Review

The Use of Unmanned Aerial Vehicles (UAVs) for Precision Weed Management in Agriculture: a Comprehensive Overview

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Article Details: Received: 2025-11-27 | Accepted: 2026-03-02 | Available online: 2026-06-30

https://doi.org/10.15414/afz.2026.29.02.227-233

Weed infestation remains a major challenge in modern agriculture, leading to reduced crop yields, increased production costs, and environmental impacts due to excessive herbicide use. Recent advances in unmanned aerial vehicles (UAVs) or drones have enabled site-specific weed control that minimizes chemical inputs while optimizing crop protection. This study summarizes the current state of UAV applications in weed detection, mapping, and targeted herbicide application, with an emphasis on the latest studies from 2020–2025. Various imaging sensors, including RGB, multispectral, and hyperspectral cameras, are discussed in terms of their accuracy, resolution, and operational limitations. Machine learning and deep learning algorithms, particularly convolutional neural networks (CNN) and YOLO models, are increasingly being used for automated weed classification and prescription map generation. Spot spraying using UAVs has shown the potential to reduce herbicide use by 30–50%, improve environmental sustainability, and reduce operating costs. Challenges such as flight stability, battery life, regulatory constraints, and field heterogeneity are also addressed. Finally, the review highlights future directions, including full automation of UAV missions, integration with robotic systems, real-time decision-making using artificial intelligence, and improved multisensory approaches. This synthesis provides a comprehensive reference for researchers, agronomists, and technology developers aiming to advance precision weed management and sustainable agriculture.

Keywords: drones, weed infestation, modern agriculture, herbicide application, spot spraying

1 Introduction

Weeds pose a persistent threat to global crop production, causing estimated yield losses of 20–40% depending on the crop type and environmental conditions (Torres-Sánchez et al., 2015; Bah et al., 2018). Traditional weed control practices rely heavily on mechanical tillage and broad-spectrum herbicide application, which can be labor-intensive, environmentally harmful, and economically inefficient (Haq, 2022). In recent years, unmanned aerial vehicles (UAVs) have become a promising tool for precision agriculture. UAVs, equipped with advanced imaging sensors, enable high-resolution monitoring of crops and weeds, allowing for site-specific interventions that minimize chemical use and increase environmental sustainability (Allmendinger et al., 2024; Kebede et al., 2025). The integration of UAVs with machine learning algorithms for automatic weed detection and prescription map generation has further improved the efficiency and accuracy of herbicide application (Shahi et al., 2023; Ariza-Sentís et al., 2024). The objectives of this review are:

1. To summarize recent advances in weed management using unmanned aerial vehicles (UAVs), focusing on studies from 2020–2025.
2. To discuss various sensor technologies and image analysis methods for weed detection.
3. To evaluate the operational performance, environmental benefits, and limitations of UAV applications.
4. To identify research gaps and suggest future directions for integrating UAVs into sustainable weed management systems.

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1.2 UAV sensors and imaging techniques

Unmanned aerial vehicles (UAVs) in precision agriculture are typically equipped with RGB, multispectral, hyperspectral, and LiDAR sensors (Haq,2022). Each type of sensor offers specific advantages for weed detection:

- RGB cameras are widely used due to their low cost and high spatial resolution. They allow visual differentiation between crops and weeds, especially in the early stages of growth. However, RGB images can be limited in different lighting conditions or dense vegetation (Bah et al., 2018).
- Multispectral sensors capture reflectance in multiple bands beyond visible light, improving weed and crop discrimination using vegetation indices such as NDVI (Normalized Difference Vegetation Index) (Torres-Sánchez et al., 2015; Allmendinger et al., 2024).
- Hyperspectral cameras offer higher spectral resolution, enabling accurate detection of subtle differences in plant physiology. These systems are more expensive and data-intensive, requiring robust image processing (Kebede et al., 2025).
- LiDAR sensors provide 3D structural information about vegetation, which aids in weed detection in heterogeneous fields and estimating plant height and density (Haq, 2022).

Recent studies emphasize sensor fusion, combining RGB, multispectral, and thermal data to improve classification accuracy. Ariza-Sentís et al. (2024) demonstrated that combining multispectral and RGB images increased weed detection accuracy by up to 15% compared to using RGB images alone. In recent years, the availability and accuracy of aerial sensors have increased significantly, which has impacted the entire precision weed management system. In addition to traditional RGB and multispectral sensors, hyperspectral systems with a high number of spectral bands are becoming increasingly popular, as they allow the identification of specific physiological characteristics of weeds, such as changes in pigmentation or water content (Sulaiman et al., 2022). Hyperspectral data provides high accuracy, but at the same time generate large volumes of data that require advanced processing methods (Villon et al., 2023). The current trend is also towards the integration of thermal sensors, which allow the monitoring of temperature differences between plants, which can help in the detection of stressed or invasive weed species (Awais et al., 2023). UAV-LiDAR is also used in some applications, especially where it is necessary to model the height of vegetation and the spatial distribution of weeds in complex polycultures (Haq, 2022).

Modern research points to the benefits of a multisensory fusion approach, i.e., a combination of RGB + multispectral + thermal data, which, when processed together, significantly improve classification accuracy. For example, Zhu et al. (2024) demonstrated that the simultaneous use of RGB and multispectral data increased weed detection accuracy by 17% compared to a single sensor. The same effect was confirmed in cereals, where multisensory models achieved an accuracy of over 95%.

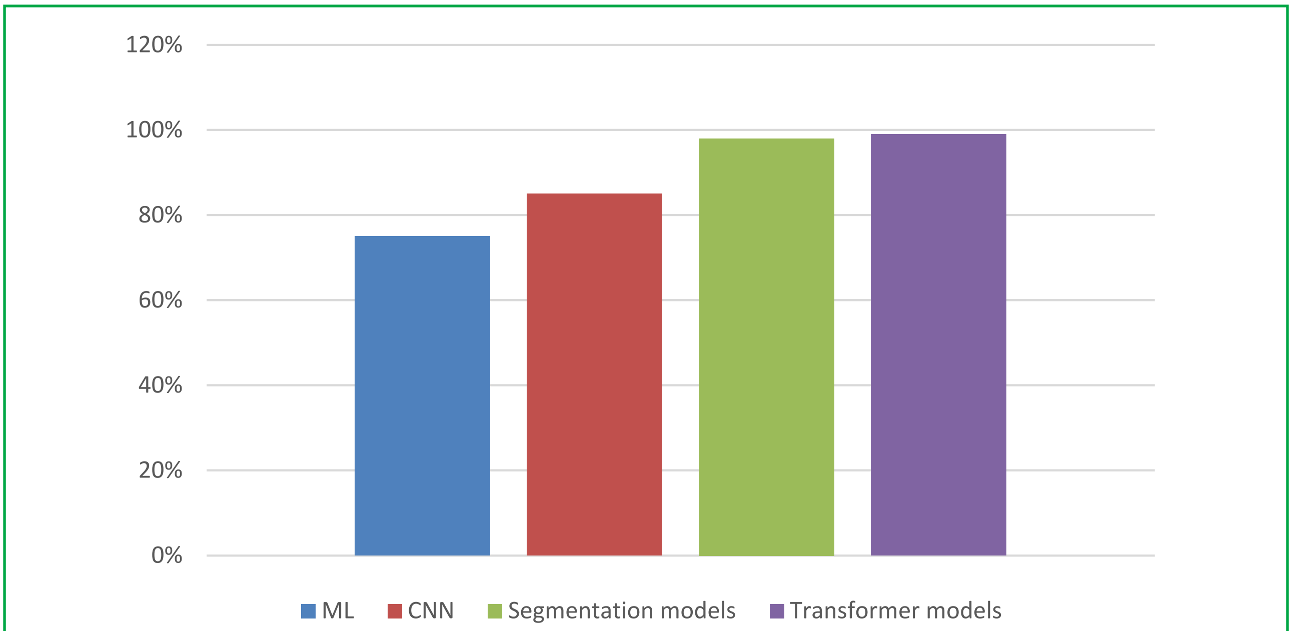

Figure 1 Weed detection accuracy by algorithm category
Source: Shahi et al., 2023; Kebede et al., 2025; Saki et al., 2025; Sandoval-Pillajo et al., 2025

1.3 Algorithms for weed detection and classification

Accurate weed identification is critical for the application of herbicides to specific locations using UAVs. Image analysis techniques have evolved from traditional visual inspection approaches to machine learning (ML) and deep learning (DL) approaches (Shahi et al., 2023; Sandoval-Pillajo et al., 2025).

- Machine learning: Random Forests, Support Vector Machines, and k-Nearest Neighbors have been successfully used to classify weeds based on UAV images (Allmendinger et al., 2024). ML models rely on feature extraction (color, texture, shape) and require manually annotated training datasets.
- Deep learning: Convolutional neural networks (CNNs) and object detection frameworks such as YOLO (You Only Look Once) enable automatic feature learning and real-time detection. Kebede et al. (2025) report > 90% detection accuracy for UAV images of teff fields using CNN.
- Prescription mapping: Weed detection outputs are converted into prescription maps that guide UAV sprayers for spot treatment. Torres-Sánchez et al. (2015) and Haq (2022) demonstrated higher herbicide efficacy when using maps generated by UAVs compared to uniform spraying.

Challenges in algorithm development include class imbalance, where weeds occupy a small portion of the field, and variability in weed appearance depending on growth stage, lighting, and environmental conditions (Shahi et al., 2023; Ariza-Sentís et al., 2024). New solutions include data augmentation, transfer learning, and multi-sensor fusion.

In addition to CNN and YOLO architecture, segmentation models such as U-Net, DeepLabV3+, Mask R-CNN, and Transformer-based models have also become widespread in recent years, providing more accurate delineation of weeds within crops (Saki et al., 2025; Picon et al., 2024). These models are capable of detailed pixel-wise discrimination between weeds and crops, which is essential for creating mapped interventions.

Another trend is the use of transfer learning, which allows models to be trained with fewer annotated images, significantly reducing the time and cost associated with preparing datasets. Research also shows that the use of synthetic data generated using GAN (Generative Adversarial Networks) can increase the robustness of models in real-world conditions (Saki et al., 2025).

State-of-the-art approaches use so-called real-time onboard detection systems, where the algorithm is implemented directly on the UAV and detection takes place during flight. This significantly reduces the time between mapping and intervention and enables immediate targeted spraying. According to Braun et al. (2023), such a system can reduce herbicide consumption by more than 60% compared to traditional broadcast spraying.

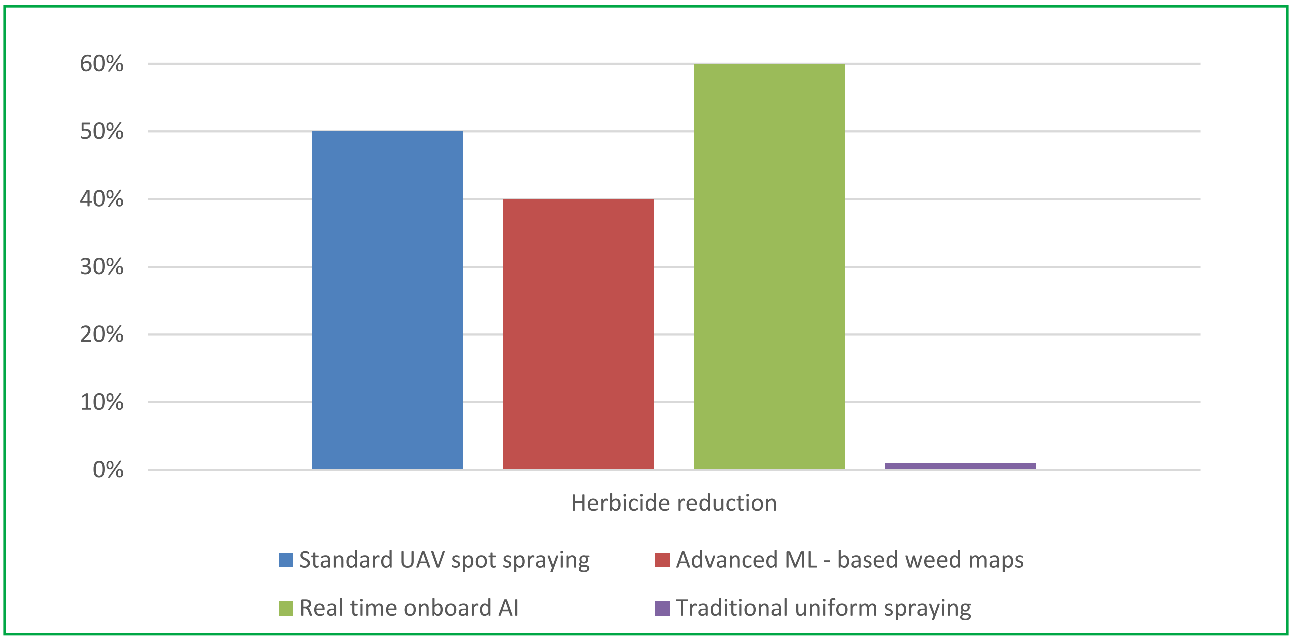

Figure 2 Herbicide reduction across UAV applications methods
Source: Meesaragandla et al., 2024; Kebede et al., 2025; Allmendinger et al., 2024; Braun et al., 2023

1.4 Application of herbicides using UAVs

UAVs facilitate the application of herbicides to specific locations, reducing chemical consumption and environmental impact. Two main strategies are used:

1. Spot spraying: Targeted application of herbicides to identified weed areas. Meesaragandla et al. (2024) report up to a 50% reduction in herbicide consumption in corn and rice fields using spot spraying with UAVs.
2. Variable rate spraying: UAVs can adjust herbicide dosages based on weed density maps, combining uniform coverage with higher efficiency (Allmendinger et al., 2024).

Studies consistently demonstrate economic and environmental benefits:

- Reduced herbicide costs and operating time (Allmendinger et al., 2024; Chen et al., 2021).
- Lower risk of chemical spillage and contamination (Cirillo et al., 2021).
- Increased accuracy on heterogeneous fields and challenging terrain (Kebede et al., 2025; Ariza-Sentís et al., 2024).

However, herbicide applications using UAVs are affected by flight altitude, spray nozzle design, wind, and UAV stability. Optimizing flight paths using TSP (Traveling Salesman Problem) algorithms or coverage planning reduces overlap and ensures even distribution (Plessen, 2025). In addition to spot and variable spraying, other strategies are also being developed, such as ultra-low volume (ULV) spraying, which minimizes the amount of liquid used while maintaining effectiveness. UAV spraying is also used in hard-to-reach areas where ground equipment fails, as demonstrated by studies from rice fields in Southeast Asia (Wongsuk et al., 2024). The precise selection of nozzles and flight parameters is also an important aspect. Chen et al. (2022) reports that turbulence from rotors can improve the penetration of spray droplets into the lower layers of vegetation, but only with precise adjustment of flight altitude and speed. In addition to chemical management, UAVs are also used for bioherbicides, which are more environmentally friendly and require precise dosing. There is also growing interest in physical methods, such as laser or microwave weed termination, which are being tested in combination with UAV visualization (Bratovcic et al., 2025).

1.5 Examples of specific herbicide use

The results of several studies confirm that the application of herbicides using unmanned aerial vehicles (UAVs) is an effective method of weed control, especially when herbicides are applied at the optimal time and in the appropriate dose. In rice, the application of cyhalofop-butyl using a drone 7 days after planting was effective against grass weeds of the genus *Echinochloa* spp. in the early stages of development. The effectiveness of the intervention was monitored using Sentinel-2 satellite images in bands B4 and B8 during the first 27 days after planting, with significant suppression of weed growth (Bautista et al., 2024). In wheat, UAV application proved to be highly effective against weeds such as *Alopecurus japonicus* and *Galium aparine*. The application of herbicides using drones suppressed more than 98% of these weeds, with only 0–2 weeds per 0.5 m^2 recorded on the treated plots. Diflufenican + isoproturon applied using UAVs achieved over 98% efficacy against *Galium aparine* and *Alopecurus japonicus* (Chen et al., 2019). Similarly, the application of fluroxypyr-metyl 20% EC at a dose of 600 ml/ha using a drone led to a significant reduction in weed growth and height (Zhang et al., 2020). Pre-emergence (PE) spraying using UAVs showed 98–100% efficacy, especially in conditions of higher soil moisture. In contrast, post-emergence (PoE) applications achieved only 10–70% efficacy, indicating partial resistance of weeds to post-emergence herbicides (Chen et al., 2019). The combination of PE application of metribuzin at a dose of 0.175 kg a.i./ha (70%) and subsequent PoE application using a drone resulted in the lowest dry weight of both monocotyledonous and dicotyledonous weeds and a control efficacy of 74.82% (Pranaswi et al., 2022). The application of a combination of isoproturon + clodinafop-propargyl + mesosulfuron using a UAV showed comparable efficacy to application with a conventional sprayer. Weed damage reached 68–72% with UAV application at low and high doses, while the sprayer achieved an efficacy of approximately 80% (Hiremath et al., 2024). Diflufenican + isoproturon applied using UAVs reduced the occurrence of *Alopecurus japonicus* by 60% and *Capsella bursa-pastoris* by 50%, while a conventional sprayer achieved higher efficacy. The combination of flufenacet + diflufenican + flurtamone applied using a UAV suppressed 70% of *Alopecurus japonicus* and 80% of shepherd's purse (Chen et al., 2019).

1.6 Technical and operational challenges

Despite promising results, weed management using UAVs faces several challenges:

- Battery life and payload limitations restrict flight time and area coverage (Allmendinger et al., 2024).
- Regulatory restrictions vary by country, affecting UAV operations in agricultural airspace (Shahi et al., 2023).
- Environmental conditions such as wind, rain, and uneven terrain affect flight stability and spraying accuracy (Chen et al., 2022).

- Data processing challenges: High-resolution images and hyperspectral data require significant computational resources (Sandoval-Pillajo et al., 2025).
- Integration with farm management systems: Linking UAV data with crop management software and robotic sprayers remains a challenge.

Addressing these challenges requires robust UAV design, improved batteries, real-time decision-making based on artificial intelligence, and standardized protocols for UAV deployment in fields (Chen et al., 2022). Regulation remains the biggest obstacle to wider use of UAVs in agriculture. The European Union has adopted strict rules for autonomous flights and spraying operations, which may limit the commercial deployment of larger UAVs. Technical limitations, such as battery life and limited payload capacity, are still being researched. Modern hybrid UAVs (combining a battery and combustion engine) significantly extend flight time, but are still financially demanding (Ren et al., 2024). Another challenge remains the data bottleneck – the extremely large data storage required for hyperspectral images. New data compression models, such as PCA reduction or spectral clustering, can reduce data volume by 70–80% without loss of accuracy (Bah et al., 2018).

1.7 Future trends

Future research and technological development will likely focus on:

1. Full automation of UAV missions for weed control, including autonomous flight, detection, and spraying (Nikolić et al., 2025).
2. Advanced sensor integration, combining multispectral, hyperspectral, thermal, and LiDAR sensors to increase detection accuracy (Ariza-Sentís et al., 2024).
3. Real-time artificial intelligence processing on board UAVs for immediate detection and prescription generation (Shahi et al., 2023).
4. Robotics integration, where UAVs work in conjunction with ground robots for comprehensive precision weed management (Chen et al., 2021).
5. Impact on sustainable agriculture, reducing chemical consumption and carbon footprint while maintaining high yields (Meesaragandla et al., 2024).

Overall, UAVs have demonstrated the potential to revolutionize precision agriculture, particularly in weed management, but their widespread adoption will require addressing technical, operational, and regulatory challenges. The future of UAV-based weed management is moving towards systems that combine UAVs, autonomous ground robots, edge-AI processors, and farm-management platforms (Zhu et al., 2024). The combination of multispectral UAVs and robotic rovers can provide continuous crop monitoring with almost zero delay. Another trend is the integration of 5G/6G communications, which will enable real-time big data transmission and cloud processing. Finally, the environmental assessment of UAV interventions is also coming to the fore, as research shows that reducing herbicide load has a demonstrable benefit for soil and water biodiversity (Braun et al., 2023). There is currently no comprehensive, separate legal framework in the European Union specifically for the use of unmanned aerial vehicles for spraying in agriculture.

2 Conclusions

Unmanned aerial vehicles (UAVs) represent a rapidly developing and highly promising technology for precision weed control, offering significant agronomic, economic, and environmental benefits. The reviewed literature clearly demonstrates that UAV-based systems can significantly improve weed detection accuracy and enable site-specific herbicide application, thereby reducing chemical inputs and minimizing negative environmental impacts. The integration of advanced imaging sensors with machine learning and deep learning algorithms has transformed weed management from uniform spraying to targeted, data-driven interventions. Analysis shows that while RGB cameras remain the most affordable option, multispectral and hyperspectral sensors provide better resolution between crops and weeds, especially in heterogeneous field conditions. Sensor fusion approaches combining RGB, multispectral, thermal, and LiDAR data consistently improve classification accuracy, exceeding 95% in some cases, demonstrating the importance of integrating data from multiple sources. From an algorithmic perspective, deep learning models such as CNN, YOLO, and segmentation architecture outperform traditional machine learning methods by enabling automated feature extraction and accurate weed delineation at the pixel level. The development of real-time onboard detection systems represents a critical step toward fully autonomous weed control using UAVs, with reported reductions in herbicide use exceeding 60% compared to conventional spraying. Empirical studies on herbicide application using UAVs confirm that spot spraying and variable rate spraying can significantly reduce herbicide consumption while maintaining or approaching the efficiency of conventional ground sprayers. Specific herbicides, such as cyhalofop-butyl, diflufenican, isoproturon, and fluroxypyr-metyl, have shown high efficacy when applied at optimal growth stages and doses using unmanned aerial vehicles. However, pre-emergence applications generally outperform post-emergence applications, highlighting the importance of precise timing and environmental conditions as well as the higher potential of UAVs for soil herbicide application. Despite these advantages, the widespread adoption of UAV-based weed management is limited by technical constraints, regulatory barriers, and operational challenges, particularly battery life, payload capacity, and restrictive legislation governing the use of UAVs. Overall, UAV-based weed management has the potential to become a cornerstone of sustainable agriculture by reducing chemical consumption, increasing operational efficiency, and promoting environmentally responsible crop systems.

Acknowledgment

The work was supported by the project VEGA 1/0591/25: "Intercrops for improvement of ecosystem services in sustainable agriculture: focus on regenerative soil processes, crop productivity and stress resistance".

Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Conceptualization, Š.T. and M.K.; data curation, M.K. and Š.T.; formal analysis, Š.T. and M.K.; funding acquisition, Š.T. and M.K.; investigation, M.K. and Š.T.; methodology, Š.T. and M.K.; software, Š.T. and M.K.; resources, Š.T. and M.K.; supervision, Š.T. and M.K.; validation, Š.T. and M.K.; visualization, M.K. and Š.T.; writing – original draft, M.K. and Š.T.; writing – review & editing, Š.T. and M.K. All authors have read and agreed to the published version of the manuscript.

AI and AI-Assisted Technologies use Declaration

No generative AI tools/AI-assisted technologies were used during the preparation of the manuscript.

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