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Prototype of a Hoeing Robot for Non-Chemical Weed Control in Vegetable Production

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ABSTRACT

The study evaluated the effectiveness of a prototype hoeing robot (HR) for non-chemical weed control in vegetable production. A controlled greenhouse experiment was conducted at BC Naklo (Slovenia) on four plots (30 × 30 cm) sown with garden cress (*Lepidium sativum*) and radish (*Raphanus sativus*). Three plots were treated with robotic hoeing, while one served as a control. Results demonstrated a progressive reduction in weed density: effectiveness ranged from 53–88% after the first hoeing, increased to 90–97% after the second hoeing, and reached 100% elimination after the third hoeing across all plots. These findings confirm the strong potential of robotic hoeing as a sustainable alternative to manual labor and herbicide use, particularly in organic farming systems. From an economic perspective, HR reduces reliance on seasonal labor and lowers long-term production costs, thereby improving farm profitability.

Keywords: robotic hoeing, weed control, smart technologies

INTRODUCTION

In a world facing rapid population growth and increasing scarcity of natural resources, the need for efficient and sustainable food production methods is more urgent than ever. Smart farming, which integrates advanced technologies such as artificial intelligence (AI), robotics, the Internet of Things (IoT), and big data analytics, offers innovative solutions to the challenges of modern agriculture. These technologies enable precise crop management, resource optimization, and reduced environmental impact, thereby contributing to food security and sustainable development (King, 2017; Raj and Prahadeeswaran, 2025).

Smart farming has already demonstrated tangible benefits: AI-based models have improved crop forecasting by 20%, while smart irrigation systems have increased productivity by 25% and reduced water consumption by up to 90%. Beyond environmental gains, these advances also translate into significant economic advantages, including reduced input costs, higher yields, and improved profitability. However, successful implementation depends on understanding not only the agronomic and ecological, but also the economic and social implications of these technologies (Bacco et al., 2019; Balafoutis et al., 2020).

One promising innovation in smart farming is robotic weeding, in which autonomous robots mechanically remove weeds. This method is particularly valuable in organic farming, where the use of herbicides is prohibited. Robotic weeding enables precise soil management, reduces labor costs, and supports biodiversity. From an economic perspective, it offers the potential to lower long-term production costs, reduce dependence on seasonal labor, and increase overall farm profitability (Pannacci et al., 2017). In the long term, these management practices are anticipated to exert cumulative and sustained effects on soil quality, encompassing progressive improvement of soil structure, continuous enrichment of organic matter, persistent mitigation of erosion processes, and stabilization of soil pH over extended periods (Ojha et al., 2015; Xu et al., 2025).

Nevertheless, there are still some limitations and challenges in the implementation of smart technologies (Akhter et al., 2023; Dalhaus and Finger, 2016; Levstek, 2024):

- technological limitations: weeding robots (WR) are still evolving; thus, current models may lack efficiency, reliability, and face issues with maintenance, durability, or transport
- terrain limitations: designed mainly for flat surfaces; thus, performance declines on uneven, rocky, or steep terrain, and battery autonomy and energy demand further constrain effectiveness
- weather constraints: adverse weather conditions markedly reduce operational efficiency
- high initial costs: equipment and installation require substantial investment, often prohibitive for small-scale farms
- training requirements: effective use and maintenance demand technical expertise, additional time, and financial resources
- The aim of this study is to evaluate the potential of robotic weeding within smart farming, focusing on its agronomic, environmental, and economic implications, and to assess its long-term viability for sustainable and organic agriculture.

MATERIALS AND METHODS

The hoeing robot (HR) was developed at the Faculty of Mechanical Engineering, University of Ljubljana, Slovenia. It is a lightweight, autonomous tool designed for home use and occasional operation on small family farms. Development focused on cost-effective production, user-friendly operation, and functional versatility, making it accessible to small farmers interested in smart farming.

HR is designed for mechanical weeding between rows and within rows, providing a practical alternative to manual labor and heavy machinery. Its compact design and flexibility allow it to be used on a variety of vegetable crops, increasing its usefulness in different agroecological environments.

HR performs uniform and completely mechanical hoeing of vegetable plants shorter than 30 cm. The center distance corresponds to the width of the bed, and the front wheels serve as drive and steering wheels. The robot is powered by a BLDC (brushless DC) motor with gears with a power of 220 W and a gear ratio of 10:1 and 50:1. The torque of the motor without a gearbox is 0.6 Nm, and with a gearbox it is significantly higher. The drive motors built into the front wheels have a power of 350 W and are also BLDC motors in the hub.

The robot uses a lithium-ion battery with a nominal voltage of 24 V and a capacity of 500 Wh. Torque is transmitted to the digging elements via a central gear (sun gear) and two planetary gears. The planetary gears rotate around the sun gear, and an additional switch allows them to rotate around their own axis. Both axes are height-adjustable, and various hoeing elements can be attached to their ends. By selecting the appropriate sizes, it is possible to adjust the distance from the plant.

The robot can be operated by a single person, although two people are recommended for transport over longer distances due to its weight.

Figure 1. 3D model of the hoeing robot and its different hoeing elements

Testing the Hoeing Robot at BC Naklo

A controlled greenhouse trial involving the HR was also conducted at BC Naklo (46.2706° N, 14.3147° E).

We sowed four plots (30 × 30 cm) with garden cress (*Lepidium sativum*) and radish (*Raphanus sativus*), which were selected due to their rapid germination and growth. These species served as substitutes for weeds targeted by the HR.

Three plots were used to test the effectiveness of hoeing, while the fourth served as a control and was left untreated. The number of plants on the control plot remained constant throughout the experiment.

Once the seedlings had developed at least two to three leaves, we counted all the plants on each plot. Hoeing was performed every week, and after each weeding, we counted the remaining undamaged plants. In addition, we recorded plants that were initially damaged but recovered over time. Weekly hoeing was carried out, with the number of undamaged plants recorded after each weeding at three key times: start, middle, and end of the experiment.

Before each hoeing, a printed model of a lettuce (*Lactuca sativa*) head was placed in the center of each plot. Hoeing was carried out by rotating the hoeing elements once around the lettuce model.

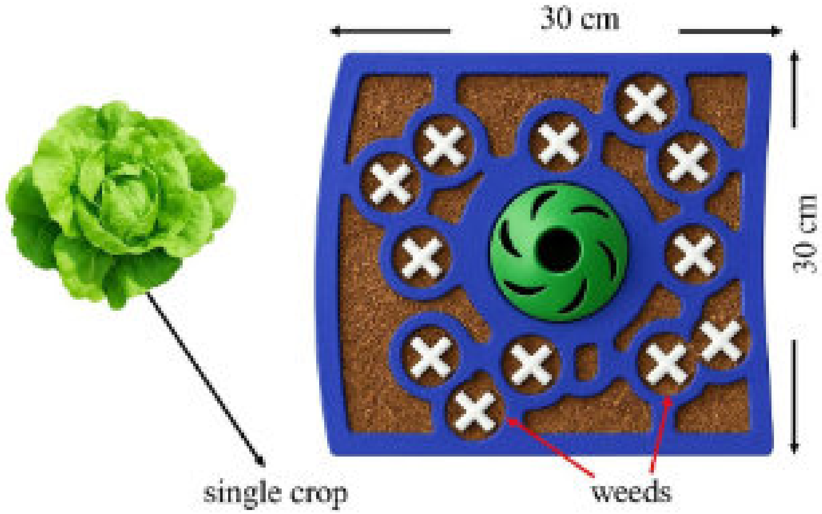

Figure 2. Lettuce crop and 3D-printed crop model

RESULTS AND DISCUSSION

In the case of garden cress, there is a noticeable reduction in the number of plants on the third plot before hoeing, which can be attributed to poorer seed germination due to the microclimatic conditions on this plot. The other two plots are almost identical (fig. 3)

In the case of radish, the number of plants on the plots was fairly uniform. The first hoeing caused significant differences in the number of "weeds" on the plots, but these differences decreased with each subsequent hoeing, and after the third hoeing, 100% destruction of plants was achieved on all plots.

If we look at the number of plants and their proportion on the plot regardless of the type of vegetable, the data is much more balanced. The first hoeing on the third plot stands out, as the number of undamaged plants is small and their proportion is low compared to the first count and the control plot. Since the number of plants before hoeing is also lower than on the other two plots, we can conclude that with a higher density of plants (plots 1 and 2), the first hoeing is slightly less effective.

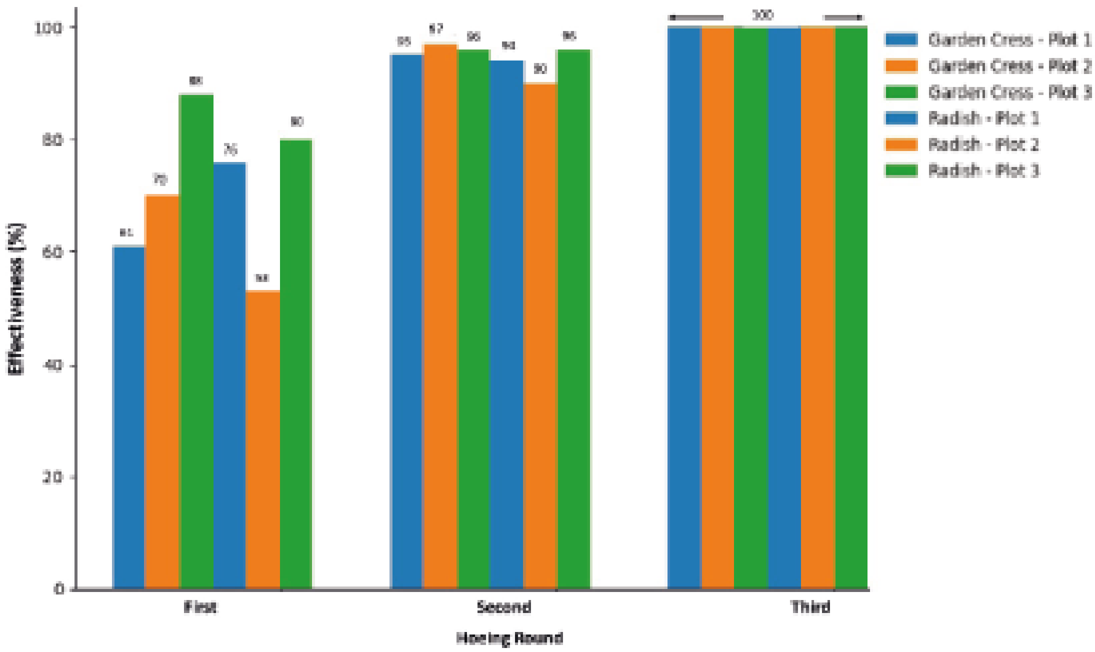

Figure 3. Effectiveness (%) of hoeing across plots

We calculated the degree of effectiveness as the proportion of destroyed plants after hoeing and the number of plants in the control group (fig. 4).

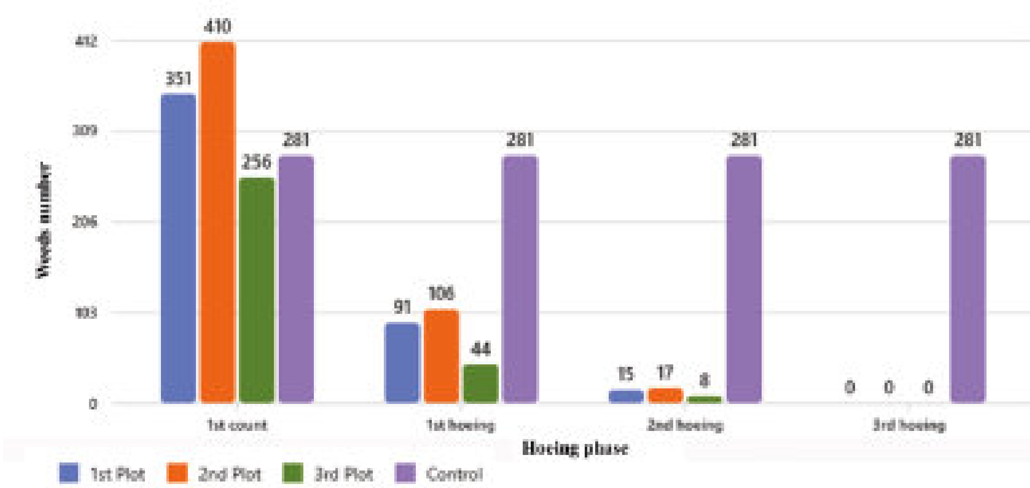

Figure 4. Number of plants after individual hoeing, total for both vegetables

Garden Cress

After the first hoeing of Plot 1, the plants control efficiency was 61%, which means that approximately 61% of plants were removed compared to the control plot and approximately 52% compared to the initial number of plants before hoeing. After the second hoeing of plot 1, the effectiveness increased to 95%, which means that approximately 95% of plants were removed compared to the control group and approximately 94% compared to the initial number. After the third hoeing, the efficiency reached 100%, indicating complete removal of the plants.

In Plot 2, the first hoeing resulted in an effectiveness rate of 70% compared to the control plot and 78% compared to the initial count. The second hoeing improved the rate to 97% compared to the control group and approximately 94% compared to the initial count. After the third hoeing, the effectiveness was 100%.

In Plot 3, the first hoeing achieved an effectiveness rate of 88% compared to the control plot and 85% compared to the initial count. The second hoeing resulted in 96% effectiveness compared to the control group and approximately 89% compared to the initial count. After the third hoeing, the effectiveness was 100% (Table 1).

Table 1: Plant control effectiveness for garden cress

Plot	Hoeing stage	Effectiveness vs. control (%)	Effectiveness vs. initial count (%)
1	First	61	52
	Second	95	94
	Third	100	100
2	First	70	78
	Second	97	94
	Third	100	100
3	First	88	85
	Second	96	89
	Third	100	100

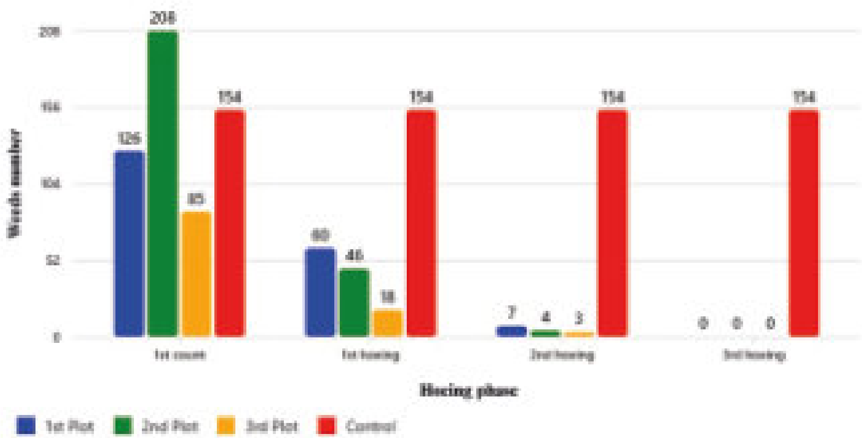

Figure 5: Garden cress—number of plants after hoeing.

Radish

After the first hoeing of Plot 1, the effectiveness of plants control was 76% compared to the control group and 86% compared to the initial count. After the third hoeing, the effectiveness reached 100%.

In Plot 2, the first hoeing resulted in an effectiveness rate of 53% compared to the control group and 86% compared to the initial count. The second hoeing improved the rate to 90% compared to the control group and approximately 96% compared to the initial count. After the third hoeing, the effectiveness was 100%.

In Plot 3, the first hoeing achieved an effectiveness rate of 80% compared to the control group and 85% compared to the initial count. The second hoeing resulted in 96% effectiveness compared to the control group and approximately 97% compared to the initial count. After the third hoeing, the effectiveness was 100% (Table 2).

Table 2. Plant control effectiveness for radish

Plot	Hoeing stage	Effectiveness vs. control (%)	Effectiveness vs. initial count (%)
1	First	76	86
	Second	94	96
	Third	100	100
2	First	53	86
	Second	90	96
	Third	100	100
3	First	80	85
	Second	96	97
	Third	100	100

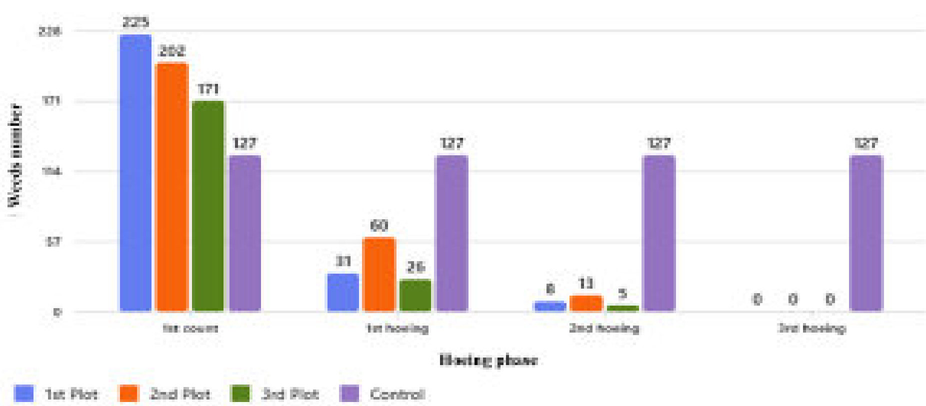

Figure 6. Radish—number of plants after individual hoeing.

CONCLUSION

The prototype hoeing robot (HR) demonstrated high effectiveness in non-chemical weed control under controlled greenhouse conditions. Across all tested plots, weed density decreased consistently with each hoeing cycle, culminating in complete elimination after the third intervention. These results confirm the potential of robotic hoeing as a reliable alternative to manual labor and herbicide use, particularly in organic farming systems.

Beyond agronomic benefits, robotic hoeing contributes to long-term soil health, biodiversity preservation, and reduced environmental impact. Economically, it offers prospects for lowering labor costs and improving profitability, although challenges such as high initial investment, terrain adaptability, weather sensitivity, and training requirements remain.

Future research should focus on larger-scale trials to ensure statistical robustness, optimization of robot design for diverse agroecological conditions, and integration with other smart farming technologies. Addressing current limitations will be crucial for enabling broader adoption, especially among small-scale and organic farmers.

Overall, the findings highlight that hoeing robots can play a significant role in advancing sustainable agriculture by combining technological innovation with ecological and economic viability.

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Prototip robota za okopavanje radi nekemijskoga suzbijanja korova u povrćarskoj proizvodnji

SAŽETAK

U radu je ocijenjena učinkovitost prototipa robota za okopavanje (HR) radi nekemijskoga suzbijanja korova u povrćarskoj proizvodnji. Kontrolirani pokus u zaštićenome prostoru proveden je u BC Naklo (Slovenija) na četiri parcele (30 × 30 cm) zasijane sjetvenom grbicom (*Lepidium sativum*) i sjetvenom rotkvom (*Raphanus sativus*). Tri su parcele bile tretirane robotskim okopavanjem, dok je jedna služila kao kontrolna varijanta. Rezultati su pokazali postupno smanjenje gustoće korova: učinkovitost se nakon prvoga okopavanja kretala od 53 do 88 %, nakon drugoga okopavanja porasla je na 90–97 %, a nakon trećega okopavanja postignuto je 100 %-tno uklanjanje korova na svim parcelama. Ovi nalazi potvrđuju izrazit potencijal robotskoga okopavanja kao održive alternative ručnomu radu i primjeni herbicida, osobito u sustavima ekološke poljoprivrede. S ekonomskoga stanovišta HR smanjuje ovisnost o sezonskoj radnoj snazi i dugoročno snižava troškove proizvodnje, čime se povećava profitabilnost poljoprivrednoga gospodarstva.

Ključne riječi: robotsko okopavanje, suzbijanje korova, pametne tehnologije