



Precision Application and New Spraying Technologies

Literature Review

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Wageningen Plant Research

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Abstract: This review assesses the current evidence base available in the scientific literature regarding the performance of different precision spraying technologies, including sprayer based spot and patch application systems and Uncrewed Aerial Spraying Systems (UASS). While numerous studies demonstrate substantial potential for pesticide use and risk reduction, often with 30-80% use reduction for herbicides and variable reductions for other products, there is limited quantified evidence to confirm associated decreases in operator exposure, environmental contamination, drift, or runoff. Reported efficacy outcomes are also inconsistent across crops and conditions, and comparable economic analyses are limited. For UASS in particular, validated drift and deposition measurements associated with precision spraying technologies and techniques remain scarce. In summary, the scientific literature indicates promising technological potential for risk reduction, but sufficient robust, standardised datasets required to support the regulatory adaptation needed to fully enable risk-based policy shifts remain lacking.

Keywords: spraying technologies, drones, robotics, UAV, UASS, patch, spot, crop protection, IPM.

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Photo cover: spraying drone in action in drift experiment – courtesy of Leks Bolderdijk | ABdrone

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Preface

Society, policy makers, science, and agricultural practitioners expect a lot from new technologies to improve and optimise applications of plant protection products. Modern automated and robotic equipment for patch and spot spraying, as well as the strongly growing potential of drones offer many opportunities to reduce product usage, reduce operator exposure risks and environmental risks, and improve sustainable agricultural production. The proposal of the Sustainable Use Regulation by the European Commission offered a new horizon for new spraying technologies involving drones. Ultimately, the EC chose to withdraw this proposal for a regulation after it was rejected in European Parliament and a lack of consensus in the Council. Effectively, the sector is therefore now still working , the current Sustainable Use Directive from 2009, which dates from a time when terms such as 'drones' or 'Artificial Intelligence' were little known or associated with crop protection.

Times have changed, and technology has progressed at an enormous pace. Policies to enable these new technologies however need to be updated. Therefore, scientific evidence, field validations and pilots and trials are indispensable to enable and underpin these policy shifts.

This study aims to provide an inventory of relevant studies that contribute to this necessary body of evidence by conducting a systematic literature review. The study was performed by Wageningen Plant Research and found an interested donor to co-finance the efforts in CropLife Europe.

The study is based on a literature review running up to September 2025, and is primarily focused on European studies. It is clear that the number of scientific studies available in this field grows daily, but setting a cut-off date is unfortunately a necessary step to perform such an analysis and provide conclusions. The policy framework also continues to evolve rapidly, and as we complete this report in December 2025 the EC has released its Food and Feed Safety Omnibus Proposal aimed among other things at simplifying the EU regulatory framework and facilitating access to the market of innovative technologies, including drone use. It is to be hoped that this will also help support the generation of the necessary data, and subsequent increased recognition and uptake of risk reducing precision application technologies in Europe.

The authors thank the colleagues and the ad-hoc study review group from CropLife Europe for their contribution and feedback.

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Summary

This literature review synthesises current scientific evidence on new spraying technologies. The study focusses specifically on 1) spot and patch application and 2) Uncrewed Aerial Spraying Systems (UASS). The study objective is to assess whether these technologies can reliably support future EU policy ambitions for more precise, lower-risk pesticide use. Across both domains, the review finds substantial technological progress but insufficient scientific evidence to conclusively demonstrate reductions in human and environmental exposure, drift, or consistent economic advantages.

For spot and patch application, many studies report significant pesticide savings – typically 30–80% for herbicides and 10–50% for fungicides – while generally maintaining comparable biological efficacy. These benefits are strongly supported for weed control in 2D crops, with robust detection and actuation technologies emerging. However, almost all studies focus on product use reduction, not on quantified operator, bystander, or environmental exposure outcomes. Evidence for reduced runoff, drift, or biodiversity impact remains largely implicit. Moreover, the research reveals a wide differentiation of methods, sensors, algorithms, and thresholds. This limits comparability between studies. The literature shows clear potential for risk reduction, but in most cases lacks directly measured exposure data, leaving room for improvement to provide the evidence needed to revise risk-assessment frameworks.

For UASS, scientific work has expanded rapidly, but most studies related to crop and pest management concern monitoring, not spraying. European field evidence for UASS spraying remains scarce, heterogeneous, and dominated by small trials, mainly in vineyards, olives, and orchards. Reported pesticide savings (up to 50%), labour reductions, and operational efficiencies suggest promising benefits. Yet efficacy is inconsistent: canopy penetration is frequently inadequate, and results vary strongly by crop architecture and disease pressure. Studies show mixed or insufficient deposition, and under high disease pressure ground sprayers remain superior. Drift measurements and exposure studies are limited. Only a handful of trials (e.g., Switzerland, Greece, Spain) report drift characteristics, and these seem not yet sufficient for robust conclusions, fit to support regulatory changes.

Across all technologies, this literature review identifies a systemic evidence gap: while product-reduction potential is well documented, risk-relevant evidence (drift, environmental fate, operator/bystander exposure, off-target movement) remains to be addressed. Very few studies follow harmonised protocols or generate data compatible with EU risk assessment requirements. Published data on economic assessments are similarly fragmented and often lack lifecycle or system-level cost modelling.

In summary, both precision ground-based spraying and UASS offer strong conceptual and early empirical potential to reduce risks in pesticide use and improve sustainability. However, to enable a future policy shift in the EU toward risk assessments aligned with precision application technologies, targeted data generation is urgently needed. Significant, coordinated experimental data collection, using standardised protocols and covering drift, deposition, efficacy under variable disease pressure, and exposure pathways, is required to provide the needed sound foundation for future policy and authorisation decisions which take into account modern technological possibilities.

Science, industry and regulatory bodies will benefit from a clear policy vision on how these new technologies become part of future farm practices, and under what conditions. In particular the delayed update regarding the use of UASS aerial spraying of the Sustainable Use Directive from 2009 is hampering progress in that field.

1 Introduction

1.1 Background & scope

Recent technological developments in robotics, automated field sprayers, sensor platforms, and Artificial Intelligence have substantially broadened the range of feasible approaches to crop protection in the European Union and internationally. The increasing availability of robotic ground units and Uncrewed Aerial Spraying Systems (UASS), combined with significant advances in computer vision, machine learning, and real-time decision support, has strengthened the capacity for more precise and adaptive pest and disease management. The agility of these platforms — together with their ability to operate without on-board personnel — enables the implementation of targeted spraying strategies, including patch and spot application, which were previously limited by technological constraints. Consequently, practitioners, regulators, and policymakers have renewed their attention to precision agriculture, recognising its potential to support more efficient and context-responsive interventions across heterogeneous agricultural landscapes. Existing research indicates that precision crop management can improve the resource-use efficiency of inputs such as plant protection products (PPPs) and fertiliser, thereby contributing to more sustainable production practices (Anastasiou et al., 2023). Against this backdrop, the present study evaluates both patch and spot application techniques and UAV-based spraying in relation to their potential for economic efficiency and environmental benefits. Special attention is given to human and ecological risk considerations, with the objective of providing a clearer and evidence-based assessment of their suitability within the European regulatory and agronomic context. By analysing these two approaches together, the study seeks to contribute to an informed and balanced understanding of how emerging technologies can support the sustainable evolution of pest and disease management in modern agriculture.

1.2 Technologies overview

Within this broader technological evolution, this study examines two central approaches that exemplify the shift toward targeted and adaptive crop protection.

Spatially selective spraying: patch and spot applications

The first technology cluster concerns spatially selective spraying, such as zone, patch and spot spraying applications. In this study, it has been decided to focus specifically on patch and spot application techniques. These approaches differ fundamentally from broadcast spraying — which refers to a full-field, non-selective application at a constant rate (EUPAF TG1, 2025, Sect. 2.5.2) — by confining treatment to those areas of a field where pest pressure exceeds pre-defined thresholds. Importantly, both patch and spot application employ the same authorised per-unit-area application rate as broadcast spraying; reductions in total PPP use arise through spatial restriction rather than dose modification (ISO 5681:2020; EUPAF TG1, 2025, Sect. 2.3.6). Patch application is typically implemented at the scale of boom-section widths (generally 3–6 m), whereas spot application enables much finer spatial resolution, usually targeting areas below 1 m in width through individual-nozzle control or high-resolution sensor guidance (EUPAF TG1, 2025, Sect. 2.3.4). The principal objective of these approaches is to maintain a level of biological efficacy comparable to broadcast spraying while limiting the treated area and, consequently, the overall quantity of PPPs applied (EUPAF TG1, 2025, Sect. 2.5.2). Any reduction in ecological impact resulting from such spatial restriction depends on the location and extent of treated zones and must be demonstrated through appropriate risk assessment methodologies (EUPAF TG1, 2025, Sect. 2.5.3).

The feasibility and potential benefits of these techniques have been documented for nearly two decades; for example, Gerhards and Oebel (2006) reported herbicide savings of 6–81% for broad-leaved weeds and 20–79% for grass weeds in winter cereals through patch spraying. With ongoing progress in sensing, robotics, and computational tools, the range of possible targets and the expected precision of these techniques continue

to expand, thereby increasing their relevance for integrated weed and pest management programmes (Anastasiou et al., 2023; EUPAF TG1, 2025).

Uncrewed Aerial Spraying Systems (UASS)

The second approach addressed in this study concerns the rapid global diffusion of Uncrewed¹ Aerial Vehicles (UAVs) Remotely Piloted Aircraft Systems (RPAS) or drones in crop protection. Drones designed for pesticide application – commonly designated as Uncrewed Aerial Spraying Systems (UASS) – have gained considerable traction, particularly in East Asian agricultural systems. Adoption rates illustrate this trend: by 2016, Japan had registered approximately 2,800 unmanned helicopters used to spray an estimated 42% of its rice paddies (Filho et al., 2020), while in China, nearly 100,000 UASS units treated more than 66 million hectares in 2020 (Yan et al., 2021). Uptake is also growing in European countries such as Germany and Switzerland, as well as in the United States (Dubuis & Jaquerot, 2022; Rodriguez, 2021). According to the Organisation for Economic Co-operation and Development (OECD, 2021), UASS present several potential advantages over conventional ground-based methods, including reduced operator exposure, improved accessibility in challenging terrain, and the capability to perform zone-, patch-, or spot-specific spraying operations. However, the OECD emphasises that realising these benefits requires improved data availability, particularly regarding spray drift behaviour, application efficacy, and operator or bystander exposure.

¹ Many archived articles refer to 'unmanned' when it comes to UAV, but in light of a more gender-neutral term, 'uncrewed' becomes more common and more used instead. In this study it is decided to follow this trend and use 'uncrewed'.

2 Methodology

The systematic review is based on the EFSA (European Food Safety Authority) guidelines, which provide scientific guidance and assessments supporting EU food safety regulations. **Figure 1** outlines the phases used to assess the documents.

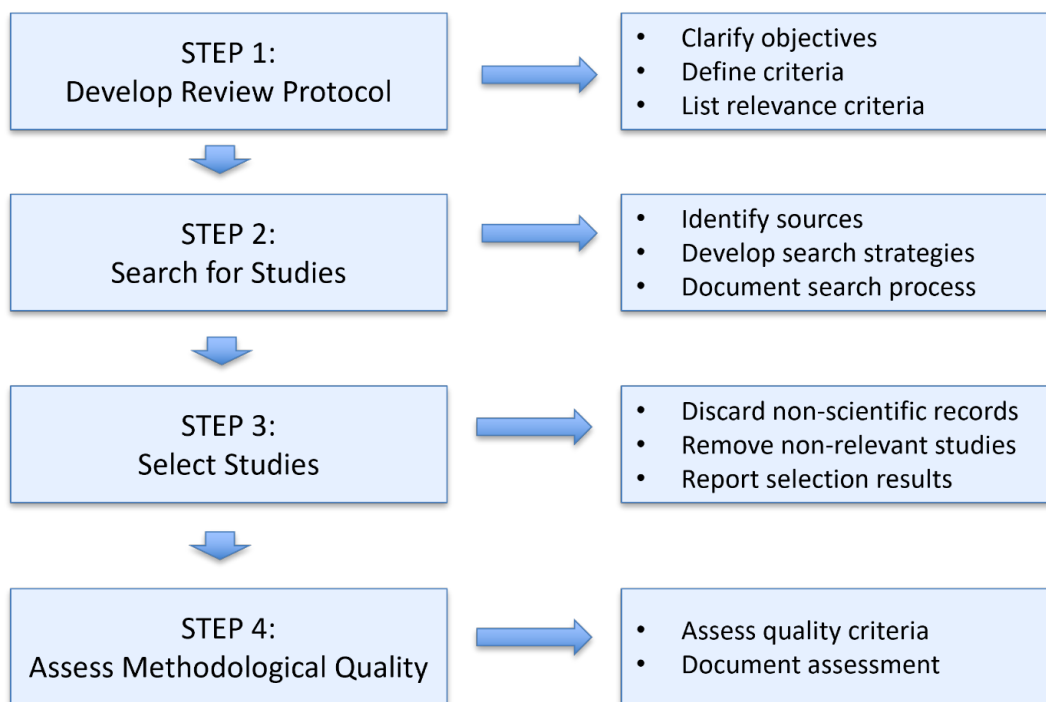


Figure 1. Flowchart of the systematic literature review (adapted from EFSA, 2010. <https://doi.org/10.2903/j.efsa.2010.1637>)

2.1 Objectives

The objective of this study was to identify and provide an overview of scientific evidence of the efficiency, efficacy and risk profiles of the new technologies 1) patch and spot spraying and 2) UASS.

2.2 Criteria

Publications were then sorted according to the following criteria:

- Authors should be from a selection of European and neighbouring countries (Russia, Turkey and Israel);
- Published from 2014 onward;
- The literature should be a scientific peer-review article (e.g., review, research paper, short-communication), a book chapter or a conference paper.

For this study, searches are conducted in the Scopus abstract and citation database. The queries used are documented in the Annex. Although the analysis aimed to cover all EU Member States, some countries (e.g. Austria, Ireland, Hungary, and the Baltic states) did not appear in the final dataset because no publications matching the search criteria were indexed in Scopus for the selected period.

The query was run in September 2025.

2.3 Results

There were 99 and 67 documents respectively for the spot and patch applications, while 241 documents were identified for the UASS applications.

The leading countries for spot/patch applications were Germany (n=33), the UK (n=14), France (n=10), Italy (n=9), Belgium (n=8), Spain (n=7), and the Netherlands and Denmark (n=6 each).

For UASS-related documents, the leading countries were Germany (n=36), Italy (n=36), the UK (n=34), Spain (n=30), the Russian Federation (n=16), and Greece (n=14).

2.4 Eligibility & screening and supplemental queries

Subsequently, the authors reviewed the abstracts of those selected documents to assess their relevance to our study. **Figure 2** provides a infographical overview of the screening and selection process.

As a result, 27 documents were selected for the section on spot/patch spraying, and 56 documents for the drone section.

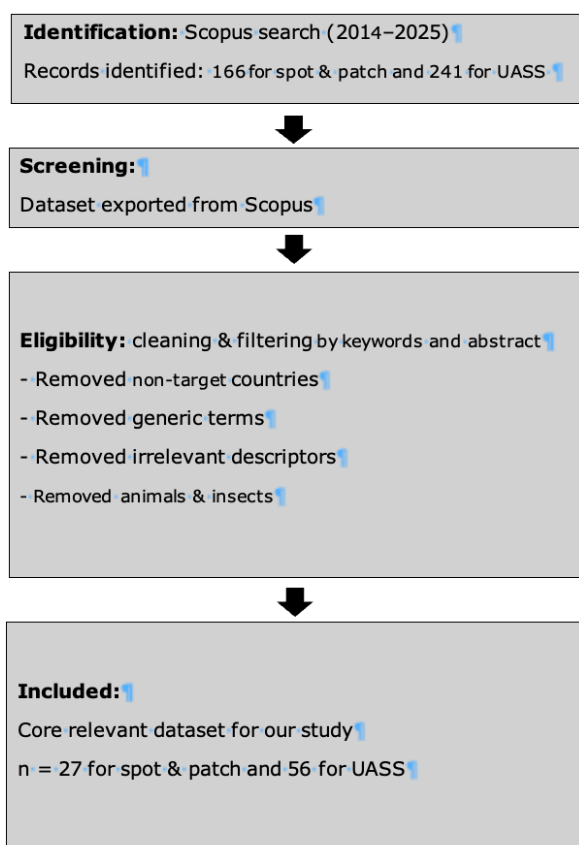


Figure 2: Chart flow of the systematic review: identification (Scopus), screening, eligibility, and final inclusion. The systematic research was conducted on the 1st of September, 2025.

In addition, we conducted 4 supplemental analyses:

1. Without country limitations, we searched for documents to identify trends in "spot and patch application" and "drone";
2. After collecting the documents, VOSviewer software was used to visualise different clusters based on keywords and authors' countries;
3. We also search other information resources such as project reports, documents from institutions;
4. For patch/spot application, we additionally searched the literature using the keywords "robots" and "autonomous" to cover missing publications.

3 Risk reduction categories

Using pesticides in agriculture is a common practice for protecting crops from pests and diseases and maintaining yield stability. However, several pathways contribute to environmental contamination, including spray drift, runoff, leaching, volatilisation, environmental persistence, and effects on non-target organisms. Among these, spray drift – defined as the unintentional movement of pesticide droplets beyond the intended area – is particularly problematic. It occurs when fine droplets are carried by wind or air currents, resulting in off-target deposition. This not only diminishes application efficiency but also risks contaminating adjacent ecosystems, water sources, and non-target crops, raising both environmental and public health concerns.

To address such risks, over the years, the European Union (EU) has proposed initiatives that promote climate-neutral and sustainable agriculture, such as the Vision for the Future of Agriculture and Food published in February 2025, where the Commission committed to publish a Digital Strategy for agriculture. In September 2024, the Strategic Dialogue on the Future of EU Agriculture also published a list of recommendations in their report for the Commission, including highlighting the benefits of digital and precision technologies as well as ways to increase the uptake of these tools. In the past the EC also published its 'Farm to Fork' strategy, which proposed non-legally binding targets including a 50% reduction in the use and overall risks of chemical pesticides by 2030. Recent monitoring results already indicate a 58% decline in the risk and use of pesticides, as measured by Harmonised Risk Indicator 1, compared with the 2015–2017 baseline (European Commission, 2025). While such strategies focus on general pesticide reduction, spray drift mitigation is primarily addressed through operational practices and technical frameworks (e.g., optimal spray volumes, drift-reducing nozzles, LERAP, JKI, DIX), which guide responsible application at the field level.

While such strategies focus on general pesticide reduction, as well as looking into ways to encourage the uptake of digital and precision tools, the mitigation of spray drift is addressed primarily through operational practices and technical frameworks (e.g., optimal spray volumes, drift-reducing nozzles, LERAP, JKI, DIX), which guide responsible application at the field level.

A 2024 report from the European Commission, "Compendium of conditions of use to reduce exposure and risk from plant protection products" [Click or tap here to enter text.](#) (EURO, 2024) addresses different use conditions that can reduce human and environmental exposure to Plant Protection Products (PPP). The compendium gives an overview of the different kinds of measures that can lead a lower exposure in the following areas:

- Human health: This includes individuals involved in handling and applying products (operators), those working in treated areas (workers), and nearby individuals (bystanders and residents).
- Environmental exposure: Covers various ecosystems and media, including surface water and aquatic life, terrestrial habitats and non-target species, and potential groundwater contamination.

The compendium gives for all these measures an indication about the expected effect on the different sub-categories within human health and within environmental exposure. For some of the measures, the expected effects are supported well by studies and data. However, it was observed that in some other categories, the supporting data was limited, and that additional data should be provided to confirm the performance level. In the categories "Field management measures", spot application is mentioned as a measure that can reduce the risk to the environment by 25-50%. However, relevant data to be used in supporting risk assessments was not found.

As part of the objective for this study to find evidence for risks and for the reduction of risks through introduction of new technologies, it became apparent that scientific literature to support the risk assessment remains limited.

4 Spot- and patch application

4.1 Description possibilities

Site-specific management using variable rate application technologies – where the pesticide dose is adjusted according to crop canopy density, pest pressure, or field conditions – is a recognised approach to reduce pesticide use while enhancing economic efficiency and minimising environmental and human health risks. Spot- and patch applications form a key part of this approach, relying on sensor-based detection and robotic technologies for precise, localised spraying. Surveys among farmers and the general public indicate broad acceptance of these emerging plant protection technologies, including autonomous agricultural robots. Notably, respondents anticipated greater ecological benefits, such as reduced chemical input and lower environmental impact, than improvements in food security or labour efficiency (Rübcke von Veltheim et al., 2022; Zeddies et al., 2024). In this section, we will describe how spot and patch applications relate to the impacts on economic and environmental benefits, as well as the five different risks described in the Compendium (Euro, 2024).

Before assessing the economic and environmental benefits, it is important to emphasize that the accurate detection of diseases and pests by the developed technologies is essential. Detection rates of infected plants vary depending on crop types, sensor configurations, and data-processing methods. For instance, Cubero et al., (2020) report detection rates of bacterial infected carrot plants ranging from 85% to 90% using robotic platforms, while Oberti et al. (2016) achieved 85% to 100% accuracy in automatically identifying diseased areas within the vineyard canopy. Recently, quite a lot of studies were published showing opportunities to improve detection rates of weeds (Allmendinger et al. (2025), insects (Aminu et al. (2025), and diseases (Zhang et al. (2025)). These studies show that state-of-the-art object detection models like YOLO, RT-DETR, and other artificial intelligence techniques can improve detection precision significantly. Studies assessing the efficacy of spot or patch applications should ideally include a direct comparison with conventional broadcast spraying. However, the reviewed studies were highly heterogeneous; some compared results with broadcast applications of chemical plant protection products (PPPs), while others lacked any reference treatment.

Analysis of the selected documents regarding spot- and patch application indicates that herbicides are the most frequently addressed topic among pest and disease control measures (e.g., fungicides, nematicides, insecticides). It was expected that herbicides would be the most addressed topic, as weeds occur locally in fields. For weed control with contact herbicides, no product is needed when no weeds are present, as this type of herbicide does not provide residual activity. Therefore, optimal weed detection followed by local herbicide application could significantly reduce herbicide use.

Table 1. Number of scientific documents and type of pesticide

Type of Pesticide	Herbicide (H)	Fungicide (F)	Insecticide (I)	Combination
Number of documents	17	1	1	3

Compared to pesticide types, the crop types in our study – based on the query conducted in September 2025 – were more diverse (**Table 2**). This diversity is partly related to the countries where the authors' institutions are located. For example, sugar beets are primarily cultivated in Northern European countries, such as Germany.

Table 2. Number of documents per crop type

Crop names	Number of documents
Multiple	11
Sugar beet	2
Maize	2
Meadows/grass	2
Lettuce	1
Apple/Pear	1
Tomato	1
Grapes	1

Table 3. Number of documents per country

Country	Number of documents
Germany	7
Multiple countries	1
Spain	1
Switzerland	1
France	1
Romania	1
Belgium	1
UK	1
Slovenia	1
Israel	1

The reduction rate of herbicide amount by technologies-mounted tractor varies from 45% to 95% (Allmendinger et al., 2022), depending on the type of sensors, target pest, implementation, and application (Keller et al., 2014). Limbourg et al. (2024) calculate even a 95% herbicide reduction with dense-positioned nozzles (4-10 cm) and a camera system in front for weed detection. The review paper (Allmendinger et al., 2022) presents a chart of the combination (see below), which includes various sensors, applications, and implementations. Some older studies showed lower potential for herbicide reduction. At national conferences out of our scientific query sometimes also data regarding herbicide reduction were presented. At a German conference, not present in Scopus, pesticide reductions were between 8 and 63%, depending on the threshold that was chosen (Leithold et al., 2018).

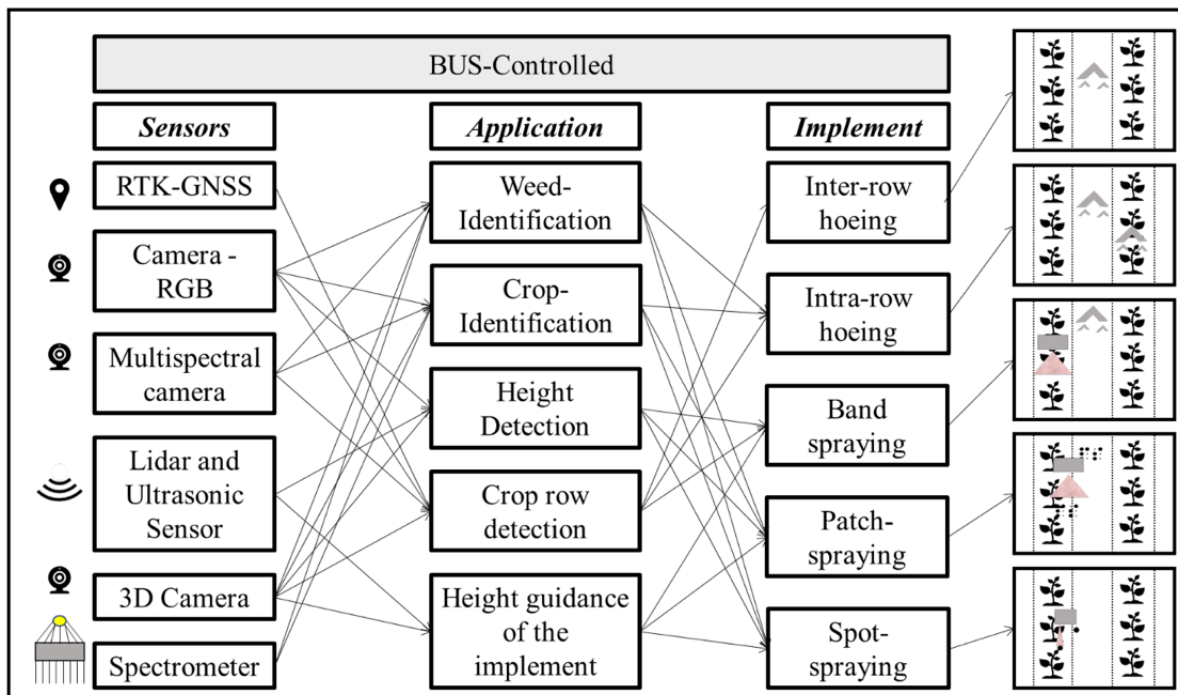


Figure 3: Connections between sensors, applications and implements (Source: Allmendinger et al., 2022).

Site-specific spot pest management offers both economic and environmental benefits compared to conventional spraying. Evidence from northern Germany indicates that this approach can substantially reduce pesticide costs and improve gross margins (Rajmis et al., 2022; Table 4). In this paper, a comparison was

made between conventional spraying and site-specific spot application in cereals (winter wheat, spring wheat, and winter barley) on a large-scale farm in Germany. Scenarios were calculated in which both herbicides and fungicides were applied by different spot application methods. All scenarios (direct injection sprayer in combination with different sensor types) resulted in a reduction in pesticide costs and in an economic advantage of on average €156/ha. The biggest reduction in pesticide inputs was achieved for herbicides.

Table 4: Comparison between conventional spraying and site-specific spot application (Rajmis et al., 2022).

Approach	Pesticide cost reduction	Extended gross margin (€/ha)
Conventional spraying	–	631
Site-specific spot application	26–66%	787

4.2 Technologies & use cases

4.2.1 Weed detection and control

Field crops (e.g., cereals, maize, "2D crop")

- In Germany, site-specific application of grass weed herbicides resulted in savings of 78% in maize and 36% in sugar beet. In comparison, broadleaf weed herbicides achieved 11% savings in the amount of PPP with a direct injection system, in sugar beet, reducing costs from €148/ha to €69/ha, and in maize from €103/ha to €95/ha (Gerhards & Sökefeld, 2003). Additionally, a reduction of herbicides of between 10% and 55% was reported without a decrease in weed control efficacy (Spaeth et al., 2024);
- In Turkey, a field study on maize showed that, compared to conventional methods, application volumes decreased by 29–32% at forward speeds of 4–8 km h⁻¹, with application accuracy of 75–82% (Karadöl et al., 2020). In the trial, a camera system was mounted in front of the tractor, and weed density was determined. A threshold value for weeds was determined, being >10 weeds/m². For species with a known damage threshold, this is rather high. The application was conducted using a small boom sprayer (4.20m width), which had 3 sections that could be switched on and off depending if the weed threshold was reached. No details regarding final result of the application were provided in the paper;
- In Denmark, grid-based on/off spraying with a machine vision algorithm (MoDiCoVi) that estimates dicot leaf cover from high-resolution images enabled real-time grid spraying in maize, potentially reducing herbicide use by 75% while maintaining weed control (Laursen et al., 2016). In this study, an autonomous spraying system was used in which application was conducted with six medium atomizing nozzles which could be controlled individually. Nozzles were mounted on a spraying boom at 187.5 mm distance of each other and were placed 250 mm above the ground. The MoDiCoVi algorithm determined the activity of each nozzle, and reduction of herbicide rate;
- On-farm sugar beet and maize trials in eastern Germany showed that the Amazone Smart Sprayer (UX 5201), combined with a weed detection system using multiple cameras and LED units, enabled herbicide savings of 10–55% without compromising efficacy (Spaeth et al., 2024). The sprayer was a spot sprayer. In this study, several trials were presented in which various crops were sprayed with the Amazone Smart Sprayer. For sugar beets, savings were 30–55% and in maize they were 12–30%. In Spain, profitability studies with herbicide on *S. halepense* in maize found that the most profitable strategy among five scenarios was when 15% of the crop was infested (Andújar et al., 2013).

Orchards and vineyards ("3D crop")

- In Italy, pesticide savings through precision technologies ranged from 10–35% (Tona et al., 2018), 65–85% (Oberti et al., 2016), and 43% in another study (Biocca et al., 2021);
- In Spain, field trial results showed that the estimated cost for site-specific flame weeding was approximately €24/ha, compared to about €52/ha for a conventional broadcast treatment, resulting in savings of €28/ha through reduced use of liquid petroleum gas by Pérez-Ruiz et al. (2015), reinforcing the practical value of this approach;
- Similar economic savings were reported in Spain. Further evidence highlights reductions of 77–95% in Germany (Shang et al., 2023).

Robotics and alternative approaches

- Robotics and autonomous technologies offer another approach to reducing pesticide use. Since 2015, more than 40 commercial weeding robots have been introduced, ranging from fully autonomous to semi-autonomous, with applications in inter-row weeding, fallow land, or specific crops (Gerhards et al., 2024). Examples include the Kverneland Optima V, which employs camera-based intra-row weeding and spot spraying with RTK-GPS guidance;
- Robotic weeding is commonly categorized into non-chemical approaches, such as hoeing and emerging physical technologies like electrical or laser-based weeding, and chemical approaches, such as targeted spraying;
- In Germany, a combined approach of band spraying and inter-row hoeing with RTK-GPS guidance achieved between 75 and 83% herbicide savings (Gerhards et al., 2024);
- Mechanical weeding remains particularly valuable for organic farming, helping reduce reliance on pesticides despite high labour costs for manual hoeing (Shang et al., 2023).

4.2.2 Disease and pest detection and control (Fungicide, Insecticide, Nematicide)

2D crops:

- In the Netherlands, field trials with a canopy density sprayer (CDS) by van de Zande et al. (2010) demonstrated that adjusting spray volume to canopy structure reduced fungicide use while maintaining control efficacy. In potatoes, spray volume for *Phytophthora infestans* control was reduced by over 75% without loss of efficacy, while in lilies, *Botrytis* blight control achieved an average 45% reduction, though with slightly lower efficacy than conventional spraying, indicating a need for further optimization of dose algorithms;
- Similarly, field trials in Germany by Kuhn et al. (2024) using farnesene isomer dispensers in sugar beet fields reported significant reductions in aphid numbers at two of three test sites. At Mannheim, reductions were substantial at 14 days ($p = 0.039$), 28 days ($p = 0.011$), and 42 days ($p = 0.0002$) after dispenser placement; at Heidelberg, significance was observed at 7 days ($p < 0.001$), 14 days ($p < 0.001$), 28 days ($p = 0.015$), 35 days ($p = 0.010$), and 42 days ($p = 0.000$). No significant differences were found at the Dettenheim site. The reductions were modest and variable across locations, suggesting that efficacy depends on site-specific conditions.

Table 5: 2D CROPS (Field crops: cereals, maize, sugar beet, potatoes, lilies)

Country	Crop Name	Citation	Highlight
Germany	Maize, Sugar beet	Gerhards & Sökefeld, 2003	Herbicide savings: 78% (maize), 36% (sugar beet) ; broadleaf herbicide savings 11% ; cost reductions: sugar beet €148→€69/ha , maize €103→€95/ha .
Germany	Maize, Sugar beet	Spaeth et al., 2024	10–55% herbicide reduction without loss of weed-control efficacy.
Turkey	Maize	Karadöl et al., 2020	Spray volume decreased 29–32% ; application accuracy 75–82% .
Denmark	Maize	Laursen et al., 2016	Machine-vision grid spraying reduced herbicide use by up to 75% .
Germany	Sugar beet	Gerhards et al., 2024	Smart Sprayer enabled 10–55% herbicide savings with full efficacy.
Spain	Maize	Andújar et al., 2013	Most profitable strategy occurred when 15% of field was infested with <i>S. halepense</i> .
Netherlands	Potatoes, Lilies	van de Zande et al., 2010	Fungicide reductions: >75% (potatoes), 45% (lilies). Slight efficacy reduction in lilies.
Germany	Sugar beet	Kuhn et al., 2024	Farnesene dispensers significantly reduced aphids at most sites (e.g., $p < 0.001$); effect was site-specific .
Germany	Field crops	Gerhards et al., 2024	Combined band spraying + inter-row hoeing achieved 83% herbicide savings .

Orchards and vineyards (3D crops):

- In Spanish vineyards, precision spraying achieved 40% savings of copper for downy mildew control (Garcia-Ruiz et al., 2023);
- In Italian viticulture, variable rate application (VRA) achieved average spray volume savings of 35%, translating into €2,599.50 in reduced costs—€2,502.50 for pesticides, €52.14 for water, and €44.86 for fuel. Savings in spray volume varied considerably, from as high as 76% in the first session to 10% in the last, reflecting the economic performance of VRA (Pagliai et al., 2023).

Table 6: 3D CROPS (Orchards & vineyards)

Country	Crop Name	Citation	Highlight
Italy	Vineyards / Orchards	Tona et al., 2018; Oberti et al., 2016; Biocca et al., 2021	Pesticide savings reported at 10–35%, 65–85%, and 43%.
Spain	Vineyards / Fruit crops	Pérez-Ruiz et al., 2015	Flame-weeding cost €24/ha vs €52/ha conventional → €28/ha savings.
Spain / Germany	Orchards / Vineyards	Shang et al., 2023	Reported pesticide reductions of 77–95%.
Spain	Vineyards	Garcia-Ruiz et al., 2023	40% copper savings for downy mildew control.
Italy	Vineyards	Pagliai et al., 2023	35% spray-volume savings; total savings €2,599.50/ha; spray-volume reduction 76%→10% across sessions.

To summarise, for both 2D and 3D crops a number of studies were conducted in which pesticide savings were calculated. Studies differed quite a bit in setup. Most studies in 2D crops were conducted with herbicides for weed control, but also few studies for disease and pest control were found (**Table 5**). For 3D crops both studies for weed control and for disease control were found (**Table 6**).

In the market, there is a wide variety of sensor technologies related to pesticide use. The list of commercialised products related to robot or tractor-mounted spraying is shown below (**Table 7**) (taken from the paper, Allmendinger et al., 2022). The table provides an overview of commercially available spot-spraying technologies, highlighting their sensing approaches, access type, crop applicability, and reported herbicide-saving potential. Systems range from AI- and CNN-based weed detection platforms (e.g., ARA Ecorobotix, Bilberry, Greeneye, Blue River’s See & Spray) to spectrometer-based Green-on-Brown sensors such as WeedSeeker and Weed-It. Reported herbicide reductions vary widely—from ~40–60% for integrated robotic systems such as Robotti to over 90–95% for high-precision vision-guided sprayers—reflecting differences in sensor modalities, computational methods, and field conditions. Several systems (e.g., Bilberry, WeedSeeker) support ISOBUS connectivity, enabling integration with diverse sprayers, whereas others operate in closed ecosystems. Collectively, the table illustrates the rapid technological diversification of spot-spraying solutions and their substantial potential for reducing herbicide inputs in real-world farming.

Table 7: List of commercialised autonomous (Full/semi-full) robots for spraying (Source: Allmendinger et al., 2022)

Product/Trade Mark	Company	Technology	Sensors	Access	Herbicide Reduce	Application
Robotti	Agrointelli	Combining Deep Learning and BigData	RTK-GPS, autonomous, Lidar, Camera	Close	40–60%	Robot
ARA	Ecorobotix	CNN-based weed detection in sugar beet and spot spraying	Multi-camera vision system	Open	Up to 95%	Tractor-mounted
Bilberry	Bilberry	AI-based weed detection and spot spraying	RGB camera	Open	More than 80%	Robot
Weedseeker	Trimble Agriculture	Infrared Sensors	High-resolution blue LED-spectrometer	Open	60–90%	Tractor-mounted
Weed-It	Weed-It	Detection of green vegetation	Blue LED-lighting and spectrometer	Open	95% (only in crop-free areas)	Tractor-mounted
FD20	Farmdroid	RTK-GPS recorded position of crop seeds and spot spraying	RTK-GPS	Open	unknown	Robot
H-Sensor	AgriCon	AI-based weed detection in cereals and maize	Bi-spectral camera	Close	50%	Tractor-mounted
Blue River's see and spray	Blue-River Technologies	CNN-based weed detection in cotton and spot spraying	RGB-cameras	Close	Up to 90%	Tractor-mounted
EcoPatch	Dimensions Agri Technologies	AI-based weed detection and spot spraying	RGB-camera	Closed	unknown	Tractor-mounted
Kilter AX-1	Kilter Systems	RTK-based crop detection and selective spraying in vegetables	robot	Open	unknown	Robot
Greeneye	GreeneyeTechnology	AI-based weed detection and spot spraying	RGB-camera	Open	unknown	Tractor-mounted
Avirtech-MIMO	Avirtech	UAV-based weed mapping and patch spraying	4D Radar imaging	Close	unknown	Drone
Smart Spraying	BASF, Bosch, Amazone	Camera-based weed coverage measurement and spot spraying	Bi-spectral camera	Close	70%	Tractor-mounted

4.3 Risk assessment

The included studies report that site-specific, technology-enabled pest and disease management can reduce pesticide and chemical use in European agriculture, with some studies also reporting economic benefits. However, direct evidence for reductions in human exposure, biodiversity impact, and water contamination is limited and often indirect. Most studies report reductions in pesticide or herbicide use, which may indicate reduced exposure; however, direct measurement is scarce. Little is known about the impact of spot and patch applications on biodiversity and risk reductions.

Below are a couple of scientific papers related to this topic:

A. Effect on human health risk reduction (Operator/worker; Bystanders/residents):

Although Holterman et al. (2025) focus primarily on environmental compartments, their analysis provides insights relevant to human health. The report demonstrates that edge-of-field spray drift remains the dominant pathway for bystander and resident exposure in EFSA's risk-assessment framework. Because precision application technologies substantially reduce drift at the field margin, the findings imply a corresponding reduction in human exposure potential. Holterman et al. (2025) further highlight that improved machinery configurations, drift-reducing technologies, and reduced treated areas can lead to markedly lower off-field deposition. These observations complement empirical results from the Rovitis 4.0 project, where robotic precision spraying achieved a 43% reduction in copper use and consistent decreases in PICHE indicators for operators, workers, bystanders, and residents (Biocca et al., 2022; Bolzonella et al., 2019).

B. Effect on environmental risk reduction (Surface water + aquatic organisms; Terrestrial area + non-target organisms; and Groundwater):

The previously mentioned report about The Rovitis 4.0 research project (Biocca et al., 2022) has a reduction in human health risk and in the water and environmental sectors. It shows the reduction indicator values across the water and environmental dimensions. Insights from Holterman et al. (2025) reinforce these findings by

demonstrating that environmental exposure is primarily driven by edge-of-field drift, spatial application patterns, and landscape structure, and that precision methods substantially reduce deposition in field margins and adjacent habitats. Holterman et al. (2025) further highlight that reduced treated areas, higher crop interception, and improved equipment configurations decrease transport to surface water and lessen exposure for terrestrial non-target organisms, supporting the broader evidence that precision spraying has meaningful mitigation potential.

Autonomous tractors, robots, and smart sprayers are deployed for site-specific application, often using Variable Rate Application (VRA) technology or spot spraying to adjust pesticide application based on weed density (Pérez-Ruiz et al., 2015; Bontsema et al., 2014; Spaeth et al., 2023). Spot sprayers generally require users to estimate the amount of product in advance, which may lead to leftover mixtures if the weed infestation is lower than expected. Direct injection, by contrast, is a separate approach that mixes pesticides and water only moments before spraying. This avoids the need for tank mixtures, eliminates residual waste, and reduces the risk of improper disposal. Moreover, direct injection systems can reduce water use for cleaning operations by up to 80% (Rajmis et al., 2022) and lower the likelihood of overapplication and runoff by enabling more precise dosing. When combined with spot spraying, direct injection can further enhance efficiency by preventing leftover pesticide solutions.

Field trials in Switzerland (Witsoe et al. 2025) showed that band and spot sprayers with robots reduced drift by over 90%, often >99%, with similar performance between devices. Run-off modelling in lettuce indicated reductions of 85%, 52%, and 14% at 6%, 25%, and 55% crop cover, respectively, highlighting strong drift and run-off reduction, especially at early growth stages.

4.4 Conclusions

While some studies have addressed the reduction of pesticide use and its monetary benefits through spot or patch applications, there is limited research on their impact on environmental and human health risks, as well as biodiversity. In studies found, often pesticide reduction was quantified. However, the effect of this reduction on environmental and human health risks was not quantified in these studies. To quantify these effects, now often theoretical assumptions have to be taken. Future research should adopt broader objectives to better assess these dimensions.

Despite progress, spot/patch applications have untapped potential. Recent technologies could help address the following challenges:

Reducing spray drift:

Drift is influenced by weather, droplet size, nozzle type, spray height, formulation, and field conditions. Smaller droplets drift more easily, while larger ones stay on target. Technologies such as low-drift nozzles, air-assisted sprayers, and drift-reducing adjuvants help minimize this risk. Regulatory measures also recommend buffer zones to protect sensitive areas. Key practices include:

- Using low-drift or air-induction nozzles;
- Employing rotary nozzles (centrifugal/spinning disc nozzles), which generate uniform droplet sizes and reduce fine droplets prone to drift, with increasing application in drones as alternatives to hydraulic nozzles;
- Keeping the spray height low;
- Reducing spray pressure;
- Applying drift-reducing additives.

Integration of recent sensor technologies, information infrastructures, and algorithms:

New sensor technologies and more advanced computing infrastructures could support more precise spraying. For instance, ultrasonic sensors can be used to measure canopy width (del Cerro et al., 2021). Another example is that UAVs equipped with Lidar sensors can fly over fields and collect high-resolution 3D data on vegetation structure and topography, which can be used to estimate biomass, plant height, and canopy cover.

5 UASS application

5.1 Regulatory context & introduction

In scientific literature, their most common name is Uncrewed (in some articles: Unmanned) Aerial Vehicles (UAVs) and drones. The term Remotely Piloted Aircraft Systems (RPAS) is also used, but to a lesser extent (Cerro et al, 2021). In recent literature, the term Uncrewed Aerial Spraying System (UASS) is used specifically for the spraying drones. In Asia, remotely piloted helicopters (single rotor) have become important as spraying equipment to enhance fixed-wing crewed aeroplane applications of PPP, in particular, in wet field conditions. The better manoeuvrability and lower speed of the helicopters provided a better application. Also, backpack equipment could be replaced, reducing the risks of human exposure to PPP. UAVs have limited use for spraying in the EU as most European countries have limited or banned the aerial application of fertilisers and PPP, enforced by Directive 2009/128/EC on the sustainable use of pesticides (SUD) in 2009. In its proposal for a Regulation on the Sustainable Use of Plant Protection Products (SUR), the European Commission already included the possibility of allowing drones for the application of plant protection agents in the European Union. However, as this proposal has been rejected, no other initiative to regulate the take up of drones as an alternative technology has surfaced. In December 2024, this 'lack of progress' was discussed in the European Council on agriculture and fisheries², asking the EC to take action. In June 2025, members of the European Parliament did a similar call to the EC to speed up the development of a European Market for civilian drones, mentioning agriculture as a main application domain³.

Farella et al (2025) report that waivers have been granted in the EU: Spain has set specific requirements, and France, despite banning drones after trials (2018-2021), is reconsidering authorisation due to reduced operator exposure and drift⁴. Italy is exploring the use of UAVs for spraying in its National Action Plan. Internationally, ISO 23117 regulates aerial spraying, with Part 1 (2023) outlining environmental requirements. Part 2 defines methods for assessing spray distribution but does not yet address drift or deposition within crop canopies. Future standards are expected to be developed to cover these aspects of UASS performance. (Farella et al, 2025).

Recently, Regulations (EU) 2019/947 and 2019/945 established detailed rules for drone operations (categories "open," "specific," and "certified") and product compliance. These regulations have applied uniformly across all Member States since 31 December 2020, replacing national rules. The European Union Aviation Safety Agency (EASA) developed these regulations and provided supporting materials, including guidance documents, Acceptable Means of Compliance (AMCs), and technical standards, forming a risk-based regulatory framework for unmanned aircraft systems (UAS). A central element in the EASA regulations is the so-called SORA, which stands for Specific Operations Risk Assessment. This is a risk assessment methodology used in drone regulations for operations beyond the basic "open" category. It is a standardised, structured process that operators use to evaluate the potential risks of a drone flight, determine appropriate safety measures, and gain approval from aviation authorities for specific, more complex missions. The regulation also works with so-called pre-defined risk assessments (PDRA), which are scenarios that have been assessed and published, as an alternative to the SORA.

On 19 October 2023, EASA Decision 2023/012/R expanded this framework, particularly for agricultural applications. The amendments specify that no type certification is required for agricultural drones with a wingspan under three metres, maintaining at least ten metres distance from uninvolved persons, and that no weight limitation applies under these conditions. This removes the airspace regulation barrier in drone applications in agriculture, in particular for spraying and spreading. Other regulations of EASA, like 2022/002/R, govern the so-called Beyond Visual Line of Sight (BVLOS) operations, allowing monitoring drones to be operated from a remote (not in/near the field) location. Since the beginning of this century, technologies have emerged and improved for drones for civil applications. Agriculture has long been recognised as a key application domain for various types of applications, including spraying (van der Wal, 2016).

² <https://data.consilium.europa.eu/doc/document/ST-16521-2024-INIT/en/pdf>

³ <https://drive.google.com/file/d/1iCL4Q7KMEtdXzD1OsIEMC0qJWOMV8ezD/view>

⁴ France has adopted law 2025-365 on 23 April 2025 to allow spraying drones under certain conditions and for a trial period of three years: <https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000051507744>

UAVs have emerged as a promising strategy for more sustainable pest and disease management. In recent years, scientific interest in this topic has grown significantly. As of September 2025, approximately 900 peer-reviewed articles on UAV applications in this area are indexed in Scopus since 2014. The leading countries in this research include India, China, the United States, and Brazil, where public regulations for UAV use in pest management have already been implemented.

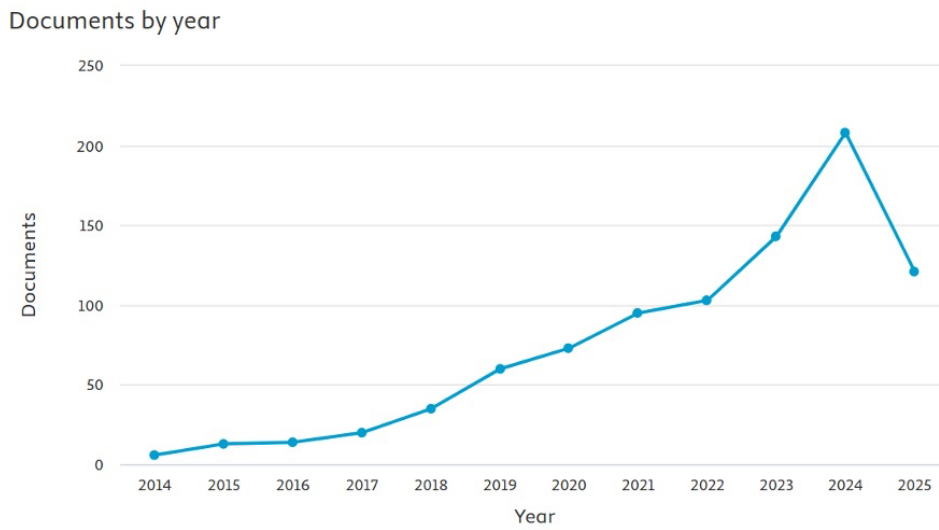


Figure 4: Number of scientific publications per year (sourced from Scopus, Sep 2025)

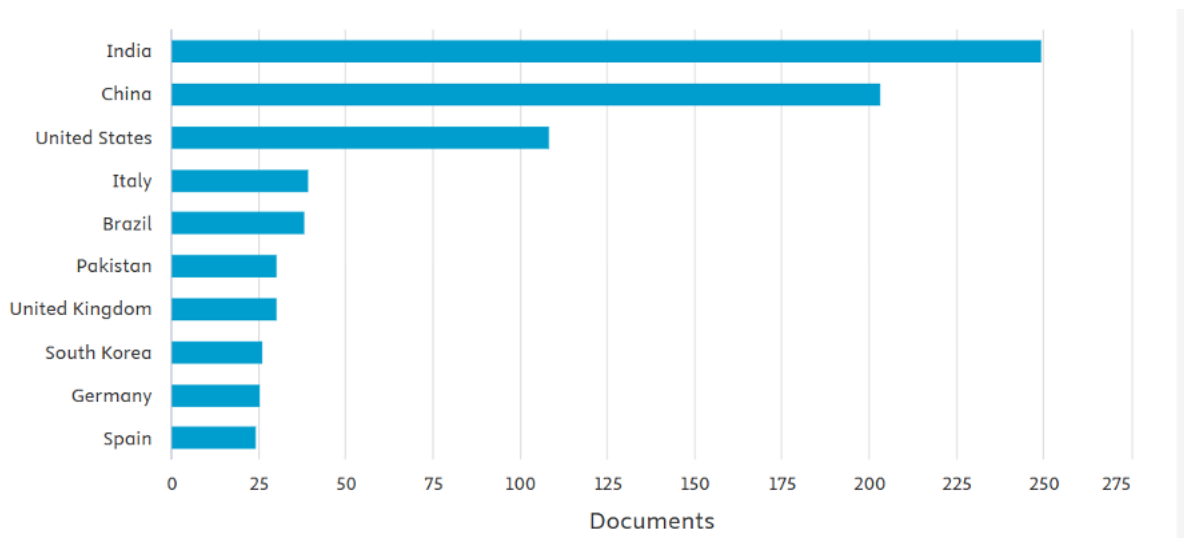


Figure 5: Number of scientific publications per country at global level (sourced from Scopus, Sep, 2025)

There are nine review papers regarding UAVs related to pest management (Calderone et al., 2025; Chen et al., 2022; Filho et al., 2020; García-Munguía et al., 2024a; Ivezic et al., 2023; Nahiyoon et al., 2024a; Zhang et al., 2023, Kartal et al., 2025) and an overview paper on drones employed in agricultural spraying (Farella et al., 2025).

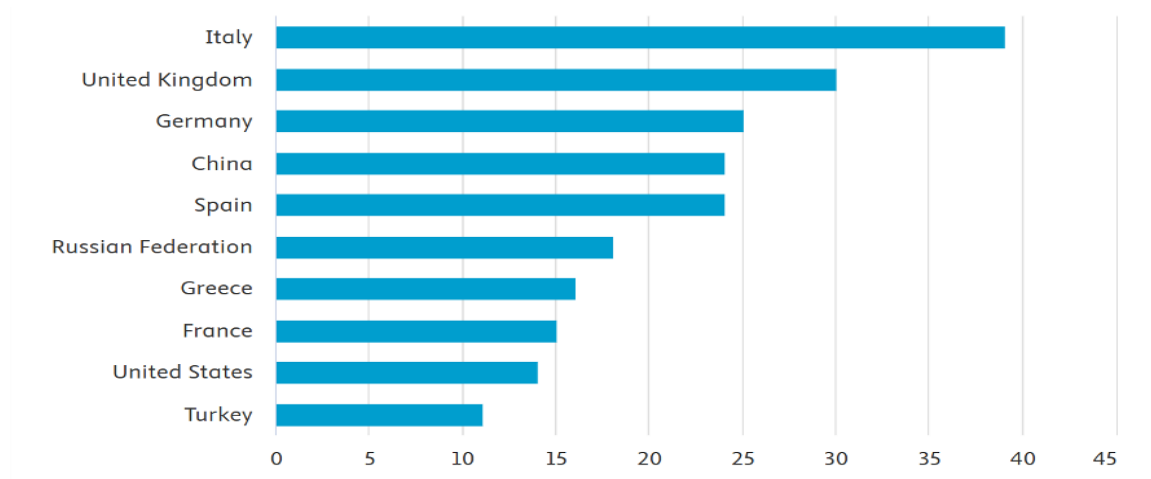


Figure 6: Number of scientific publications per country in Europe (sourced from Scopus, Sep, 2025).

Basically, there are two different types of UAV applications:

1. Sensing Drone: monitoring field conditions, including plant, soil, and surroundings;
2. Actuation Drone: actualization of treatments, including pesticides, biopesticides, and biological enemies.

The majority of scientific publications to date have primarily addressed applications of type 1, focusing on monitoring pest presence (Longhi et al., 2024) and weed presence (Esposito et al., 2021), assessing plant health affected by pests and diseases (Faroque et al., 2023), and detecting specific crops such as artichoke (Sassu et al., 2023). Despite growing interest in UAVs for sustainable agriculture, most applications remain focused on sensing rather than actuation.

In many cases, UAVs are integrated with other technologies: aerial surveys are conducted to monitor field conditions and generate digital maps, while pesticide application is carried out by (autonomous) ground-based tractors equipped with sprayers. A significant obstacle to broader UAV adoption in active roles is the limited field validation and the absence of standardised calibration protocols. Additionally, ensuring application precision and controlling spray drift remain technical challenges, raising concerns over treatment accuracy and the risk of unintended environmental impacts.

However, there are a number of papers related to UASS. In European countries, UAV spraying is most applied in vineyards, olives, orchards, and high-value horticultural crops, where the focus is on targeted and localised pest control rather than large-area blanket spraying. Those papers are published mainly from southern European countries, including Italy (Testa et al., 2025) and Spain (Calderone et al., 2025; Sánchez-Fernández et al., 2025; Farfarella et al., 2025).

Regulatory restrictions also pose significant obstacles, as many countries enforce strict guidelines on aerial spraying due to safety and environmental concerns. The UAV regulation in EU member states follows the regulations set out by the EU Aviation Safety Authority (EASA). In October 2023, EASA amended the drone regulation by expanding its so-called pre-defined risk assessment (PDRA- S01) to remove the weight limit. This allows drones that can be used for spraying or spreading tasks to take off with a higher weight than 25 kg (EASA, 2023). EASA clearly mentions that this expansion of the regulation does not relieve operators from respecting the rules for spraying laid down in Directive 2009/128/EC (also known as the Sustainable Use Directive).

In addition, current UAV designs face limitations in payload capacity and battery life, making them less suitable for large-scale interventions. The use of biological agents introduces additional complexity, as many require careful handling and are sensitive to environmental stress during aerial release. Finally, the high cost of actuation drones and the farmers' limited awareness or technical capacity further constrains broader adoption, particularly in smallholder contexts. The limitations and challenges will be described later in more detail.

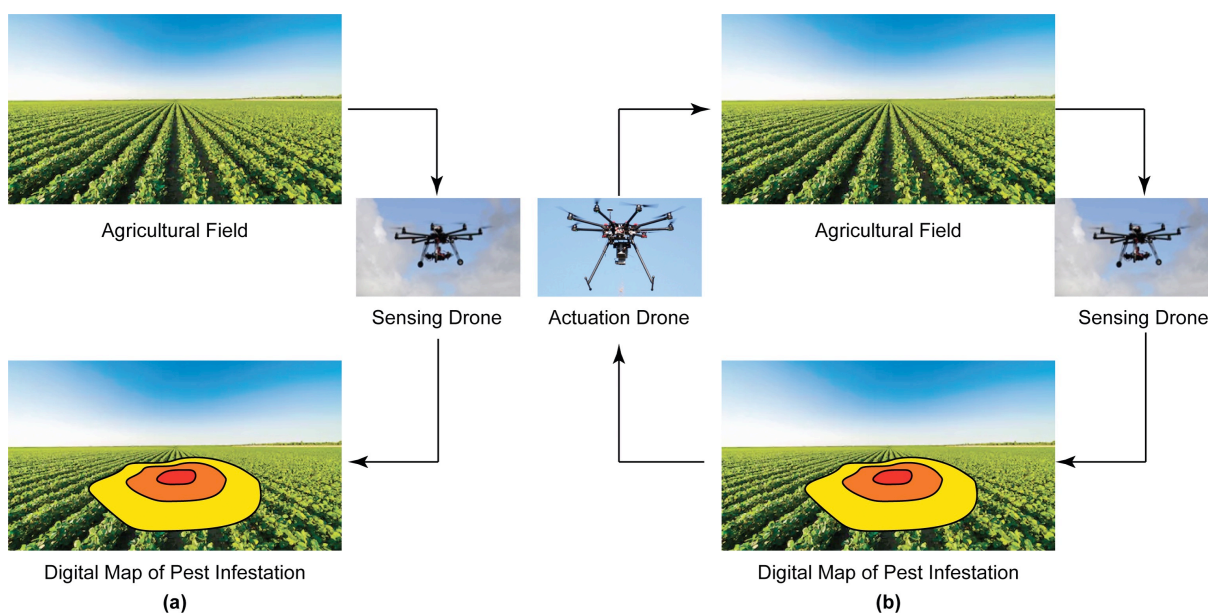


Figure 7: Sensing drone and actuation Drone (From Lost Filho et al. 2020). <https://doi.org/10.1093/jee/toz268>

5.2 Types of UAVs & spraying systems

Various types of UAVs are currently used for pesticide applications, ranging from single-rotor helicopters to multirotor systems, such as quadcopters, hexacopters, and octocopters (**Figure 8**) (Nahiyoon et al., 2024b). Single-rotor UAVs, often powered by petrol engines, provide higher payload capacity and longer flight duration, making them suitable for large-scale fields, though they require more advanced operation and maintenance. In contrast, multirotor drones are typically battery-powered and are becoming increasingly popular due to their stable hovering capability, manoeuvrability, and ability to perform precise, low-altitude spraying. They also offer motor redundancy, allowing safe landing even if one or two engines fail. Depending on the model, Octocopters typically support payloads between 10-30 kg (approximately 10-30 L) and are often used in rice, maize, and vegetable fields for localized treatment. Among these types, octocopters are currently widely adopted in agricultural practice, particularly in countries like China and Japan, due to their balance between efficiency, ease of use, and compatibility with automated flight planning systems. Their versatility makes them well-suited for targeted pest and disease control, especially in fragmented or smallholder farming landscapes. With eight rotors, octocopters offer superior stability, making them capable of maintaining position more accurately under challenging conditions such as strong winds. Octocopters can carry heavier payloads ranging from 6 to 20 kg or more, allowing for the use of larger and more advanced equipment or sensors (Anam et al., 2024). The drawback of the octocopters is that they are highly expensive.

Also, hexacopter is considered a popular device with relatively more stable devices compared with the quadcopter and with a high payload (heavier payloads, typically ranging from 3 to 6 kg). According to a previous study about UASS in orchards (Calderone et al., 2025), hexacopters account for about 40% of the UASS used, followed by quadcopters with 30% and octocopters with 24%.

A quadcopter is a relatively economical product and feasible for a wide range of users. According to the review report (Calderone et al., 2025), the 4-rotor UASS performed better than the 6-rotor and 8-rotor UASS in terms of deposition efficiency due to the 1.5 m working width corresponding to the canopy diameter, minimizing drift and ground losses while optimizing lateral coverage.

Regulatory frameworks in Europe remain strict, but pilot projects and digital agriculture initiatives have helped demonstrate the value of drones in improving application accuracy while reducing chemical inputs and operator exposure. Octocopters are one of the most widely adopted types for pest and disease control in European agriculture (Calderone et al., 2025), while quadcopters are also another product often used (Karam et al., 2024).

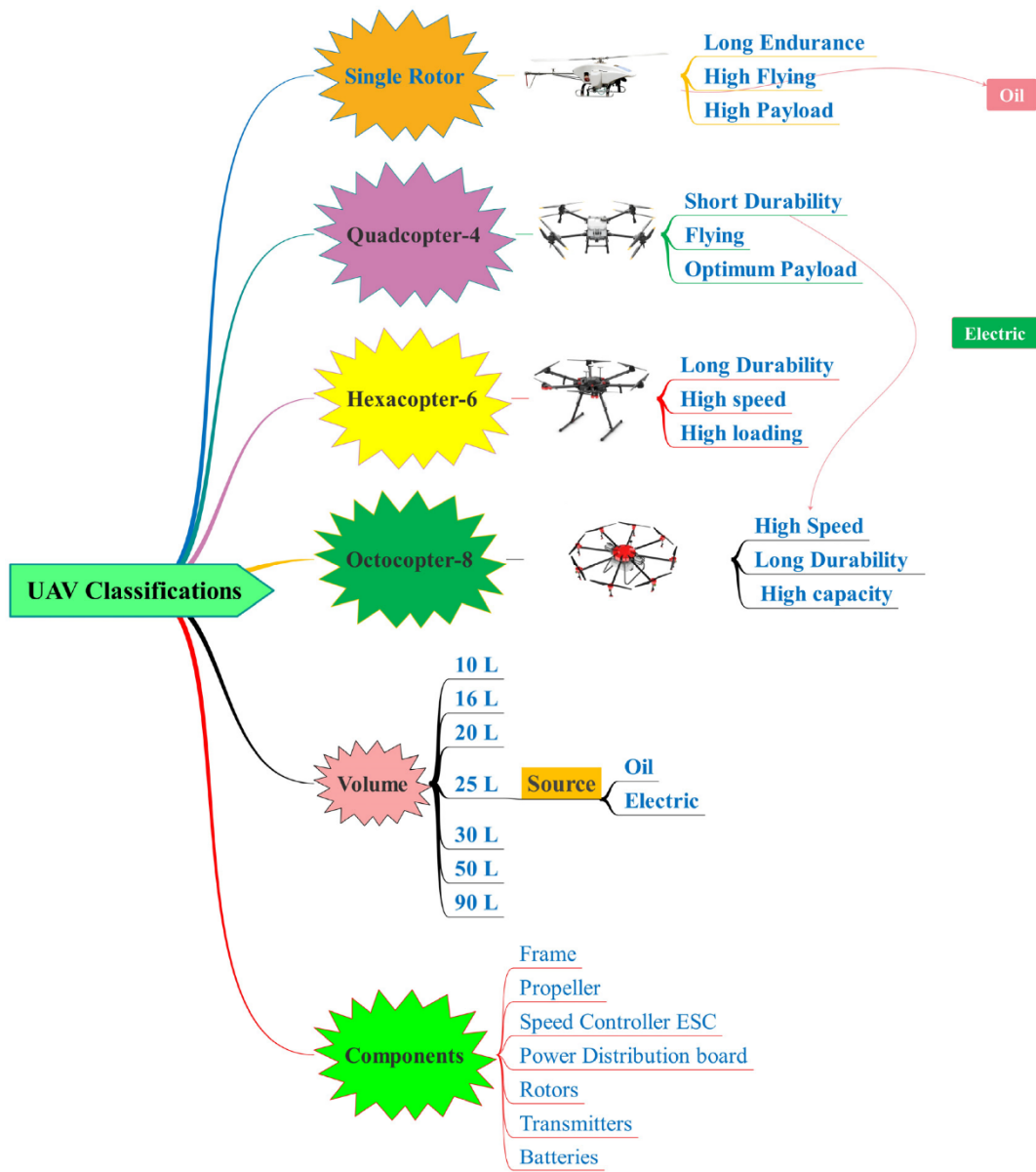


Figure 8: A wide range of different UAVs in the agriculture sector (Source: Nahiyoon et al., 2024). <https://doi.org/10.3390/drones8090457>

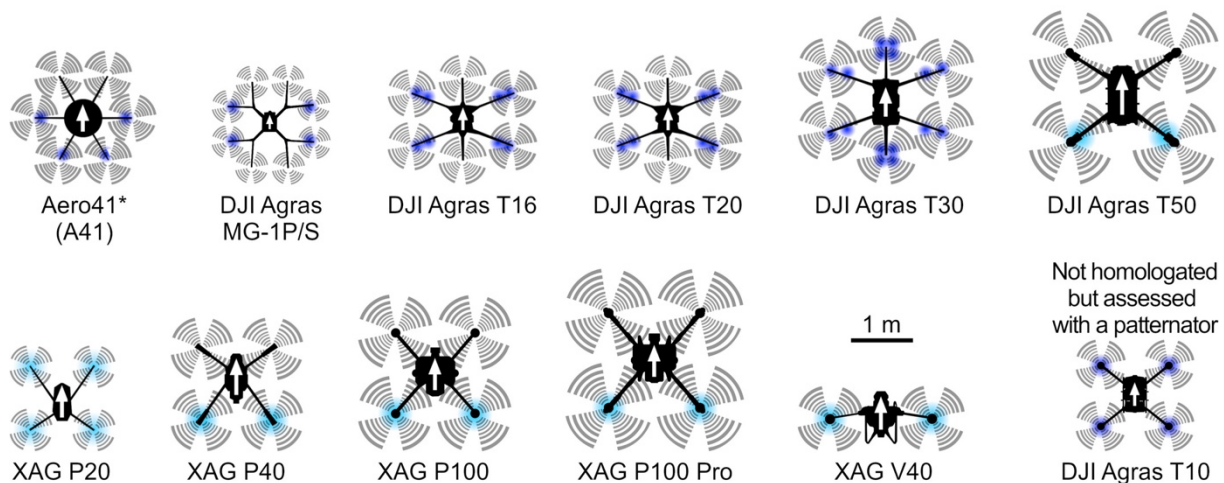


Figure 9: Example overview of UAV-models and their associated spraying systems. The front of each UAV is indicated with a white arrow. Nozzle/atomizer positions are indicated by coloured circles (dark blue = hydraulic nozzle, light blue = rotary atomizer). The scale applies to all UAV models shown. Original source: Anken et al., 2025.

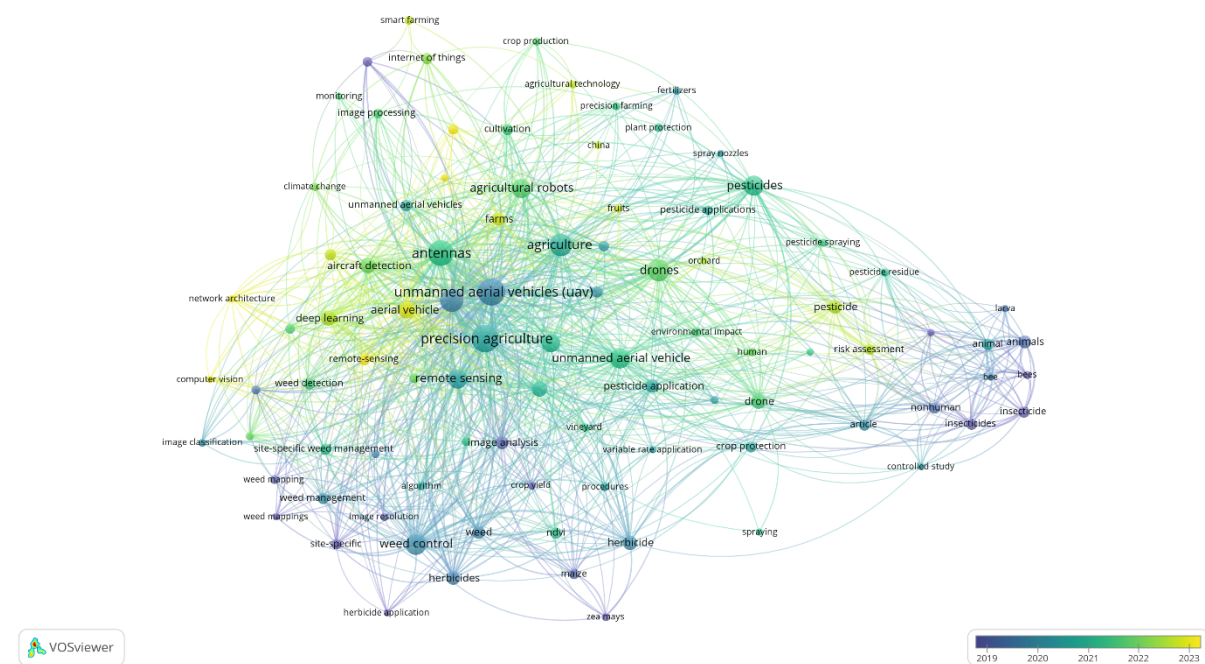


Figure 10: Clustering map of publication years generated through a bibliometric analysis of UAV-based pesticide application research using VOSviewer. The figure presents keyword co-occurrence networks, where node size reflects keyword frequency, link strength represents co-occurrence intensity, and colors denote temporal clusters. This visualization highlights emerging themes and shifts in research focus over time.

5.3 Evidence in Europe

5.3.1 Countries

Initially, 241 scientific publications were identified with the researchers affiliated with European institutions. After a relevance screening, 111 documents were retained for further analysis. The most active countries in this domain include Germany (n=36), Italy (n=36), the United Kingdom (n=34), and Spain (n=30). Figure 11

illustrates collaborative clusters among European researchers, with notable partnerships such as UK, Italy, Germany and Spain.

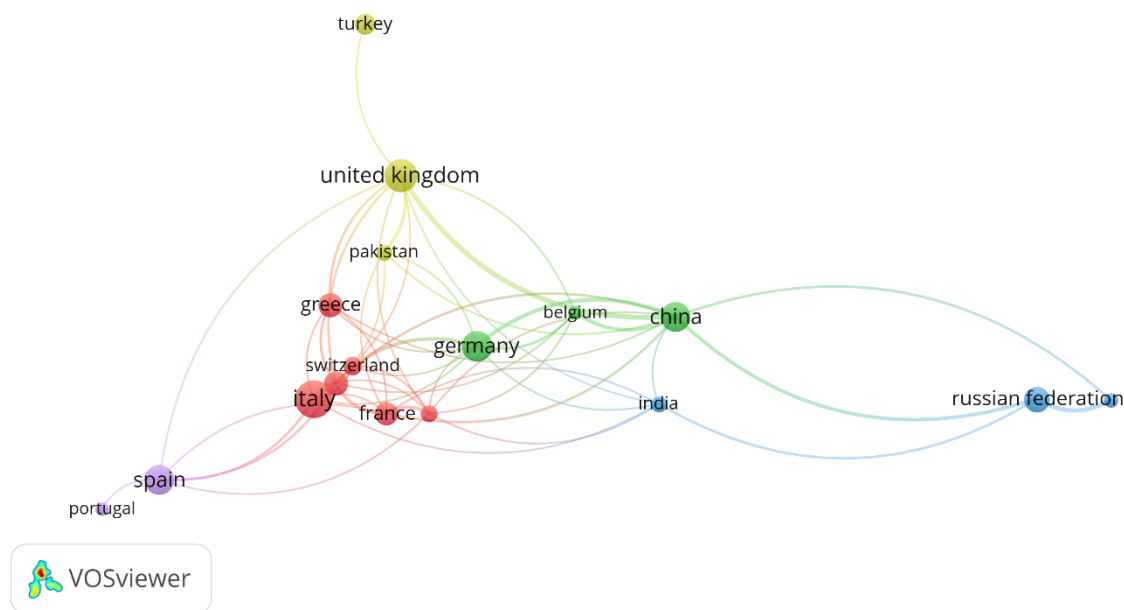


Figure 11: Clustering map with different countries, focusing on Europe in relation to the research on pesticide application by UAV.

Although a relatively higher number of scientific publications are released by authors from Germany, the context in most of them is related to sensing drones for monitoring field conditions and detecting pests and diseases, or ethical assessments about the UAV application (Frankelius et al., 2019; Reger et al., 2018). The reports on the application of PPP with UASS from Spain and Italy are more relevant findings for our assessment (Biglia et al., 2022; García-Munguía et al., 2024b; Martínez-Guanter et al., 2020; Sánchez-Fernández et al., 2025; Sarri et al., 2019a; Sassu et al., 2024; Farella et al., 2025). Recent reports are also originating in Greece, with trials on the environmental impact (Maritan et al., 2025). Regarding field trials, 7 documents out of 39 selected documents are related to them. However, only a couple of field trials were conducted in European countries. It is worth noting that several scientific papers have been published in Switzerland, covering a wide range of topics, including risk assessment and economic benefits, as Swiss regulation differs from that of the European Union (Anken et al., 2024, 2025). Switzerland is, however, a large UAV user, as a survey found that 11,3% of the total Swiss vineyards were treated with UAV sprayers in 2024 (Anken et al., 2025).

5.3.2 Crop types & field size

Major crops for UAV application for pest management are perennial crops such as vineyard, olive, orchard and rice (Bautista et al., 2024). Another report from Southern Italy (Testa et al., 2025)(Testa et al., 2025), which analyses the minimum farm size (break-even point) for introducing precision agriculture sprayers (PAS), revealed that the UAV sprayer—if permitted by law—could be the most convenient option for farms larger than 2.27 ha, counting on the annual cost of the pesticide treatments (equipment and pesticide costs).

5.4 Effect on PPP volume used

Several factors determine the performance of aerial pesticide application, including (1) release height, (2) droplet size distribution, and (3) wind speed, which together affect drift. In addition, flight speed, nozzle type and spacing, application volume, and spraying strategies (e.g., threshold-based or spot spraying guided by scouting) strongly influence coverage, deposition efficiency, and overall savings (Le et al., 2025; Chen et al., 2022; Yallap et al., 2024).

Across European crops, precision application has demonstrated pesticide savings ranging from 26% to over 96% (Table 6), depending on crop type and target—spanning herbicide use in cereals and maize to fungicide and general pesticide applications in grapevine—underscoring its strong potential to reduce plant protection product (PPP) volumes while maintaining effective crop protection.

Table 8: Reported reductions in pesticide use through precision application technologies across different crops, countries, and application targets. Savings are expressed as a percentage reduction in plant protection product (PPP) volume compared to conventional broadcast spraying.

Authors	Year	Country	Saving pesticide (%)	Crop Type	Pesticide Type/ Target
Melnychuk et al.	2024	Ukraine	~92.5%	Rapeseed	General spraying (not weed-specific)
Rasmussen et al.	2022	Denmark	26%	Barley	Herbicide (weed control via UAV)
López-Granados et al.	2016	Spain	85–96%	Maize	Herbicide (site-specific weed control)
Nikolić et al.	2021	Italy	42–93%	Maize	Herbicide (AI-based weed control)
Maritan et al.	2025	Greece	Up to 50%	Grape	General pesticide (spot-spraying)
Anken et al.	2025	Switzerland	Up to 66%	Grape	fungicide

5.5 Effect on efficacy and economics

Efficacy:

According to the Unmanned Aerial Pesticide Application System Task Forces (UAPASTF), the efficacy of UASS pesticide application is assessed by comparing performance with conventional methods. Current evidence is limited, but early studies suggest comparable performance to conventional methods, warranting cautious adoption (Portillo et al., 2025). Key determinants include: 1) target pest and crop; 2) pesticide characteristics (e.g., product mobility, required droplet size, the role of adjuvants), and 3) tank preparation and mixtures (e.g., timely spraying and using adjuvants). Overall, efficacy is not only about biological control but also about matching pesticide characteristics, application technology, and operational practices under UASS conditions (Portillo et al., 2025).

Economics:

A report from Spain in perennial crop fields shows that reducing the amount of pesticide applied by aerial vehicle reduces application costs to €/ha, compared to the conventional approach using hydro-pneumatic equipment (Martinez-Guanter et al., 2020). Allmendinger et al. (2024) estimated around 50% savings in herbicide use through spot spraying. The studies also revealed a notable reduction in labour time, saving approximately 10–15 minutes per hectare when using UASS in maize (*Zea mays* L.) fields. In addition, operating costs for conventional sprayers were 38% higher than those for UASS. A separate study from Greece confirmed that deploying UASS – specifically, medium-sized units with a capacity of over 10 L – becomes more cost-effective in olive groves when used for at least 70 hours per year (Cavalaris et al., 2022). Another study from Greece (Maritan et al., 2025) reports that the UASS approach in Greek viticulture generates total cost savings in the range of 278-377 €/ha on a flat field and 367-538 €/ha on a steep-slope field. An overview of UAV spraying applications in Italy found that UAV adoption involves high initial equipment costs, which are recouped through long-term benefits. A case-based assessment of the economic viability is essential (Farella et al, 2025). This study also reports on integrated technologies, in which conventional sprayers focus on the middle and lower canopy layers, while drones focus on the upper canopy layers. As such, the efficacy of this integrated approach can be higher than with individual techniques. A hybrid drone-rover system is also identified by Kartal et al. (2025), suggesting a best-of-both-worlds concept for optimising efficiency in complex terrain.



Figure 12: A UAV aerial application using a single-nozzle configuration. b Conventional spraying application of commercial product in orange trees using tractor+implement equipment. (From Jorge Martinez-Guanter et al., 2020: Doi:10.1007/s11119-019-09665-7)

5.6 Risk assessment

- Although not based in a European context, a study from China (Quan et al., 2023) provides valuable insight into the economic benefits of UAV adoption. In wheat cultivation, the use of UAV-based pesticide spraying increased farmers' revenue by approximately \$434–\$ 488 per hectare. Revenue peaked at an adoption intensity level of 3, reaching \$2,750/ha, but declined to \$1,500/ha at level 7, indicating diminishing returns. The decreasing marginal revenue suggests moderate UAV use yields the highest economic efficiency.
- A study in Southern Italy (Testa et al., 2025) found that UAV sprayers reduced pesticide use in vineyards by up to 32%, achieving disease control levels of 90–95% against downy mildew (*Plasmopara viticola*) and powdery mildew (*Erysiphe necator*) while lowering operational costs per hectare by 18–22%, equivalent to savings of roughly €55–70 per hectare compared to conventional tractor spraying. Testa et al. (2025) further showed that UAV spraying becomes the most convenient option for vineyards larger than ~2.3 ha, although cost-effectiveness is case-specific and depends on equipment price and pesticide costs. Most fixed costs for UAV spraying are linked to additional drone flights required to generate task maps, and variable costs are driven more by labour than in conventional spraying. Nevertheless, pesticide costs are consistently lower for UAV applications due to substantial reductions in product use, underscoring their strong performance in both economic and efficacy terms.
- In Switzerland, trials with UAVs were performed and compared with backpack applications. The trials concluded that the efficacy of UAVs for these cases was less than that of ground-based applications. This is particularly due to the much lower deposition at the lower parts of the plants – vines in this case (Anken et al., 2025). The UAV application used approximately one-third of the volume of the backpack sprayer, which is a significant benefit; however, its lower efficacy has limitations. Anken et al. (2025) therefore conclude that, particularly under high disease pressure, a combination of UAV and backpack spraying is recommended. Also, they expect that future UAV sprayer models might overcome this issue.
- Depending on fungal disease pressure, using a spray drone in Greek viticulture generated total cost savings in the range of 278–377 €/ha on a flat vineyard and 367–538 €/ha on a steep-slope vineyard. Nevertheless, in Greece, the application of UAVs for spraying is considered not economically advantageous, as the savings did not compensate for the additional costs of hiring UAV spraying. Farmers then prefer traditional methods despite the reported lower pesticide inputs (up to 50%) and the reduced labour inputs (Maritan et al, 2025). Also, the lower efficacy of UAV spraying reported here, in particular for higher disease pressure conditions, is a reason not to use UAVs (Maritan et al, 2025).

Table 9: Effect of UAV application on Efficacy and Economics

Country	Crop	Citation	Quantitative Highlight
Italy	Vineyards	Testa et al., 2025	32% pesticide reduction; disease control 90–95%; operational cost reduction 18–22% (€55–70/ha); UAV becomes most cost-effective for vineyards >2.3 ha.
Switzerland	Vineyards	Anken et al., 2025	UAV uses 1/3 of the spray volume of a backpack sprayer; lower efficacy in a lower canopy; combined UAV + backpack recommended under high disease pressure.
Greece	Vineyards	Maritan et al., 2025	Cost savings 278–377 €/ha (flat) and 367–538 €/ha (steep); pesticide use reduced up to 50%; not economically advantageous due to UAV service fees and lower efficacy under high pressure.
Spain	Perennial crops	Martínez-Guanter et al., 2020	UAV spraying reduces application costs by 7 €/ha vs. hydro-pneumatic machinery.
Germany	Maize	Allmendinger et al., 2024	50% herbicide savings; labour savings 10–15 min/ha; conventional sprayers have 38% higher operating costs than UASS.
Greece	Olive groves	Cavalaris et al., 2022	Medium-sized UAVs (>10 L) become cost-effective when used ≥170 hours/year.
Italy	Mixed crops / Vineyards	Farella et al., 2025	High initial cost; long-term benefits are case-specific; integrated drone + ground sprayer improves canopy-level efficacy.
Global	Diverse (e.g., rice, cotton, citrus)	Kartal et al., 2025	A review paper introducing a hybrid drone-rover spraying system to enhance field spraying efficiency; no quantitative results reported.
China	Wheat	Quan et al., 2023	UAV spraying increased revenue \$434–\$488/ha; peak revenue \$2,750/ha at adoption level 3; decline to \$1,500/ha at level 7 (diminishing returns).

5.6.1 Human health

1) Operator/worker and 2) Bystanders/residents

- Spray drift, volatilisation, and residues can lead to inhalation or dermal exposure. A recent study from Spain in high-density olive fields (Sánchez-Fernández et al., 2023) reports that downward UAV spraying shows a substantial reduction in airborne drift.
- Another study (Dubuis et al., 2023) assessed how pesticide spray drift from drone-assisted orchard spraying—specifically using the DJI Agras T30—may affect bystanders and nearby residents. The field study, conducted in accordance with ISO 22866, used fluorescent tracers and mannequins equipped with air sampling devices to simulate real-world exposure. The results revealed that both spray drift and human exposure levels declined as the height and distance from the treated area increased. Notably, 90% of the drift was confined within a 5-meter radius — more contained than results from earlier UAV or traditional spraying trials. Wind conditions, especially speed and direction, played a substantial role in influencing drift, whereas the crop's growth stage had minimal effect. Importantly, skin exposure from droplet contact on clothing was much greater than inhalation exposure, suggesting that dermal contact is the dominant pathway for pesticide exposure among bystanders and residents. Measured values for drift and exposure remained below thresholds predicted by EU and U.S. regulatory models, indicating potentially lower risks than conventional methods. While initial comparisons suggest the DJI drone may cause less off-target exposure than manned aircraft or ground sprayers, direct comparative trials are needed to confirm this.
- In Greece, reported exposure risk reductions are 0,5 for low disease pressure conditions and 0,4 for high pressure conditions - even without pesticide savings (Maritan et al., 2025).
- A Spanish study on operator exposure concluded that exposure risks when using UASS are lower than with conventional spraying. However, mixing and loading tasks resulted in higher than expected exposure, expected to be due to the higher frequency of mixing and loading operations (Sanchez-Fernandez et al, 2025). This study also concluded that exposure levels for residents and bystanders are lower than estimates from the EFSA OPEX Guidance 2022 and AgDRIFT®. Therefore, the study considers (the potential of) UASS as a safer technology for reducing residents' and bystanders' exposure, while improved procedures and techniques must be developed to minimise operator exposure.
- The report from Gao et al (2025), which the study adhered to the principles outlined in the OECD. Thus, it is relevant document for our study, although it is conducted in non-European context: Drones are safer than conventional methods, as they significantly reduce potential dermal exposure for both operators and bystanders compared to knapsack or tractor-mounted spraying. For instance, at 5 m from the spray area, mean dermal exposures were 91.8 mg/kg tracer on bare soil, 29.3 mg/kg on soybean, and 301.6 mg/kg in peach orchards, with the 95th percentile in orchards reaching >1000 mg/kg tracer. By contrast, exposures

from knapsack applications are several-fold higher than drone spraying under comparable conditions. Still, risk hotspots remain: within 5 m of the spray edge, orchard applications can produce exposure values 3–10 times higher than field crops, and windy conditions (>5 m/s) increase exposure more than threefold. Protective measures such as maintaining buffer zones of at least 10–20 m, monitoring wind conditions, and applying crop-specific strategies are critical to further reduce bystander exposure and safeguard human health.

- A study conducted in Ukraine on inhalation risks and respiratory impacts concluded that, for the pesticides examined, inhalation represents the dominant exposure pathway. The highest risk occurs during drone tank refueling, though exposure levels remained below permissible limits. No risks were detected outside the application zone, including downwind areas. Nevertheless, the study recommends the use of personal respiratory protective equipment when operating drones for pesticide application (Borysenko et al, 2025).
- A study from Germany (Felker et al., 2024) presents the evaluation of operator exposure during mixing and loading phases of drone-based pesticide application. Using Brilliant Blue G (wetable powder and suspension concentrate) as a surrogate pesticide, the study identified the mixing of concentrated products, particularly powders, as the primary exposure source, with dermal levels several-fold higher than during loading or piloting. Protective clothing and chemical-resistant gloves reduced exposure by 95–99%, confirming their essential role in risk mitigation. Bystander exposure during drone spraying was low, with meaningful risk limited to unprotected presence during mixing of concentrates. Stratified assessment indicates that stringent protection is required for mixing, moderate for loading, and minimal for piloting.
- Even though it is not conducted in a European country, a comparative study in Thailand on the operator exposure between handheld spray equipment and drones (Kuster et al., 2023) concludes that the use of drones for the application resulted in an exposure reduction of 90–99%. Farella et al. (2025) also report on Chinese evaluations of exposure risks. In mango fruit tree experiments, a higher exposure risk to bystanders is observed with coarser droplet sizes, particularly on the legs and chest.
- The UAPASTF, a consortium of nine agricultural chemical companies formed in December 2021, pools technical and financial resources to generate regulatory data for risk assessment of Unmanned Aerial Spray Systems (UASS). Its work supports evaluations of off-site movement, operator/handler exposure, and crop residues contributing to human dietary exposure, in line with recommendations outlined in the OECD Working Party on Pesticides Drone Subgroup. The proprietary data produced are intended to inform pesticide regulatory approval processes and are available to member companies or others who compensate for access. Recently, a scientific document was released to outline the overview of the “best management practices” guidance developed by the UAPASTF (Portillo et al., 2025).
- The Phytodron Operational Group, co-funded by the Spanish Ministry of Agriculture and the European Agricultural Fund for Rural Development, was created to assess the safety of Unmanned Aerial Spraying Systems (UASS) as an alternative to conventional spraying. Field trials in vineyards, citrus, pine trees, and olive groves evaluated human health risks, focusing on operator, pilot, auxiliary worker, resident, and bystander exposure. Non-dietary exposure protocols during grapevine treatments, alongside drift and residue assessments, provided comparative data against ground and manned aerial applications. Configured under ISO standards, UASS demonstrated potential to reduce occupational and non-occupational risks while maintaining efficacy, supporting evidence for revising Directive 2009/128/EC. In their result (Sánchez-Fernández et al., 2025), although not statistically significant, the results indicate that during UASS operations, the highest potential exposure occurs on the hands, followed by the legs, arms, and torso. This distribution reflects task characteristics: direct hand contact with plant protection products during mixing and loading, and increased exposure of the lower body during pump purging due to downward-oriented nozzles.
- In Horizon Europe, the project CHAMELEON (www.chameleon-heu.eu – finished in June 2025) developed a new drone for – amongst others – crop spraying. According to its public information, the project did not work on crop protection or related issues, such as efficacy, drift, or other aspects. It focused more on the drone's technical development and low-risk applications, such as fertilising.
- Another Horizon Europe project is ICAERUS (www.icaerus.eu - June 2022 until July 2026), which has drone spraying for crop protection as one of its use cases. The project builds experience and concrete results by testing and assessing spraying configurations for optimal drone spraying applications in field conditions. The Agricultural University of Athens is the lead partner in these activities, together with the Hellenic Crop Protection Association (HCPA). Although their main focus is on vineyards, the project also appears to examine spraying operations for other crops. The project's results are also mentioned in scientific papers (e.g., Sassu et al, 2024).

5.6.2 Environmental

3. Surface water + aquatic organisms:

UAV spraying increases the risk of pesticide drift to surface waters and non-target organisms. According to Albasser et al (2025), up to 25% of pesticides can become airborne, contaminating nearby water bodies and harming aquatic life. Drift can reduce wild plant diversity by over 50% within 500 m of fields, affecting pollinators and other species. Despite improved precision, UAV spraying produces 5–8 times more drift than ground methods, highlighting the need for strict buffer zones and weather-based controls to protect ecosystems (Albasser et al., 2025).

4. Terrestrial area + non-target organisms:

While plant protection products (PPPs) help control pests and increase yields, they can also harm non-target organisms through soil and water contamination, particularly via airborne drift. In a comparative study (D'Alessandro et al., 2024) of traditional tractor-mounted spraying versus drone-based application of Spintor® Fly in olive orchards, both methods showed no significant difference in impact on soil microarthropods and earthworm behaviour. However, the drone application showed a slightly lower impact, suggesting a potentially safer alternative for non-target soil organisms. These initial findings support the sustainable use of drones in agriculture, though further long-term research is needed. A study conducted in olive orchards in southern Spain reported significantly higher pesticide deposition in intra-row areas when using conventional ground-based orchard sprayers than when using UAV sprayers. In contrast, no significant difference was observed between the two methods in inter-row zones. The study also highlighted that UAV spraying showed greater variability in spray patterns, with a tendency toward lower droplet density and less uniform deposition than terrestrial sprayers (Sanchez-Fernandez et al., 2024).

A recent literature review by Norwegian researchers (Nibio, 2024) examines environmental exposure risks associated with drone-based pesticide application. After comparing drone and aerial spraying methods across multiple studies, the review finds no consistent or conclusive patterns. The authors highlight the need for drone-specific spray drift values to improve environmental exposure assessments within the EU regulatory framework.

The Phytodon Operation Group also addressed environmental risks for non-target organisms, generating evidence on potential reductions in unintended exposure. Configured in accordance with ISO standards, UASS demonstrated promise for reducing human and environmental risks while maintaining efficacy, informing the possible revision of Directive 2009/128/EC. According to their article, the measured dermal exposure of residents and bystanders was lower than estimates predicted by EFSA OPEX Guidance (2022) and AgDRIFT®. These results suggest that UASS may offer a safer alternative to conventional ground and aerial spraying methods (Sánchez-Fernández et al., 2025).

5. Groundwater risks:

A targeted search found no peer-reviewed European studies directly assessing groundwater contamination from UAV spraying. Current European literature centres on drift and operator exposure, as well as regulatory implementation, indicating a clear data gap for groundwater risk under UAV-specific operating conditions. Until such data are available, FOCUS groundwater models (PEARL/PELMO/PRZM) should be parameterised for UAV applications (e.g., spray volume, timing) to support screening assessments.

5.7 Limitations & challenges

Research output on UAV-based pesticide application remains relatively limited in European countries compared to the USA, China, India, and Brazil. This disparity stems in part from the EU's stricter regulations and the lower number of approved biopesticide-active substances, which constrain experimentation and innovation (Balog et al., 2017). Meanwhile, East Asian countries such as China, Japan, and South Korea have a long history of UAV applications due to the suitability of their use for the field conditions (e.g., smaller fields and paddy rice) and have increasingly adopted UAVs as efficient alternatives to manual spraying (He et al., 2017). The USA, by contrast, continues to permit many pesticides that have already been banned in the EU, Brazil,

and China (Donley, 2019). In China, the adoption of UAVs for pesticide application has had measurable economic benefits, notably increased farmer revenue and reduced labour time (Quan et al., 2023).

This study has shown that, across the available literature, there is a consistent trend toward reduced pesticide use and decreased environmental risk from drift when using UAV-based spraying approaches. However, the diversity of crops, geographic contexts, UAV platforms, application parameters, and the frequent lack of detailed reporting limit the generalisability of these findings.

Moreover, only a small number of studies have directly assessed different risk indicators. Future research should address key technical limitations identified in current practices, including:

1. Droplet Drift

UAV spraying is susceptible to wind-induced droplet drift, leading to off-target deposition and environmental contamination. Achieving optimal droplet size is critical yet challenging under variable weather conditions. Three interrelated factors influence spray drift (Sassu et al., 2024; Gil et al., 2015; Ling et al., 2018).

- Droplet size is influenced by the type of nozzle and the formulation of the product.
- Weather conditions, including wind speed and direction;
- Mode of application, such as flight height, speed, positioning (over rows or inter-rows), and rotor-generated airflow.

A study in Italian vineyards (Biglia et al., 2022) highlights this complexity, showing that ground deposition varied by application type (air-inclusion vs. conventional), application speed, and altitude. Uniform droplet distribution in large or irregular fields is difficult, often resulting in untreated or over-treated areas.

In Switzerland, a study has been done to relate the lateral wind produced by the UAV rotors. The study shows that lateral wind speeds are relatively low and are not associated with the drone's size or weight. When compared to ground-based sprayers with fans, the UAVs are less likely to cause drift (Anken et al., 2025)

2. Uneven Coverage

Ensuring uniform droplet distribution is challenging, especially in large or irregularly shaped fields, often leading to untreated or over-treated zones. Several studies report improved coverage with UAV spraying, particularly in orchards, trees, and complex terrains (Kartal et al., 2025; Farfella et al., 2025). Farfella et al. (2025) found that, when properly calibrated, UAVs can achieve up to 70% leaf coverage, enhance efficiency, and reduce chemical use. However, uneven spray distribution remains a limitation—fine droplets (<200 µm) drift easily, and UAVs deposit more spray on the upper canopy (~43%), whereas conventional sprayers concentrate on the middle and lower canopy (~61%). Improving nozzle design, flight parameters, and multi-device coordination, while applying ISO 23117 standards, is essential to achieving uniform and effective spray coverage.

3. Limited Payload Capacity

Most UAVs have limited payload capacity, requiring frequent refuelling for large-scale operations. This increases operational time and labour requirements. The amendment to EASA Decision 2023/012/R raised the weight limit for agricultural drones, enabling higher payload capacity. For this extended risk assessment, weight is not considered to impose additional risks. Although this decision has been welcomed by the industry, it keeps drones limited to a 3-meter span width, which is another constraint that has, of course, an impact on payload capacity.

4. Battery Life and Flight Range

Battery life limits flight duration and the area that can be treated in a single operation.

5. Spray Quality Variability by Target Position

Droplet size, density, and coverage can vary depending on the sprayer type and the target canopy zone (upper, middle, or lower parts of the plant/tree) (Sarri et al., 2019).

6. Payload Volume Changes During Flight

As the spray tank empties, changes in rotor speed and airflow may alter the spray pattern, potentially increasing drift risk (Weicai & Panyang, 2023)(Weicai & Panyang, 2023). While skilled pilots can partially compensate through flight adjustments, this underscores the importance of training and calibration to maintain consistent application (Weicai & Panyang, 2023).

7. Swath Width Management

Maintaining a proper swath width is critical to avoiding off-target spray drift. According to Sánchez-Fernández et al. (2024), UAV sprayers should ideally allow for swath-width adjustments to accommodate field heterogeneity. In addition, it is important to note that UAVs require careful calibration to account for swath displacement, which depends on both the UAV model and the nozzles used. Proper calibration is crucial to prevent applications in unintended areas and minimise overlaps.

5.7.1 Mitigation & solutions (nozzles, adjuvants, PWM)

Nozzle Optimisation:

The choice of nozzle significantly affects spraying precision and efficacy. Selecting the appropriate nozzle type for specific conditions and crops is essential (Anken et al., 2024; Kovalev et al., 2024). The air induction nozzle is considered environmentally safer due to its drift reduction capability, as it produces larger, air-filled droplets that are less likely to be carried off-target by wind (Szwedziak et al., 2020)

Recently, differences between centrifugal and pressure nozzles have been highlighted. Pressure nozzles rely on liquid pressure to force spray through an orifice, whereas centrifugal (rotary) nozzles use a rotating cup or disc to fling liquid outward by centrifugal force. Furthermore, deposition efficiency can be improved by equipping UAVs with multiple centrifugal nozzles instead of a single atomizing unit (Xu et al., 2025)—computers and electronics in agriculture.

Table 10: Key features of rotary (centrifugal) and pressure-based spraying systems commonly used in UAV pesticide application, comparing mechanisms, droplet characteristics, operational requirements, and suitability for drone use.

Feature	Rotary (Centrifugal) spraying	Pressure-based spraying
Mechanism	Spinning disc/cup, droplets by centrifugal force	Liquid forced through an orifice
Droplet control	By rpm and flow rate	By pressure and orifice size
Droplet spread	Narrow, uniform	Wide, less uniform
Clogging	Low	Higher
Energy	Motor (adds weight/power use)	Pump (moderate demand)
Maintenance	More complex	Simple
Cost	Higher	Lower
Use in drones	Precision, drift control, low volume	Light, low cost, general use

Use of Adjuvants:

Incorporating adjuvants into spray mixtures can improve droplet size, reduce drift, and enhance adhesion to plant surfaces. Few field studies, particularly in paddy fields, have investigated the application of adjuvants in UAV-based spraying (Eun et al., 2024)(Eun et al., 2024). Beyond conventional tank-mix adjuvants, several patent families found on patents.google.com explicitly target UAV applications and low-volume aerial spraying, proposing adjuvant systems optimized for drift control, droplet retention, and anti-evaporation under UAV operating conditions (e.g., WO2020225276 A1; CN110583636 A; EP3994981 A1; US20220217973 A1). These patents indicate an active formulation pipeline for UAV spraying that is not yet widely reflected in the peer-reviewed literature.

Advantages of Solenoid Valve Nozzle Systems with PWM in UAV Spraying:

Solenoid valve nozzle systems with adjustable pressure and Pulse Width Modulation (PWM) provide a precise and responsive solution for variable-rate UAV spraying. The solenoid valve acts as the hardware—rapidly opening and closing—while PWM controls it by pulsing at high frequency, adjusting the duty cycle to regulate flow without altering pressure. Unlike traditional pressure-based systems, which adjust flow by changing pressure (often causing delays and inconsistent droplet sizes), PWM maintains constant pressure and delivers uniform droplet sizes across varying rates. This improves canopy coverage and reduces drift. PWM also allows

instant nozzle control for site-specific applications and maintains spray consistency regardless of speed or nozzle count. Although mostly studied on ground-based platforms, this technology shows strong potential for UAV-based precision agriculture due to its accuracy and efficiency (Sebayang et al., 2024; Wang et al., 2024; Zhu et al., 2010).

5.8 Conclusions

Drone-based spraying systems show clear potential for more precise and adaptive crop protection, particularly in challenging terrain and high-value or 3D crops. Existing studies indicate that UASS can reduce pesticide use and achieve efficacy comparable to ground sprayers, while lowering operator and bystander exposure. Nevertheless, spray drift remains a major concern, and adoption in Europe is hindered by regulatory constraints, limited field evaluations, and technical limitations such as payload and battery capacity. UASS is therefore a promising yet still evolving technology that requires further validation and standardisation before wider implementation.

Significant evidence gaps persist, particularly the scarcity of large-scale, geographically diverse field trials, limited data on long-term environmental outcomes, and insufficient understanding of drift behaviour across varying microclimatic and crop conditions. The absence of harmonised testing protocols also restricts meaningful comparison with conventional application methods. Addressing these gaps—including generating robust dose–response data, developing standard drift-mitigation guidelines, and improving models that reflect real operational variability—is essential for supporting science-based regulation and ensuring the safe and effective integration of UASS into crop protection strategies.

6 General conclusions & future perspectives

This study has identified extensive recent research demonstrating the potential of spot and patch application techniques and UAVs to support more precise and adaptive pest and disease management. These technologies offer the possibility to reduce pesticide inputs, limit environmental contamination, and support biodiversity while maintaining productivity, thereby contributing to broader EU policy goals aimed at reducing pollution and combating climate change. However, important gaps remain in the publicly available data necessary to fully incorporate these technologies into European exposure and risk assessment frameworks.

At present, European risk assessment remains largely anchored in broadcast spraying under worst-case assumptions, which does not capture the risk-mitigating potential of spatially restricted or sensor-guided precision applications. Evidence from recent UAV-focused studies further shows that UAS-mediated applications can produce distinct drift and deposition profiles, and that these profiles vary substantially with flight height, speed, droplet spectrum, and payload design (Morgan et al., 2024). Such findings reinforce the need for risk assessments that reflect realistic operational conditions rather than relying solely on generic broadcast-based defaults. As some of the information required for this transition may already exist in private or non-public datasets, while other essential elements still need to be generated, multi-stakeholder collaboration will be essential to identify, prioritise, and fill these knowledge gaps in a timely manner.

The modalities of use of emerging technologies remain central to determining their contribution to precision application and associated risk-mitigation benefits. This is particularly relevant for UAVs, which may function as precision-application devices under specific operational conditions but not under others. Clarifying these conditions is essential for robust regulatory assessment. Recent work by the European Precision Application Task Force (EUPAF) highlights the need for harmonised definitions, use categories, and GAP-table descriptions across Member States (Alix et al., 2025).

The uneven geographical distribution of publications highlights disparities in research activity on UAV-based pesticide application across Europe. Notably, several EU Member States—such as Austria, Ireland, Hungary, Bulgaria, Croatia, and the Baltic States (Estonia, Latvia, and Lithuania)—do not appear in the dataset because no publications meeting the defined search criteria were indexed in Scopus. This absence reflects the current state of the published literature rather than a limitation of the search strategy or bibliometric analysis. Future studies should examine these geographical gaps in greater detail and document how research activity on UAV-based pesticide application is distributed across EU Member States under varying regulatory, agronomic, and technological contexts. These geographical gaps further reinforce the need for risk assessment frameworks that are informed by a broader and more representative evidence base.

Emerging regulatory discussions further show that many exposure outcomes depend not only on reduced application volume but also on the location, spatial pattern, and resolution of treatment, which influence run-off, drift, soil exposure, and non-target organism interactions. Regulatory toxicology research emphasises the value of probabilistic, multi-scenario exposure assessment approaches to address the variability inherent in precision applications, especially UAV- and sensor-triggered treatments that do not follow uniform patterns (Morgan et al., 2024). As a result, future EU frameworks will require flexible, tiered modelling approaches—from simple conversion factors to refined drift models and population-level ecological models—to represent heterogeneous application patterns (Isemer et al., 2025; Alix et al., 2025). Spatially explicit datasets, including UAV detection logs, prescription maps, and georeferenced application documentation, will therefore play a central role in enabling more realistic exposure estimation.

To support a future policy shift toward EU risk assessments that explicitly consider precision application, we recommend targeted data generation in the following priority areas:

- High-resolution spray drift and deposition data for patch, spot, and UAV applications under representative meteorological and operational conditions.

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- Field-validated operator, bystander, resident, and environmental exposure scenarios that reflect actual precision-application practices rather than broadcast-based defaults.
 - Quantification of biological efficacy thresholds to confirm that reduced-area treatments maintain acceptable pest control performance.
 - Environmental fate and transport studies that incorporate the spatial heterogeneity created by precision applications.
 - Standardised performance metrics and operational definitions, especially for UAVs, specifying when these systems constitute precision applications.
 - Interoperable digital data frameworks, building on standards such as ISO-11783 (ISOBUS), to support transparent data exchange and integration into farm management and risk-assessment systems (Calliera et al., 2013).

Several current initiatives already illustrate the importance of improved data availability. Responsible agrochemical use must align with EU policy frameworks such as Directive 2009/128/EC, which encourages integrated pest management and non-chemical alternatives (Yu et al., 2025). Large-scale projects such as SPRINT are generating extensive residue datasets to improve understanding of human and ecological exposure pathways (Silva et al., 2021). Advances in digital technologies—including autonomous spraying systems, adaptive nozzles, real-time sensing, and AI-based decision support—demonstrate clear potential for increasingly accurate variable-rate applications. The integration of UAV-generated data into Farm Management Information Systems has also been successfully demonstrated in European test farms, highlighting the relevance of digitalisation for transparency, traceability, and cross-stakeholder collaboration (Merz et al., 2022).

Once robust, standardised data are available, EU regulatory frameworks can be refined to better recognise the contribution of precision application technologies to risk reduction. This will support appropriate use and wider adoption of UAVs and targeted spot or patch treatments, improve alignment with sustainability objectives, and help deliver on EU commitments to reduce pollution, protect biodiversity, and strengthen climate resilience.

To enable a future policy shift in the EU toward risk assessments aligned with precision application technologies, targeted data generation is urgently needed. Priority areas include: (1) field-validated drift and deposition datasets for UASS, variable-rate sprayers, and autonomous platforms across different crops, canopy structures and meteorological conditions; (2) dose–response studies demonstrating whether reduced use rates enabled by precision targeting maintain agronomic efficacy and resistance management outcomes; (3) run-off and environmental exposure measurements comparing precision application with conventional broadcast spraying; (4) standardised protocols for capturing real-world operator and bystander exposure under precision systems; and (5) longitudinal datasets showing cumulative reductions in pesticide load at landscape scale. Collectively, these datasets would provide the empirical foundation regulators need to adapt EU risk assessment frameworks to reflect the lower exposure profiles and improved environmental performance inherent to precision application technologies.

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Annex 1: Search Queries

For spot and patch application:

(TITLE-ABS-KEY (spray* OR appl*) AND TITLE-ABS-KEY (spot OR patch) AND TITLE-ABS-KEY (pesticide OR herbicide OR insecticide OR nematicide) AND TITLE-ABS-KEY (agricul* OR farm* OR horti*)) AND PUBYEAR > 2013 AND PUBYEAR < 2026 AND (LIMIT-TO (AFFILCOUNTRY , "United Kingdom") OR LIMIT-TO (AFFILCOUNTRY , "Germany") OR LIMIT-TO (AFFILCOUNTRY , "Spain") OR LIMIT-TO (AFFILCOUNTRY , "Italy") OR LIMIT-TO (AFFILCOUNTRY , "Russian Federation") OR LIMIT-TO (AFFILCOUNTRY , "Greece") OR LIMIT-TO (AFFILCOUNTRY , "Switzerland") OR LIMIT-TO (AFFILCOUNTRY , "France") OR LIMIT-TO (AFFILCOUNTRY , "Turkey") OR LIMIT-TO (AFFILCOUNTRY , "Belgium") OR LIMIT-TO (AFFILCOUNTRY , "Ukraine") OR LIMIT-TO (AFFILCOUNTRY , "Portugal") OR LIMIT-TO (AFFILCOUNTRY , "Netherlands") OR LIMIT-TO (AFFILCOUNTRY , "Denmark") OR LIMIT-TO (AFFILCOUNTRY , "Finland") OR LIMIT-TO (AFFILCOUNTRY , "Serbia") OR LIMIT-TO (AFFILCOUNTRY , "Sweden") OR LIMIT-TO (AFFILCOUNTRY , "Romania") OR LIMIT-TO (AFFILCOUNTRY , "Norway") OR LIMIT-TO (AFFILCOUNTRY , "Israel") OR LIMIT-TO (AFFILCOUNTRY , "Czech Republic") OR LIMIT-TO (AFFILCOUNTRY , "Slovenia") OR LIMIT-TO (AFFILCOUNTRY , "Slovakia") OR LIMIT-TO (AFFILCOUNTRY , "Poland") OR LIMIT-TO (AFFILCOUNTRY , "Maldives") OR LIMIT-TO (AFFILCOUNTRY , "Cyprus") OR LIMIT-TO (AFFILCOUNTRY , "Iceland") OR LIMIT-TO (AFFILCOUNTRY , "Ireland") OR LIMIT-TO (AFFILCOUNTRY , "Hungary")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "cr")) AND (LIMIT-TO (LANGUAGE , "English")))

For UASS application:

(TITLE-ABS-KEY (spray* OR appl*) AND TITLE-ABS-KEY (uav OR "unmanned aerial vehicle" OR "uncrewed aerial vehicle" OR drone* OR uass OR rpas) AND TITLE-ABS-KEY (pesticide OR herbicide OR insecticide OR nematicide) AND TITLE-ABS-KEY (agricul* OR farm* OR horti*)) AND PUBYEAR > 2013 AND PUBYEAR < 2026 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "cr")) AND (LIMIT-TO (AFFILCOUNTRY , "United Kingdom") OR LIMIT-TO (AFFILCOUNTRY , "Germany") OR LIMIT-TO (AFFILCOUNTRY , "Spain") OR LIMIT-TO (AFFILCOUNTRY , "Italy") OR LIMIT-TO (AFFILCOUNTRY , "Russian Federation") OR LIMIT-TO (AFFILCOUNTRY , "Greece") OR LIMIT-TO (AFFILCOUNTRY , "Switzerland") OR LIMIT-TO (AFFILCOUNTRY , "France") OR LIMIT-TO (AFFILCOUNTRY , "Turkey") OR LIMIT-TO (AFFILCOUNTRY , "Belgium") OR LIMIT-TO (AFFILCOUNTRY , "Ukraine") OR LIMIT-TO (AFFILCOUNTRY , "Portugal") OR LIMIT-TO (AFFILCOUNTRY , "Netherlands") OR LIMIT-TO (AFFILCOUNTRY , "Denmark") OR LIMIT-TO (AFFILCOUNTRY , "Finland") OR LIMIT-TO (AFFILCOUNTRY , "Serbia") OR LIMIT-TO (AFFILCOUNTRY , "Sweden") OR LIMIT-TO (AFFILCOUNTRY , "Romania") OR LIMIT-TO (AFFILCOUNTRY , "Norway") OR LIMIT-TO (AFFILCOUNTRY , "Israel") OR LIMIT-TO (AFFILCOUNTRY , "Czech Republic") OR LIMIT-TO (AFFILCOUNTRY , "Slovenia") OR LIMIT-TO (AFFILCOUNTRY , "Slovakia") OR LIMIT-TO (AFFILCOUNTRY , "Poland") OR LIMIT-TO (AFFILCOUNTRY , "Maldives") OR LIMIT-TO (AFFILCOUNTRY , "Cyprus") OR LIMIT-TO (AFFILCOUNTRY , "Croatia") OR LIMIT-TO (AFFILCOUNTRY , "Austria") OR LIMIT-TO (AFFILCOUNTRY , "Bulgaria") OR LIMIT-TO (AFFILCOUNTRY , "Ireland") OR LIMIT-TO (AFFILCOUNTRY , "Iceland")))

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