayer is an innovative system developed by the startup company ATAR AGTEK d.o.o. It enables precise identification and treatment of weeds and can be easily integrated with any type of sprayer. The system consists of cameras that record area in front of the sprayer as it moves. The images are transmitted to an advanced artificial intelligence chip, which analyzes them in real time and activates the necessary nozzles to target and effectively treat only the detected weeds. In 2023 and 2024, the precision of this system in recognising and controlling *Sorghum halepense* from rhizomes in soybean crops was tested in field trials. Fields with a highly uneven distribution of *S. halepense* plants, where control was considered justified were selected for testing. In both trials, a clethodim-based product (144 g a.i. ha^{-1}) was applied either broadcast over the entire area of the plots or only targeted where the presence of this weed was detected. Herbicide was applied post-emergence at stages 13-31 of the BBCH scale for *S. halepense* and at stages 12-13 of the BBCH scale for soybean. In 2023, a trial was conducted on a large plot without replication, while the 2024 trial was set up according to a randomized block design with three replications. To confirm the effective recognition and treatment of weeds in each basic plot, water-sensitive papers placed horizontally next to the weed plants and the SnapCard application was used to analyze percentage coverage. The most important parameter was efficiency, defined as the proportion of controlled weed plants 15 days after herbicide application, evaluated on a 400 m^2 area in the middle of each basic plot. For each basic plot, a map of the treated areas was created and the percentage of the treated area was calculated. Analysis of water-sensitive papers confirmed that weeds were fully identified and treated using this innovative approach.

The treatment maps showed that in 2023 only 19% of the total area was treated, while in 2024 this ranged from 29-75%. These differences depended on the number and spatial distribution of weeds, as well as the setting of the required treatment area in front of and behind the detected weeds in order to achieve maximum system reliability. By analyzing the number of controlled and uncontrolled (newly sprouted) plants from the rhizome 15 days after herbicide application in the 2023 trial, the effectiveness of *S. halepense* control was 92.5%. In 2024, similarly high efficacy was achieved with all four tested treatments: at speeds of 6 and 8 km h^{-1} whole-surface treatments achieved 91.2% and 94.2% control, while spot spraying achieved 90.8% and 93.5% at the same speeds. The results confirm that this system can provide reliable control of *S. halepense* with significant herbicide savings, thereby reducing the risk to non-target organisms and the environment.
Keywords**:** *Sorghum halepense*, control, computer vision, smart sprayer, spot spraying, soybean, clethodim.

INTRODUCTION

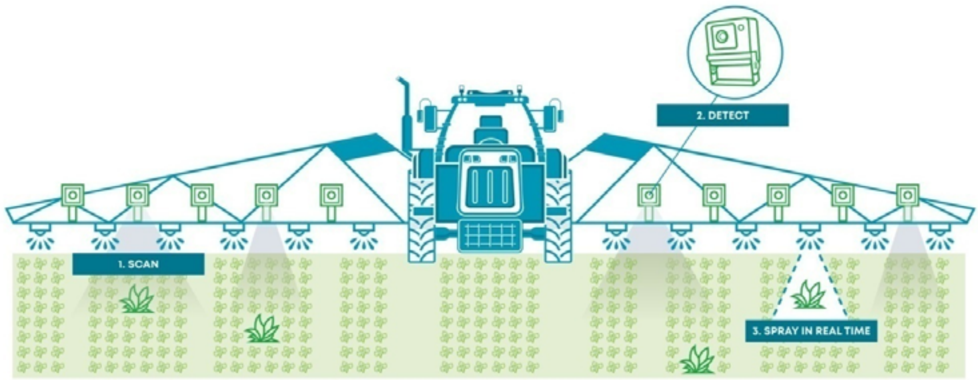
Weed management in the 21st century is moving towards precision and smart approaches. Herbicide application technology has advanced significantly in recent decades, enabling targeted application through precision systems that use machine vision and artificial intelligence to recognize weeds and control nozzles, applying herbicides in real time only where needed (such as John Deere's See & Spray or BASF and Bosch's One Smart Spray systems) (Monteiro and Santos, 2022; Avent et al., 2024, Xuan et al., 2025). Smart sprayers use high-resolution cameras mounted on the application boom to capture real-time images of the field. AI models are trained to detect, classify, and locate weeds instantly against the crop or soil background. These targeted spot spraying methods can provide weed control efficacy comparable to broadcast application while reducing total herbicide use and costs by up to 90%, depending on the weed density and specific system used (San and Kakani, 2025). Although some tests of these smart sprayers were carried under field conditions using water-sensitive or coloured papers, most were performed in controlled conditions rather than in the field which can significantly affect precision and efficiency. The precision of weed detection and spraying in the field can be influenced by factors such as sprayer speed, wind, lighting, shadows, and occlusion. For these reasons, many field trials are required to evaluate these smart spraying technologies (Vijayakumar et al., 2023). Weed control between broadcast and spot herbicide application in maize, sugar beet, and sunflower did not differ significantly (Spaeth et al., 2024). The ATAR smart sprayer retrofit, like other similar systems, uses a camera-based system and artificial intelligence developed by the Serbian start-up ATAR AGTEK d.o.o. from Novi Sad (www.atar.ai) to enable real-time detection and spraying of weeds during the same pass, selectively applying herbicides only where weeds are present rather than across the entire field. Thanks to this innovation, it is possible to test smart sprayers and benefit from their advantages even before powerful multinational companies and expensive systems enter our market. *S. halepense*, a competitive invasive perennial grass, is particularly suitable for this system as it often appears in patches or as individual plants (Vrbničanin and Janjić, 2004), making it unnecessary to apply herbicides to the entire field. Additionally, due to prolonged sprouting, two treatments are often required for crops with a lower habitus, which can be a deterrent if broadcast application over whole field is necessary.

The aim of our field trials was to determine whether machine learning and spot treatment with clethodim provide a reliable approach to recognising and controlling *S. halepense* from rhizome, specifically whether this approach is as effective at controlling this weed as the broadcast application of herbicides over the entire field.

MATERIAL AND METHODS

Field trials were conducted in 2023 and 2024 near Novi Sad on soybean grown on chernozem soil. The soybean variety NS Deneris was sown on 9 May 2023, and NS Adonis on 13 May 2024, with an inter-row spacing of 50 cm and a density of 450,000 plants per hectare. After sowing, pre-emergence herbicides *s*-metolachlor (1,440 g a.i. ha^{-1}) + metribuzin (280 g a.i. ha^{-1}) were applied in both years, achieving excellent control of annual weeds and *S. halepense* from seed. To control *S. halepense* from rhizomes, a clethodim-based product (Select super, 120 g L^{-1} active ingredient, manufacturer UPL) was applied at the recommended rate (1.2 L ha^{-1}) post-emergence at the target weed stages 13-31 BBCH scale, and soybean stages 12-13 BBCH. A specially adapted sprayer with the ATAR smart sprayer system was used, employing computer vision to detect the target and enabling herbicide application only where the target weed was previously detected, significantly reducing herbicide use (Pictures 1 and 2). An additional benefit of the system is its integration with the cloud platform, where, after treatment, spray data and generated spray maps are automatically uploaded and thus become available to users. This enables easy monitoring and analysis of treatment efficiency, as well as improved organization and planning of future treatments. In 2023, a tractor-mounted Hardi sprayer equipped with previously described retrofit was used with a working width of 12 m, LU 120-03 nozzles (manufacturer Lechler), a pressure of 4 bar, a speed of 8 km h^{-1} and 200 L ha^{-1} of working solution. In 2024, herbicide was applied on 31st May using a sprayer with a working width of 15 m, AIXR11002VP nozzles (manufacturer TeeJet), speeds of 6 and 8 km h^{-1}, pressures of 3 and 5 bar and 150 L ha^{-1} of water. In 2023, the trial was conducted without replication over a total treated area of 3 ha, while in 2024, the trial was established using a randomized block design with three replications and a basic plot area of 1,875 m^2 (plot length 125 m, width 15 m).

Based on the map of the treated areas where selective spraying was applied and the entire field, the percentage consumption of herbicides and water in the selective spraying treatments was calculated. Water-sensitive papers (26 x 76 mm, manufacturer Syngenta, Basel) were previously placed next to the weed plants to check the accuracy of recognition of randomly selected *S. halepense* plants by the camera system and computer vision in nozzle control. A total of 35 water-sensitive papers were placed per treatment in 2023 and 30 in 2024, to analyze percentage coverage after spraying using the SnapCard application for mobile phones.



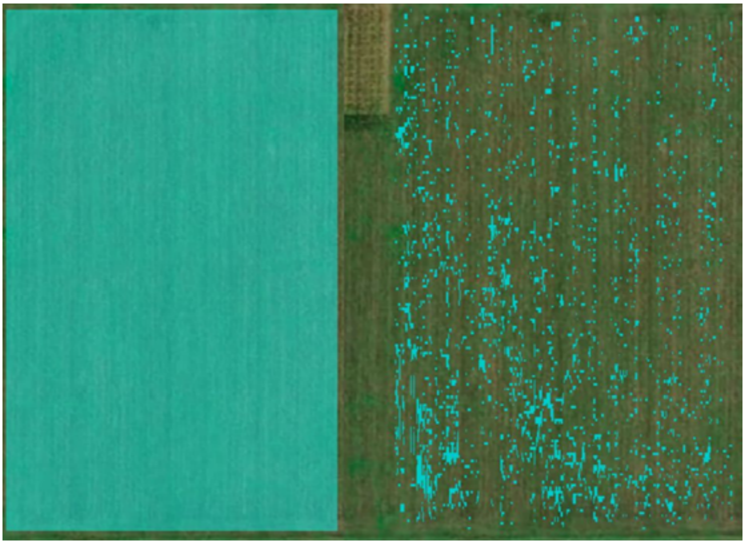
Picture 1. Artificial intelligence system on the ATAR Smart Sprayer.

Picture 2. Camera and system that analyze images using a machine learning algorithm to identify weeds in real-time.

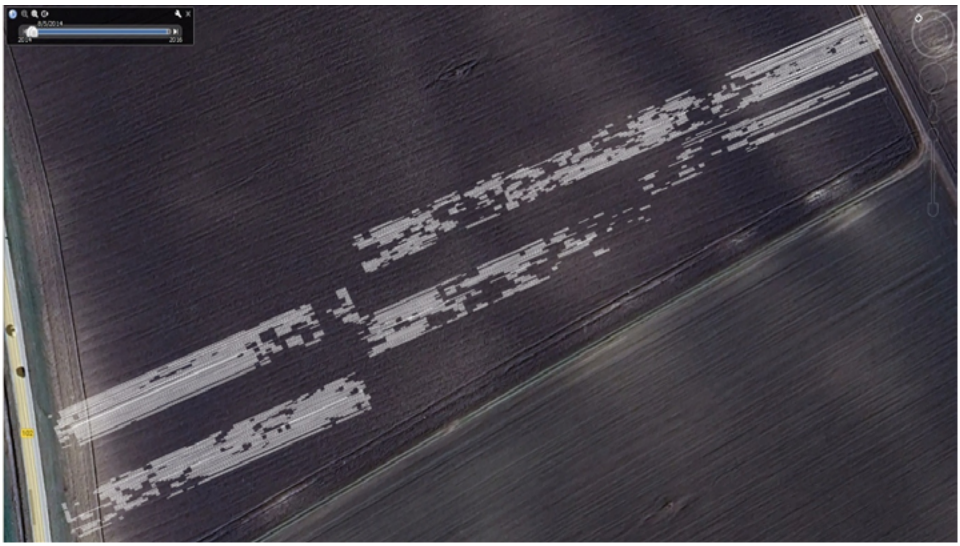
Weed control efficiency (%) was calculated 15 days after herbicide application based on the proportion of controlled *S. halepense* plants from the rhizome in relation to the total number in the central part of the basic plot which was 4 m wide and 100 m long.

RESULTS

The artificial intelligence and real-time nozzle control system identified and treated almost all *S. halepense* plants with herbicide, as confirmed by the response of all treated water-sensitive papers placed next to the weed plants. The system recognized *S. halepense* very well, but did not recognize or treat two patches of *Cynodon dactylon* in 2023, as confirmed by untreated water-sensitive papers placed next to this weed. In addition, equal coverage was achieved on water-sensitive papers with both spot spraying and broadcast (total) spraying. This further confirms that there was no reduction in the rate of herbicide applied to treated weed leaves with spot spraying due to untimely nozzle opening and closing. In the first year of testing, targeted spot spraying achieved excellent *S. halepense* control efficiency (92%), comparable to broadcast spraying of the entire field (93.1%). This was confirmed by the total and almost equal percentage of controlled plants showing symptoms of herbicide action, ranging from pronounced anthocyanin colouration on the leaves to complete plant necrosis. In 2023, due



Picture 3. Spraying map in 2023: on the left is broadcast spraying (100% treated), and on the right is spot spraying (19% treated).



Picture 4. Spraying map in 2024: the area treated with the ATAR smart sprayer system ranged from 29 to 75%.

to the lower number of weeds, only 19% of the area was treated (Picture 3), resulting in significant savings of herbicide (0.23 instead of 1.2 L ha^{-1}) and water (39 instead of 200 L ha^{-1}).

Depending on the abundance of *S. halepense* in each individual basic plot, the area treated with the ATAR smart sprayer system in 2024 ranged from 29-75% (Picture 4).The average treated area at a sprayer speed of 8 km h^{-1} was 49.3%, and at 6 km h^{-1} it was 61.7%.

The average coverage on water-sensitive papers in 2024 ranged from 23-25.8%, with no significant differences between treatments (Figure 1).

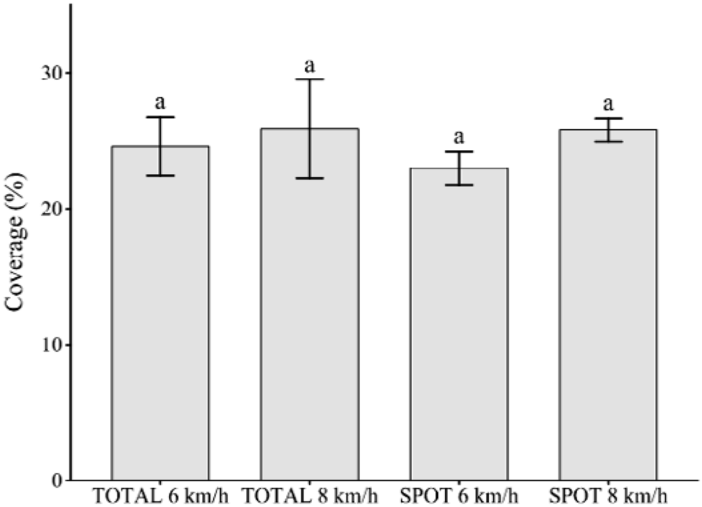


Figure 1. Coverage on water-sensitive papers (%) in 2024 with spot spraying and broadcast spraying across the entire plot.

The saving of herbicides and water in 2023 was as much as 81%, while in 2024 it ranged from 50.7% at a speed of 8 km h^{-1} to 38.3% at a speed of 6 km h^{-1} (Figure 2). The smaller savings in 2024 are due to differences in the number of weeds and their uneven spatial distribution, rather than the speed of the sprayer.

The speed of the sprayer was included in the testing to more accurately assess the reliability and efficiency of the entire system in weed recognition, nozzle control response, and herbicide consumption which depended on the number and spatial distribution of weeds in the field. In 2024, the total average number of *S. halepense* plants at the time of assessment in a sample area of 400 m^2 in the central part of the basic plots was 417.7 when treating the total area at 8 km h^{-1}, 572.7 when treating the whole basic plot at 6 km h^{-1}, 347.3 when spot spraying at 6 km h^{-1}, and 536 when spot spraying at 8 km h^{-1}. We found that the average number of *S. halepense* plants was generally low (0.87-1.43 plants m^2), but this can be misleading because plant distribution was uneven, with higher densities sometimes occurring in smaller patches. Therefore, control was justified. This situation was ideal for testing and justifying the use of spot spraying. The efficiency of *S. halepense* control was over 90% with no significant differences

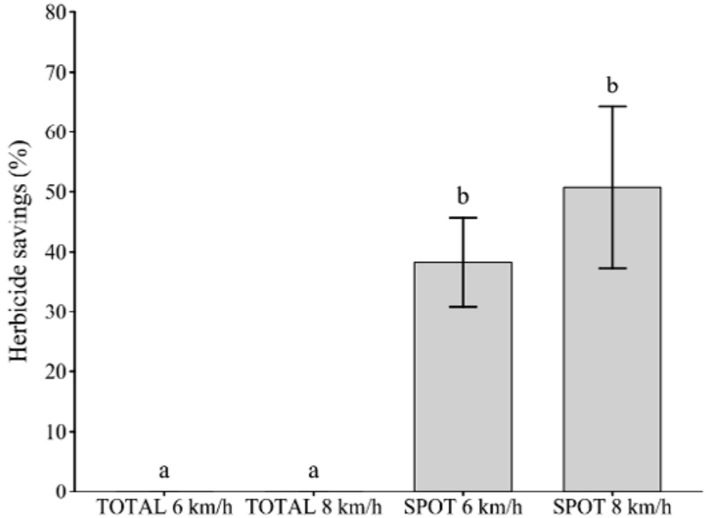


Figure 2. Herbicide savings (%) in 2024 with spot spraying compared to broadcast spraying of total basic plots.

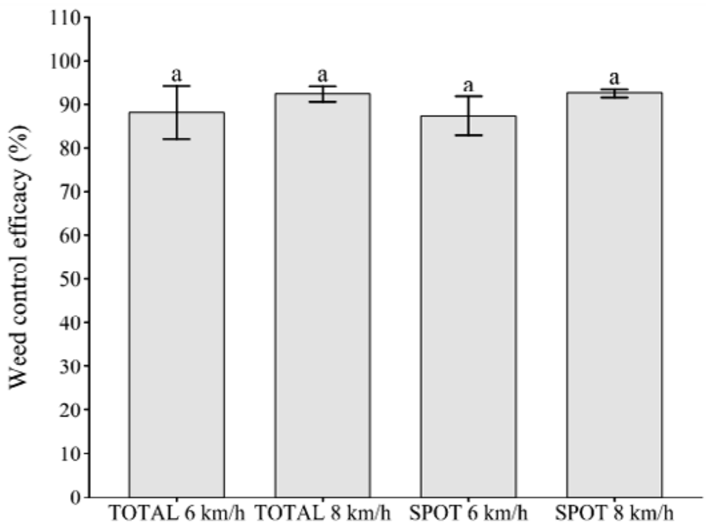


Figure 3. Efficacy of *S. halepense* control (%) in 2024 with targeted spot spraying and broadcast spraying of the entire basic plot.

in efficiency between the tested treatments (Figure 3). Newly emerged *S. halepense* plants had 1-4 leaves at the time of evaluation, confirming that they emerged between the herbicide application and evaluation, and were present in equal proportions across all treatments.

DISCUSSION

In our trials, the AI-driven vision system consistently achieved high accuracy in distinguishing *S. halepense* from crop plants. Accuracy was confirmed using water-sensitive papers and created spray maps, which enabled visualization and quantification of spray coverage, demonstrating a very high accuracy which is in agreement with the results of other authors (Darbyshire et al., 2023; Vijayakumar et al., 2023; Spaeth et al., 2024; Al-Ahmadi and Subr, 2025). High detection accuracy is directly associated with increased herbicide savings and consistent weed control efficacy, particularly for perennial weeds exhibiting patchy distributions.

Our field trials with *S. halepense* recorded up to 81% reduction in herbicide application compared to conventional broadcast spraying. For example, general precision weed management reviews report potential herbicide savings ranging from 5% to nearly 90%, with typical spot and patch-spraying systems reducing herbicide use from 30% to more than 70% (Christensen et al., 2009; Riar et al., 2011; Jensen et al., 2012; Monteiro and Santos, 2022; Castaldi et al., 2024; Spaeth et al., 2024).

Despite substantial reduction in sprayed area, weed control efficacy remained high in our system at levels comparable to conventional broadcast application. Literature on precision weed management reinforces that smart sprayer systems often match broadcast efficacy when detection accuracy is high. We could not compare our results of *S. halepense* efficacy control in soybean with the smart sprayer, as no comparable data exist specifically for this weed–crop combination. However, studies on other weeds and crops demonstrate strong performance: spot sprayers maintained ≥93% weed control efficacy in soybean (Avent et al., 2024), 72-99% in maize, sugar beet, and sunflower (Spaeth et al., 2024), and 97% efficacy in sugarcane (Rahimi Azghadi et al., 2024) while employing targeted applications.

These outcomes confirm that precision application does not necessarily compromise efficacy, even for difficult-to-control perennial weeds, provided the algorithm reliably identifies weed plants and applies herbicide accordingly. Overall, our results not only demonstrate superior herbicide savings with maintained or improved control efficacy compared with many published field systems, but also emphasize the value of AI-based spot spraying for perennial weeds with complex spatial patterns. This reinforces that precision technologies can make a significant contribution to sustainable weed management.

CONCLUSION

Based on the results obtained, we conclude that: (a) The ATAR smart sprayer is a reliable system that enables any sprayer to detect weeds using a camera and artificial intelligence, allowing precise herbicide application to detected plants of *S. halepense* in soybean by controlling each individual nozzle. (b) It is possible to save up to 80% of herbicides and water by spraying only where weeds are detected, thus avoiding unnecessary treatment of unweeded soil and crop plants. This is particularly important both ecologically and economically, and aligns with integrated plant protection strategies, especially regarding the reduction of herbicide use. (c) Further tests should be conducted to confirm the precision and effectiveness of this method of herbicide application for other weeds and in other crops.

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Suzbijanje *Sorghum halepense* u soji prskalicom sa ATAR smart sprayer sistemom

REZIME

ATAR Smart Sprayer predstavlja inovativni sistem, kreiran od strane startap firme ATAR AGTEK d.o.o, koji omogućava precizno prepoznavanje i tretiranje korova i može se jednostavno integrisati na bilo koju vrstu prskalice. Sistem se sastoji od kamera koje tokom kretanja snimaju površinu polja ispred prskalice, a snimci se prosleđuju naprednom čipu veštačke inteligencije koji ih u realnom vremenu analizira i aktivira potrebne rasprskivače kako bi se ciljano i efikasno tretirao samo identifikovan korov. Tokom 2023. i 2024. godine na oglednim poljima Instituta za ratarstvo i povrtarstvo ispitivana je preciznost ovog sistema u prepoznavanju i efikasnost u suzbijanju divljeg sirka iz rizoma u usevu soje. Za ispitivanja su odabrana polja sa veoma neujednačenom distribucijom biljaka divljeg sirka i gde je procenjeno da je opravdano njegovo suzbijanje. U oba ogleda je posle nicanja primenjen preparat na bazi kletodima (144 g a.s. ha^{-1}) u fazama 13-31 BBCH skale divljeg sirka i fazama 12-13 BBCH soje, po celoj površini i samo gde je detektovano prisustvo biljaka divljeg sirka ATAR Smart Sprayer sistemom. Tokom 2023. godine izveden je ogled bez ponavljanja, dok je ogled 2024. godine postavljen po slučajnom blok sistemu u tri ponavljanja. Za potvrdu o efikasnom prepoznavanju i tretiranju korova na svakoj osnovnoj parceli korišćeni su horizontalno postavljeni vodosenzibilni papiri pored biljaka korova i SnapCard aplikacija za analizu procenta pokrovnosti. Najvažniji parametar bila je efikasnost, odnosno udeo broja suzbijenih biljaka korova, 15 dana posle primene herbicida, a koji je ocenjen na uzorku površine 400 m^2 na sredini svake osnovne parcele. Takođe, za svaku parcelu kreirana je mapa tretiranih delova parcela i obračunat procenat tretirane površine. Analiza vodosenzibilnih papira potvrdila je da je korov u potpunosti bio prepoznat i kvalitetno tretiran korišćenjem ovog inovativnog pristupa. Kreirane mape tretiranja potvrdile su da je 2023. godine tretirano samo 19% od ukupne površine, dok se 2024. godine ta površina kretala od 29-75%. Ove razlike su zavisile od brojnosti i prostornog rasporeda korova, ali i podešavanja potrebne površine za tretiranje ispred i iza detektovanih korova radi postizanja maksimalne pouzdanosti sistema. Analizom broja suzbijenih i nesuzbijenih (novoniklih) biljaka divljeg sirka iz rizoma 15 dana posle primene herbicida u ogledu 2023. godine ostvarena je efikasnost u suzbijanju 92,5%. Takođe, 2024. godine ostvarena je visoka i približna efikasnost kod sva četiri ispitivana tretmana, odnosno pri brzinama od 6 i 8 km h^{-1} kod tretiranja cele površine efikasnost je bila 91,2 i 94,2%, a kod precizne tačkaste primene herbicida 90,8 i 93,5% pri istim brzinama. Dobijeni rezultati su potvrdili da je ovim sistemom moguće ostvariti pouzdano suzbijanje divljeg sirka uz velike uštede herbicida i samim tim smanjen rizik za neciljane organizme i životnu sredinu.

Ključne reči: *Sorghum halepense*, suzbijanje, kompjuterski vid, pametna prskalica, tačkasto prskanje, soja, kletodim.