

RESEARCH ARTICLE

Optimizing Drone Spraying Parameters to Minimize Wind Drift Under Varying Wind Speeds

Dheebakaran Ga¹ *, Ragunath KP² , Sathyamoorthy NK¹ , Kokilavani S¹ ,
Panchulakshmi M¹, Ravikumar R¹, Sendhilvel V¹

¹Agro Climate Research Centre, ²Centre for Water and Geo Spatial Studies, Tamil Nadu Agricultural University, Coimbatore – 641 003

ABSTRACT

Drone-based agrochemical application has gained rapid momentum in Indian agriculture, yet spray drift continues to pose a major operational and environmental challenge. This study quantified wind drift from agricultural drone spraying under varying wind speeds, spray fluid concentrations, and drone flying heights over two consecutive years (2023–24 and 2024–25) at the Agro Climate Research Centre, Tamil Nadu Agricultural University, Coimbatore. In 2023–24, nine treatment combinations involving three wind speeds (6, 9, and 12 kmph) and three spray fluid concentrations (30, 60, and 90 per cent) were evaluated using a fixed drone height of 2.0 m. In 2024–25, the experiment was expanded to include four drone heights (1.2, 1.5, 1.8, and 2.1 m), resulting in 36 treatment combinations. Spray drift was measured using water-sensitive papers placed at regular intervals downwind of the spray line. Across both years, drift increased consistently with increasing wind speed, the spray volume, and drone height. The lowest drift occurred at 6 kmph wind speed, 30 per cent spray fluid, and 1.2 m drone height, where drift was confined to 3–6 m. In contrast, the highest drift was recorded at 12 kmph wind speed, 60 to 90 per cent spray fluid, and 2.1 m height, extending up to 18.5 m. Strong interaction effects indicated that the levels of the others amplified the influence of any single factor. The study highlights the need for careful operational planning to minimize off-target deposition and ensure safe, efficient drone spraying. The findings provide evidence-based thresholds for drone height, spray volume, and allowable wind speed, supporting the development of practical guidelines for drift-minimized drone application in field conditions.

Received: 31 Mar 2026

Revised: 25 May 2026

Accepted: 27 May 2026

Keywords: Agricultural drone, Spray drift, Wind speed, Drone height, Spray volume, UAV spraying, Drift mitigation

INTRODUCTION

The adoption of unmanned aerial vehicles (UAVs) for pesticide and nutrient application has brought a major shift in modern agriculture. Drone-based spraying enables precise input delivery, reduces

labour dependence, improves operational efficiency, and facilitates access to hard-to-reach areas, making it an indispensable component of precision farming systems. In Tamil Nadu, where labour scarcity and

*Corresponding author mail: gadheebakaran@tnau.ac.in



Copyright: © The Author(s), 2026. Published by Madras Agricultural Students' Union in Madras Agricultural Journal (MAJ). This is an Open Access article, distributed under the terms of the Creative Commons Attribution 4.0 License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited by the user.

the need for timely crop protection are critical, drone intervention has rapidly expanded due to its simplicity, user-friendliness, and capacity to achieve faster field coverage.

However, spray drift remains a major concern in drone-based agrochemical application. Wind drift can lead to off-target deposition, affecting neighbouring crops, livestock, beneficial organisms, and human settlements. Tamil Nadu experiences highly dynamic wind speeds due to intense solar radiation and its proximity to the equator, making the region particularly vulnerable to drift-related risks, especially where multiple sensitive crops are grown in close proximity. Tamil Nadu's diverse cropping systems, frequent intercropping patterns, and proximity of sensitive crops increase the risk associated with off-target drift. The state also experiences rapid fluctuations in wind speed during peak radiation hours, making it essential to establish operational thresholds tailored to local field conditions.

Drift potential increases with smaller droplet sizes, higher wind speeds, greater drone heights, and larger spray volumes, underscoring the need for optimized operational parameters. Although several studies have examined UAV spray characteristics under controlled or semi-controlled environments, very limited field-based evidence exists for Indian agro-climatic conditions, particularly for regions with highly variable wind regimes such as Tamil Nadu. Most available studies focus on nozzle performance or wind-tunnel behaviour, leaving a critical gap in understanding how operational parameters interact under real field conditions.

With the rapid expansion of drone service providers and government-supported mechanization initiatives, establishing scientifically validated drift-minimization guidelines has become essential for safe pesticide application, environmental protection, and regulatory compliance. Existing research consistently highlights the influence of wind speed and droplet characteristics on drift behaviour. A wind-tunnel assessment demonstrated that faster wind speeds and finer droplets significantly increase drift distance (Grant *et al.*, 2022). Similarly, nozzle type plays a critical role: centrifugal nozzles exhibit higher drift risk than hydraulic nozzles, and the drift rate increases linearly with wind speed (Wang *et al.*, 2023).

A broader review of unmanned aerial spraying systems emphasized the importance of optimizing structural layout, operating parameters, and

establishing drift buffer zones to reduce off-target movement (Chen *et al.*, 2022). Despite these insights, field-based quantification of drift under realistic operational conditions remains limited, particularly for Indian agro-climatic environments. With Tamil Nadu emerging as a leading state in agricultural drone deployment, there is an urgent need to identify optimal wind speed thresholds, spray volumes, and drone flight heights to minimize drift while ensuring effective spray coverage.

Therefore, the present study was undertaken to quantify spray drift under varying wind speeds, spray fluid concentrations, and drone flying heights, and to identify operational thresholds that minimize drift while ensuring effective spray coverage under field conditions.

MATERIALS AND METHODS

The field investigation on wind drift from agricultural drone spraying was carried out in the uncropped field at the Wetlands Farms of the Agro Climate Research Centre, Tamil Nadu Agricultural University, Coimbatore, during the years 2023–24 and 2024–25. These locations represent open irrigated ecosystems with naturally fluctuating wind regimes, making them ideal for evaluating drift behaviour under realistic field conditions. The study was conducted in two phases. The first phase (2023–24) involved a preliminary assessment of drift at a fixed drone height, while the second phase (2024–25) expanded the experimental setup to include multiple drone heights, thereby enabling a more comprehensive understanding of the interactions among wind speed, spray volume, and flight altitude.

In the 2023–24 phase, the experiment followed a factorial Completely Randomized Design (CRD) with three wind speed levels (6, 9, and 12 kmph) and three spray fluid concentrations (30, 60, and 90 per cent), resulting in nine treatment combinations replicated twice. The drone was operated at a constant flying height of 2.0 m for all treatments. Water mixed with different coloured inks served as the spray fluid to facilitate visual identification of drift droplets. White water-sensitive filter papers of 0.03 m² area were placed at 1.5 m intervals along a 30 m downwind transect to capture drift deposition. Each spray run was conducted only when the natural wind speed matched the target class, and the filter papers were collected immediately after spraying to measure drift distance and droplet density.



During 2024–25, the study was expanded by incorporating drone height as an additional factor. This phase employed a factorial CRD with three wind speeds (6, 9, and 12 kmph), four drone heights (1.2, 1.5, 1.8, and 2.1 m), and three spray fluid concentrations (30, 60, and 90 per cent), resulting in 36 treatment combinations with two replications. The drone was operated with a constant nozzle type, flow rate, and forward speed across all treatments to ensure uniformity. Water-sensitive filter papers of the same size were placed at 0.5 m intervals up to 20 m downwind, and additional papers were positioned at selected heights to assess vertical drift distribution. As in the first phase, coloured inks were used to distinguish treatments, and drift deposition was assessed immediately after each spray pass.

Across both years, the parameters recorded included wind speed during application, drift distance, droplet density, drift width, and drift height. The coloured droplets on the filter papers enabled clear visual quantification of drift patterns.

All data were subjected to factorial analysis of variance (ANOVA) to determine the main effects of wind speed, spray volume, and drone height, as well as their two-way and three-way interactions. The combined dataset from the two years enabled a robust evaluation of drift *behaviour* under varying operational conditions, supporting the development of practical recommendations to minimize wind drift during drone spraying.

RESULTS AND DISCUSSION

The results from the two years of experimentation clearly demonstrate that wind speed, spray fluid concentration, and drone flying height exert strong and consistent effects on spray drift behaviour under field conditions. During 2023–24, when the drone was operated at a fixed height of 2.0 m, drift was minimal at low wind speeds and low spray volumes. At a 6 kmph wind speed and 30 *per cent* spray fluid, the drift extended only up to 6 m, and the droplet density on the water-sensitive papers was sparse, indicating limited off-target movement. As wind speed and spray volume increased, drift distance increased proportionately, reaching 18 m at 12 kmph and 90 *per cent* spray fluid. These observations are consistent with earlier findings that higher wind speeds and finer droplets significantly increase drift due to enhanced horizontal momentum acting on the spray plume (Grant *et al.*, 2022; Wang *et al.*, 2023). The 2023–24 drift pattern is presented in Figure 1.

The expanded experiment conducted during 2024–25 provided deeper insights into the combined effects of wind speed, spray volume, and drone height. When the drone was flown at the lowest height of 1.2 m, with a wind speed of 6 kmph and a spray fluid concentration of 30 *per cent*, the drift was extremely low and restricted to about 3 m. This confirmed that lower flight altitudes substantially reduce drift. The expanded experiment in 2024–25, which incorporated multiple drone heights, further strengthened these trends.

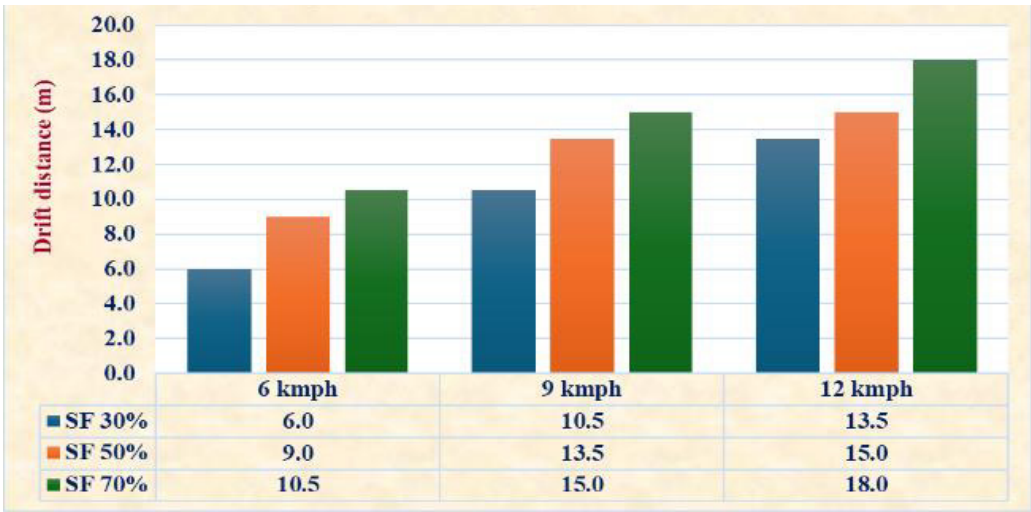


Figure 1 Drone spray drift distance (m) observed with different wind speeds and spray fluid levels (2023–24).



At the lowest height of 1.2 m, with 6 kmph wind speed and 30 per cent spray fluid, drift was restricted to about 3 m, confirming that lower flight altitudes reduce droplet residence time and limit wind exposure. However, at a height of 2.1 m, a wind speed of 12 kmph, and 70 per cent spray fluid, drift reached 18.5 m, the highest recorded during the study. Similar to the previous year, droplet density decreased gradually with distance, but the presence of one or two fine droplets beyond half the drift path indicated continued transport of small droplets. These results align with global UAV drift studies that show increased drift at higher altitudes due to prolonged droplet suspension and greater interaction with ambient wind fields (Chen *et al.*, 2022; Qin & Chen, 2023). The 2024–25 drift patterns are shown in Figure 2. Wind speed consistently emerged as the most dominant factor influencing drift. Across all heights

and spray volumes, drift increased sharply as wind speed increased from 6 to 12 kmph. At lower wind speeds, the effects of height and spray volume were less pronounced, whereas at higher wind speeds, both factors substantially amplified drift. This behaviour is consistent with the aerodynamic principles governing droplet transport and with recent UAV spray-drift models that highlight wind velocity as the primary determinant of off-target movement (Gatkal *et al.*, 2025). The deviations in drift between wind speed levels are illustrated in Figure 3.

Spray fluid concentration also played a significant role. Higher spray volumes (50 and 70 per cent) consistently produced greater drift distances than 30 per cent under the same wind and height conditions. For example, at 1.5 m height and 9 kmph wind speed, drift increased from 5 m at 30 per cent to 7 m at 50

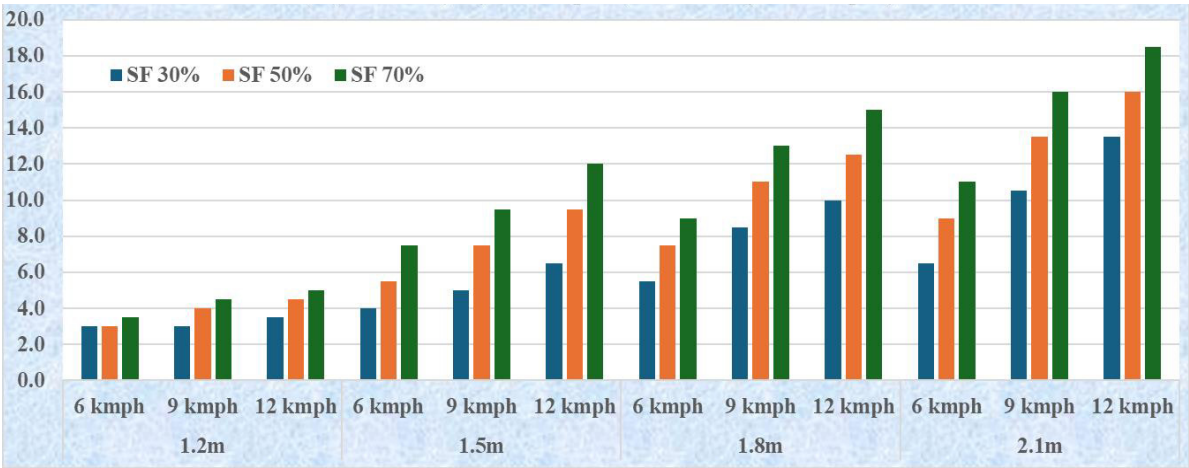


Figure 2. Drone spray drift (m) under varying wind speed, drone height and spray fluid levels (2024–25)

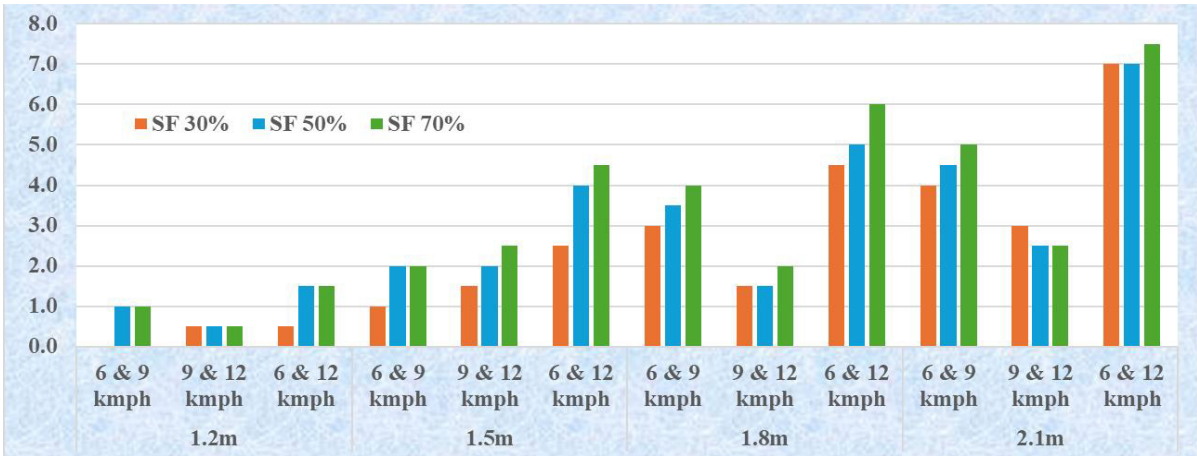


Figure 3 Deviations in drone spray drift (m) between two wind speed levels with varying drone height and spray fluid levels



per cent and 9.5 m at 70 per cent. Increased spray volume likely alters droplet size distribution and plume density, making droplets more susceptible to wind displacement. Similar observations have been reported in controlled wind-tunnel studies, in which increased spray discharge rates produced finer droplets and greater drift potential (Grant *et al.*, 2022; Wang *et al.*, 2023). The comparative effects of spray fluid levels are depicted in Figure 4.

Drone height strongly influenced drift, particularly at higher wind speeds. As flight altitude increased, droplets remained airborne longer, allowing wind to carry them farther. At 6 kmph and 30 per cent spray fluid, drift increased from 3.0 m at 1.2 m height to 6.5 m at 2.1 m height. This trend is consistent with multi-rotor UAV studies showing that rotor-induced turbulence interacts with ambient wind to increase drift at higher altitudes (Weicai & Panyang, 2023). These combined effects are summarized in Figure 5.

A clear three-way interaction among wind speed, spray volume, and drone height was evident. The difference in drift between 30 and 70 per cent spray fluid was minimal at 6 kmph but substantial at 12 kmph. Similarly, the effect of wind speed was amplified at higher drone heights. These interactions confirm that operational parameters cannot be optimized independently; instead, drift management requires simultaneous consideration of wind conditions, spray volume, and flight altitude. This aligns with recent modelling studies that emphasize the need for integrated parameter optimization to minimize UAV spray drift (Chen *et al.*, 2022; Qin & Chen, 2023).

Overall, the results from both years consistently show that spray drift increases with increasing wind speed, spray fluid concentration, and drone height. The lowest drift occurred at 1.2 m height, 6 kmph wind speed, and 30 per cent spray fluid, while the highest drift occurred at 2.1 m height, 12 kmph wind speed,

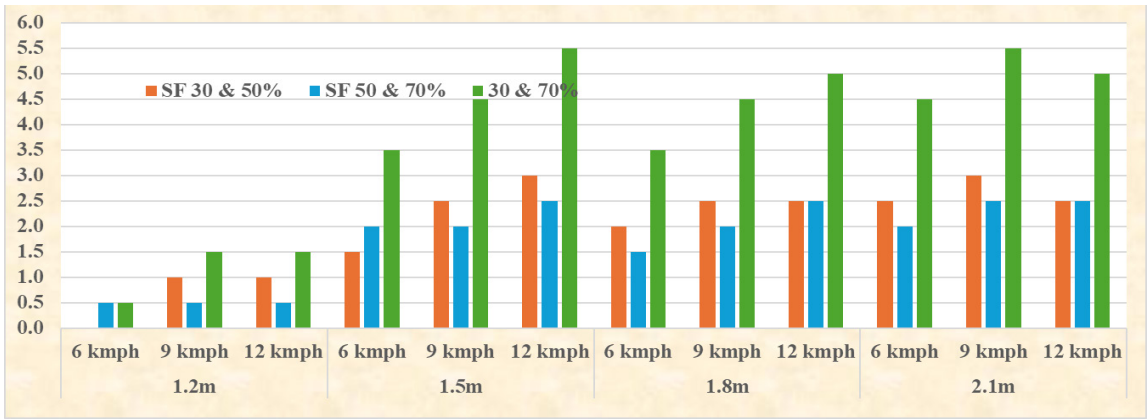


Figure 4 Deviations in drone spray drift (m) between two spray fluid levels with varying drone height and wind speeds

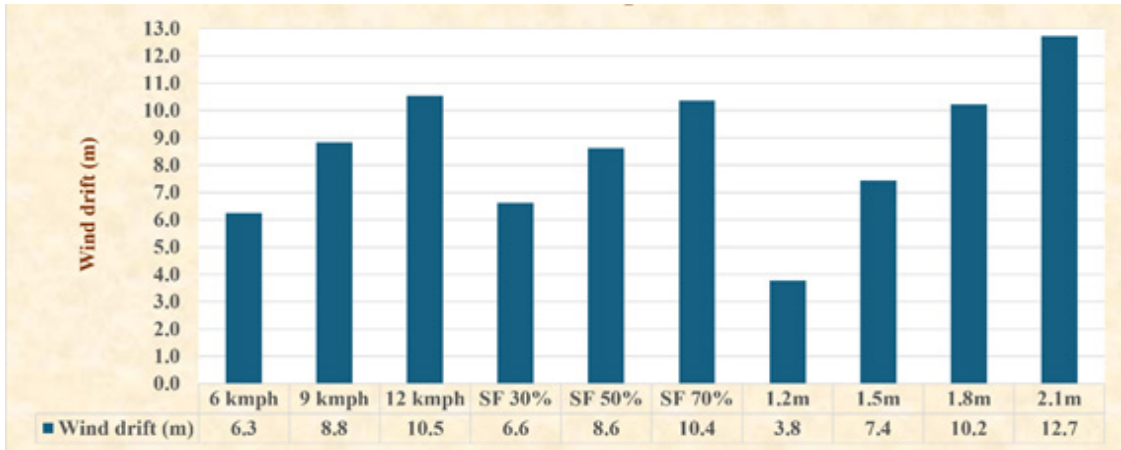


Figure 5 Mean drone spray drift with varying wind speed, spray fluid and drone flying height

and 70 per cent spray fluid. These findings reinforce the importance of selecting appropriate operational parameters to minimize off-target movement during drone spraying.

Implications for Drone Spraying with Minimum Drift

The findings of this study highlight the importance of carefully selecting operational parameters to minimize spray drift during drone-based agrochemical application. Wind speed emerged as the most critical factor influencing drift, indicating that drone spraying should ideally be carried out in low-wind conditions, preferably below 6 kmph, to ensure accurate and safe application.

Drone flying height must also be adjusted based on prevailing wind conditions, as lower flight altitudes substantially reduce the horizontal displacement of droplets. Although operational constraints and crop architecture may limit the extent to which height can be reduced, maintaining the lowest feasible altitude is essential for minimizing drift. Spray fluid volume should be optimized to the minimum level required for effective coverage, particularly under moderate wind conditions, as higher volumes tend to produce finer droplets that are more susceptible to wind transport. Overall, careful planning and real-time assessment of environmental conditions are necessary to avoid off-target deposition, prevent environmental contamination, and ensure the efficacy of drone spraying operations.

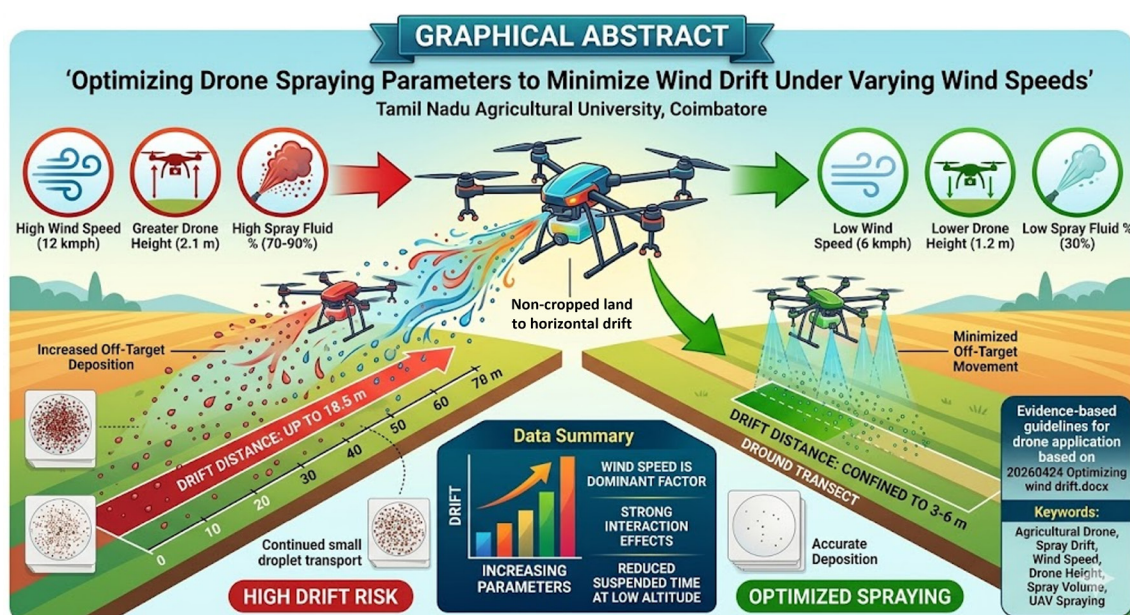
CONCLUSION

The results from the two years of field experimentation clearly demonstrate that spray drift increases consistently with increasing drone height, wind speed, and spray fluid volume. The lowest drift was recorded when the drone operated at a height of 1.2 m, at a wind speed of 6 kmph, and with a spray fluid concentration of 30 per cent, with drift confined to a short distance from the spray line. In contrast, the highest drift occurred at the maximum tested height of 2.1 m, the highest wind speed of 12 kmph, and a spray fluid concentration of 70 per cent, with drift extending beyond 18 m. These results reveal a direct and predictable relationship between operational parameters and drift magnitude, indicating that even incremental increases in any single factor can significantly elevate the risk of drift. The consistency of these patterns across both years underscores the need for stringent operational guidelines to ensure safe and effective drone spraying.

Way Forward

Future work should focus on refining drift prediction and mitigation by incorporating droplet size measurements, nozzle performance evaluation, and real-time wind monitoring into drone operations. Expanding trials across different crop canopies, seasons, and agro-climatic zones will help develop more robust and region-specific operational guidelines. Integrating automated height-adjustment systems and decision-support tools into drone platforms can

Graphical Abstract





further enhance precision and reduce the risk of drift. These advancements will support safer, more efficient, and environmentally responsible drone-based agrochemical application.

ACKNOWLEDGMENTS

We the authors cordially thank the Tamil Nadu Agricultural University authorities for approving the University Research Project on “Wind Speed and Drone drift”. We the authors acknowledge the support of Farm Unit, Department of Agronomy and Centre for Water and Geo Spatial Studies for providing experiment field and Drone facility, respectively.

Funding and Acknowledgment:

This study was undertaken as part of a University Research Project, and no dedicated budget was provided for its execution

Ethics Statement:

No ethical approval is required

Originality and Plagiarism:

We, the authors, confirm that this manuscript is an original work and no parts of it has been published elsewhere in any form.

Consent for Publication:

We, all authors, agree to the content of the article and its publication in the journal.

Competing Interests:

We, the authors, hereby declared that there is no potential conflicts of interest, financial or otherwise, that could affect the research or its interpretation.

Data Availability:

The data related to this study are included within the manuscript.

Author Contributions:

Dheebakaran Ga, conceived the research idea, designed the study, and prepared the first draft of the manuscript. Ragunath K.P, executed the field

experiments, including drone-based operations. Ravikumar R, carried out data compilation, statistical analysis, and interpretation. Sathyamoorthy N.K., Kokilavani S., Panchulakshmi M., and Sendhilvel V, supported during observations, contributed to manuscript editing, technical corrections, and preparation of the final draft.

REFERENCES

- Chen, P., Douzals, J.P., Lan, Y., Cotteux, E., Delpuech, X., Pouxviel, G. and Zhan, Y. (2022). Characteristics of unmanned aerial spraying systems and related spray drift: A review. *Frontiers in Plant Science*, 13: 870956. <https://doi.org/10.3389/fpls.2022.870956>
- Gatkal, N.R., Nalawade, S.M., Shelke, M.S., Deshmukh, M.S., Bhanage, G.B., Sahni, R.K. and Mikeska, M. (2025). Effect of operational parameters on spray performance and drift characteristics of a UAV-based agrochemical application in pigeon pea crop. *Frontiers in Plant Science*, 16: 1570272. <https://doi.org/10.3389/fpls.2025.1570272>
- Grant, S., Perine, J., Abi-Akar, F., Lane, T., Kent, B., Mohler, C., Scott, C. and Ritter, A. (2022). A wind-tunnel assessment of parameters that may impact spray drift during UAV pesticide application. *Drones*, 6(8): 204. <https://doi.org/10.3390/drones6080204>
- Qin, W. and Chen, P. (2023). Analysis of research progress on deposition and drift of spray droplets by plant protection UAVs. *Scientific Reports*, 13: 14935. <https://doi.org/10.1038/s41598-023-40556-0>
- Wang, G., Zhang, T., Song, C., Yu, X., Shan, C., Gu, H. and Lan, Y. (2023). Evaluation of spray drift of plant protection drone nozzles based on wind tunnel test. *Agriculture*, 13(3): 628. <https://doi.org/10.3390/agriculture13030628>