

Article

Improving Resource Efficiency in Plant Protection by Enhancing Spray Penetration in Crop Canopies Using Air-Assisted Spraying

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Abstract

Efficient pesticide application remains a critical resource-management challenge in modern agriculture, where limited spray penetration reduces treatment efficacy, wastes chemical inputs, and increases environmental losses. This study quantified the effect of air-assisted spraying (AAS) on droplet deposition in two contrasting field crops, oilseed rape and wheat. Field trials were conducted using a sprayer equipped with an adjustable airflow module, and spray coverage was measured with water-sensitive papers at multiple canopy heights and orientations. In oilseed rape, AAS improved deposition on front-facing and top surfaces in the lower canopy, for example, increasing top-surface coverage at 90 cm from 53.4% to 65.5% at $6 \text{ km} \cdot \text{h}^{-1}$, indicating more uniform distribution and enhanced penetration. In wheat, which typically exhibits a more open canopy structure compared to oilseed rape, AAS effects were smaller and less consistent, with the greatest gain on front-facing lower surfaces (from 13.3% to 21.9% at $7 \text{ km} \cdot \text{h}^{-1}$). Although drift was not measured in this experiment, previous studies using the same sprayer prototype demonstrated measurable reductions, supporting the environmental relevance of improved deposition. These results highlight the role of canopy architecture in determining AAS performance and underscore the technology's potential to reduce pesticide inputs, minimize off-target losses, and improve the resource efficiency of crop protection in line with EU Farm to Fork objectives.

Keywords: canopy penetration; air-assisted spraying; spray deposition efficiency; resource-efficient plant protection; food as a resource; pesticide use reduction; sustainable agriculture; water-sensitive paper; wheat canopy; oilseed rape canopy



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1. Introduction

The application of pesticides in agriculture is essential to protect crops from pests and diseases as well as to ensure high yields [1–4]. Consequently, the efficient and sustainable use of plant protection chemicals remains one of the critical challenges in modern crop production [5–8]. One of the key limitations to effective pesticide application is the insufficient penetration of spray droplets into dense or structurally complex plant canopies, resulting in uneven coverage, increased chemical waste, and environmental contamination [9–12]. This issue is particularly pronounced in crops such as cereals, oilseed rape, legumes, and leafy vegetables, where conventional spraying methods often fail to ensure uniform distribution of spray liquid across vertical and spatial zones of the plant structure [11,13–15].

To address this problem, technologies that enhance canopy penetration while reducing pesticide losses are gaining increasing attention. Among these, air-assisted spraying (AAS) technology has emerged as one of the solutions. The additional airflow introduced into the crop canopy generates turbulence, which helps to open the plant structure and improve droplet deposition on both upper and lower leaf surfaces, as well as on vertical plant parts [8,16–18]. This can lead to more effective pest and disease control using smaller volumes of spray liquid and fewer active ingredients, thereby supporting agronomic performance while minimizing environmental impact and resource use.

However, most existing research on AAS has been conducted in orchards, vineyards, or controlled environments, with limited evidence available for open-field crops such as wheat and oilseed rape. Moreover, previous studies often lack detailed assessments of spatial deposition patterns across different canopy zones under realistic field conditions. This knowledge gap restricts the ability to optimize AAS settings for diverse crop architectures and operational parameters.

The issue of efficient resource use in pesticide applications is not limited to chemical savings alone. Sprayer design also affects energy demand, fuel consumption, and associated greenhouse gas emissions [19–21]. These findings highlight the importance of optimizing spraying systems not only for droplet deposition but also for sustainability-related performance indicators, such as power consumption and environmental load. Therefore, innovations that enhance spray effectiveness, such as AAS, not only improve coverage but may also contribute to more efficient use of plant protection products and enable informed decisions on whether to activate air assistance based on crop type, canopy structure, and prevailing weather conditions.

In the context of increasing regulatory pressure to reduce pesticide use and mitigate environmental risks, improving the efficiency of spray applications has become a priority in both research and agricultural practice [22–24]. The European Union’s Farm to Fork Strategy, for example, aims to reduce the use and risk of chemical pesticides by 50% by 2030, further emphasizing the need for innovative and sustainable plant protection technologies [24,25].

Therefore, the objective of this study is to provide empirical field-based evidence on the performance of AAS in two contrasting crop canopies, i.e., wheat (*Triticum aestivum*) and oilseed rape (*Brassica napus*), under realistic operating conditions. Using a mobile sprayer prototype equipped with an adjustable air-assistance module, we evaluated spray deposition at multiple canopy heights and orientations to capture spatial distribution patterns.

By addressing this gap, our study contributes to the development of more resource-efficient and environmentally responsible spraying practices, in line with integrated pest management and sustainable agriculture principles.

The findings may inform precision spraying guidelines for field crops, support future equipment design, and guide policy recommendations. Moreover, the insights gained can facilitate the development of decision-support tools for farmers and manufacturers, encouraging the adoption of precision spraying technologies in large-scale crop production.

2. Materials and Methods

The primary objective of the experiment was to evaluate the canopy penetration efficiency of the mobile boom sprayer with and without the use of air assistance. The experimental setup used to assess canopy penetration is shown in Figure 1.

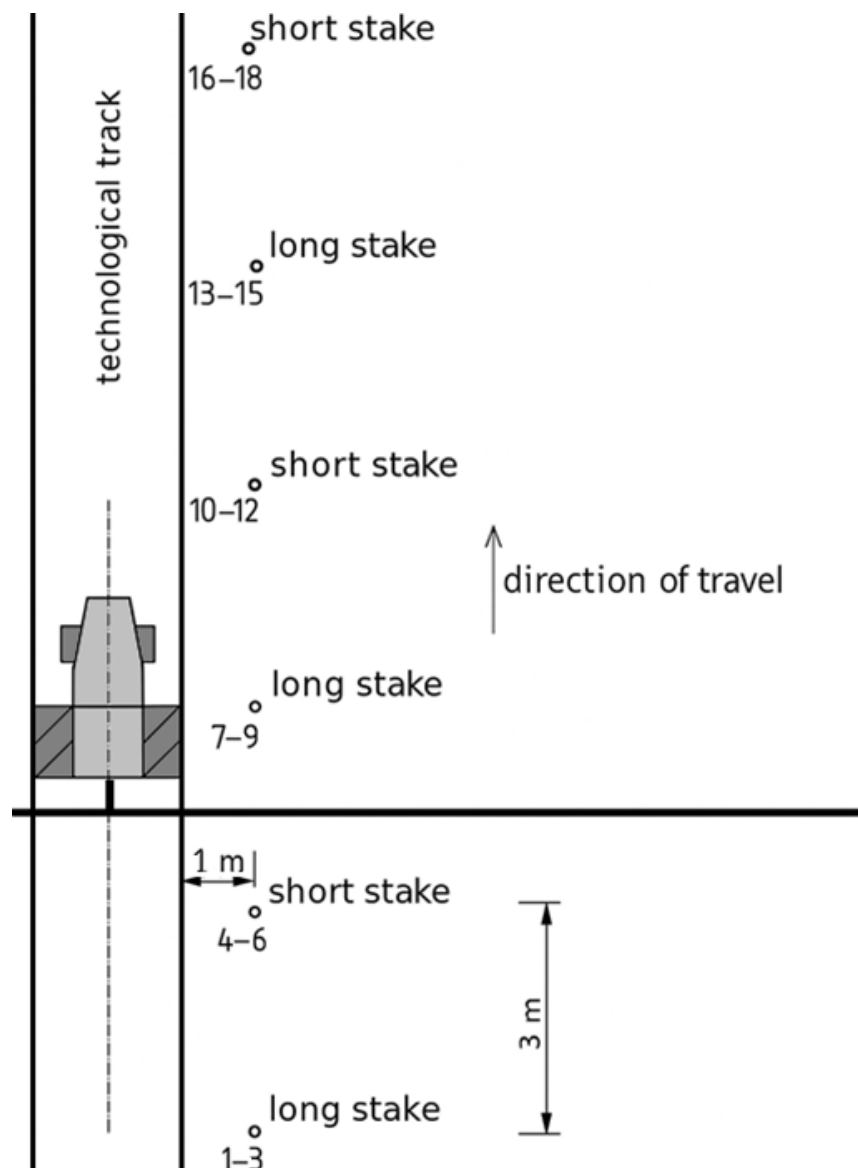


Figure 1. Schematic representation of the experimental setup showing the arrangement of wooden stakes (short and long) and the positions of water-sensitive papers (indicated by numbers); the diagram also shows the direction of sprayer movement and key dimensions.

The experimental setup consisted of a Claas AXOS 330 tractor (CLAAS Group, Harsewinkel, Germany) [26] paired with a detachable field sprayer equipped with an air-assisted spraying system. This sprayer was a prototype developed by AGROLA Zdzisław Niegowski (Płatkownica, Poland) as part of the research project “A family of field sprayers with an air-assisting stream” [27]. The prototype sprayer (Figure 2) featured a 3000 L tank and a hydraulically operated boom with a working width of 21 m. For transport, the boom could be folded inward on both sides. The unit was mounted on two wheels fitted with 270/95R42 tires (Michelin Group, Clermont-Ferrand, France) [28].

Both experiments, i.e., conducted in wheat and oilseed rape, took place in June 2023 at the Teaching and Experimental Station of the University of Warmia and Mazury in Olsztyn. Figure 3 shows representative photographs from the field experiments.



Figure 2. Photograph of the prototype field sprayer used in the study.



(a)



(b)

Figure 3. Sample photographs documenting the experiment in oilseed rape (a) and wheat (b).

Spraying was performed using Lechler 110-03 standard flat-fan nozzles (Lechler GmbH, Metzingen, Germany). The operating pressure of the spray liquid was maintained at 0.3 MPa, and clean water was used as the spraying medium. In treatments with air assistance, airflow velocity was calibrated following a procedure previously applied and described in [29]. Briefly, air velocity was measured using a Testo 410 anemometer (Testo SE & Co. KGaA, Lenzkirch, Germany) [30] at multiple positions along the boom and at approximately 0.5 m from the air outlets.

The working speeds of the sprayer unit were set to 6, 7, and 8 km/h. These values were selected based on common field practice, as reported in [31], where typical working speeds in agricultural spraying fall within this range.

The experiment was carried out under appropriate spraying conditions [32], with wind speeds ranging from 0.50 to 1.5 m/s, ambient temperatures between 15 and 20 °C, and relative humidity levels of 60–70%. Weather parameters were recorded directly at the test site using the same Testo 410 anemometer as mentioned above. This device offers a measurement range of 0.4 to 20 m/s for air velocity (accuracy: ± 0.2 m/s + 2% of the measured value; resolution: 0.1 m/s), -10 to $+50$ °C for temperature (accuracy: ± 0.5 °C;

resolution: 0.1 °C), and 0 to 100% RH for humidity (accuracy: $\pm 2.5\%$ RH within the 5–95% RH range; resolution: 0.1% RH).

Temperature and humidity were measured both before and during each spraying run. Although minor fluctuations were observed, all runs were conducted under stable and controlled environmental conditions.

Spray deposition is typically assessed using either fluorescent tracers or water-sensitive papers (WSPs) [5,8,33–35]. Both methods provide reliable estimates of spray coverage [35] and are widely applied under laboratory and field conditions. In this study, WSPs were selected because they offer a practical and well-established approach for evaluating relative spray coverage in field experiments [35,36]. However, their sensitivity to very fine droplets is lower than that of fluorescent tracers, which should be considered when interpreting absolute deposition values.

The WSPs used in the experiment were manufactured by Syngenta (Syngenta Global AG, Basel, Switzerland) and had standard dimensions of 76 mm in length and 26 mm in width, resulting in a surface area of 1976 mm² [37].

Before each sprayer pass, short and long wooden stakes were alternately positioned in a single row within the crop canopy. These stakes served as mounting points for the WSPs, which were placed at different heights. The long stakes corresponded to the full canopy height, while the short stakes were half as tall.

Each stake carried three WSPs: one mounted horizontally at the top and two mounted vertically on opposite sides. The horizontal paper was used to capture droplets falling from above, while the vertical papers registered droplet impact from the direction of sprayer travel and from the leeward side.

As illustrated in Figure 1, each sprayer pass resulted in 18 WSPs being exposed. With six replications conducted for each crop species, a total of 108 WSPs were collected per crop for canopy penetration analysis. Number of replications per crop was in line with commonly adopted designs in on-farm and agronomic trials, where 4 to 6 blocks replications are considered a pragmatic balance between logistical constraints and statistical reliability [38,39].

The experiment was performed in two stages:

- stage I (NAA—No Air Assistance): spraying without the air assistance;
- stage II (WAA—With Air Assistance): spraying with the air stream activated.

Both stages were carried out at a constant application rate of 300 L/ha and included all three forward speeds (6, 7, and 8 km/h).

For rapeseed, WSPs were positioned at heights of 130 cm (top of canopy) and 90 cm (mid-height). In the case of wheat, the respective heights were 70 cm and 40 cm.

The collected water-sensitive papers were scanned at a resolution of 600 dpi in *.bmp format using an HP Deskjet 3520 scanner (Hewlett-Packard Company, Palo Alto, CA, USA). All image processing and analyses were conducted in the MATLAB R2014a (MathWorks, Natick, MA, USA) environment [40], employing previously validated image analysis procedures [8,41,42].

The first step of the analysis involved image binarization, which was carried out using Otsu's automatic thresholding method [43,44]. This method, one of the most widely used and cited thresholding techniques [42,45–47], determines an optimal binarization threshold by minimizing the weighted sum of within-class variances for foreground and background pixels [43–45]. Otsu's algorithm is widely recognized for its high effectiveness, simplicity of implementation, and low computational requirements. As demonstrated in the studies by Lipiński and Lipiński [41,42], this method is particularly well suited for processing water-sensitive paper images.

Exemplary scanned images of the water-sensitive papers used in the analysis are presented in Figure 4.

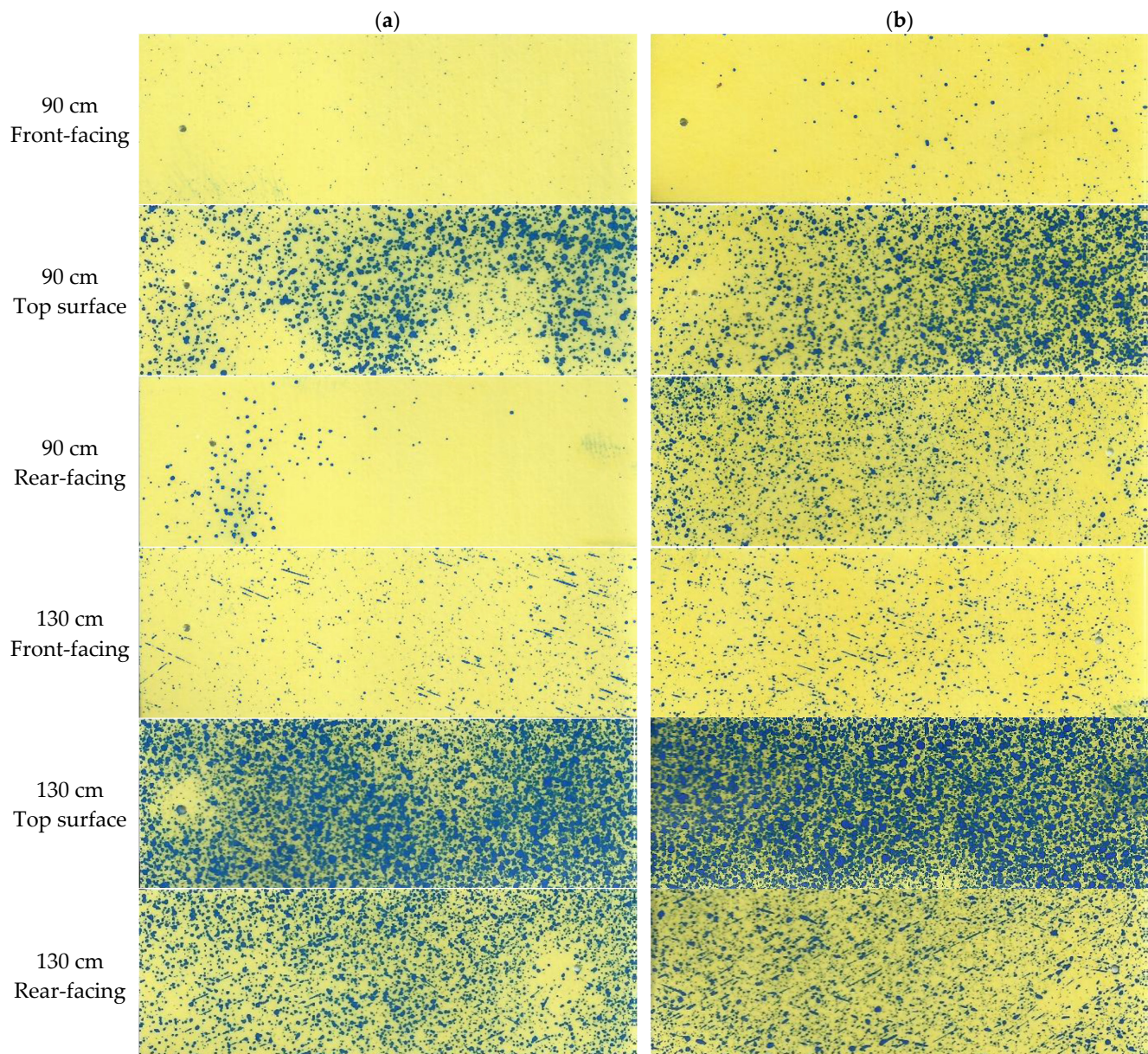


Figure 4. Representative scanned images of water-sensitive papers collected during spraying in oilseed rape at an aggregate speed of 6 km/h. Panels show WSPs obtained without air assistance (a) and with air assistance (b), for each mounting surface, i.e., facing sprayer approach, facing sprayer departure, and top. Blue areas indicate regions wetted by spray droplets, while yellow areas correspond to unwetted (dry) surfaces.

Based on the digitized and subsequently binarized images, the spray coverage was calculated as the percentage of the paper surface area covered by liquid droplets. The formula used for calculating the coverage was as follows:

$$coverage[\%] = \frac{covered\ surface\ area\ [mm^2]}{1976\ [mm^2]} [\%]. \quad (1)$$

To evaluate whether the differences between groups were statistically significant, we applied an independent samples Student's *t*-test at a significance level of $p = 0.05$. Before

performing the test, the assumptions of normality and homogeneity of variances were verified using the Shapiro–Wilk and Levene’s tests, respectively.

The analysis focused on pairwise comparisons between spraying configurations (with and without AAS) within each experimental scenario. Although the experimental design included multiple factors, our primary research question was whether AAS provides a significant improvement under each specific condition rather than testing interactions between factors. Therefore, the *t*-test was considered appropriate for this purpose. All statistical computations were carried out in the MATLAB R2014a environment (MathWorks, Natick, MA, USA) [40].

3. Results

The results of the experiments are presented separately for oilseed rape and wheat to account for differences in canopy structure. The analysis focuses on the impact of air-assisted spraying on canopy penetration, evaluated through the coverage of water-sensitive papers placed at two heights and exposed in three orientations: front-facing, top surface, and rear-facing.

3.1. Spray Penetration in Oilseed Rape Canopy

Table 1 summarizes the spray coverage results for oilseed rape, illustrating the effects of air assistance across three forward speeds, two measurement heights, and three exposure directions.

Table 1. Influence of air assistance on coverage of water-sensitive papers in oilseed rape at two heights (130 cm and 90 cm), three aggregate speeds (6, 7, and 8 kmph), and three exposure directions (front, top, rear). Air-assisted spraying notably increased deposition on rear- and front-facing surfaces, particularly at lower canopy levels, while the top surfaces already showed high coverage under non-assisted conditions.

Aggregate Speed	Air Assistance	Front-Facing		Top Surface		Rear-Facing	
		130 cm	90 cm	130 cm	90 cm	130 cm	90 cm
6 kmph	No	0.94%	2.06%	22.56%	53.38%	0.60%	27.04%
	Yes	1.77%	6.69%	41.93%	65.48%	9.47%	9.77%
7 kmph	No	0.33%	3.08%	19.53%	43.31%	1.03%	29.99%
	Yes	2.79%	4.49%	20.93%	44.76%	8.60%	13.64%
8 kmph	No	0.37%	1.69%	23.58%	61.35%	0.78%	22.19%
	Yes	0.67%	2.80%	20.19%	47.85%	7.70%	26.40%

Overall, air assistance tended to increase spray coverage on the front-facing surfaces and the top surfaces, particularly at the lower measurement height (90 cm), which is typically more sheltered by the canopy. For example, at 6 km/h, front-facing coverage at 90 cm increased from 2.06% without air assistance to 6.69% with air assistance, while top-surface coverage at the same height rose from 53.38% to 65.48%. In contrast, coverage on the rear-facing surfaces generally decreased under air assistance, likely due to airflow displacing droplets away from the sheltered side of the plants.

At intermediate speed (7 km/h), similar trends were observed, albeit with slightly lower rear-facing values. However, at the highest speed tested (8 km/h), the effects of air assistance were less consistent across exposure directions, suggesting that excessive forward speed may reduce the effectiveness of air assistance in transporting droplets deeper into the canopy.

These observations suggest that moderate driving speeds combined with air assistance offer the most favorable conditions for improving canopy penetration in oilseed rape.

Figure 5 illustrates the distribution of spray coverage on vertical surfaces within the oilseed rape canopy, based on water-sensitive papers placed on the front- and rear-facing sides of vertical collectors at two canopy depths (90 cm and 130 cm), comparing spraying with and without air assistance.

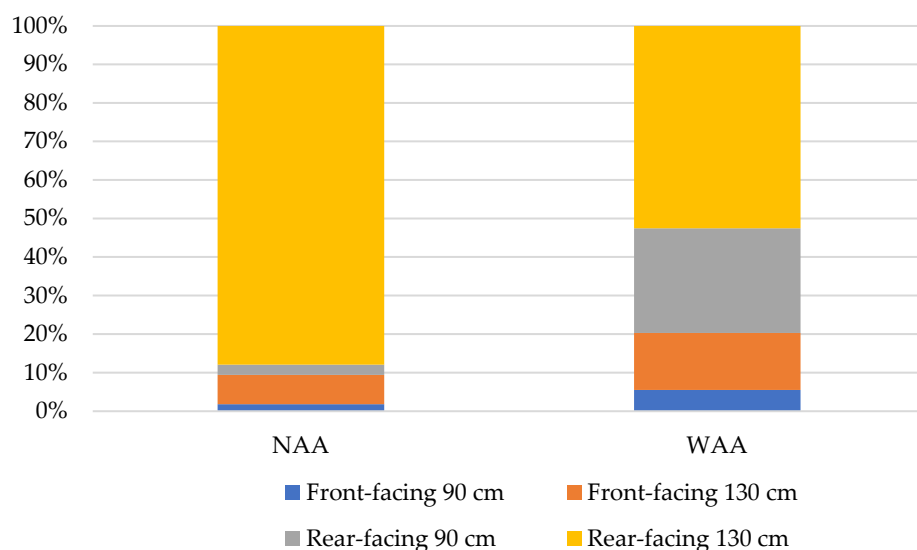


Figure 5. Distribution of spray coverage on vertical surfaces of water-sensitive papers in oilseed rape, placed at two canopy depths (90 cm and 130 cm) and oriented either toward the sprayer (front-facing) or away from it (rear-facing)—comparison between treatments with no air assistance (NAA) and with air assistance (WAA). Air-assisted spraying markedly improved deposition at the lower canopy depth (90 cm), indicating better penetration into the dense canopy, and reduced the dominance of rear-facing coverage.

The observed distribution of spray coverage in oilseed rape reveals a substantial shift in deposition patterns when air assistance is applied. In the NAA configuration, most of the deposition was concentrated on the rear-facing surfaces at 130 cm, indicating limited canopy penetration and poor distribution uniformity. In contrast, WAA resulted in a more balanced coverage pattern, with a notable increase in deposition on both front- and rear-facing surfaces at both depths. These findings highlight the role of air assistance in promoting deeper penetration of spray droplets and improving coverage uniformity across multiple orientations. Such improvements are especially relevant for crops with dense and structurally complex canopies, where passive spray deposition tends to be inefficient.

Figure 6 presents the total spray coverage in the oilseed rape canopy at two heights (90 cm and 130 cm), including all orientations of the water-sensitive papers (front-facing, rear-facing, and top-facing surfaces), under spraying with and without air assistance.

The results in Figure 6 highlight the impact of air assistance on overall spray coverage within the oilseed rape canopy. In the NAA configuration, deposition was highly concentrated in the upper canopy (130 cm), where total coverage exceeded 80%, while significantly lower values (23%) were observed deeper in the canopy (90 cm). When air assistance was applied, coverage at 90 cm increased markedly to over 38%, suggesting improved penetration and more uniform distribution of spray droplets. Although total coverage at 130 cm decreased slightly under WAA, it remained high at approximately 74%, indicating that deeper deposition was enhanced without substantially compromising upper canopy coverage. These results confirm the effectiveness of the air-assisted system in improving overall spray distribution in dense crop structures like oilseed rape.

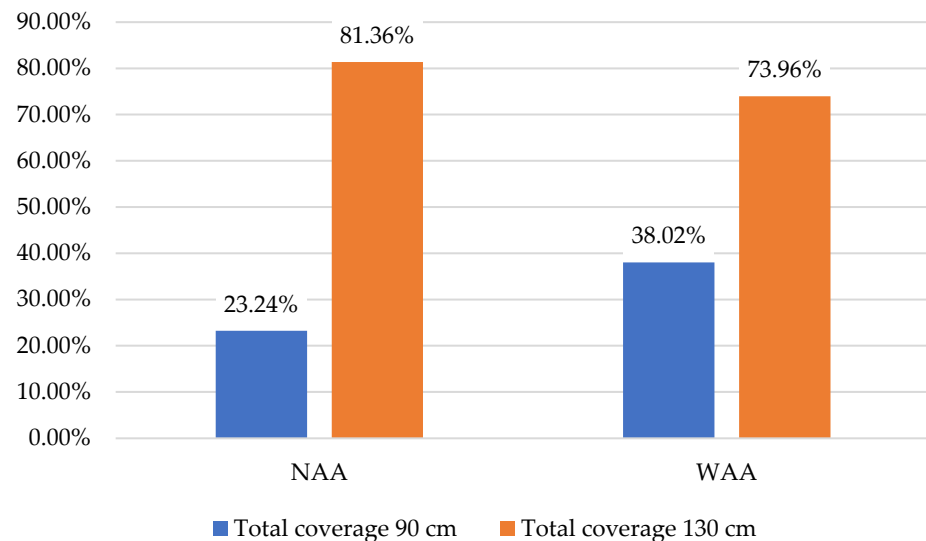


Figure 6. Total spray coverage in oilseed rape canopy at two heights (90 cm and 130 cm), based on combined data from front-facing, rear-facing, and top-facing water-sensitive papers, for treatments with (WAA) and without (NAA) air assistance. Air assistance increased coverage at the lower canopy level while reducing it at the upper level, resulting in more uniform distribution.

3.2. Spray Penetration in Wheat Canopy

Table 2 presents the results of spray coverage measurements in wheat, similarly to those obtained for oilseed rape, illustrating the influence of air assistance across three aggregate speeds, two paper heights, and three exposure directions. Compared to oilseed rape, the wheat canopy is more open and vertically less complex, which generally facilitates droplet movement through the canopy [48–51].

Table 2. Influence of air assistance on coverage of water-sensitive papers in wheat at two heights (70 cm and 40 cm), three aggregate speeds (6, 7, and 8 kmph), and three exposure directions (front, top, rear). Air-assisted spraying had a limited and variable effect on deposition in wheat, with slight increases on front-facing surfaces at lower heights, while top and rear surfaces showed minor or inconsistent changes depending on speed, indicating that airflow benefits are less pronounced.

Aggregate Speed	Air Assistance	Front-Facing		Top Surface		Rear-Facing	
		70 cm	40 cm	70 cm	40 cm	70 cm	40 cm
6 kmph	No	0.51%	2.54%	28.33%	58.34%	3.05%	20.46%
	Yes	1.42%	13.52%	31.43%	59.05%	4.43%	20.15%
7 kmph	No	2.08%	13.33%	34.61%	68.30%	2.06%	6.05%
	Yes	2.74%	21.92%	28.41%	42.92%	3.72%	2.55%
8 kmph	No	3.53%	12.31%	37.47%	64.19%	2.02%	7.86%
	Yes	1.54%	15.90%	27.82%	47.76%	4.75%	4.06%

Overall, the results shown in Table 2 demonstrate that air-assisted spraying had a positive but less uniform effect on droplet deposition in wheat. The most notable improvements were observed at the lower paper height (40 cm), especially in the front-facing orientation—for example, at 7 km/h, front-facing coverage increased from 13.33% (no air assistance) to 21.92% (with air assistance).

However, the impact of air assistance varied more strongly with speed. At the highest speed (8 km/h), air assistance did not consistently increase spray coverage, and in some cases (e.g., top surface at 70 cm), coverage decreased compared to NAA conditions. This

suggests that excessive air flow velocity combined with high forward speed may disrupt droplet trajectory, especially in less dense canopies.

Additionally, rear-facing coverage remained relatively low across all speeds, indicating that even with air assistance, deeper penetration from behind was limited in wheat.

Figure 7 illustrates the distribution of spray coverage on vertical surfaces within the wheat canopy, based on water-sensitive papers attached to the front- and rear-facing sides of vertical collectors at two canopy heights, comparing spraying with and without air assistance.

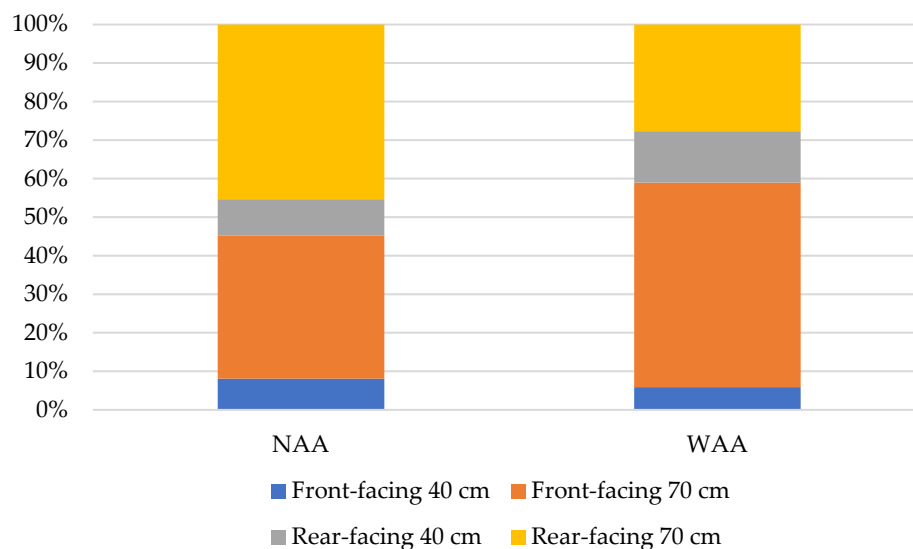


Figure 7. Distribution of spray coverage on vertical surfaces of water-sensitive papers in wheat, placed at two canopy depths (40 cm and 70 cm) and oriented either toward the sprayer (front-facing) or away from it (rear-facing)—comparison between treatments with no air assistance (NAA) and with air assistance (WAA). Air assistance had a less pronounced effect on canopy penetration than in oilseed rape but again reduced rear-facing coverage.

The spray coverage pattern in wheat shows a different response to air assistance compared to oilseed rape. Even without air assistance (NAA), a relatively high proportion of spray was deposited on front-facing surfaces at both canopy depths, indicating that the canopy structure of wheat allows for easier droplet penetration than that of oilseed rape. The introduction of air assistance (WAA) led to only a slight increase in rear-facing deposition, primarily at 40 cm, while the overall distribution remained front-focused. These findings suggest that in wheat, due to its less complex and more open canopy architecture, air support plays a less critical role in achieving vertical surface coverage than in denser crops. Nonetheless, air assistance still contributes to an improvement in uniformity, particularly in the lower canopy zones.

Figure 8 illustrates the total spray coverage in the wheat canopy at two heights (40 cm and 70 cm), incorporating data from all orientations of water-sensitive papers (front-facing, rear-facing, and top-facing), under both air-assisted and non-air-assisted spraying conditions.

As shown in this figure, air assistance (WAA) led to a redistribution of spray coverage within the wheat canopy. Without air assistance (NAA), coverage was significantly higher in the upper canopy (70 cm), reaching over 84%, while coverage deeper in the canopy (40 cm) remained below 38%. The use of air assistance slightly reduced upper canopy coverage (to ~76%) but did not substantially improve deposition at 40 cm, where coverage remained around 35%. These results suggest that in the case of wheat, i.e., a crop with a more open canopy structure compared to rapeseed, the effect of air assistance on deeper penetration was less pronounced.

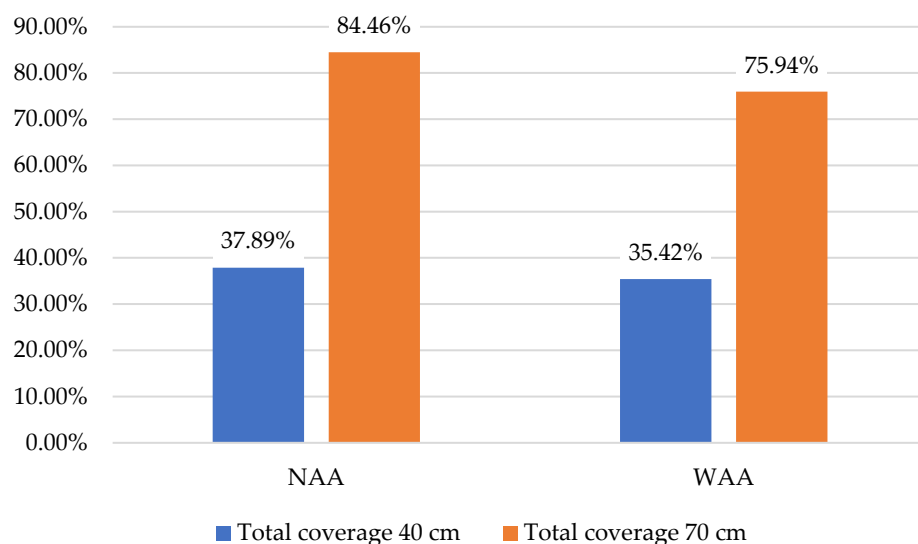


Figure 8. Total spray coverage in wheat canopy at 40 cm and 70 cm heights, based on the sum of coverage from front-facing, rear-facing, and top-facing water-sensitive papers, under treatments with (WAA) and without (NAA) air assistance. Air assistance improved coverage uniformity but reduced overall coverage, which is an undesirable effect.

4. Discussion

The spray coverage results obtained for oilseed rape and wheat reveal important differences in the effectiveness of air-assisted spraying, largely driven by canopy architecture and aggregate speed. Oilseed rape, characterized by a dense and complex canopy, showed significant improvement in droplet penetration with the use of air assistance, particularly on rear-facing surfaces and at lower canopy levels. This indicates that air support effectively transports droplets deeper into compact structures, overcoming the natural barrier formed by overlapping leaves and stems.

In contrast, wheat, with its more open and vertically oriented canopy, exhibited less consistent benefits. While some improvement was observed, especially on front-facing surfaces at lower heights, the overall gains were smaller and more variable. In certain scenarios, the introduction of air assistance even reduced coverage, most likely due to droplet deflection or overshooting caused by excessive airflow at higher forward speeds.

Although the primary focus of this study was to evaluate general trends in canopy penetration under different air-assisted conditions, the observed differences were statistically significant ($p < 0.05$) in oilseed rape, confirming that the effects of air assistance are systematic rather than random. However, the variability observed in wheat, particularly at higher forward speeds, suggests that further multivariate or interaction analyses could reveal additional dependencies between airflow, travel speed, and canopy structure.

The contrasting deposition responses between oilseed rape and wheat can be further understood via mechanistic insights from air-leaf-droplet interactions. As recent reviews emphasize, the structure and porosity of the canopy strongly influence the wind field and turbulence within the crop [18,52]. In dense canopies (e.g., oilseed rape), airflow meets considerable resistance, generating turbulence and localized low-pressure zones that assist droplet transport into interior layers. Additionally, modest airflow-induced leaf motion (deflection and/or vibration) can intermittently expose abaxial surfaces, enhancing deposition [18,53]. Conversely, in more open, vertically structured canopies (e.g., wheat), the air jet may pass through with limited turbulence. At higher forward speeds, this can produce bypass flows, droplet deflection or overshooting, reducing net deposition on target surfaces [52]. Thus, while air assistance improves penetration in dense structures, in

open canopies careful calibration of airflow intensity is critical to avoid perturbing droplet trajectories detrimentally.

These observations suggest that

- air assistance is more beneficial in dense canopies, where natural droplet penetration is limited;
- in more open canopies like wheat, the optimal airflow intensity and travel speed must be carefully balanced to avoid negative effects on spray deposition;
- the interaction between airflow, canopy structure, and forward speed plays a critical role in determining the effectiveness of air-assisted spraying.

A comparative analysis of vertical surface spray coverage (Figures 5 and 7) supports these conclusions. In oilseed rape, spraying without air assistance (NAA) led to highly uneven deposition, with most spray deposited at the top rear-facing surfaces (130 cm) and very limited coverage on front-facing or lower surfaces. This illustrates poor penetration and strong directional bias in passive spray applications.

In contrast, wheat showed more balanced spray distribution even under NAA conditions. Most droplets reached front-facing surfaces at both 40 cm and 70 cm heights, and although rear-facing deposition was lower, it was observed at all levels. Air assistance improved rear-facing deposition in both crops, but the effect was more pronounced in oilseed rape, confirming that denser canopies benefit more significantly from enhanced droplet transport and turbulence induced by the air assistance.

The comparison of total spray coverage across canopy depths (Figures 6 and 8) further underlines these differences. In oilseed rape, air assistance improved spray penetration into the middle canopy layer (90 cm), increasing coverage from 23.24% (NAA) to 38.02%, albeit with a slight reduction at the top (from 81.36% to 73.96%). In wheat, air assistance led to a small reduction in coverage at both 40 cm (from 37.89% to 35.42%) and 70 cm (from 84.46% to 75.94%). This indicates that in open canopies, where passive deposition already reaches inner layers, additional airflow may sometimes redistribute droplets in less favorable ways.

The variability observed in wheat supports this interpretation, reflecting less stable aerodynamic behavior. This variability warrants further factorial or mixed-effects analysis to quantify the relative contribution of canopy type, airflow, and travel speed.

These patterns emphasize the need for precision in spraying parameters. By integrating canopy-specific airflow settings, sprayers can minimize drift and maximize on-target deposition, aligning with principles of precision agriculture and sustainable pest management [54–57].

Our findings align with previous research [18,33,58–61] and underscore the importance of adapting spraying strategies to the specific canopy architecture of each crop. As noted by [60], air-assisted spraying proves particularly effective in crops with a high leaf area index (LAI) and a closed canopy structure. In contrast, for crops with lower LAI or upright foliage, excessive airflow may hinder deposition and reduce spraying efficiency. Notably, most previous studies have focused on orchard trees, making our results especially relevant for low-growing field crops, where canopy density and structure differ substantially from orchard settings [62–64].

While this study focused on wheat and oilseed rape, the observed relationships between canopy architecture, air assistance, and spray coverage have broader relevance. In crops with similarly dense or complex canopies, such as maize, sunflower, or soybean, air-assisted spraying may offer comparable benefits in improving droplet penetration and coverage uniformity. Conversely, in crops with more open or upright foliage, such as barley or rye, the effectiveness of air support may be limited or require careful calibration. Future research should investigate these dynamics across diverse crop types, considering not only deposition but also energy consumption for a full sustainability assessment.

From a practical perspective, the integration of air-assisted systems should be prioritized for dense-canopy crops like oilseed rape [11,18,52,65], where they significantly enhance deposition on otherwise shielded surfaces. For open-canopy crops such as wheat, airflow may still support rear-facing coverage but must be carefully calibrated to avoid unnecessary droplet drift or reduced penetration. Farmers implementing air-assisted spraying can directly benefit from reduced chemical use, fewer application passes, and lower fuel consumption, aligning operational practices with sustainable agriculture guidelines. This practical linkage strengthens the policy relevance of our findings, particularly in contexts where regulations limit pesticide drift and emissions.

While the present study specifically focuses on canopy penetration, it is part of a broader research framework addressing both on-target deposition and spray drift reduction. The latter aspect, although not directly quantified here, has been experimentally verified using the same air-assisted system under drift-focused conditions [8]. That previous study reported substantial reductions in off-target spray dispersion: approximately 40.74% lower coverage and 37.55% lower droplet density compared to no air assistance, with the greatest reduction (up to 80%) observed 1 m from the boom at 6 km·h⁻¹. It should be noted, however, that these tests were conducted over grassland, without canopy structures.

Beyond the general resource-efficiency benefits, the differences in spray coverage observed between treatments in this study suggest important economic and energy implications. For instance, the significant increase in rear-facing and lower-canopy deposition in oilseed rape achieved through air assistance indicates that equivalent pest-control efficacy might be attainable with reduced spray volumes or fewer repeated applications. This would directly lower pesticide usage, tractor operating time, and fuel consumption, reducing input costs and energy demand per hectare. In contrast, the smaller and more variable effects seen in wheat imply that such savings may be limited unless airflow parameters are carefully optimized.

It should also be emphasized that the statistical framework used here focused on identifying main treatment effects. More advanced analyses, such as mixed-effects or multivariate approaches, could further clarify the interaction between airflow dynamics and canopy morphology. This represents a promising direction for future work, particularly in integrating deposition and drift data within a unified experimental design.

In addition to improving canopy penetration, air assistance also holds promise for enhancing resource efficiency in crop protection [66,67]. By directing more droplets onto target surfaces and minimizing off-target losses, air-assisted systems can reduce the total pesticide volume required for effective pest and disease control. This not only decreases chemical waste and the need for re-application but also lowers operational costs—resulting in more sustainable use of inputs such as pesticides, fuel, and labor. The resulting efficiency gains contribute directly to reducing the environmental footprint of crop production, as fewer active ingredients are released into the surrounding ecosystem [8,31,32,68,69].

Viewed through the broader lens of food as a resource [70–72], optimized spray deposition is a key factor in ensuring both crop yield and quality. Effective pest management with minimal input ensures that finite agricultural resources, i.e., land, water, fertilizers, are used more productively, supporting the sustainable intensification of agriculture. By maximizing the proportion of pesticide that reaches the intended target, air-assisted spraying helps preserve beneficial organisms, maintain soil and water quality, and safeguard the long-term capacity of agricultural land to produce food. In this sense, technological improvements in spray application are not only about operational efficiency but also about protecting the resource base on which global food security depends.

5. Summary and Conclusions

Our paper evaluated the effectiveness of air-assisted spraying (AAS) technology in enhancing canopy penetration in open-field conditions for two structurally different crops—oilseed rape (*Brassica napus*) and wheat (*Triticum aestivum*). Using a mobile prototype sprayer equipped with an adjustable airflow module, spray distribution was assessed at multiple canopy heights and orientations. Obtained results confirm that canopy structure plays a decisive role in shaping the benefits of AAS.

In oilseed rape, i.e., plant characterized by a dense and vertically stratified canopy, the use of AAS significantly improved spray penetration into the middle canopy zone, increasing coverage by over 14 percentage points compared to spraying without air assistance. While this was accompanied by a slight reduction in top-layer coverage, the overall vertical distribution was more balanced, suggesting improved resource efficiency and potential for enhanced pest and disease control throughout the canopy.

In contrast, results obtained for wheat, which has a more open and uniform structure, showed smaller and less consistent effects. Spray coverage was already high in both upper and lower layers without air assistance, and AAS did not substantially enhance droplet deposition. In some cases, air assistance even reduced coverage, likely due to the disturbance of droplet trajectories or increased droplet bounce-off and drift, highlighting the importance of tailoring airflow parameters to crop-specific conditions.

From a resource management perspective, these results underscore that AAS can be a valuable tool for improving agrochemical (pesticides, foliar fertilizers, etc.) utilization and spray efficacy, particularly in crops with dense canopies where conventional methods have problems ensuring uniform distribution. However, the effectiveness of AAS is not universal and must be carefully adjusted to canopy architecture and crop phenology to avoid counterproductive effects.

In the broader context of sustainable agriculture and integrated pest management, the strategic use of air assistance in spraying operations offers a dual benefit—it supports agronomic performance through improved coverage and simultaneously reduces chemical inputs and potential environmental contamination. As regulatory pressures increase and the agricultural sector seeks to align with the goals of the EU Farm to Fork Strategy, technologies like AAS represent a promising pathway toward more precise, efficient, and environmentally responsible crop protection and thereby, food production.

In our opinion, future research should focus on the development of adaptive spraying systems capable of real-time adjustment to canopy conditions, aiming to maximize coverage uniformity and minimize environmental losses. Additionally, the inclusion of energy use and emission metrics is recommended to further evaluate the sustainability impact of air-assisted technologies across different crop types and operational scales.

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Abbreviations

The following abbreviations are used in this manuscript:

AAS	Air-assisted spraying
LAI	Leaf area index
NAA	No air assistance
WAA	With air assistance
WSP	Water-sensitive paper

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