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Review

Mechanical Weed Control Systems: Methods and Effectiveness

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Abstract: This article presents a division of methods to support mechanical weeding based on mechatronic control systems and estimates their effectiveness. The subject was undertaken due to the noticeable increase in interest in machine weeding methods, which is the result of the need for farmers to meet the growing awareness of customers focusing on healthy and high-quality products and the European Union policy promoting environmental protection programs, such as the European Green Deal and supporting commission priorities like the Mission Soil as a flagship initiative of the long-term vision for the EU's rural areas. Mechanical weeding meets the stringent conditions set by organic farming, and automation favours the development of these methods. Based on sources in the literature, it has been shown that it is possible to increase the weeding speed by at least 1.6 times by using the tool position correction system for row crops. In the case of crops requiring weeding, and in the spaces between plants in a row, the use of specialised weeding machines allows for an increase in the weeding efficiency by up to 2.57 times compared to manual weeding. Each of the analysed methods used to support weeding are subject to a certain error due to the use of sources in the literature, including manufacturers' materials; however, it shows an upward trend in the effectiveness of using mechatronic weeding support systems, which was part of the thesis. This article presents the division of these systems and analyses the specific market solutions of machines, which is its distinguishing feature.

Keywords: agriculture; automation; efficiency; mechanical weeding; mechatronics; precision; sustainable agriculture

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1. Introduction

The current trends in agriculture focus on finding new methods or improving existing crop care methods. Activities aimed at reducing the use of plant protection products and the development of mechanical care methods are particularly noticeable. Both approaches meet the requirements of sustainable agriculture, which is becoming a quality determinant for farmers and food producers [1].

Sustainable agriculture primarily comprises activities aimed at reducing the impact of crops on non-agricultural areas and reducing the amount of waste that is not used in production processes [2]. The characteristic features include striving to reduce production on industrial farms, protecting soil and biological resources by organising agricultural production in a way that does not adversely change the natural environment, or making minor changes to reduce negative phenomena such as erosion. Sustainable agriculture is a management system that combines economic, social and ethical aspects with ecological safety [3]. It should be noted that the use of plant protection products is allowed in justified cases. The postulates of sustainable agricultural production are achieved through appropriate management, the use of knowledge on the self-regulation of ecosystems, the use of modern technologies, research and scientific findings. A more radical type of cultivation is organic farming, which, by definition, excludes the use of synthetic plant protection products and artificial fertilisers [4].

The European Green Deal is a package of initiatives combining the previously mentioned aspects, and its main idea is to be climate-neutral. A systemic approach to environmental issues is noticeable in many areas, such as industry, transport, research and innovation, energy and, of course, agriculture [5]. One of its key actions is the "farm to fork" strategy, which aims to achieve climate neutrality by 2050, while turning the EU food system into a sustainable model. The main priorities include ensuring sufficient quantities of inexpensive and nutritious food and halving the use of pesticides and fertilisers. The measures also include supporting the development of organic farming [6].

The common feature of these selected cultivation models is the desire to minimise the use of plant protection products, which, in many cases, have led to local environmental disasters, causing groundwater contamination or ecosystem extinction. The most frequently identified group of pesticides in groundwater is herbicides, which directly affect the organisms of humans and animals living in a given area [7–9]. The negative effects of the use of herbicides contributed to the search for alternative methods of crop care and influenced the development of technologies that are often consistent with precision agriculture.

These cultivation and farming models have contributed to the development of alternative weed control methods to herbicides. The most common group is mechanical weed control by undercutting the roots with tools that penetrate the soil. Many research units and machine manufacturers are developing methods to increase the efficiency and precision of mechanical weeding. Vision systems are used to detect plants and correct weeding tools, enabling faster driving of a tractor or an autonomous platform, e.g., CultiCam, Garford, K.U.L.T., Steketee, FarmDroid, Robovator, etc. [10–24]. There are also other weeding methods based on the visual recognition of weeds and burning them with a laser beam. In this case, it is possible to obtain average errors of 0.62 mm in position at the distance of 535 mm, and the dynamic weeding efficiency is around 0.72 s/weed [25]. Flame control methods are also used. The nozzles mounted on the weeding sections are equipped with special covers that protect the plants in the rows against the influence of temperature [26]. A particularly important role in precise weeding is played by the use of artificial intelligence algorithms to detect crops and highly specialised mechatronic equipment—these are more and more often used on autonomous field robots [15]. The search for weed control methods that reduce the impact on the natural environment is in line with the principles of integrated pest management, which is a part of sustainable agriculture activities [27].

This article presents the solutions selected by the authors for weed control according to the proposed division of mechanical weed control support methods [28]. The discussed topic is consistent with the development of autonomous vehicles as specialised carriers of working tools for weed control. It is estimated that the field robot market will reach USD 87.9 billion worldwide by 2025 [29]. Combining modern technology with natural cultivation methods allows us to meet the stringent conditions set by ecological farms; therefore, one can expect newer and more efficient weeding machines. This article proves the validity of the actions mentioned in the introduction and presents the division of the methods of mechanical weeding support. It has been hypothesised that the use of mechatronic weeding support methods increases the quality and speed of weeding compared to traditional weeding machines. Previous publications focus on determining the effectiveness of weeding in the field of conventional methods—without systems based on automation [30,31].

2. Division of Methods of Mechanical Weeding Support

The digitisation of machines resulting from the development of precision agriculture, the EU policy and, at the same time, the growing consumer awareness of the quality of purchased products have contributed to the investment in natural methods of crop care. The reversion to conventional cultivators runs the risk of not achieving sufficient performance. This is especially noticeable in the case of large-scale farms. Given the labour problems on farms and population growth, machinery manufacturers face a huge challenge [32,33].

As a consequence of the analysis of the technical solutions available on the market, a division based on selected evaluation criteria was proposed. The first criterion was the use of weeding machines for specific plant species, and thus, the need to meet specific agronomic guidelines. The second criterion was the kinematics of the tool movement in the soil and the necessity to adapt the machine to the current working conditions. Therefore, work automation is the main criterion qualifying the machines for the proposed division of weed control techniques. The authors distinguished the following methods of mechanical weeding support by taking into account the following criteria:

- Mechatronic systems supporting inter-row weeders;
- Mechatronic systems supporting intra-row weeders;
- Hybrid systems combining mechanical weeding with other methods, e.g., chemicals.

3. Characteristics of Weeding Support Methods

3.1. Mechatronic Systems Supporting Inter-Row Weeders

This is currently the most common group of machines designed to support the care of row crops, where the specialised tools for cutting weeds and loosening the soil move between the plants planted in rows. Conventional weeding tools are often used to operate the machine, which can be seen in standard weeders. A characteristic feature of machines assigned to a given method of weeding support is having a mechatronic control system that combines a vision system for detecting rows with actuators to correct the position of the soil cutting elements. The speed of the weeding tool in the space between the rows of plants results from the vehicle speed with which the machine is aggregated. The most important feature is that it enables the cultivator to increase its efficiency by ensuring that the tools are positioned to maintain a safe distance from the plants. The use of automation elements contributes to the compensation of possible losses resulting from the inaccuracy of the trajectory of a human-driven tractor—it is influenced by work ergonomics and operator fatigue. These are the main reasons for limiting the speed of conventional row cultivators and the reasons for using automatic tool correction systems.

Currently, there are several commercial solutions on the market that operate according to the described performance characteristics. The precursors in this field of machines are, for example, the Steketee with the Ec-weeder [10], the Claas with the Culti Cam [11] and K.U.L.T. with iVision SV [12]. The Łukasiewicz Research Network–Poznan Institute of Technology and Expom Krośniewice Ltd. also designed a unique system to correct the tools' positions between crop rows (Figure 1). Each of the above-mentioned solutions is characterised by the use of a camera and a computing unit to implement a control algorithm to correct the positions of the tools. Based on the manufacturers' data, thanks to the weeding support system, it is possible to perform work at speeds of up to 20 $km \cdot h^{-1}$ [12].

3.2. Mechatronic Systems Supporting Intra-Row Weeders

The presented group of machines is dedicated, in particular, to vegetable crops. The main characteristic is the use of drives for each weeding tool. The geometry of each of them is specified in detail by the manufacturer, and the flexibility is rather unacceptable as in the case of systems intended for weeding along rows. For the proper operation of the devices, it is necessary to combine the geometry of the tool, driving speed and the positions of plants in rows so as to obtain the assumed precision of weeding. The operating speeds of the weeding systems in rows range from 2 to 8 $km \cdot h^{-1}$ [14]. Weeding support systems in rows are characterised by a high precision—even 8 mm from the stem of the weeding plant [14]. Due to the need to weed the area around the plants in rows, vision systems are more complex. There are solutions that assign a dedicated camera to each row of plants [13] and machines that analyse the area of four rows with one camera [14]. There are solutions, the tools of which, as a result of combining the rotational movement of the weeding blade and the driving path, define a cycloid [34]. It is then necessary to precisely control the rotational speed of the tool and its instantaneous position. The second variant involves the cyclic extension and retraction of the knives, which weed the spaces between the plants in the row.

Figure 1. An example of a mechanical weeding support system designed by Łukasiewicz Research Network–Poznań Institute of Technology and Expom Ltd. (source: own work).

The commercial solutions included in a given group are, among others, the Garford Robocrop inrow with one camera for four rotating weeding sections [14], Robovator with spring-loaded tools that move along a specific angle [13] and the IC-weeder by Steketee with pneumatics forcing the movements of the soil cutting knives and a vision system with a cover that minimises the influence of light on the operation of the algorithm [35]. The Łukasiewicz Research Network–Poznan Institute of Technology also owns an intra-row weeder solution, which was so far combined with the Agrorob agricultural robot (Figure 2).

Figure 2. An example of an intra-row weeding support system designed by Łukasiewicz Research Network–Poznań Institute of Technology (source: own work).

3.3. Hybrid Weeding Support Systems

This is a new group of weeding support systems that combines the advantages of the two selected methods, e.g., chemical and mechanical or thermal and mechanical methods.

A characteristic feature of the machines included in this group is that they have a vision system to correct the positions of tools in the rows and nozzles that apply the chemical to the plants in the row. Thanks to the technology used, it is possible to save up to 60% of the chemical agent compared to standard spraying [36,37]. Spraying is carried out only in the protected zone of the plants, where the tools do not cut the soil. When analysing the case of maize crops (Figures 3 and 4), the row spacing, *r*, is 0.75 m, while the protection zone, *p2*, for the hybrid weeding method is about 0.15 m. This means that only 40% of the row width is sprayed. This method is ideal for spraying maize as there are specialised and highly effective herbicides that prevent weed growth. Further development of the presented method is expected, e.g., via spot application of the fluid in the spaces between the plants or the use of thermal weed control. This will further reduce the use of herbicides and further reduce the negative impact on the ecosystem. The automation elements used in hybrid weeding support systems significantly improve weeding efficiency.

An example of hybrid weeding assistance systems is the newly developed SprayHub solution by Steketee [36] and the Venterra 2K cultivator developed by Schmotzer [38]. Both machines are equipped with an herbicide tank, specialised nozzles and tool guidance systems.

Figure 3. View of the nozzles for the strip spraying of plants placed between the mechanical weeding tools [39].

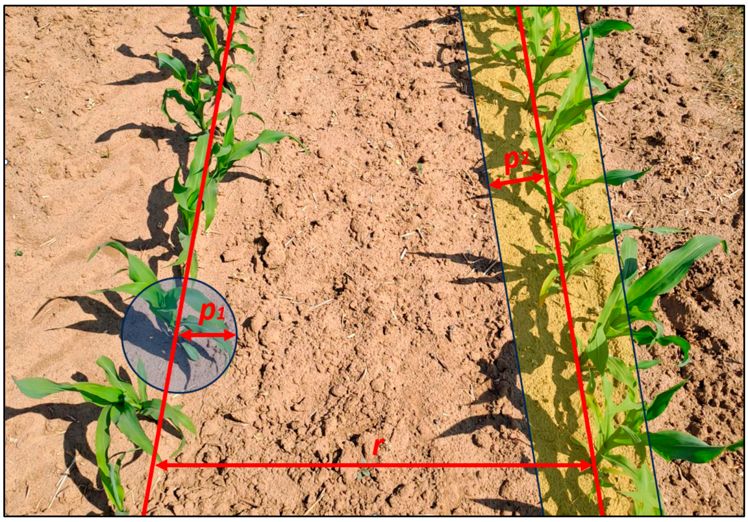

Figure 4. Plant protection zones for weeding methods, where *p1*—weeding accuracy for mechatronic systems supporting intra-row weeders; *p2*—weeding accuracy for mechatronic systems supporting inter-row weeders or hybrid systems; *r*—row spacing.

4. Methods

This article is based on an analysis of sources in the literature from the Google Scholar and Scopus databases. Articles were searched for the following keywords: precision inter-row weeding; precision strip spraying; precision intra-row weeding; mechanical weeding efficiency. In addition, sources from websites and brochures of leading manufacturers of automatic weed control systems were included in the analysis—these are reliable companies with established positions in the agricultural machinery market.

In the analysis of individual sources, the main criterion for inclusion in the analysis was an unambiguous indication of the weeding speed for a given meto-method and/or the weeding precision achieved using the system described. Sources were excluded if the above parameters were not described or if there were problems with a clear understanding of the material analysed. This was influenced by a lack of access to the full text of the publication or language barriers—the vast majority of publications were analysed in English and Polish. The analysed sources were systematised according to four categories: conventional inter-row weeding, conventional intra-row weeding, automated inter-row weeding and automated intra-row weeding. Several cases of weeding methods from one source in the literature were allowed to be included in the analysis, e.g., from review articles. On the basis of the categories mentioned above, the coefficients of increase in the mechanical weeding efficiency were determined for the three identified methods of mechanical weeding assistance: inter-row, intra-row and hybrid weeding. The reported results are subject to error because the speed of weeding depends on many factors, including soil type, plant size and soil moisture. In most cases, the sources in the literature provided values for the minimum and maximum speeds, which were assumed to represent the accuracy of the method used. Such an assumption made it possible to homogenise the data that were compared; the weeding methods included in the analysis were averaged.

The authors declare that there are no conflicts of interest that could have an effect on the selection of sources or the interpretation of results.

5. Evaluation Metrics

The article used a systematic search strategy for the sources in the literature. The aim was to find materials containing information on the speed v and performance p of mechanical weeding using mechatronic control systems and to classify them into the categories listed. On this basis, the rates of increase in the weeding efficiency due to the use of mechatronic control systems were determined.

Weeding accuracy p is understood as the space in which the tools do not penetrate the soil—this is the protective distance from the centre of the plant (Figure 4). The article used a systematic search strategy for the sources in the literature.

The speed v and weeding precision p are the main parameters that directly influence productivity. The width of the machine depends on the number of duplicated weeding sections and the power of the tractor combined with it or the power of the autonomous robot. The authors therefore decided not to include it in the analyses, as it is a subjective parameter that is irrelevant to the weed control methods analysed. Weeders are usually available in many different widths, which are often determined by the number of seeding sections used.

The main aim and objective of this article was to determine the coefficients of increase in the efficiency of mechanical weeding through the use of mechatronic control systems. This was evaluated on the basis of the following metrics:

- *Conventional weeding*—a conventional weeding method for the intra-row and inter-row categories. It is a general mechanical weeding method that is not equipped with automatic control systems, plant detection sensors, vision systems and actuators to make automatic lateral corrections or to automatically move the weeding tools between plants in the rows.

- *Weeding with assist*—mechanical weeding methods equipped with plant detection systems and automatic guidance of the weeding tools in a way that reduces crop damage and/or increases the speed of the weeding process.
- *Improvement index = weeding with assistance/conventional weeding.*
- v—the arithmetic mean of the weeding speeds of the selected sample for each category.
- p—the arithmetic mean of the weeding accuracy of the selected sample for each category.
- s—standard deviation.
- c_v—coefficient of variation = standard deviation/arithmetic mean *100.

These evaluation metrics, especially the averaging of different weeding methods, are subject to error due to the wide variety of data analysed. However, the indicators obtained are very useful from the point of view of providing guidelines for new weed control methods, for all kinds of economic analyses, for precision farming systems and for Agriculture 4.0.

6. Results—Weeding Efficiency Increase Indicators

The proposed division of weeding support methods was supported by examples of commercial machines that meet the criteria and characteristics assumed for a given method. The advantages of their functionality are obvious and range from improving user ergonomics to increasing the tractor speed while maintaining an accuracy that is no worse than conventional mechanical weeding. However, it should be considered to what extent these methods improve the work. The aim of this publication was to show the relationship between the use of modern weeding support systems in relation to conventional methods.

Based on the sources from the literature listed in Table 1, it was shown that the use of mechatronic systems to correct the positions of the weeding tools enables an average weeding speed of 10.33 km·h^{-1}. The speed for conventional weeding methods is 6.46 km·h^{-1}. The results were obtained from the analysis of the literature and from the analysis of a sample consisting of 28 items for assisted weeding and 14 items for conventional weeding, respectively. The standard deviations, s, are 5.2 km·h^{-1} and 3.61 km·h^{-1}, respectively. The variation coefficients c_v for the tested weeding speed with an automatic correction is 50.32, which proves the average variability of the parameter. The same coefficient for conventional weeding is 55.93, which proves a large scatter of the analysed values.

Table 1. The effect of using the mechatronic support system for inter-row weeders in terms of parameters: v—averaged speed of the treatment; s—standard deviation; c_v—coefficient of variation.

	$\overline{v}$ (km·h^{-1})	s	c_v	Ref.
Conventional weeding	6.46	3.61	55.93	[16,21,26,40–43]
Weeding with assistance	10.33	5.2	50.32	[10–12,16,20–22,24,39,41–49]
Improvement index	1.6	-	-	-

In the case of methods of supporting intra-row weeding, a significant increase in speed is noticeable compared to the method of manual weeding (Table 2). The speed of conventional (manual) weeding was estimated based on the analysis of a sample consisting of nine elements at 1.1 km·h^{-1}. The automation of the process with the use of specialised control systems enables weeding at an average speed of 2.83 km·h^{-1}, according to an analysis of 29 elements. The standard deviations, s, were 1.58 km·h^{-1} for manual weeding and 2.97 km·h^{-1} for assisted weeding, respectively. The coefficients of variation for the obtained data were, respectively, 143.26 and 105.13, which proves the high variability of the analysed data.

Table 2. The effect of using the mechatronic support system for intra-row weeders in terms of parameters: v—averaged speed of the treatment; s—standard deviation; c_v—coefficient of variation.

	$\overline{v}$ ($\mathbf{km \cdot h^{-1}}$)	s	c_v	**Ref.**
Conventional weeding	1.1	1.58	143.26	[31,40,43]
Weeding with assistance	2.83	2.97	105.13	[13–17,23–25,34,50–53]
Improvement index	2.57	-	-	-

Hybrid methods (Table 3) were compared in relation to conventional intra-row mechanical weeding. The adopted conditions were identical to those in the comparative analysis for mechatronic intra-row weeding support systems because hybrid methods achieve the same weeding results. The conventional weeding speed was estimated at 1.1 km·h^{-1} based on a 9-item test. The hybrid weeding speed was 10.33 km·h^{-1}, which was the same as that for inter-row weeding with assistance. Hybrid systems usually combine a chemical weed control method that is applied only in a small area with mechanical weeding with a vision system.

Table 3. The effect of using hybrid methods for support weed control process—in this case, a combination of using strip spraying and a mechatronic support system for inter-row weeders compared to conventional weeding method in terms of parameters. v—averaged speed of the treatment.

	$\overline{v}$ ($\mathbf{km \cdot h^{-1}}$)	**Remarks**	**Ref.**
Conventional weeding	1.1	Compared to conventional intra-row weeding	[31,40,43]
Weeding with assistance	10.33	Speed like inter-row weeding with assist. It is not fully ecological.	[10–12,16,20–22,24,36,38,39,41–49]
Improvement index	9.39	-	-

The average weeding accuracy p for inter-row weeding with assistance is 39.54 mm, the standard deviation s is 15.73 mm and the coefficient of variation c_v is 39.79, which proves the low variability of the data. The average weeding accuracy p for intra-row weeding with assistance is 46.88 mm, the standard deviation, s, is 17.42 mm and the coefficient of variation, c_v, is 37.17, which proves the strong variability of the data. The results were estimated on the basis of trials of 24 elements for inter-row weeding with assistance and 25 items for intra-row weeders with assistance.

7. Discussion

Based on the sources from the literature listed in Table 1, it has been shown that the use of mechatronic systems to correct the positions of the weeding tools in the rows allows for the speed to be increased by 1.6 times compared to conventional weeding using a mechanical drill hoe aggregated with a tractor. The use of automatic tool correction systems allows one to significantly increase the efficiency of mechanical weeding without the need to engage a second operator. Attention should also be paid to the accuracy of weeding, which, according to the analysis, is, on average, 39.54 mm relative to the centre of the plants (Table 4).

Table 4. Weeding methods precision: p—averaged precision of weeding, i.e., weeding distance from the plant stalk; s—standard deviation; c_v—coefficient of variation.

Weeding Method	$\overline{p}$ (mm)	s	c_v	Ref.
Inter-row weeding with assistance	39.54	15.73	39.79	[11,12,20–22,24,39,41–49]
Intra-row weeding with assistance	46.88	17.42	37.17	[13–16,24,35,50–53]
Hybrid method	The whole field	-	-	[37,42]

In the case of intra-row weeding, thanks to the use of control systems, it is possible to increase the weeding speed by 2.57. This is a significant value considering the increase in efficiency, taking into account the problem of the lack of seasonal workers faced by modern farms. For the comparative analysis of effectiveness, the authors decided to adopt the methods of manual weed removal, because only these methods can obtain an effect that is similar to that obtained with specialised machines. The analysed method showed an average weeding precision of 46.88 mm relative to the centre of the plant stems.

This article adopts a comparative criterion of speed in order to show differences in the effectiveness of the methods themselves. Modern machines equipped with vision systems and active weeding elements can be equipped with many weeding sections, which allows for a significant increase in work efficiency—the standard is weeding 4–6 rows at the same time. In the case of intra-row weeders, the number of weeding sections must be matched to the number of seeder sections—the standard is to use up to 13 weeding sections selected for the type of crop.

The authors decided to compare the hybrid weeding method with conventional manual weeding because they ensure a similar accuracy of weed removal. Hybrid weeding increases the weeding speed by 9.39 times, and it is the only method to provide weed protection across the entire field. A high precision of weed control is only possible at the cost of resigning from complete chemical indifference to the environment. However, these methods are compatible with sustainable agriculture because they significantly reduce the use of herbicides on the field surface.

The dispersion of the results analysed in the tables results from the diversification of the technical capabilities of the producers and the research units that published the results regarding the speed and precision of weeding. There is a noticeable increase in interest in mechanical weeding and automatic control systems based on vision systems. This is related to the continuous development of plant detection algorithms based on artificial intelligence.

The presented results numerically outline the profitability of using individual weeding methods. It is obvious that modern automatic weeding systems are expensive, but the demonstrated efficiency figures based only on speed and precision show their great potential.

8. Conclusions and Future Work

The main goal of this study was to divide the methods of mechanical weeding support based on automatic elements and to demonstrate the impacts of their applications. In this article, it was hypothesised that the use of mechatronic methods of weeding support increases the quality and efficiency of weeding, which was proven by the examples collected during the analysis of the literature and the data presented in the tables. The proposed division of mechatronic weeding support methods is consistent with the current trends in agriculture, i.e., sustainable agriculture, ecological agriculture and the European green deal. The above-mentioned examples of machines are consistent with their postulates, which positively influences the further development of mechanical weeding technology. An increase in the effectiveness of weeding was demonstrated for individual methods on the basis of the selected comparative criteria.

The use of mechatronic weeding support methods causes at least a 1.6 increase in the weeding speed. Each of the described methods is characterised by a different accuracy of weeding. For methods supporting intra-row weeding dedicated to vegetable crops, a 2.57-fold increase in the weeding speed is noticeable, which is the best evidence of the sense of automation and digitisation of agriculture.

Only in the case of hybrid weeding support methods is it possible to achieve the protection of the entire field surface from weeds; however, this comes at the expense of using herbicides and, as a result, not meeting the requirements of organic farming. The development of autonomous agricultural vehicles supports the development of mechanical weeding methods. The necessary condition, however, is the use of selected weeding support methods during the treatments, which are described in the article. It is also worth mentioning the additional benefits of using mechanical methods of crop care. They have a beneficial effect on soil aeration and positively influence the regulation of water management by breaking the pores in the soil, preventing water from escaping and evaporating. Thus, it indirectly counteracts the effects of droughts. Methods are expected to be further developed to increase machine productivity while minimising human involvement in tedious but important field work such as weeding. In particular, an important aspect from the point of view of autonomous field robots and a further direction of development of automatic weeding systems will be to reduce the energy consumption of the process, which will additionally increase its profitability.

The next step should be to relate the results to the specific weeding treatments of selected crops, calculate their productivity in hectares per hour and compare them with conventional methods. The method presented in this article to compare the efficiency of weeding with the listed methods can be developed to include a group of autonomous machines used for weeding in order to assess the efficiency and profitability of farms using these machines.

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References

1. Laurett, R.; Paco, A.; Mainardes, E.W. Measuring sustainable development, its antecedents, barriers and consequences in agriculture: An exploratory factor analysis. *Environ. Dev.* **2021**, *37*, 100583. [CrossRef]
2. Ekielski, A.; Wesołowski, K. *Systemy Agrotroniczne*; Polska Izba Gospodarcza Maszyn i Urządzeń Rolniczych: Torun, Poland, 2019; p. 13, ISBN 978-83-955096-0-5.
3. Kołodziejczak, A. Sustainable development of agriculture in Poland. In *Rozwój Regionalny I Polityka Regionalna*; Adam Mickiewicz University Poznan: Poznan, Poland, 2018; pp. 89–102.
4. Nandwani, D.; Nwososo, S. Global Trends in Organic Agriculture. *Springer Sustain. Dev. Biodivers.* **2016**, *7*, 18–35. [CrossRef]
5. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_pl (accessed on 16 July 2022).
6. Available online: https://www.consilium.europa.eu/pl/policies/from-farm-to-fork/ (accessed on 16 July 2022).

7. Aktar, M.A.; Sengupta, D.; Chowdhury, A. Impact of Pesticides Use in Agriculture: Their Benefits and Hazards. *Interdiscip. Toxicol.* **2009**, *2*, 1–12. [CrossRef]
8. Ustuner, T.; Al Sakran, M.; Almhemed, K. Effect of Herbicides on Living Organisms in The Ecosystem and Available Alternative Control Methods. *Int. J. Sci. Res. Publ.* **2022**, *10*, 633–641.
9. Available online: https://www.theguardian.com/us-news/2022/jul/09/weedkiller-glyphosate-cdc-study-urine-samples (accessed on 5 August 2022).
10. Available online: https://www.steketee.com/producten/ec-weeder/ (accessed on 16 July 2022).
11. Available online: https://www.claas-group.com/press-corporate-communications/press-releases/claas-wins-one-gold-and-four-silver-medals/1335418 (accessed on 16 July 2022).
12. Available online: https://www.kult-kress.de/en/produkte/K.U.L.T.iVision-SV.php (accessed on 16 July 2022).
13. Available online: https://www.robovator.com/ (accessed on 16 July 2022).
14. Available online: https://garford.com/products/robocrop-inrow-weeder/ (accessed on 16 July 2022).
15. Quan, L.; Jiang, W.; Li, H.; Li, H.; Wang, Q.; Chen, L. Intelligent intra-row robotic weeding system combining deep learning technology with a targeted weeding mode. *Biosyst. Eng.* **2022**, *216*, 13–31. [CrossRef]
16. Bruciene, I.; Buragiene, S.; Šarauskis, E. Weeding Effectiveness and Changes in Soil Physical Properties Using Inter-Row Hoeing and a Robot. *Agronomy* **2022**, *12*, 1514. [CrossRef]
17. Su, D.; Qiao, Y.; Kong, H.; Sukkarieh, S. Real time detection of inter-row ryegrass in wheat farms using deep learning. *Biosyst. Eng.* **2021**, *204*, 198–211. [CrossRef]
18. Pallottino, F.; Menesatti, P.; Figorilli, S.; Antonucci, F.; Tomasone, R.; Colantoni, A.; Costa, C. Machine Vision Retrofit System for Mechanical Weed Control in Precision Agriculture Applications. *Sustainability* **2018**, *10*, 2209. [CrossRef]
19. Zawada, M.; Legutko, S.; Szczepaniak, J.; Rogacki, R.; Wojciechowski, J.; Szymczyk, S. Possibilities of using automatic systems for correcting the position of working units of tools including soil cultivation. *MATEC Web Conf.* **2021**, *343*, 08010. [CrossRef]
20. Saile, M.; Spaeth, M.; Gerhards, R. Evaluating Sensor-Based Mechanical Weeding Combined with Pre- and Post-Emergence Herbicides for Integrated Weed Management in Cereals. *Agronomy* **2022**, *12*, 1465. [CrossRef]
21. Kunz, C.; Weber, J.F.; Gerhards, R. Benefits of Precision Farming Technologies for Mechanical Weed Control in Soybean and Sugar Beet—Comparison of Precision Hoeing with Conventional Mechanical Weed Control. *Agronomy* **2015**, *5*, 130–142. [CrossRef]
22. Jiao, J.K.; Wang, Z.M.; Luo, H.W.; Chen, G.L.; Liu, H.L.; Guan, J.J.; Hu, L.; Zang, Y. Development of a mechanical weeder and experiment on the growth, yield and quality of rice. *Int. J. Agric. Biol. Eng.* **2022**, *15*, 92–99. [CrossRef]
23. Perez-Ruiz, M.; Slaughter, D.C.; Fathallah, F.A.; Gliever, C.J.; Miller, B.J. Co-robotic intra-row weed control system. *Biosyst. Eng.* **2014**, *126*, 45–55. [CrossRef]
24. Melander, B.; McCollough, M.R. *Advances in Mechanical Weed Control Technologies*; Burleigh Dodds Science Publishing: Cambridge, UK, 2021. [CrossRef]
25. Wang, M.; Leal-Naranjo, J.-A.; Ceccarelli, M.; Blackmore, S. A Novel Two-Degree-of-Freedom Gimbal for Dynamic Laser Weeding: Design, Analysis, and Experimentation. *IEEE/ASME Trans. Mechatron.* **2022**, *27*, 5016–5026. [CrossRef]
26. Bowman, G. Steel in the Field A Farmer's Guide to Weed Management Tools. *Sustain. Agric. Netw.* **2002**, *2*, 19–20.
27. Available online: https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/integrated-pest-management-ipm_en (accessed on 18 June 2023).
28. Monteiro, A.; Santos, S. Sustainable Approach to Weed Management: The Role of Precision Weed Management. *Agronomy* **2022**, *12*, 118. [CrossRef]
29. Available online: https://www.businesswire.com/news/home/20190501005406/en/Agricultural-Robot-Shipments-to-Reach-727000-Units-Annually-by-2025-According-to-Tractica (accessed on 16 July 2022).
30. Naruhn, G.P.; Peteinatos, G.G.; Butz, A.F.; Möller, K.; Gerhards, R. Efficacy of Various Mechanical Weeding Methods—Single and in Combination—In Terms of Different Field Conditions and Weed Densities. *Agronomy* **2021**, *11*, 2084. [CrossRef]
31. Narwariya, B.S.; Tiwari, K.B.; Shrivastava, P. Performance evaluation of different manual operated weeding equipment for Paddy crop in vertisols. *Eco. Environ. Cons.* **2016**, *22*, 357–363.
32. Tipples, R.; Morriss, S. The Farm Labour Crisis—A Problem for the New Millennium? In Proceedings of the Conference of the Association of Industrial Relations Academics of Australia and New Zealand, Queenstown, New Zealand, 6–8 February 2002; pp. 257–266.
33. Gu, D.; Andreev, K.; Dupre, M.E. Major Trends in Population Growth Around the World. *China CDC Wkly.* **2021**, *3*, 604–613. [CrossRef]
34. Rueda-Ayala, V.; Gerhards, R.; Rasmussen, J. Mechanical Weed Control. In *Precision Crop Protection—The Challenge and Use of Heterogeneity*; Springer: Berlin/Heidelberg, Germany, 2018; Volume 17. [CrossRef]
35. Available online: https://www.steketee.com/producten/ic-weeder-2/ (accessed on 16 July 2022).
36. Available online: https://lemken.com/en-en/news/agriculture-news/detail/steketee-sprayhub (accessed on 16 July 2022).
37. Loddo, D.; Scarabel, L.; Sattin, M.; Pederzoli, A.; Morsiani, C.; Canestrale, R.; Tommasini, M.G. Combination of Herbicide Band Application and Inter-Row Cultivation Provides Sustainable Weed Control in Maize. *Agronomy* **2020**, *10*, 20. [CrossRef]
38. Available online: https://amazone.pl/pl-pl/agritechnica/neuheiten-details/schmotzer-venterra-2k-hoes-979096 (accessed on 16 July 2022).
39. Available online: https://www.farmer.pl/technika-rolnicza/maszyny-rolnicze/oprysk-podczas-pielenia (accessed on 16 July 2022).

40. Lorencowicz, E. *Poradnik Użytkownika Techniki Rolniczej w Tabelach*; Agencja Promocji Rolnictwa i Agrobiznesu: Bydgoszcz, Poland, 2002; Volume 67, p. 43. ISBN 83-914532-2-7.
41. Wiltshire, J.; Tillett, N.; Hague, T. Agronomic evaluation of precise mechanical hoeing and chemical weed control in sugar beet. *Weed Res.* **2003**, *43*, 236–244. [CrossRef]
42. Kunz, C.; Weber, J.F.; Peteinatos, G.G.; Sökefeld, M.; Gerhards, R. Camera steered mechanical weed control in sugar beet, maize and soybean. *Precis. Agric.* **2018**, *19*, 708–720. [CrossRef]
43. Peruzzi, A.; Martelloni, L.; Frasconi, C.; Fontanelli, M.; Pirchio, M.; Raffaelli, M. Machines for non-chemical intra-row weed control in narrow and wide-row crops: A review. *J. Agric. Eng.* **2017**, *48*, 57–70. [CrossRef]
44. Available online: https://www.horsch.com (accessed on 18 June 2023).
45. Home, M.; Tillett, N.; Hague, T.; Godwin, R. An experimental study of lateral positional accuracy achieved during inter-row cultivation. In Proceedings of the 5th EWRS Workshop on Physical Weed Control, Pisa, Italy, 11–13 March 2002; pp. 101–110.
46. Tillett, N.D.; Hague, T.; Miles, S.J. Inter-row vision guidance for mechanical weed control in sugar beet. *Comput. Electron. Agric.* **2002**, *33*, 163–177. [CrossRef]
47. Griepentrog, H.W.; Noerremark, M.; Nielsen, J.; Ibarra, J.S. Autonomous Inter-Row Hoeing using GPS-based side-shift control. *Agric. Eng. Int. CIGR J.* **2007**, *IX*, Manuscript ATOE 07 005.
48. Åstrand, B.; Baerveldt, A.J. An Agricultural Mobile Robot with Vision-Based Perception for Mechanical Weed Control. *Auton. Robot.* **2002**, *13*, 21–35. Available online: https://link.springer.com/article/10.1023/A:1015674004201 (accessed on 27 September 2023). [CrossRef]
49. Gerhards, R.; Andújar Sanchez, D.; Hamouz, P.; Peteinatos, G.G.; Christensen, S.; Fernandez-Quintanilla, C. Advances in site-specific weed management in agriculture—A review. *Weed Res.* **2022**, *62*, 123–133. [CrossRef]
50. Gobor, Z.; Schulze Lammers, P.; Martinov, M. Development of a mechatronic intra-row weeding system with rotational hoeing tools: Theoretical approach and simulation. *Comput. Electron. Agric.* **2013**, *98*, 166–174. [CrossRef]
51. Nørremark, M.; Griepentrog, H.W.; Nielsen, J.; Søgaard, H.T. Evaluation of an autonomous GPS-based system for intra-row weed control by assessing the tilled area. *Precis. Agric.* **2012**, *13*, 149–162. [CrossRef]
52. Nørremark, M.; Griepentrog, H.W.; Nielsen, J.; Søgaard, H.T. The development and assessment of the accuracy of an autonomous GPS-based system for intra-row mechanical weed control in row crops. *Biosyst. Eng.* **2008**, *101*, 396–410. [CrossRef]
53. Li, N.; Zhang, C.L.; Chen, Z.W.; Ma, Z.H.; Sun, Z.; Yuan, T.; Li, W.; Zhang, J. Crop positioning for robotic intra-row weeding based on machine vision. *Int. J. Agric. Biol. Eng.* **2015**, *8*, 20–29.