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A short review of the environmental impact of automated weed control

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Abstract. Agricultural food production is in constant struggle to meet the market demands. Weed control is used to increase the per land unit production from agricultural field. The process of weed removal is usually performed manually and is a time-consuming and labor demanding task. Since mechanical removal is a difficult process, the plantations use herbicides to remove unwanted plants. Herbicides are applied in large quantities, thus often have a degenerative effect on the land. Sometimes, they even endanger the health of the workers who apply them and the end users which consume the harvested product. We review the technologies used for automated weed control and its environmental impact, specifically on the pollution reduction. We also review the herbicides reduction reported in implemented and tested approaches for precision agriculture with emphasis on the weed control environmental impact. Based on the reviewed papers, we conclude that automated weed detection can identify unwanted plants with decent accuracy. Consequently, this can facilitate building autonomous spraying systems that can significantly reduce the quantity of applied herbicides by precisely applying the chemicals only on the plants or mechanically removing unwanted plants. We also review the challenges that need to be overcome, such as precise weed plant type detection, speed of the process and some security considerations that arise from the involvement of information and communication technologies.

Keywords: weed control · herbicide reduction · clean agriculture · pollution reduction

1 Introduction

The agricultural production has an upward trend owing to the increased area of the land used for production and due to the mechanized land and plant processing. Nevertheless, this trend is insufficient and according to [31], it will not be able to reach the demand in the future. One of the most effective way to increase the per land unit production is to introduce automation. The introduction of automated robots in agriculture could increase the food production [9].

The main advantage of the introduction of automation is the increased precision where the land is no longer treated as a whole, but individual small parts of the land are treated differently based on their specific needs.

According to [29] “Precision agriculture is the management of an agricultural crop at a spatial scale smaller than the individual field”. Such management of the fields is a time consuming task when performed by workers, so an automated approach is needed to overcame this challenge. The introduction of precision agriculture arises some problems that need to be addressed, but on the long run, it can provide an increased production per land unit and in the same time, can reduce the cost of managing the land by reducing the amount of minerals, herbicides, pesticides and other resources that are essential for the production.

Weed control is one of the processes that can be considered as part of the precision agriculture. It is a process of removing unwanted plants from the land mechanically by manual removal, chemically by using herbicides, or by other alternative means. When used on the full fields, herbicides are needed in large amounts and have negative effect of polluting the land because they affect the wanted plants, as well. Besides the obvious land pollution from using herbicides, [23] shows that there is evident pollution in surface and ground waters too, which makes the problem of herbicide pollution even greater. The economic benefits of using precision agriculture is recognized in [7] by analyzing the specific sites for particular weed plants and applying appropriate herbicides. Other parameters, such as humidity, temperature, light etc. are also important. Several systems for precision agriculture monitoring, such as [40], have been proposed. Our main focus, however, is on the weed control, weed monitoring and herbicide reduction.

In this paper we review several state-of-the-art approaches in sensing technologies and actuators used for weed control. We also discuss the benefits of using precision agriculture for both the environment and the financial benefits for the farmers in terms of decreased expenses and increased yield from the farms. While the positive effects are well recognized in the literature, there are still many challenges that need to be addressed for applying precision agriculture for weed control in agricultural fields.

The paper is organized as follows: in section 2 we describe the research methodologies of existing approaches reviewed in this paper. Next, in section 3 we analyzed the related works from the impact on the environment point of view. We also examine some of the novel sensing technologies that are essential for the weed detection process. In the end, we discuss the benefits of using the proposed approaches and sensing technologies in section 4 we conclude the paper.

2 Review methodology

To provide thorough overview of the existing approaches for precision agriculture in the process of weed control, we selected papers with the search words: “precision agriculture”, “herbicide reduction”, and “weed control”. We selected papers published after 2007 (i.e. the last 10 years). The search results in December 2016 showed a total of 2848 papers on which we performed quantitative analysis. From those papers, we selected 48 papers based on their relevance that we analyzed qualitatively in more detail.

The distribution of search results for papers per year from Google Scholar, using the same search words is shown in Fig. 1. Obviously, there is an increasing trend in publishing papers concerning precision agriculture for weed control.

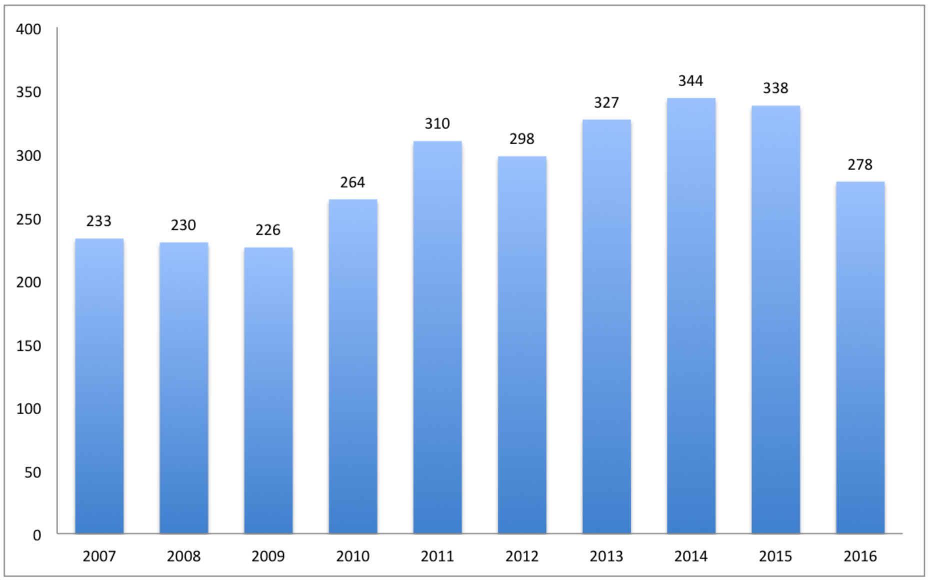

Fig. 1. Search result distribution per year of the terms: "precision agriculture", "herbicide reduction", and "weed control"

After the selection of papers, we organized them in groups that cover several aspects of weed control:

(i) Papers that explicitly report analysis of the herbicide usage reduction and of the percentage of weeds reduced by the proposed approach.
(ii) Papers that report results from using specific actuators that reduce the pollution with herbicides.
(ii) Papers that review the most important advancements of sensing technologies for application in systems for precise weed detection.
(iv) Papers that review the challenges for adoption and application of new technologies.

The organization of the reviewed papers includes the main challenges of the automated weed detection and removal. The main motivation for adopting any new technology in any production field is the cost reduction and yield increase. The quantification of these measurements is very important and in the first group we include papers that quantify the estimated weed reduction and the estimated herbicide reduction. We consider these factors as a very important motivation for further adoption of any reported approach for automated weed reduction, especially in the production phase or marketing phase of a weed control system.

The two most important things for weed control when using an automated approach are:

(i) Sensing technologies for weed detection
(ii) Actuators for mechanical or chemical weed treatment

The sensing technology for automated weed control is a challenge that is being intensively tackled by the scientific community. Therefore, we give a brief overview of the existing approaches. A common pattern can be observed when describing weed detection approaches where most authors use a combination of vision sensors and multi-spectral vision sensors and machine learning to solve the problem of weed detection. The actuators are commonly divided in two groups: actuators for mechanical removal and sprayers. Some of the available actuators use traditional mechanical control while others incorporate the so-called 'smart' trend, where some more complex sensing technologies are included in the control loop. As any modern technology, automated weed control needs to be adopted in the farm production process, which is a considerable obstacle. We include several papers that aim to describe and propose solutions of the existing challenges. While future challenges are hard to predict, we can to certain degree, anticipate some of the challenges based on the way older technologies have been introduced and adopted by the agricultural industry.

3 Overview of weed control approaches

Automation in the weed control process has received increased attention by the scientific community and is already being used in the agricultural industry [38]. According to [16], there is a large number of papers describing weed population mathematical models. The authors conclude that most of the prototype applications were directed towards the process of decision making in weed management. It is an important process for efficient weed removal that can reduce the costs for weed control and increase the net profit per land unit. By reducing the usage of herbicides, the production of crops becomes cleaner and healthier. There are plenty of weed control approaches described in the literature and there are also some commercially available systems that can be used for weed control. Some of them specify novel actuators that mechanically target weeds, and other consider novel sensing technologies that allow detection and measurement of weed infestation. In this paper we review several such approaches. One of the most important benefit of precise weed control is the reduction of herbicides and thus the reduction of pollution. We also review some of the currently published results that report specific percentage of herbicide reduction. Finally, we highlight some of the challenges that arise from the adaptation of the new technologies, especially in the small and mid-sized organic farms.

3.1 Herbicide reduction analysis

Herbicide reduction is one of the main benefits of precision agriculture. There are even approaches that aim to detect and eliminate the weed in real time. According to [32], there are both economic and ecological reasons to perform site-specific weed management.

Authors in [17] report that the precise application of the herbicides on the plants is an effective way to reduce the unwanted plants, while using only 22% of the quantity needed when applying the herbicide on the full field.

Another study presented in [11], used sensor controlled herbicide sprayers to reduce the amount of herbicides used in the fields. The described method was tested on 13 fields and the analysis of the results discovered average herbicide savings of 24.6% without yield reduction from the fields.

Authors in [42] describe an experimental automated robotic system that used micro-dosage system to spray small amounts of herbicide on detected weeds. The weeds were detected using computer vision approach and the vehicle navigated autonomously trough the field. Reduction of the recommended herbicide usage by two orders of magnitude by using the proposed system can be achieved, according to the experimental results.

In [19] authors compare site specific and uniform distribution of herbicides. They measured 69.5% herbicide savings in the site specific application compared to the uniform distribution of herbicides.

The approach presented in [6] used multi-spectral imagery of fields to discriminate weed in cruciferous field patches. Authors applied machine learning methods and color indexes to discriminate patches that contained significant amounts of weed from other patches. Using the best models on weed maps of the field, resulted in herbicide savings from 71.7% to 95.4% for the no-treatment areas and from 4.3% to 12% for the low-dose herbicide.

In [22] authors evaluated the automated boom section control on agricultural sprayers. They assessed the application inaccuracy for 21 study fields and detected a reduction of over-application from 12.4% to 6.2%. Further, they analyzed manual boom section control, which comparing to the automated approach increases the over-application.

Precision Experimental Design is proposed in [13] to model the yield loss based on the competition between weeds and crops in fields. By using precision agriculture methods for mapping the different kinds of weed species in the fields, authors were able to derive a model for yield loss based on different kinds of weed and different combinations of weeds due to the heterogeneous placement of the weed species in the field patches.

A micro sprayer system for guided sprayers using sensing technologies to discriminate weed from crops and to sprays only the weeds is evaluated in [25]. The system was tested in laboratory conditions and authors report up to 94% limited growth of the weeds found in the crops fields.

The study presented in [5] analyses the potential of using images from Unmanned Aerial Vehicles (UAVs) to support patch herbicide spraying in maize crops. Authors found significant reduction of herbicide usage without significantly reducing the crop yield. Savings in herbicide were between 14% and 39.2% compared to broadcast spraying, yielding savings between 16 and 45 euro per ha.

In [8] authors studied the problem of integration between UAVs and automated ground vehicles for weed detection and removal. They found that such systems have the potential of reducing the herbicide usage significantly and in worst case, this can leave less than 40% of weed untreated.

A system for weed sensing and herbicide spraying based on real time cameras is compared to the conventional broadcast spraying in [10]. The experiment was conducted in a period of four years and herbicide savings between 30% and 43% were detected without finding any significant difference in yield.

A machine vision algorithm was applied in [2] to select patches of cereals fields that need to be sprayed in winter and spring. The approach used relative weed cover and relative mayweed cover metrics from the Weedcer algorithm to estimate the spraying decisions. Authors reported savings of 22% to 97% in different trials.

An autonomous systems for precise spraying is described in [39], listing the main features of such robot. The results of the field tests demonstrated that it is accurate enough to accomplish treatment of over 99.5% of the detected weeds, thus significantly reducing herbicide usage.

In Table 1 we provide an overview of the reviewed papers related to herbicide reduction and impact on yield quantity:

Table 1. Reported Herbicide Reduction per study

Reference	Herbicide Reduction	Yield quantity impact
[17]	88%	insignificant
[11]	24.6%	insignificant
[42]	Two orders of magnitude	insignificant
[19]	69.5%	insignificant
[6]	71.7% to 95.4%	insignificant
[5]	14% to 39.2%	insignificant
[2]	22% to 97%	insignificant

All of the reviewed studies suggest that by applying precise approaches there is significant reduction in herbicide usage and there are no reported disadvantages in regards to the yield quantity from the fields. Application of precision agriculture approaches reduces the pollution of the plants and of the land, thus creating environment of cleaner agricultural food production. Lowering herbicide usage and reduction of weed are the main motivations for investments in the field of automated weed control. However, novel sensing technologies are required to achieve a precise detection of weeds in the fields.

Next, we review some of the sensing approaches that are available in the literature.

3.2 Novel sensing technologies

One of the main challenges in precise weed control is the process of weed detection. Plenty of approaches were adapted for weed sensing and many of them use machine learning to build models of the plants and to discriminate between crops and weeds.

Techniques based on computer vision can be used for weed mapping in the fields [36]. They could speed up the process of weed detection and this information can be used for site specific weed control measures.

The spatial pattern of weeds based on multi-species infestation maps from images was studied in [20]. Authors found out that it is not always possible to detect an aggregated spatial pattern in weed infestation in maize fields, and concluded that there is a need of techniques for assessment of weed aggregation prior to conducting site-specific weed management.

In [44] a vision-based method for detecting specific weed Avena sterilis in cereal crops is described. The method used image segmentation and decision making to select cells in the field that needed to be sprayed. The goal was to reduce the quantity of applied herbicides for effective weed removal from the fields.

Significant improvements in precision agriculture sensing technologies that allow significant improvements in the methods used for soil and plant treatment were analyzed in [26]. New sensing technologies which use spectral imaging with high spatial accuracy and allow continuous recording of data are becoming available. They can be utilized for near real time decision making in precision agriculture.

An approach for mapping the fields using UAVs with multispectral camera in visible and near infrared range is described in [28]. The mapping process generated a weed infestation map and the average reported accuracy is 86%. Authors in [4] described a system for weed, crop and soil percentage evaluation in images under different light and weather conditions. Their system allowed choosing of the best method for evaluation based on the images. The different color indexes were evaluated in [24] for plant biomass identification from images.

In [33] authors described an approach for small-grain weed species discrimination with special regard to two types of weed: Cirsium arvense and Galium aparine. Feature ranking algorithms were applied for selection of the most informative features and three different Support Vector Machines (SVM) models were used for classification. The authors concluded that it is feasible to use image processing and classification to detect and map weeds in the field.

The accuracy of ground placed optoelectronic sensors for weed detection is evaluated in [1]. Authors compared the that data with data obtained from image processing and concluded that optoelectronic sensors could be used for inter-row weed detection and for building a cheap system for generation of maps of inter-row weeds. Machine learning approaches for weed identification from images were examined in [45]. Support Vector Machines were compared with other approaches and the results of the identification were evaluated. One of the most important tasks for specific plant targeting systems is the segmentation of the plant species. In [15] an overview of image processing techniques for plant species segmentation from images is provided.

The study presented in [47] describes the usage of UAV for mapping of weed patches using multi-spectral camera from different altitudes in Sunflower crops. Different color indexes for their ability to discriminate between plants, weed and bare soil from images recorded at different altitudes were compared. Authors conclude that it is possible to define a flight plan and a configuration to obtain optimal results in terms of weed-plant discrimination with desired spatial resolution.

Any sensing technology available should offer high enough precision to be useful in practical implementations. According to the results presented in [14], UAVs flying at altitudes of 30m to 100m could provide very high spatial resolution ortho-images with geo-referencing accuracy. This is required for mapping small weeds in wheat fields at very early phenological stage, which is also important for the process of early site-speciic weed management.

Another hyper-spectral sensing approach was examined in [41]. Hyper-spectral sensing to detect the damages from herbicide drift on cotton growth was examined. It was concluded that hyper-spectral sensing is a good non-destructive alternative for yield prediction after simulated herbicide drift.

To overcome the differences in different fields, authors in [49] propose a self-supervised training for unsupervised learning of weed appearance model for hyper-spectral crop/weed discrimination with prior knowledge of the seeding patterns only. Authors use unmanned ground vehicles for the image acquisition and for the experiments.

Deep Convolutional Networks are a very powerful and trending method for machine learning and pattern recognition. They were employed for crop/weed discrimination in [30] based on images from multispectral camera mounted on a ground vehicle. The reported accuracy for pixel-wise classification is 97.4% and blob-wise classification is up to 98.7%. These results show that the usage of deep learning approaches could be applied for crop/weed discrimination.

Based on the analyzed studies, in 2 we list the main characteristics of some of the proposed sensing technologies, such as accuracy, specific weed type targeting and false positive rate, where they are applicable and available. Other reviewed papers take into consideration other important issues in sensing, such as geo-spatial detection of plants, plant/soil segmentation, etc.

Table 2. Characteristics of proposed sensing approaches

Reference	Reported max accuracy	False positives	Specific weeds	Multiple weeds
[44]	92%	Not reported, calculated	Yes	No
[28]	86%	Calculated, reported	No	Yes
[33]	97.74%	Calculated, reported	Yes	Yes
[1]	83%	Calculated, reported	No	Yes
[30]	98.7%	Not reported, calculated	No	Yes

All of the reviewed approaches use machine vision and machine learning for automated weed detection. The usage of UAVs is becoming a necessity for initial land mapping and information gathering. When using UAVs it is important to be able to detect the weed infestation and objectively assessing it without underestimating the weed infestation in the observed regions. This factor should be reported when performing an experiment with UAVs sensing approaches.

Some approaches used automated land vehicles to directly detect and remove weed on site. All of the above mentioned approaches have certain precision reported, even though not all of the approaches report the false positive weed detection rate, where a useful plant is incorrectly recognized as weed. This rate is a must when designing a fully automated weed removal system, especially because it would be mechanically or chemically target specific plants directly. This is a particularly important problem in the early growth phases of the young seedlings. Authors must address this in future weed detection approaches. Another important characteristic, especially for patch spraying based weed detection systems, is the understatement of the weed quantity.

Another challenge is the plant species detection for even more precise treatment. While distinguishing the useful plant from the weed is a challenge by itself, recognizing the plant species is even more difficult. The reason for that is because the two class classification problem becomes a multi-class classification problem. Very few approaches exist that can detect a specific weed type directly for direct plant treatment and specific plant type recognition. To perform this at different stages of growth is a very challenging task that will need to be addressed in the future. A fully automated weed control system would also need an adaptive learning capability where the system would be able to adapt to different circumstances during the detection process. Such system would need to be capable of on-line learning, as well.

3.3 Actuators that allow specific weed targeting

Several studies discuss new technologies that allow specific weed targeting using mechanical limitations of the sprayers and mechanical actuators that remove the weeds on site. One such example is presented in [12], where specialized hardware was used to limit the spraying of herbicides only in between rows, which in turn reduces the plant pollution with herbicides.

The most widely used and state of the art mechanical weeders with mechanical tools to exterminate weed in between rows of seedlings are described in [48]. According to that study, there is a variety of available commercial machines that can be used for mechanical weeding, however their speed and usefulness is limited compared to than machines that use herbicides. Additionally, they require a favorable land and cannot work on stony or thick lands due to limitations of the tools. The need for improvement of low cost vision sensors in order to make weeding systems more robust is also highlighted.

Another study presented in [46] used computer controlled hydraulic disks to eliminate weed between the plants in the plant rows. The described approach used machine vision and special kind of disks that allow the weed around the crops to be reduced by 62%-87% with minimal damage to the crops. It achieved higher speed than manual weed removal, but it still achieves lower speed than the commercial standards.

While being a potential cheaper alternative, mechanical weed removal has several drawbacks, especially when considering the irregularities of the land and the demand of strict plant seedling placement to allow the usage of such approaches.

All of the above-mentioned technological advancements are already present and some of them are in pre-production phase or even available on the market. According to [3], several robotic systems exist that are already in pre-production phase and that the market demand for agricultural robots is growing. Most of the technological challenges have already been resolved, however there are still some security and other types of challenges that need to be assessed, before the robots are placed on the market.

One such challenge is the application of actuators for mechanical treatment of plants that use active moving parts. These moving parts need to have embedded safety mechanisms that could protect unwanted damages and hazards. The automated system should be able to detect the presence of a living being and stop. Because the automated system will probably be connected to a computer network for additional data acquisition, the problem of network security should also be addressed properly. Any device connected to a network is potentially exposed to external attacks that could use the device for malicious purposes. So far, these issues have not been adequately studied by the scientific communities.

3.4 Challenges in new technology adoption

While in bigger corporate farms, new technologies are quickly adopted, mid-sized and small-sized organic farms usually have difficulties adopting new technologies and trends. The problems of using high-end technologies for weed detection in fields are recognized and discussed in [21]. This study identifies: that there is a need of education of farmers about the new technologies; that the technologies used are still too expensive; and recognizes the need for accurate weed maps and the use of robots for weeding, which is still a challenge. According to this study, the solution lies in education of farmers, high quality UAV maps, investments in weed robots that would commercialize the existing prototypes, lowering the technology costs by introducing cheaper approaches and standards and the need of multidisciplinary teams that would work on the problem.

According to [37], due to the rapid development in robotics, nanotechnologies, molecular biology and information technologies, it is very hard to predict the future of weed control technologies. There are very dynamic changes in all research areas and also in the field conditions which are influenced by many man-caused and natural factors such as climate change and herbicide resistance. In such dynamic environment, agricultural production and technology must adopt at a very fast pace.

The study presented in [43] reviews the diversity in weed management used in organic farms in northwest United States. The influence of several factors on the diversity of applied weed management techniques were analyzed. They authors determined that the probability of diverse techniques applied for weed controls increases with the education level of the farmers, the awareness of the farmers that weed presence decreases yield, the size of the organic fields, etc. To better assess the problem of weed control in farms, researchers must bear in mind the diverse requirements of farmers.

The challenges of applying precision agriculture on grass lands is discussed in [34]. While the economic impact of such endeavor remains uncertain, the authors recognize the need for adequate sensing technologies to be able to gather more information from grass lands, which in turn can be used in the process of decision making.

The study [50] presents the results of a simulated study on 16 fields. It also compared site specific weed management with one, two or more herbicides with broadcast application of herbicides. Authors concluded that there is a minor economic benefit of site specific management due to the increased costs for the management of the fields, but the benefit is dependent on the type of fields. They also concluded that identifying the characteristics of the weed population in the fields would be beneficial because specific herbicides can be applied to specific patches.

An analysis of the profitability of the adaptation of precision agriculture technologies is presented in [35]. According to this study, precision agriculture has an impact on the net profit, while also positively influencing the implementation of precision agriculture.

The benefits of usage of herbicides and pesticides for the increase in yield per land unit are reviewed in [18]. They conclude that most of the yield increases are due to the more efficient pest treatments. The study also identifies the implications on both the environment and the human health from increased usage of conventional herbicides and pesticides. They authors describe the new legislation of the European Union for herbicide and pesticide reduction and determine that there is an opportunity to reduce the usage significantly by means of advanced technologies and integrated management.

There are, however, certain challenges that need to be addressed especially from the evident climate changes. Further research is needed to predict the possible conditions under which the crops production would be executed. Authors in [27] discussed the main implications of climate change and proposed a method for developing Life Cycle Assessment scenarios that could deal with the uncertainty introduced by the climate changes.

4 Conclusion

The application of precision agriculture methods in the agricultural food production is evident. All of the reviewed papers show significant reduction in the quantity of herbicides used and they conclude that the application of precision agriculture approaches for weed control has several benefits. The environmental benefit is that the usage of pollutants can be significantly reduced, while the plants collected from the fields sustain reduced pollution and are healthier to consume. The weed decreasing is proven to increase the yield per land unit and is the obvious consequence of the weed control. Finally, the economic benefits are reduced costs for chemical or mechanical weed removal by applying the adequate amount of effort or quantity of herbicides on specific sites instead of broadcasting approach on the full field.

Site specific applications or even per-plant direct applications introduce additional management costs. New technologies for precise identification of specific weed types, such as image processing systems for plant identification and autonomous robot vehicles for specific plant treatment, can be utilized. They could further lead to savings in applied herbicide quantities and reducing the pollution of the useful crops, which would justify the additional costs. Several challenges still need to be overcome, such as: the price decrease of the sensing technologies and the available mechanization and increase of its effectiveness by increasing the land area per time unit speed of processing.

Based on all of the reviewed papers, a fully automated weed control system is possible within the next decade. Most of the technologies are mature enough to be implemented in a real system. While such system is possible, several challenges still exist that need to be properly addressed. Further improvements are necessary for the weed detection systems and many security risks still exist and need to be resolved.

Overall, we can conclude that the weed control is becoming autonomous and that precision agriculture methods improve the production quality and yield cleaner and healthier products. Farmers must adapt to the changes because even the lawmakers are gaining on the trend to introduce cleaner organic farm production in every aspect of the production process. This is especially valid in the weed control process where the reduction of herbicide usage is essential, and an already set long-term target in the developed countries.

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