



Precision UAV-Based Biostimulant Delivery in Tall Sugarcane: Field Evaluation with Airflow-Informed Deposition Analysis in Northern India [†]

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Abstract

Efficient foliar delivery of biostimulants in tall, dense crops remains a major challenge under conventional spraying practices. This study evaluated precision UAV-based biostimulant application in tall sugarcane through field experimentation supported by airflow-informed deposition analysis. A randomized block field trial compared manual spraying, UAV coarse-droplet spraying, and UAV ultra-low-volume (ULV) spraying. Vertical spray deposition, canopy physiological response (NDVI and SPAD), yield, and operational performance were assessed. UAV-ULV spraying achieved enhanced upper-canopy deposition, stronger early physiological responses, and higher yield with substantially reduced carrier volume. Airflow-informed analysis highlighted the role of droplet residence time in improving canopy interception.

Keywords: UAV spraying; biostimulants; sugarcane; spray deposition; ultra-low-volume application; NDVI; SPAD; rotor downwash; precision agriculture

1. Introduction

Biostimulants are increasingly recognized as an important component of sustainable crop production systems due to their ability to enhance plant metabolic activity, nutrient-use efficiency, and tolerance to abiotic stress without directly contributing to nutrient loading [1]. Their agronomic effectiveness, however, is strongly dependent on efficient foliar delivery and uniform canopy interception. In tall crops such as sugarcane, where canopy heights commonly exceed 2.5 m and leaf-area density is high, achieving uniform spray deposition using conventional ground-based methods remains a persistent challenge.

Manual knapsack spraying continues to be widely practiced in sugarcane cultivation, yet it is inherently constrained by limited vertical reach, high carrier-volume requirements, labor intensity, and inconsistent droplet distribution within the canopy. These limitations often lead to excessive ground losses and poor penetration into mid- and upper-canopy layers, reducing the effective utilization of applied biostimulants and resulting in variable physiological crop responses [2].

Unmanned aerial vehicles (UAVs) have recently emerged as a promising alternative for crop spraying, offering low-volume application, flexible deployment, and the ability to



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operate above dense canopies without direct crop contact. Beyond logistical advantages, UAV rotors generate a characteristic downwash airflow that can significantly influence droplet transport, residence time, and interception within crop canopies. Previous studies have demonstrated that the structure and regularity of rotor-induced airflow play a critical role in determining spray deposition patterns beneath UAVs, particularly in relation to vertical penetration and lateral dispersion [3].

Despite these advances, many existing investigations have relied either on laboratory-scale measurements or on high-fidelity computational fluid dynamics (CFD) simulations that are difficult to directly translate into field-scale agronomic outcomes. Moreover, limited field-based studies have simultaneously coupled spray deposition measurements, crop physiological response, and airflow-informed interpretation in tall, dense crops such as sugarcane [4]. Bridging this gap requires field-oriented evaluations supported by simplified airflow analysis capable of explaining observed deposition trends under practical operating conditions.

In this context, the present study evaluates the feasibility and efficiency of precision UAV-based biostimulant application in tall sugarcane using an integrated field and modeling approach. Specifically, the objectives were to (i) quantify vertical spray deposition patterns across canopy strata under different application methods, (ii) assess crop physiological response using NDVI and SPAD measurements at key post-application intervals, and (iii) compare yield and economic performance between manual and UAV-based spraying. A lightweight airflow-informed deposition analysis framework was employed to interpret observed deposition behavior and to support optimization of droplet size and application strategy under field conditions, without reliance on computationally intensive CFD simulations.

2. Materials and Methods

2.1. Experimental Site and Crop Conditions

Field experiments were conducted during the 2023 growing season in Saharanpur district, Uttar Pradesh, India, a major sugarcane-producing region within the Upper Gangetic Plains agro-climatic zone. The experimental crop consisted of sugarcane (*Saccharum officinarum* L.) cultivar Co-0238, a widely cultivated high-yielding variety in northern India known for its vigorous canopy growth and commercial adaptability. The crop was maintained under standard regional agronomic practices with row spacing of approximately 0.9–1.0 m. At the time of UAV application during the Grand Growth and Elongation stages, average crop height exceeded 2.5 m with dense canopy development, creating substantial interception challenges for conventional foliar spray systems. These canopy conditions were considered suitable for evaluating UAV-assisted aerial biostimulant delivery under tall sugarcane conditions [5,6].

The experiment was laid out in a randomized complete block design (RCBD) with three treatments and three replications. The experiment was laid out in a randomized complete block design (RCBD) with three treatments and three replications. Individual experimental plots measured approximately 10 m × 8 m, with buffer zones of approximately 3 m maintained between adjacent plots to minimize spray drift and cross-treatment interference during UAV operations. All plots were managed uniformly with respect to irrigation, nutrient management, and crop husbandry practices, ensuring that observed differences could be attributed primarily to the spray application strategy. Spray applications were conducted under relatively low-wind conditions (approximately 1–4 m·s⁻¹) to further reduce the potential for off-target drift.

2.2. Spray Treatments and Application Systems

Three foliar application strategies were evaluated:

- T1 (Manual spray): Knapsack sprayer fitted with a flat-fan nozzle, operating at a carrier volume of 150 L·ha⁻¹.
- T2 (UAV-coarse droplets): UAV-based spraying using pressure nozzles operating at a carrier volume of 30–40 L·ha⁻¹ and producing coarse droplets with an approximate volumetric median diameter (VMD) of 250–300 µm.
- T3 (UAV-ULV fine droplets): UAV-based ultra-low-volume spraying using rotary atomizers operating at 20–30 L·ha⁻¹ and generating finer droplets with an approximate VMD of 120–150 µm.

All treatments received the same seaweed-based foliar biostimulant at equivalent active ingredient rates to ensure comparability across application methods. UAV operations were conducted at a flight altitude of approximately 2.5–3.0 m above ground level with a forward flight speed of approximately 3–4 m·s⁻¹ under relatively low ambient wind conditions ranging from 1 to 4 m·s⁻¹. Flight paths were maintained with partial swath overlap to improve deposition uniformity and reduce untreated gaps between adjacent passes [6,7]. The selected operational envelope (approximately 2.5–3.0 m flight altitude and 3–4 m·s⁻¹ forward speed) was chosen to balance canopy penetration, droplet interception efficiency, and drift minimization under dense sugarcane field conditions. These operational settings were maintained consistently across UAV treatments to support comparative evaluation of droplet-spectrum effects under stable application conditions.

2.3. Spray Deposition and Canopy Interception Assessment

Spray deposition within the canopy was evaluated using water-sensitive paper (WSP) cards, a widely accepted method for characterizing droplet distribution and coverage in plant protection studies [8]. WSP cards were positioned at upper-, mid-, and lower-canopy strata prior to spraying and retrieved immediately after application for analysis.

To enable quantitative comparison of deposition across canopy layers, a fluorescent tracer was added to the spray solution. Tracer recovery from different canopy levels was used to estimate relative interception efficiency and ground loss, complementing the qualitative information provided by WSP analysis.

2.4. Canopy Physiological Response Measurements

Crop physiological response to foliar biostimulant application was assessed using the normalized difference vegetation index (NDVI) and SPAD chlorophyll measurements. NDVI data were derived from multispectral imagery acquired using a micro-UAV platform, based on established reflectance relationships between red and near-infrared wavelengths [9].

SPAD measurements were recorded using a handheld chlorophyll meter on representative leaves from each plot [10]. NDVI and SPAD observations were collected at 0 (pre-treatment), 7, 14, and 28 days after treatment (DAT), consistent with standard protocols for monitoring short-term physiological responses to foliar interventions [9].

2.5. Yield, Economic Assessment, and Airflow-Informed Deposition Interpretation

At harvest, plot-level yield data were recorded and expressed on a per-hectare basis. Operational metrics including carrier volume, labor input, and application efficiency were documented to support the comparative economic evaluation of manual and UAV-based spraying approaches.

To interpret observed deposition behavior within the sugarcane canopy, a lightweight rotor-canopy airflow analysis framework was employed. The approach was based on

a simplified momentum-disk representation of UAV rotor downwash interacting with a porous crop canopy characterized by varying leaf-area density (LAD) across upper-, mid-, and lower-canopy strata. The airflow analysis incorporated approximate vertical downwash decay within the canopy and a simplified droplet settling-advection framework for droplet classes ranging from approximately 120 to 300 μm . Droplet transport behavior was evaluated using a Lagrangian-style residence-time interpretation in which finer droplets exhibited longer canopy residence and greater probability of interception within upper- and mid-canopy regions.

Under rotor-assisted spraying conditions, downward airflow generated by UAV rotors can temporarily alter local canopy orientation and reduce droplet settling velocity through turbulent recirculation effects within the upper canopy layers. Although direct airflow velocity measurements were not performed in the present study, the analytical framework assumed that finer droplets subjected to rotor-induced airflow would exhibit longer effective residence times within the canopy volume prior to gravitational settling. This increased residence duration was expected to improve the probability of leaf-surface interception relative to larger droplets characterized by faster vertical settling behavior.

The framework was implemented analytically to support the interpretation of relative deposition trends observed under field conditions rather than to reproduce fully resolved computational fluid dynamics (CFD) airflow structures. Sensitivity analysis was additionally performed across droplet size classes and residence-time conditions to evaluate the influence of aerodynamic transport assumptions on canopy deposition fractions. The airflow analysis should therefore be interpreted as an airflow-informed mechanistic framework intended to support field observations rather than a fully validated CFD simulation.

2.6. Statistical Analysis

All experimental observations were obtained from three replicated plots per treatment and are presented as mean $\pm$ standard deviation (SD). Treatment effects on the NDVI, SPAD chlorophyll index, and yield were evaluated using one-way analysis of variance (ANOVA) under the randomized complete block design framework. Mean separation among treatments was performed using Tukey's honestly significant difference (HSD) test at a significance level of $p < 0.05$. Statistical analyses and graphical visualizations were performed using Python version 3.12 (Python Software Foundation, Wilmington, DE, USA), employing the NumPy (v2.2.6), Pandas (v2.3.0), SciPy (v1.16.0), Statsmodels (v0.14.4), and Matplotlib (v3.10.3) libraries.

3. Results

3.1. Vertical Spray Deposition Patterns

Clear differences in vertical spray deposition were observed among the three application methods (Figure 1). Manual knapsack spraying (T1) resulted in relatively high deposition at the lower canopy and ground level, with limited penetration into the upper canopy layers. In contrast, UAV-based spraying exhibited improved vertical distribution, particularly under ultra-low-volume (ULV) conditions.

The UAV-ULV treatment (T3) achieved the highest proportion of deposition in the upper canopy, accounting for approximately 70–72% of total intercepted spray, with negligible ground loss. The UAV-coarse droplet treatment (T2) showed intermediate performance, with improved penetration relative to manual spraying but lower uniformity across mid-canopy layers compared to ULV application. These results indicate that droplet size and application strategy strongly influence canopy interception efficiency in tall sugarcane.

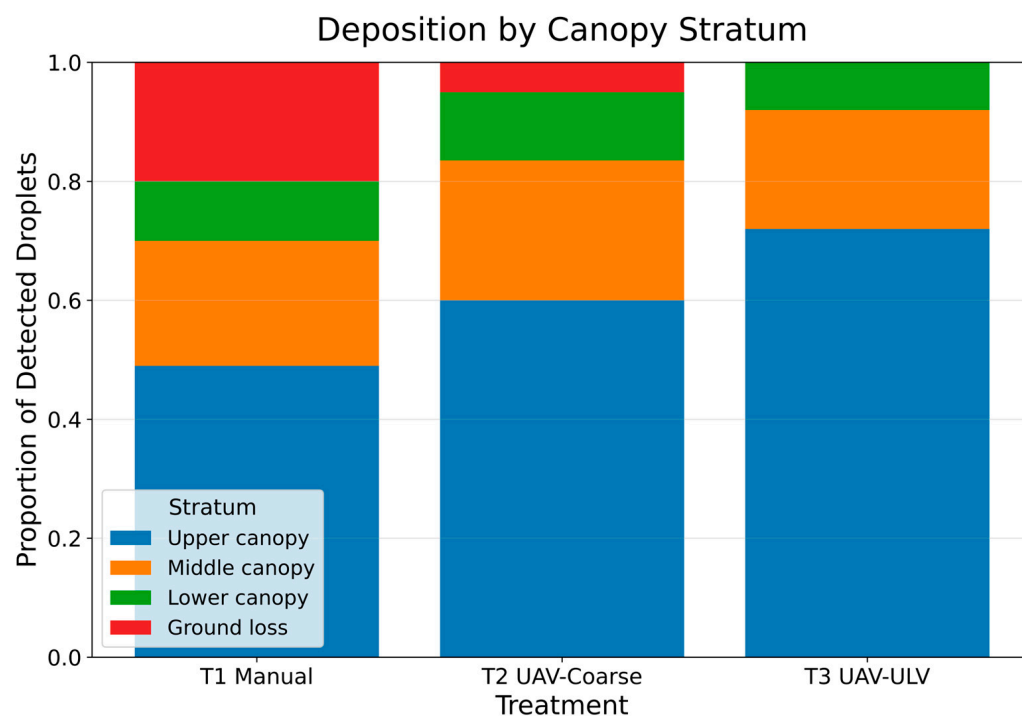


Figure 1. Deposition by canopy stratum under different application methods. Vertical distribution of spray deposition across upper-, mid-, lower-canopy layers and ground for manual spraying (T1), UAV-coarse droplets (T2), and UAV-ULV fine droplets (T3). UAV-ULV shows enhanced upper-canopy interception and minimal ground loss compared to manual application, indicating improved penetration and deposition uniformity in tall sugarcane.

3.2. NDVI Response Following Biostimulant Application

Temporal NDVI trends following biostimulant application are presented in Figure 2. All treatments exhibited gradual increases in canopy vigor after application; however, the UAV-ULV treatment consistently demonstrated the strongest NDVI enhancement during the 7–14 DAT period.

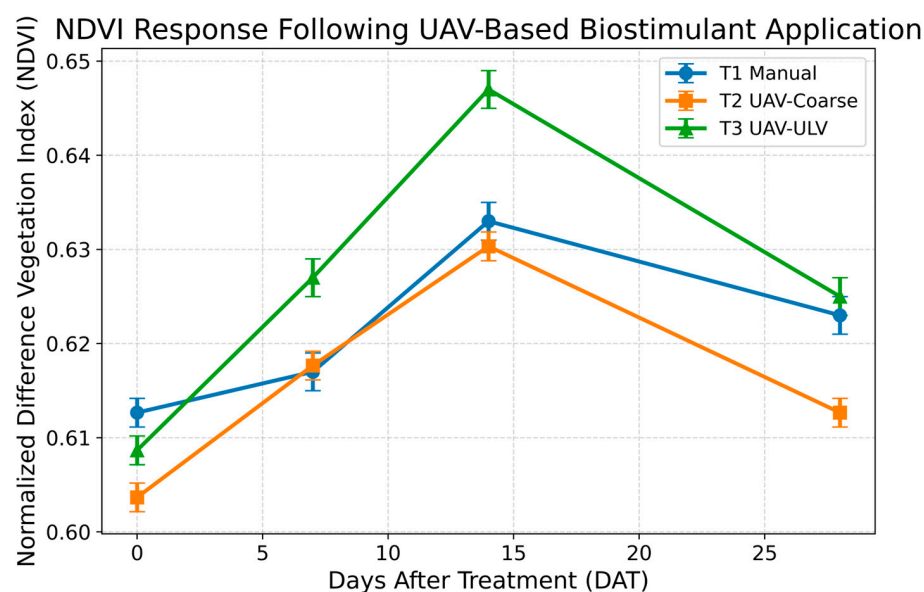


Figure 2. NDVI response over time following biostimulant application. Temporal NDVI response following UAV-based biostimulant application in tall sugarcane under different spray delivery treatments. Error bars represent standard deviation among replicated plots.

The stronger NDVI response observed under UAV-ULV application likely reflected improved canopy-level distribution and interception of the applied biostimulant under the selected spray delivery conditions, although the physiological response remained inherently dependent on environmental and crop-specific factors. Variability among replicated plots remained relatively low across treatments, supporting the consistency of observed field responses.

3.3. SPAD Chlorophyll Dynamics

SPAD chlorophyll index trends are shown in Figure 3. The UAV-ULV treatment exhibited the highest chlorophyll response during the early and mid-evaluation period, followed by the UAV-coarse and manual treatments. Maximum SPAD enhancement was observed between 7 and 14 DAT under UAV-assisted treatments. The observed trends may indicate more uniform canopy-level delivery and interception of the applied biostimulant under finer droplet conditions, although chlorophyll response remains influenced by environmental variability and crop physiological status under field conditions.

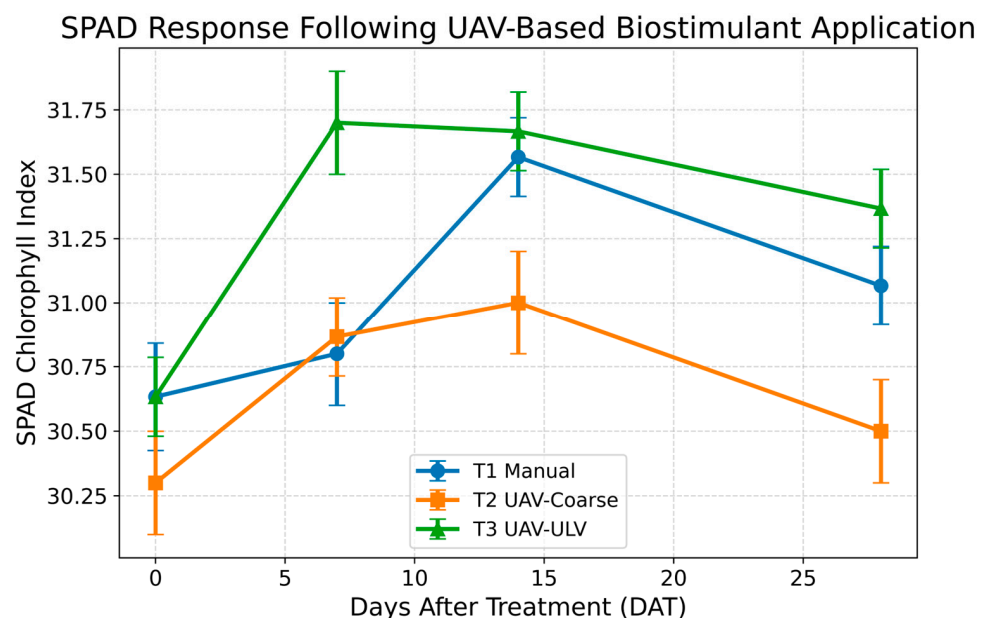


Figure 3. SPAD chlorophyll response over time. Temporal SPAD chlorophyll index response under manual and UAV-assisted biostimulant spray treatments in sugarcane. Error bars represent standard deviation among replicated plots.

3.4. Yield and Operational Performance

Yield distribution across treatments is presented in Figure 4. The UAV-ULV treatment produced the highest mean cane yield, followed by the UAV-coarse and manual spray treatments. One-way ANOVA indicated significant treatment-associated differences in yield response ($F = 24.10$, $p = 0.0014$). Tukey's HSD grouping further indicated significantly higher yield performance under UAV-ULV application compared with the manual treatment, while the UAV-coarse treatment exhibited intermediate statistical response characteristics. The observed improvements were accompanied by substantially reduced carrier volume requirements and improved operational efficiency during field spraying.

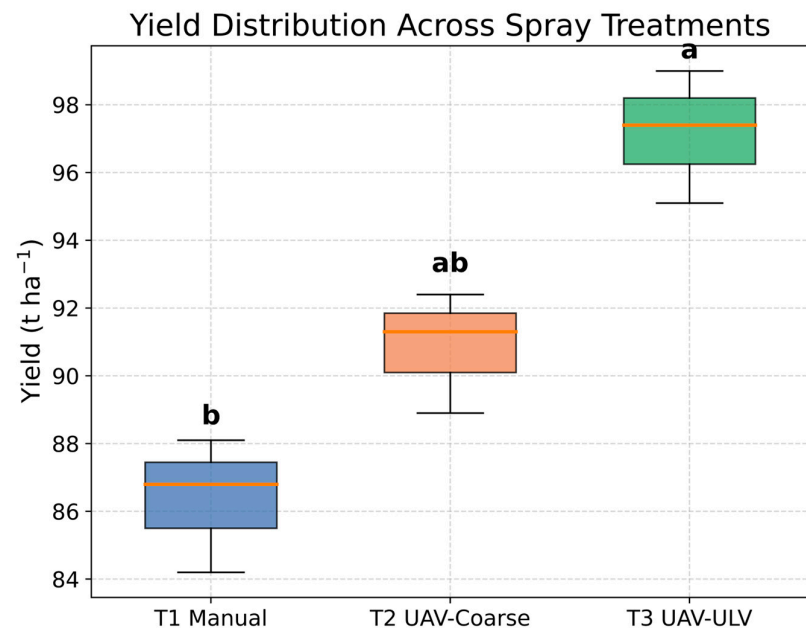


Figure 4. Yield distribution across application treatments under field conditions in tall sugarcane. Different letters above boxplots indicate significant differences among treatment means according to Tukey's HSD test at $p < 0.05$. Treatments sharing at least one common letter are not significantly different from each other.

3.5. Airflow-Informed Interpretation of Deposition Trends

The airflow-informed analytical framework supported a mechanistic interpretation of the observed deposition patterns across canopy strata (Figure 5).

Deposition Sensitivity to Residence Time and Droplet Size

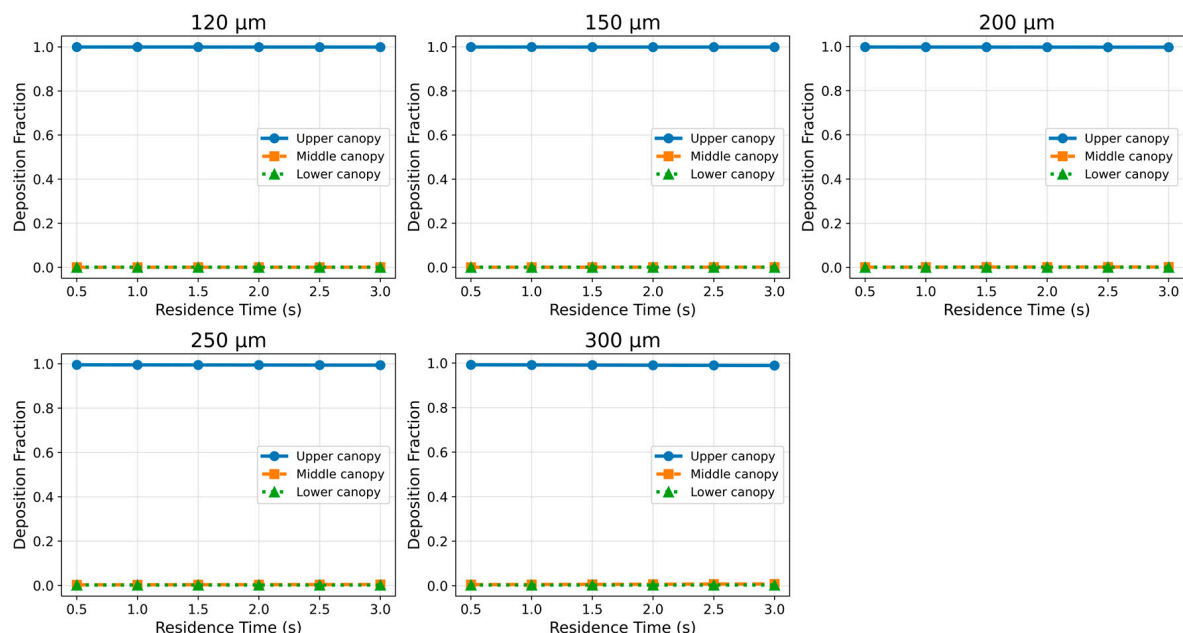


Figure 5. Sensitivity of deposition to droplet size and residence time. Airflow-informed sensitivity analysis of deposition response as a function of droplet size and residence time. Deposition fractions exhibited limited variation across the evaluated residence time range (0.5–3.0 s), indicating that droplet size was the dominant factor controlling canopy interception within the model. Distinct line styles are used to improve the visualization of upper-, middle-, and lower-canopy deposition fractions.

The analytical interpretation suggests that finer droplets remained suspended within the upper canopy region for longer durations under rotor-assisted airflow conditions, thereby increasing the likelihood of interception by vertically oriented sugarcane foliage. In contrast, larger droplets exhibited greater gravitational settling and faster penetration toward lower canopy layers and ground surfaces. Although direct aerodynamic measurements were not conducted, the observed deposition patterns were consistent with previously reported UAV downwash behavior influencing droplet transport and canopy interaction dynamics [3]. These airflow-mediated trends provide a plausible mechanistic explanation for the enhanced upper-canopy deposition and reduced ground loss observed under UAV–ULV application. The sensitivity analysis demonstrated that deposition partitioning was primarily governed by droplet size rather than residence time within the evaluated range (0.5–3.0 s). Consequently, canopy deposition fractions exhibited only minor variation across residence time scenarios, resulting in relatively flat response curves. This behavior reflects the underlying model structure, where droplet diameter exerted a substantially stronger influence on interception probability than the residence time interval considered in the present study.

A strong positive relationship was additionally observed between upper-canopy deposition and NDVI enhancement across treatments (Figure 6), supporting the interpretation that differences in canopy-level spray interception may have contributed to variation in short-term physiological response under equivalent biostimulant application rates.

Relationship between Canopy Deposition and Physiological Response

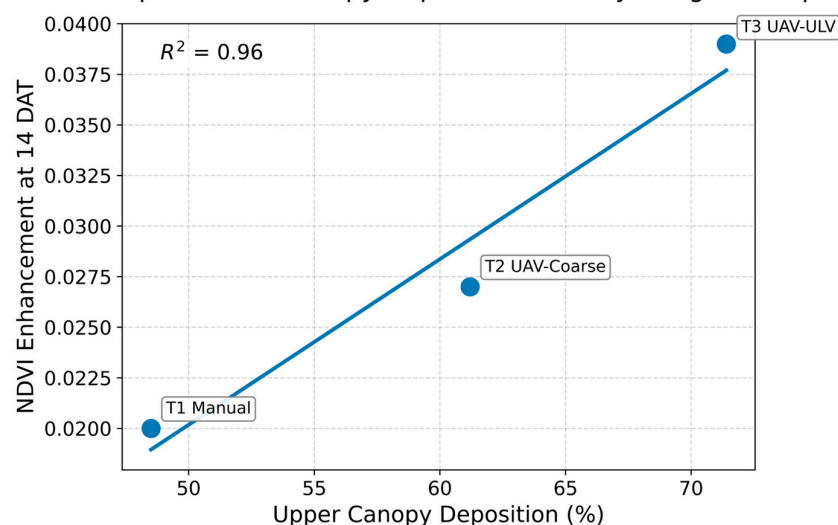


Figure 6. Relationship between upper-canopy deposition and NDVI enhancement at 14 DAT across spray treatments. Higher canopy interception under UAV-assisted application corresponded to stronger physiological response trends under equivalent biostimulant dosage conditions.

The selected UAV operational conditions likely influenced the observed deposition behavior within the sugarcane canopy. Lower flight altitudes and moderate forward flight speeds were expected to maintain stronger rotor-assisted airflow interaction with the upper canopy while limiting excessive lateral drift and rapid droplet dissipation. Under these conditions, finer droplets exhibited improved interception within upper and mid-canopy regions relative to coarse droplets, whereas excessive settling of larger droplets contributed to greater lower-canopy and ground deposition. Although operational parameter optimization was not independently evaluated in the present study, the observed trends suggest that flight altitude and forward speed remain important variables influencing canopy penetration behavior in dense sugarcane systems.

4. Discussion

The present study demonstrated that UAV-assisted ultra-low-volume (ULV) biostimulant application improved canopy deposition characteristics and physiological response in tall sugarcane relative to conventional manual spraying. Enhanced deposition within the upper- and mid-canopy regions under UAV-ULV treatment was consistent with the observed NDVI and SPAD response patterns, suggesting that finer droplet transport under rotor-assisted airflow conditions contributed to improved foliar interception efficiency. Because all treatments received equivalent active ingredient rates of the same seaweed-based biostimulant formulation, the observed physiological differences were interpreted primarily in relation to variation in spray deposition behavior and canopy interception efficiency rather than differences in chemical composition. Although direct biochemical uptake measurements were not performed, the temporal correspondence between deposition behavior and physiological response supports the hypothesis that physical spray distribution characteristics contributed to variation in short-term canopy response under field conditions. This interpretation was further supported by the positive association observed between upper-canopy deposition and NDVI enhancement across treatments (Figure 6), suggesting that canopy interception efficiency may have influenced the physiological expression of the applied biostimulant under field conditions. Nevertheless, NDVI and SPAD responses in field-grown sugarcane remain inherently influenced by environmental conditions, crop physiological status, and localized canopy microclimate variability.

In dense sugarcane canopies, rotor-assisted downward airflow may additionally contribute to transient canopy movement and localized turbulence, potentially increasing droplet exposure to leaf surfaces and improving interception opportunities within upper foliage layers. The selected UAV flight altitude and forward speed likely contributed to maintaining sufficient rotor-assisted airflow interaction with the canopy while minimizing off-target drift under field conditions. Previous UAV spray studies have similarly reported that operational parameters such as flight height, travel speed, and droplet spectrum strongly influence canopy penetration and vertical deposition distribution in dense crop systems [2,3].

The observed canopy deposition trends are consistent with previous UAV spray studies reporting the importance of droplet size, rotor downwash, and canopy structure in determining aerial spray distribution behavior [5,7]. Nahiyoony et al. [7] highlighted the growing importance of UAV operational optimization, droplet spectrum management, and precision aerial delivery in modern plant protection systems, while Ramteke et al. [6] demonstrated the practical integration of UAV-assisted sensing and precision input management under northern Indian sugarcane cultivation conditions. Similar airflow-mediated deposition behavior under agricultural UAV rotor systems has also been reported by Liu et al. [3], who demonstrated that rotor downwash structure strongly influences droplet transport and canopy penetration dynamics.

Fine droplet atomization under controlled UAV flight conditions likely increased canopy residence time and interception probability within the dense sugarcane canopy, thereby improving short-term physiological response following foliar biostimulant application. The stronger NDVI and SPAD enhancement observed during the 7–14 DAT window further suggests that UAV-assisted deposition improved early canopy-level uptake dynamics under field conditions. Similar applications of UAV-based multisensor systems for crop physiological monitoring and precision management have been discussed by Matese and Di Gennaro [4] in precision viticulture systems.

Operationally, UAV-based application substantially reduced carrier volume requirements relative to manual spraying while maintaining favorable yield response. Such reductions in spray volume and labor dependence may offer practical advantages for

large-area sugarcane management under precision agriculture frameworks. The results therefore support the broader potential of UAV-assisted foliar input delivery systems in dense-canopy cropping environments where conventional ground spraying often faces penetration and operational constraints.

The airflow-informed analytical framework further supported interpretation of deposition behavior by highlighting the influence of droplet residence time and canopy interaction on vertical interception patterns. Sensitivity analysis across droplet classes indicated that finer droplets exhibited greater upper-canopy interception potential under rotor-assisted airflow conditions, consistent with the field observations obtained during UAV-ULV application. The findings additionally highlight the importance of UAV operational parameters, including flight altitude and forward speed, in influencing canopy deposition efficiency under dense sugarcane field conditions.

Although the airflow analysis provided a useful mechanistic interpretation of deposition behavior, the framework was intentionally simplified and did not incorporate fully resolved transient CFD turbulence structures or direct in-field airflow validation measurements. Future research integrating advanced CFD-based airflow modeling, field-scale aerodynamic validation, operational parameter optimization (including flight altitude, forward speed, and payload conditions), multisensor UAV guidance systems, and multi-location agronomic trials may further strengthen optimization of UAV-assisted foliar delivery systems for dense-canopy crops under precision agriculture frameworks.

5. Conclusions

This study demonstrated that precision UAV-based biostimulant application is a technically feasible and agronomically effective strategy for tall sugarcane canopies. Compared with conventional manual spraying, UAV-based application—particularly under ultra-low-volume (ULV) conditions—significantly improved vertical spray deposition, with enhanced interception in the upper canopy and minimal ground loss.

Physiological indicators, including NDVI and SPAD chlorophyll measurements, showed stronger and earlier responses under UAV-ULV application, particularly during the 7–14 day post-treatment window. These physiological trends were broadly consistent with the observed deposition behavior and suggest that canopy-level spray distribution may influence the effectiveness of foliar biostimulant delivery under field conditions. Yield outcomes further reflected these trends, with UAV-ULV treatment achieving higher mean yield and reduced variability across plots.

The lightweight airflow-informed analytical framework provided mechanistic support for the observed deposition behavior by highlighting the role of droplet residence time and canopy interception dynamics under rotor-assisted airflow conditions. Overall, the integration of field observations with airflow-informed interpretation demonstrates the potential of UAV-ULV spraying as a precise, low-volume, and operationally efficient strategy for foliar biostimulant delivery in tall sugarcane canopies. The framework was not intended to directly resolve transient turbulence structures or quantify detailed rotor aerodynamic parameters such as velocity vectors or pressure fields.

Future research integrating advanced CFD-based airflow modeling, field-scale aerodynamic validation, multisensor UAV guidance systems, and multi-location agronomic trials may further strengthen the optimization of UAV-assisted foliar delivery systems for dense-canopy crops under precision agriculture frameworks.

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Conflicts of Interest: The authors declare no conflicts of interest.

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