International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V73I10P122

Volume 73 Issue 10, 278-288, October 2025

Original Article

Image-Based Static Evaluation of Spray Pressure and Distance for UAV Cleaning Performance Assessment

Fathan Fadzulli[1], OMF Marwah[2], M Zulafif Rahim[3], SJM Mohd Salleh[4], Haris Hamizan Hamzah[5]

[1,2,3,4,5]*Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Johor, MALAYSIA*

[2]*Corresponding Author : mdfaizan@uthm.edu.my*

Received: 05 June 2025 Revised: 14 October 2025 Accepted: 28 October 2025 Published: 31 October 2025

Abstract - *The Integration of Unmanned Aerial Vehicles (UAVs) for cleaning applications offers a safer and more efficient alternative to manual operations, particularly on high-rise building surfaces. This study aims to evaluate the spraying quality and cleaning performance of TiungLap, the UTHM-developed drone system, by examining parameters affecting both safety and effectiveness. The experimental work involved methods that include a spraying quality assessment using nozzle configurations at varying distances of 0.5m, 1m, and 1.5m to measure spray width, acting force, and droplet behavior, and an artificial dirt cleaning test to evaluate the cleaning efficiency based on coverage and residual dirt. Results show that 1m achieved the best balance between acting force and spray pattern uniformity, resulting in the highest cleaning efficiency, ranging from 36.95% to 65.96%, and a peak acting force of 3.92 N. This study contributes to optimizing drone-based cleaning operations by improving cleaning output while ensuring operational safety within effective spraying zones.*

Keywords - *UAV, Window Cleaning, Spraying Evaluation, Image Processing, Cleaning Efficiency, Acting Force, Nozzle Selection.*

1. Introduction

Cleaning high-rise building façades using traditional methods remains a hazardous task that frequently results in accidents and operational inefficiencies[1-3]. UAVs offer a safer alternative, but still have challenges in terms of regulations restricting drones from flying too close to buildings for less than 50m [4]. Drones struggle to remain stable near surfaces like glass or metal, especially in misty and wet conditions without the sensors [5]. Another issue is the lack of data on how high-pressure spraying works at different distances. Without this information, it is difficult to establish the pressure and distance selection for cleaning.

Previous research has examined spray nozzle characteristics, droplet behaviour, and cleaning performance in agricultural or industrial applications [6-8]. While these studies provide valuable insights, there remains a lack of experimental evidence correlating spray pressure, distance, acting force, and cleaning efficiency specifically for UAV cleaning operations. Most works report theoretical spray models or droplet dispersion patterns but do not experimentally validate the force impact on vertical surfaces at UAV-relevant operating distances [9]. Furthermore, limited studies integrate image-based analysis with force measurements to objectively quantify cleaning performance. This study addresses the above research gap by conducting a static spray evaluation of the TiungLap UAV cleaning system developed at UTHM. A gantry-mounted pressurized washer was tested at distances of 0.5m, 1.0m, and 1.5m at different pressures, 50bar, 100bar, and 150 bar. The acting force on target panels was measured using a force gauge, while image processing techniques quantified cleaning efficiency. By combining force measurements with pixel-based cleanliness analysis, this work provides new evidence on the relationship between spray parameters and cleaning outcomes. The findings contribute to optimizing UAV cleaning configurations for safer and more efficient drone-based façade cleaning operations.

The need for systematic evaluation of spraying force performance at different distances and pressures to inform drone configuration for high-rise cleaning operations [10]. Without understanding how much impact force is delivered to the Surface, drone cleaning parameters cannot be calibrated for efficiency. This study fills that gap by experimentally measuring the force output of a pressure washer mounted at static positions using controlled pressure levels and fixed distances.

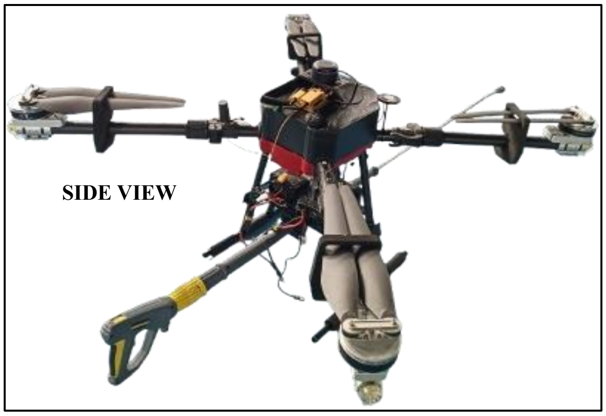


Fig. 1 TiungLap drone

2. Literature Review

2.1. Spraying Pressure in Cleaning Applications

High-pressure water jets have been widely used for industrial and façade cleaning due to their ability to dislodge stubborn contaminants without chemicals. When increasing Pressure significantly reduces droplet size, resulting in a more focused and penetrating spray [1, 2]. However, cleaning performance declines as the spray distance increases, due to the natural dissipation of force and spray dispersion. For example, droplet velocity and impact force both decrease beyond 1m, making lower pressures like 50Bar ineffective at longer ranges [8]. Despite the availability of theoretical pressure-flow models, very few works have examined quantitative acting force at various spray distances, especially in the context of drone cleaning systems.

2.2. Impact Pressure on Cleaning Efficiency Plateau

Efficiency gains in water jet applications plateau near 150Bar due to the increasing significance of energy dissipation during droplet impact. The primary loss mechanisms are droplet bouncing and reflection. The efficiency of this process is measured by the restitution coefficient, which is itself a function of complex fluid-structure interactions like contact-line pinning and inertial-capillary effects [12]. These interactions dissipate kinetic energy, and their effect is magnified on superhydrophobic surfaces, where droplets undergo several bounce cycles before coming to rest [13].

2.2.1. Droplet Bouncing

At high velocities, water droplets tend to rebound from the Surface rather than disperse, thereby diminishing the energy transfer essential for effective cleaning. The coefficient of restitution, a measure of energy retained following an impact, is influenced by the wettability of the Surface. The degree of energy retention is determined by the Surface's wetting characteristics, with hydrophobic surfaces incurring the most significant losses. As Pressure increases, droplets may not spread effectively across the Surface, and instead, they bounce off[13]. Energy is wasted through this bouncing action, which energy is critical for contaminants removal and thus reduces cleaning efficiency.

2.2.2. Surface Wetting Dynamics

The wetting behavior of surfaces is essential for understanding how fluids interact with them. Hydrophilic surfaces, which have a water contact angle of less than 90°, promote the rapid spreading and firm adhesion of droplets [14]. This enhances cleaning efficiency by ensuring optimal energy dissipation, with superhydrophilic surfaces below 10° enabling perfect wetting for uniform fluid distribution. In contrast, hydrophobic surfaces, with contact angles above 90°, cause droplets to bead up and rebound, reducing energy transfer and cleaning effectiveness as in Figure 2.

Superhydrophobic surfaces exceeding 150° exhibit extreme liquid repellence, "Lotus Effect" often requiring alternative methods such as increased impact energy or mechanical agitation for cleaning [14]. Modern engineering techniques such as nano-texturing are useful for the development of self-cleaning superhydrophobic surfaces and superhydrophilic coatings.

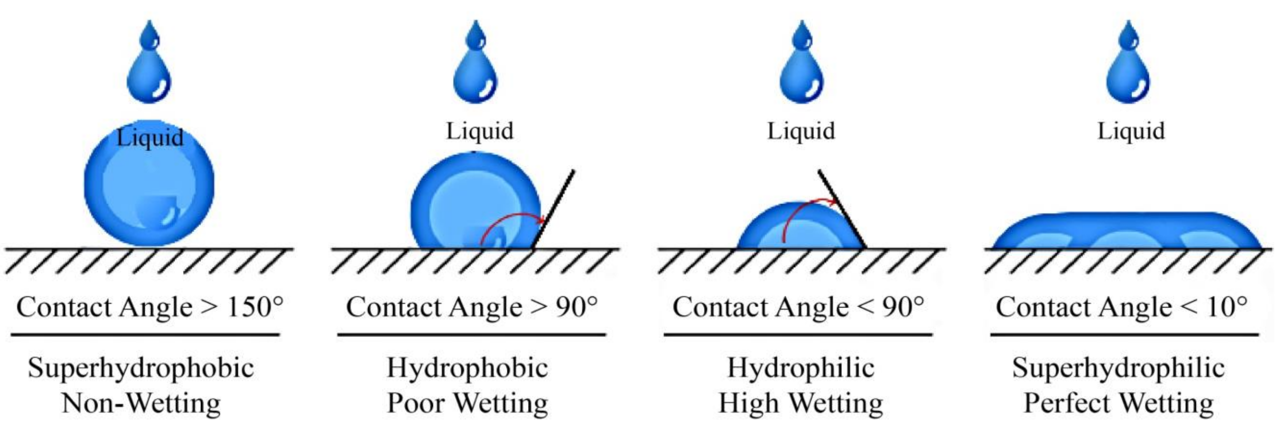


Fig. 2 Surface wetting properties

2.3. Image Processing Evaluation

Image processing tools such as OpenCV and MATLAB are often used in recent studies to evaluate cleaning quality. MATLAB and OpenCV enable pixel-by-pixel analysis using masking, thresholding, and segmentation to identify cleaned versus contaminated regions. This method provides a non-subjective way to quantify cleaning success, especially useful in robotics, where repeatability is essential. For instance, comparing the number of dark-light pixels before and after cleaning helps determine surface cleanliness percentage. However, integrating such evaluation methods with acting force and spray distance parameters remains limited in current UAV-cleaning literature.

2.4. Acting Force and Surface Impact Analysis

The acting force of the water jet is a crucial parameter in evaluating cleanliness. As the spray distance increases, the force exerted by the water jet diminishes because the kinetic energy of the water droplets dissipates over distance, reducing the force necessary to dislodge particles from surfaces[15].

Some works have modeled force based on pressure and nozzle configuration, but very few experiments directly measured the acting force exerted on the Surface using a pressure transducer. In one related study, force values were mapped against pressure settings to estimate potential surface damage during industrial cleaning [11, 12]. Yet, none of these studies focus on drone washer-mounted systems for variable spray distances, which are a major operational concern in UAV-based cleaning, especially when hovering stability may change with altitude and wind[18].

3. Methodology

3.1. Gantry Setup

The gantry testing method provided consistent and repeatable conditions critical for assessing the acting force across different spraying distances and pressures, thereby replicating the drone's operational cleaning range without airborne disturbances. A grounded gantry testing rig was utilized to evaluate the static cleaning force and droplet behavior exerted by the UTHM-developed cleaning drone accurately. The gantry system was designed to support a high-pressure washer nozzle. This setup ensured a stable spraying condition by eliminating external influences such as drone drift or vibration, thereby allowing a pure evaluation of spraying pressure impact and cleaning performance. The cleaning evaluation process followed a systematic approach to correlate the acting force exerted by the pressure spray with the resulting cleaning quality. Figure 3 was developed to map the relationship between applied Pressure, distance from the Surface, and resultant cleaning efficiency. Subsequently, post-cleaning images were analyzed to determine the percentage of residual contaminants. This framework enabled the evaluation of how variations in distance and pressure settings directly influenced cleaning effectiveness, offering critical insights for drone-based operations.

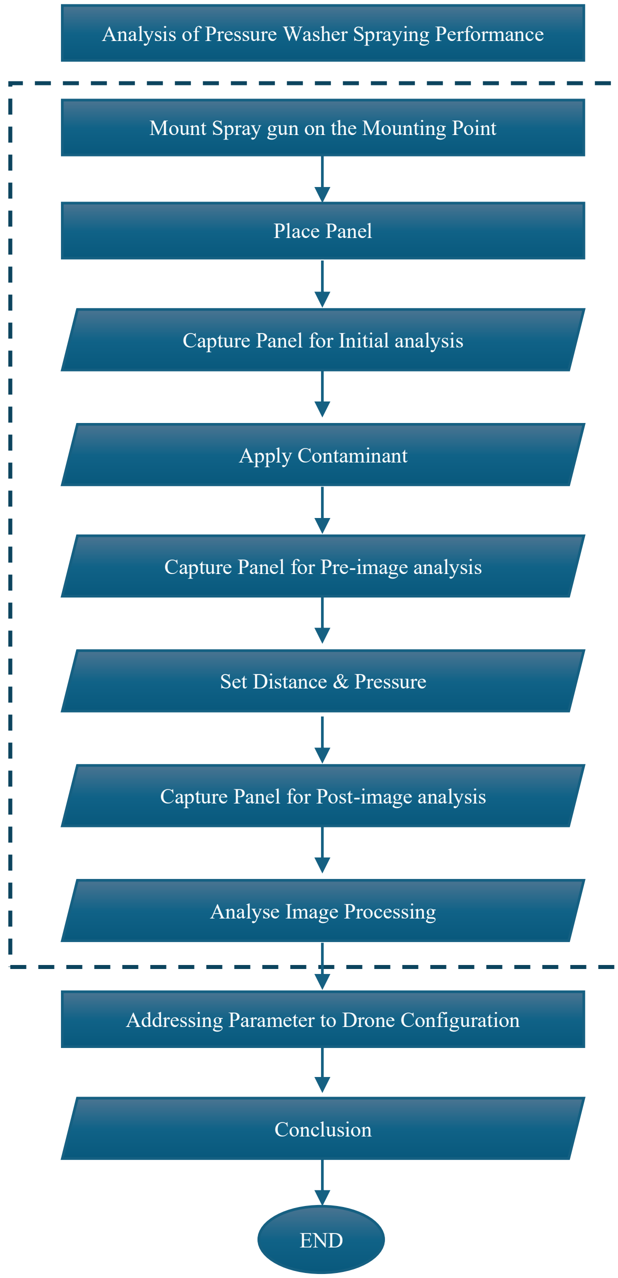


Fig. 3 Flowchart cleaning quality influenced by force and distance

Figure 4 involved mounting a high-pressure washer on a gantry frame and directing the spray perpendicularly towards the test panels at designated distances. Pressure washer used Karcher HDS 6/14C model, capable of output pressures ranging from 5Bar -15Bar from the pressure gauge reading. A flat-fan nozzle with a 45° spray angle was selected to replicate typical drone cleaning applications that reduce drift[14, 15].

The nozzle distances were precisely adjusted to 0.5 m, 1.0 m, and 1.5 m from the load cell surface due to the sensor capability of TiungLap RPLidar A2. It is capable of detecting a minimum of 20cm[20]. Acting force measurements were recorded using a digital force gauge mounted behind the panel to capture real-time impact forces at various pressures and distances. This setup was designed to eliminate variables such as wind and drone instability, ensuring a controlled experimental environment for data consistency.

3.2. Image Processing

Image processing techniques are used to evaluate the cleaning efficiency using MATLAB software objectively. Pre- and post-cleaning images of panels were captured under standardized lighting conditions.

The images in Figure 4 were then converted to grayscale, and an adaptive thresholding technique was applied to differentiate between clean and contaminated regions. The cleaned area is quantified using the following formula:

$$\text{Cleaning Efficiency}(\%)= \left(\frac{A_i - A_o}{A_i}\right)\times 100\% \tag{1}$$

Where; A_i is an area (in pixels) of the Surface that is initially contaminated before cleaning. A_o is a residual area (in pixels) that still appears dirty after the cleaning process. The captured image pixel count is standardized to 1920×1920 resolution at 3686400px, representing the designated surface area. Using pixel segmentation, the cleaned area was quantified and expressed as a percentage relative to the total panel surface[21]. This method provided a reliable, non-subjective measurement of cleaning success, allowing a robust correlation between spray force and cleaning performance to be established. A higher cleaning efficiency percentage indicates greater success in removing contaminants from the panel surface.

3.3. Load Cell Pressure Conversion

The acting force exerted on the Surface was measured using a force gauge mounted directly behind the impact area on the target panel. The acting force was calculated using Newton's second law, derived from Pressure and contact area as:

$$F = m\times g = P\times A \tag{2}$$

Where F is the Acting Force (N), m is the load cell reading (g), g is the gravitational Force, P is the Pressure of the jet (Pa), and A is the effective area impacted by the spray (m²)

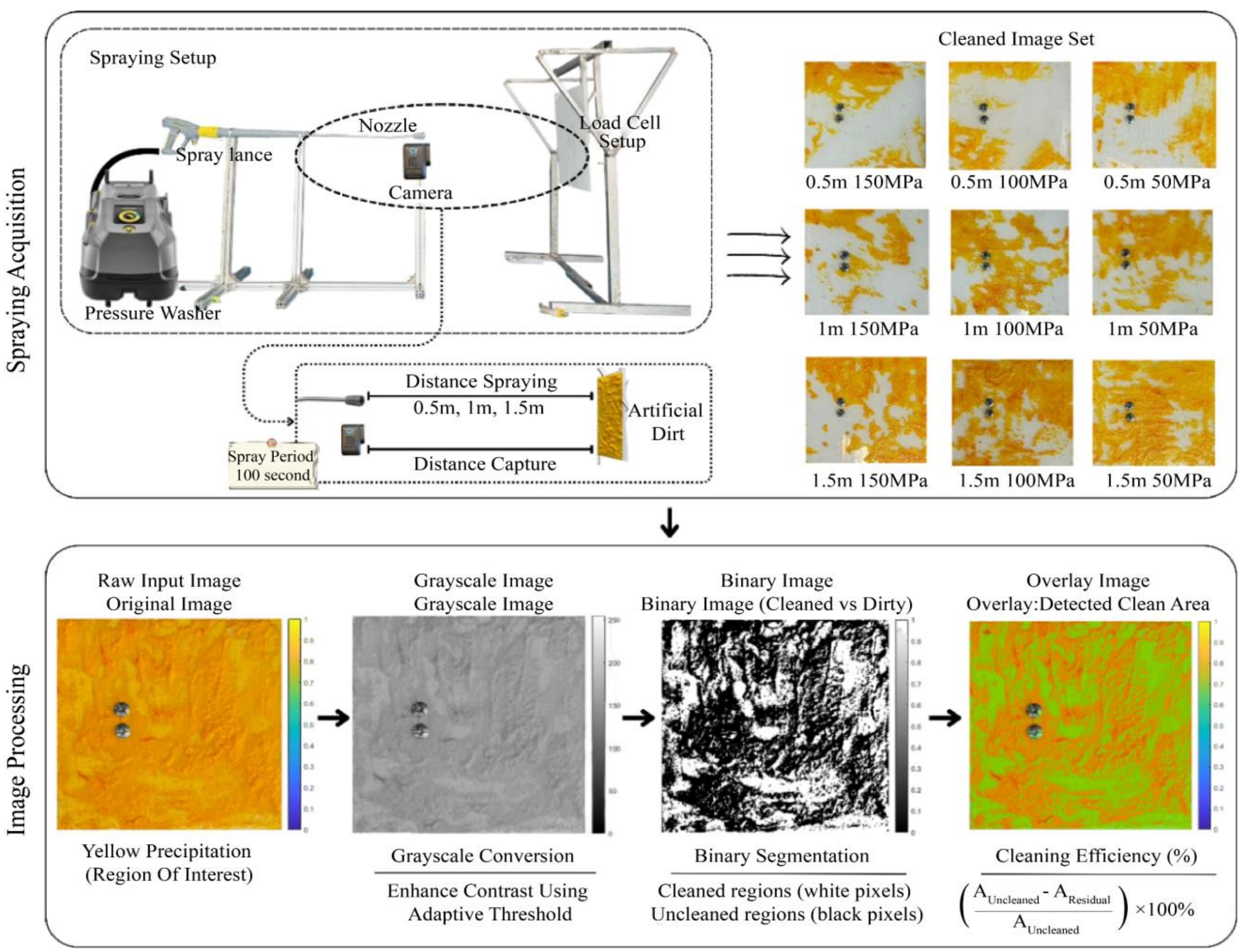
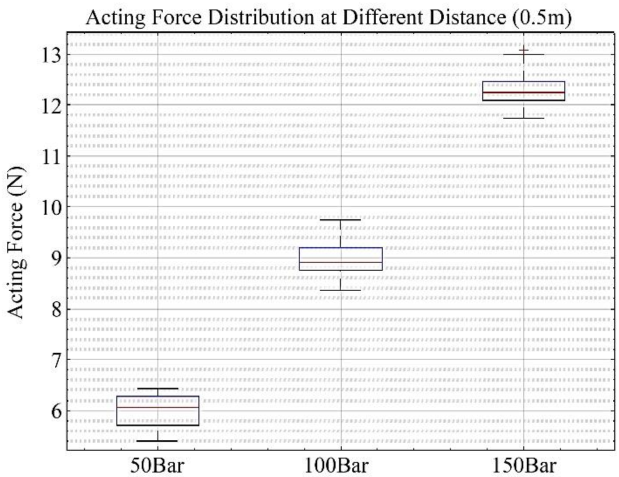


Fig. 4 MATLAB image conversion procedure

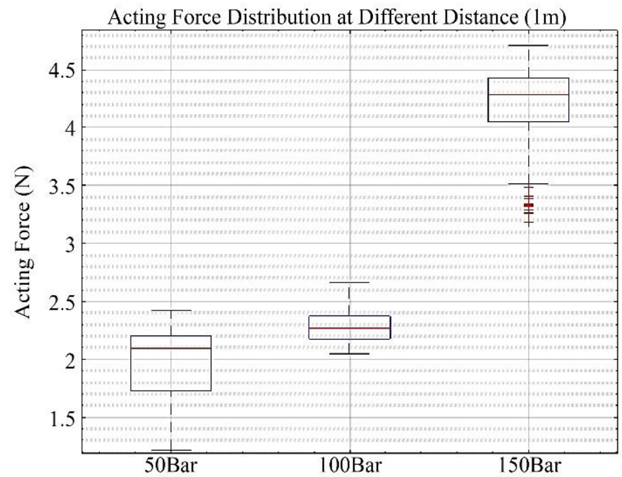
4. Results and Discussion

4.1. Acting Force on the Attacked Surface

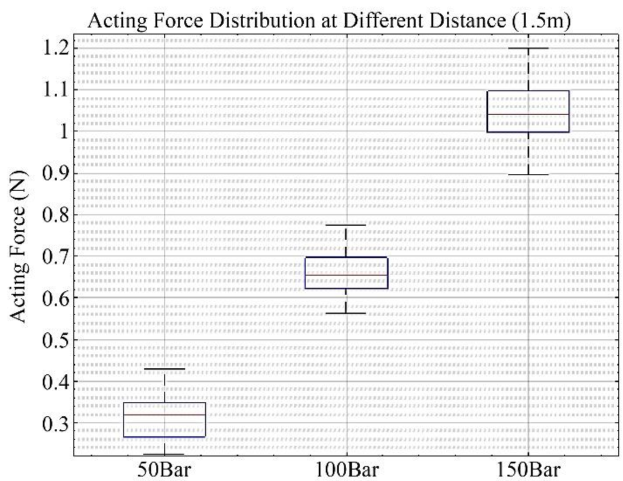
The acting force exerted by the spray jet on the panel surfaces varied significantly with both spraying Pressure and distance. As illustrated in Figure 5, the maximum force recorded at 0.5m distance was 13.0776N at 150Bar, while at 1.0m, the peak force slightly reduced to 4.7077N. At 1.5 m, the acting force dropped more noticeably to a maximum of 1.2002N. These results confirm that spray impact force dissipates with increasing distance due to air drag and droplet breakup[8]. This trend highlights the importance of maintaining an optimal spraying distance close to 1.0 m for effective drone cleaning operations, balancing impact force with operational safety[8].



(a)



(b)



(c)

Fig. 5 Acting force on Surface at (a) 0.5m, (b) 1.0m, and (c) 1.5m.

Table 1. Acting force exerted on panel surface

Distance, m	Pressure, Bar	Lower Limit, Q0	Lower Quartile, Q1	Median, Q2	Upper Quartile, Q3	Upper Limit, Q4
0.5	50	5.3992	5.7069	6.0525	6.2737	6.4431
	100	8.3702	8.7600	8.9188	9.2088	9.7394
	150	11.7473	12.0954	12.2452	12.4616	13.0776
1.0	50	1.2192	1.7304	2.0959	2.2033	2.4190
	100	2.0455	2.1753	2.2656	2.3724	2.6630
	150	3.1855	4.0545	4.2862	4.4282	4.7077
1.5	50	0.2248	0.2662	0.3181	0.3489	0.4296
	100	0.5644	0.6215	0.6554	0.6970	0.7759
	150	0.8963	0.9973	1.0417	1.0967	1.2002

Table 1 shows the distribution of the acting force measured at different spray pressures and distances. At 0.5m, the acting force was the highest, ranging between 6.0525 N at 50bar and 12.25N at 150bar. However, the large force at this range may lead to splash-back and uneven cleaning. At 1m, acting forces were moderate, 2.09N to 4.28N at 50 and 150bar, ideal for safety impact and uniform spraying as said by Hament and Liu et al. [22, 23]. At 1.5m, the acting force dropped significantly, with maximum readings only 1.04N at 150bar, proof that droplet energy dissipates rapidly with distance. Overall, the optimal range for UAV cleaning is within 1m, as the distribution trend shows that higher pressure increases the acting force. However, some outliers were seen in Table 2, indicating distribution instability.

Table 2. Outliers' presence in the boxplot diagram

Dist.. (m)	Pressure	Acting Force Outlier(N)	No. outlier
0.5	150Bar	13.0776	1
1.0	150Bar	3.1855, 3.2583, 3.2919, 3.3182, 3.3256, 3.3369, 3.3841, 3.4051	8

4.2. Cleaning Efficiency Evaluation

Figure 6 shows the image of dirt replication on the surface panel for a constant initialization to compare with all the post images taken in the following Figure 8, and Figure 9.

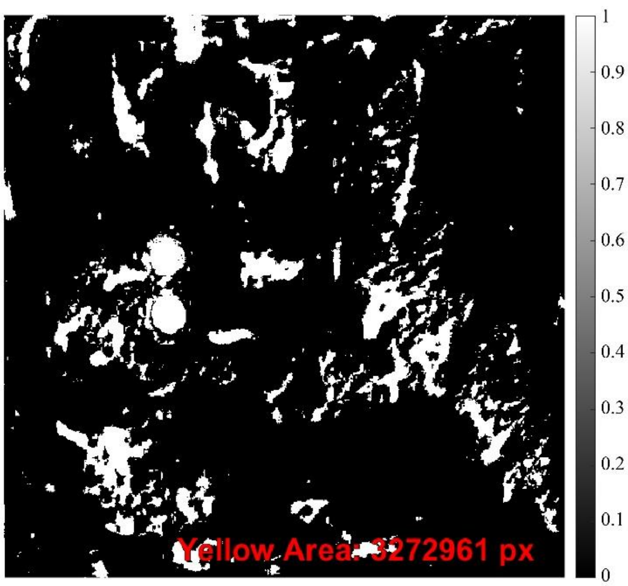


Fig. 6 Pre Image capture at origin

In Figure 7, the result shows the image was captured at a distance of 0.5m with three pressure supplies. The pixelation value within 1m distance at 50Bar, 100Bar, and 150Bar are 1389756px, 1977446px, and 1332923px, respectively. At a distance of 0.5 m, although the acting force was highest, the spray pattern exhibited significant dispersion. Although the spray exerts the highest acting Force up to 12.298 N with 150Bar, the pixel data show less effective cleaning compared to 1 m. A higher acting force at close range causes excessive dispersion and splashing, as seen in the images, resulting in lower cleaning efficiency. For instance, efficiency is 39.58% at 50Bar and improves to 59.27% at 150Bar.

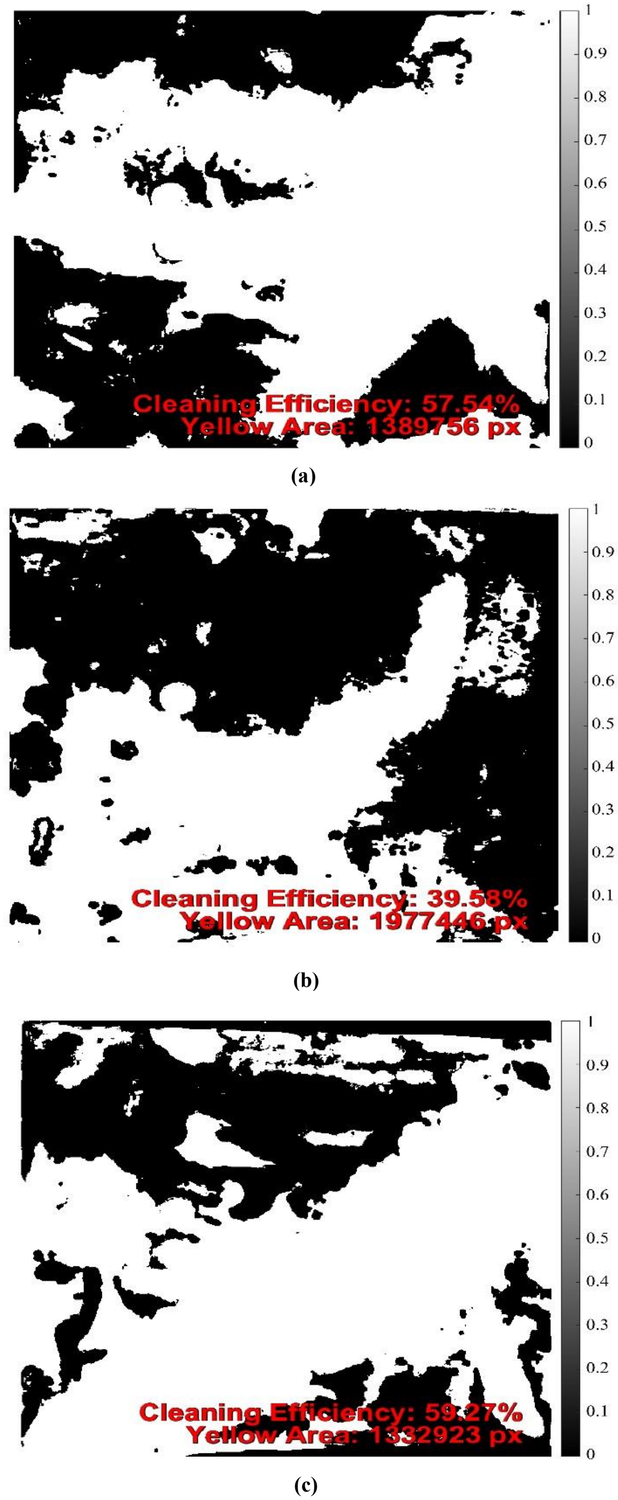
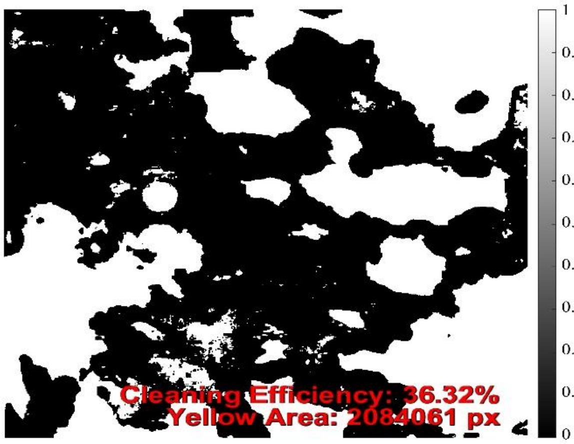


Fig. 7 Post Image 0.5m at (a) 50Bar, (b) 100Bar, and (c) 150Bar.



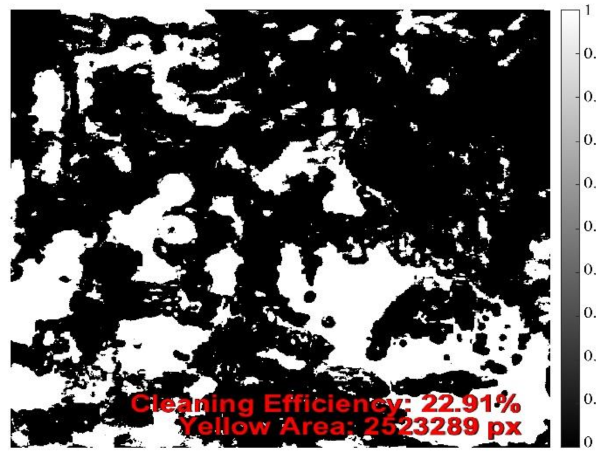
(a)

(b)

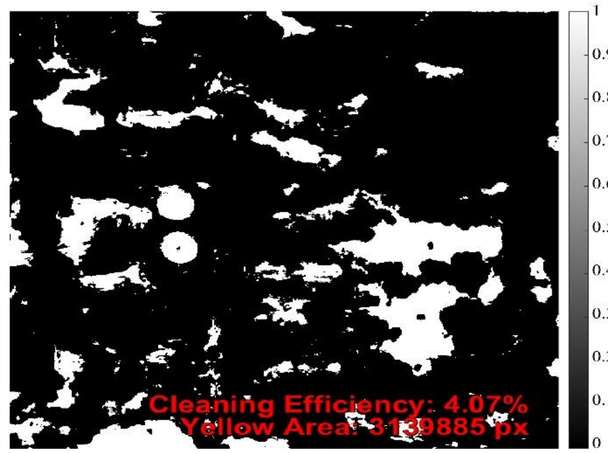
(c)

Fig. 8 Post Image 1m at (a) 50Bar, (b) 100Bar, and (c) 150Bar.

In Figure 8, the result shows the image was captured at a distance of 1m with three pressure supplies. The pixelation value within 1m distance at 50Bar, 100Bar, and 150Bar are 2084061px, 2063717px, and 1114046px, respectively.



(a)



(b)

(c)

Fig. 9 Post Image 1.5m at (a) 50Bar, (b) 100Bar, and (c) 150Bar.

Despite the lower force maximum of 4.185 N, this distance produces the highest cleaning efficiency, where it reaches 65.96% at 150Bar with the lowest post-cleaning pixel count 1,114,046px. The results depict that it is an optimal spray coverage without excessive splash-back or uneven distribution. At 1m, the balance between sufficient impact force and uniform spray distribution resulted in the highest cleaning efficiency, ranging between 36.95% and 65.96%.At 1.5 m, a notable decrease in cleaning performance was observed, consistent with reduced acting force and increased droplet dispersion. Therefore, a 1.0 m spraying distance emerged as the optimal configuration for cleaning drone operations, achieving a superior balance between droplet concentration, force, and surface coverage[8]. By contrast, Figure 9 clearly shows degraded cleaning quality. The acting force records the weakest, only 1.048 N at 150Bar in 1.5m distance, and the spray pattern becomes highly dispersed[24]. As a result, residual dirt is prominent, such as 3,139,885px at 50Bar, and cleaning efficiency drops significantly, with a low of 4.07% at 50Bar and only 38.90% at 150Bar. Based on Table 3 and Figures 7 to Figure 9, the cleaning performance varies by distance and Pressure.

At 0.5m, 150Bar achieved the best result, followed by 100Bar and 50Bar, though excessive force led to some splashing. At 1m, cleaning was most effective overall, especially at 150Bar, with 50Bar and 100Bar showing similar performance. At 1.5m, cleaning was weakest across all pressures, with 150Bar still performing better than lower pressures. Overall, 1m was the optimal distance, providing the best balance between spray force and coverage. Meanwhile, at 0.5m, there was the possibility of oversaturation, and at 1.5m, there was sufficient impact to wash the contaminant[9, 18].

4.3. Relation Acting Force

The correlation between acting force and cleaning efficiency was further evaluated, as summarized in Table 3. A positive relationship was observed, where increased acting forces generally led to improved cleaning percentages.

Table 3. Correlation of acting force, spraying distance, and cleaning efficiency

Nozzle	Distance, (m)	Pressure, (Bar)	Average Acting Force (N)	Pixelate amount		Efficiency, (%)
				Pre	Post	
Flat fan 45°	0.5	50	5.989	3272961	1389756	39.58
		100	8.980		1977446	57.54
		150	12.298		1332923	59.27
	1.0	50	1.987		2084061	36.95
		100	2.287		2063717	36.32
		150	4.185		1114046	65.96
	1.5	50	0.314		3139885	4.07
		100	0.661		2523289	22.91
		150	1.048		1999935	38.90

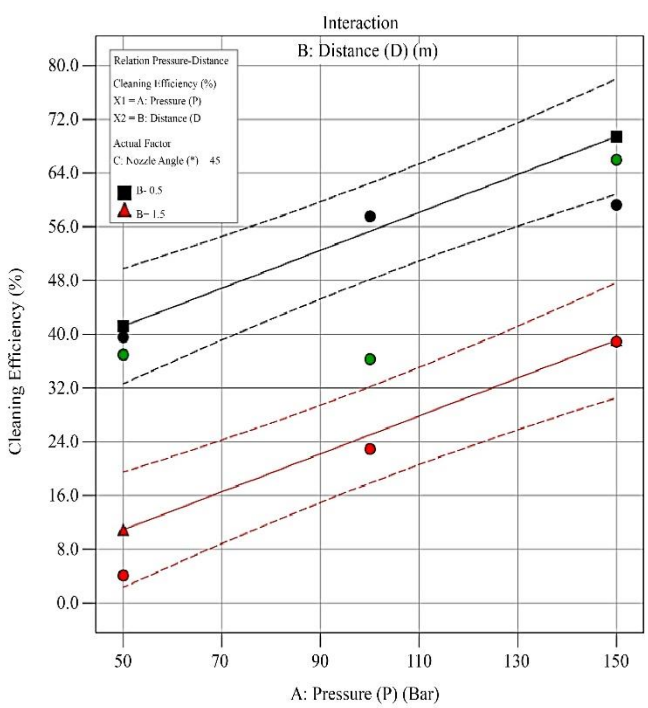


Fig. 10 Interaction between distance and pressure with cleaning efficiency at 45° nozzle

However, beyond certain thresholds, additional force did not proportionally enhance cleaning due to spray saturation and splashing effects[26]. Specifically, at pressures beyond 100Bar at 1m, the increase in cleaning efficiency plateaued, suggesting that further increasing pressure yields diminishing returns. This highlights the need for optimizing force magnitude along with spraying uniformity to maximize cleaning results while reducing energy consumption and surface damage.

At a nozzle angle of 45°, the interaction plot in Figure 10 shows a generally moderate cleaning efficiency trend across all pressures. When the distance is short at 0.5m (black line), cleaning efficiency increases with Pressure at a more gradual rate. In short, Figure 10 shows a rubric for expected efficiency for Pressure if other than the designated Pressure is used during cleaning. Efficiency may vary depending on environmental factors such as temperature and spray speed[27].

At a longer distance of 1.5m (red line), the cleaning efficiency remains low and shows only a slight improvement with increasing Pressure. The separation between the two lines is minimal and remains constant across the pressure range, indicating a weaker interaction effect. This suggests that the influence of Pressure becomes less pronounced when the spray is more dispersed due to the wider nozzle angle, especially at longer distances[24].

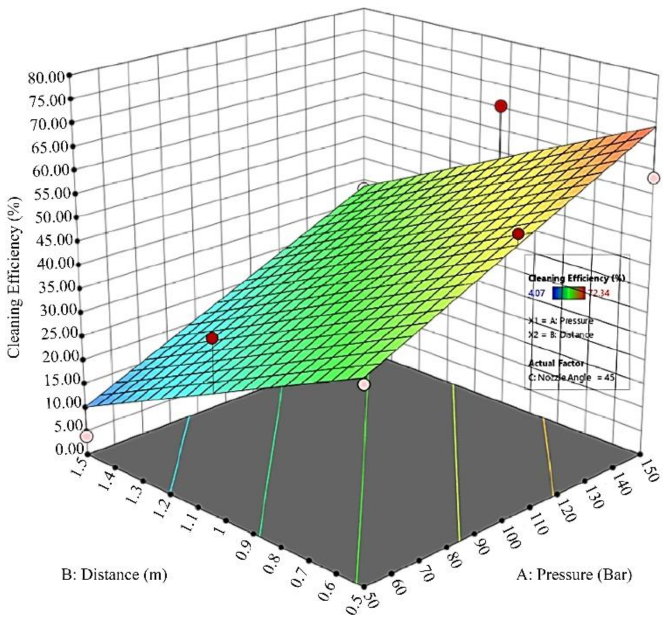


Fig. 11 3D Surface plot Cleaning Efficiency for 45° Nozzle

Figure 11 plot at a 45° nozzle angle exhibits a relatively gentle slope rising from the front-left corner, where both pressure and cleaning efficiency are low, to the back-right corner, where Pressure is highest and distance is shortest. The highest cleaning efficiency is still observed at high Pressure and short distances, but at proximity distances, the safety factor will be a concern, which can lead to property obstruction. The Surface appears flat and the curvature less pronounced, reflecting a more linear interaction. This flattening suggests that the combined effect of Pressure and distance is more synergistic, likely due to the wider spray angle diffusing the cleaning force over a broader area and diminishing its impact on surface contaminants[26].

5. Conclusion

This study experimentally evaluated the effect of spray pressure and distance on cleaning performance for UAV-based façade cleaning applications. Using a stable gantry setup, results showed that a spraying distance of 1.0 m at 150 bar achieved the best cleaning efficiency (up to 65.96%), offering an optimal balance between acting force, spray uniformity, and operational safety. At shorter distances (0.5 m), excessive force led to splash-back and reduced coverage, while at longer distances (1.5 m), the acting force dropped significantly, resulting in poor cleaning efficiency. These findings confirm that cleaning performance depends on both force magnitude and spray uniformity, not solely on pressure levels. The practical implication is that UAV cleaning systems should be configured to operate within 1m distance with moderate to high pressures, ensuring effective contaminant removal while minimizing stability risks and water wastage. The integration of image-based analysis with acting force measurement in this study offers a replicable framework for evaluating drone cleaning systems.

Future research should extend this static evaluation into dynamic UAV flight testing to examine the effects of wind, vibration, and hovering instability on cleaning outcomes. Investigating different surface types, nozzle configurations, and water consumption strategies will further enhance the adaptability of UAV cleaning systems. Additionally, integrating real-time sensing and AI-based control for adjusting spray distance and Pressure could improve efficiency and autonomy in real-world high-rise cleaning operations.

Author Distribution

The authors have no disclosure conflict of interest to declare and are satisfied with their own contribution to the whole project and writings. Fathan Fadzulli led the research activities, including data tabulation, experimental execution, and manuscript preparation. He was primarily responsible for designing and conducting the gantry-based pressure and distance experiments, performing the image-based cleaning efficiency analysis using MATLAB, organizing the data tables and figures, and formatting the manuscript according to journal requirements.

O. M. F. Marwah conceptualized the study framework, supervised the overall research direction, contributed to the development of the methodology, reviewed and refined the manuscript, and provided the funding support essential for this work. M. Zulafif Rahim contributed to the supervision and technical implementation of the methodology, assisted in data acquisition and processing, and developed the coding and sensor integration procedures used for the RPLiDAR and force measurement system.

S. J. M. Mohd Salleh supported the supervision process, assisted in apparatus selection and calibration of the experimental setup, and ensured data reliability and methodological transparency. Haris Hamizan Hamzah assisted in the execution of the experimental setup, including rig assembly, operation of the TiungLap UAV and pressure washer system, and collection of pre- and post-cleaning image data. All authors reviewed and approved the final version of the manuscript and agreed on their individual contributions.

Acknowledgments

Communication of this research is made possible through monetary assistance from Universiti Tun Hussein Onn Malaysia and the UTHM Publisher’s Office via Publication Fund E15216. This research was also supported by Universiti Tun Hussein Onn Malaysia through the UTHM Contract Grant (vot Q540).

References

[1] A.R.A. Hamid et al., "Causes of Fatal Construction Accidents in Malaysia," *IOP Conference Series: Earth and Environmental Science, Institute of Physics Publishing*, Johor, Malaysia, vol. 220, pp. 1-12, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[2] HealthDay, Window Washers, 2024. [Online]. Available: https://www.healthday.com/a-to-z-health/public-health/window-washers-646930.html

[3] Ines Bula, Edin Bula, and Edmond Hajrizi, "Cost Oriented Autonomous Window Cleaning Robot from Mechatronic Scrap-MechCleanBot," *IFAC-PapersOnLine*, vol. 54, no. 13, pp. 233-238, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[4] Civil Aviation Authority of Malaysia, Unmanned Aircraft System (UAS), 2025. [Online]. Available: https://www.caam.gov.my/public/unmanned-aircraft-system-uas/

[5] Robu.In, SLAMTEC Slamtec RPLiDAR A2M12 360 Degree Laser Scanner Kit-12M Range, 2024. [Online]. Available: https://robu.in/product/slamtec-rplidar-a2m12-360-degree-laser-scanner-kit-12m-range/

[6] Joshua A. McGinty et al., "Herbicide Formulation, Spray Nozzle Design, and Operating Pressure Affects the Droplet Size Spectra of Agricultural Sprays," *Journal of Experimental Agriculture International*, vol. 38, no. 3, pp. 1-7, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[7] Guobin Wang et al., "Field Evaluation of Spray Drift and Environmental Impact using an Agricultural Unmanned Aerial Vehicle (UAV) Sprayer," *Science of the Total Environment*, vol. 737, pp. 1-14, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[8] Dashuai Wang et al., "Analysis of the Influence of Parameters of a Spraying System Designed for UAV Application on the Spraying Quality based on Box-Behnken Response Surface Method," *Agriculture*, vol. 12, no. 2, pp. 1-14, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] Haiyan Zhang et al., "Downwash Airflow Field Distribution Characteristics and their Effect on the Spray Field Distribution of the DJI T30 Six-Rotor Plant Protection UAV," *International Journal of Agricultural and Biological Engineering*, vol. 16, no. 2, pp. 10-22, 2023. [Google Scholar] [Publisher Link]

[10] Youngjoo Lee et al., "Automated Technique for High-Pressure Water-Based Window Cleaning and Accompanying Parametric Study," *Plos One*, vol. 15, no. 12, pp. 1-13, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[11] Jung Wook Park, Yeon Je Shin, and Woo Jun You, "Analysis of Correlations between Flow Rate, Pressure and Average Size of Droplet with Hydraulic Diameter of Water Curtain Nozzle," *Journal of the Korea Academia-Industrial Cooperation Society*, vol. 21, no. 4, pp. 317-323, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[12] A. Lallart et al., "The Fluid Mechanics of Spray Cleaning: When the Stress Amplification at the Contact Lines of Impacting Droplets Nano-Scraps Particles," *Journal of Fluid Mechanics*, vol. 1000, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[13] Calvin Thenarianto et al., "Energy Loss for Droplets Bouncing Off Superhydrophobic Surfaces," *Langmuir*, vol. 39, no. 8, pp. 3162-3167, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[14] Kosmas Ellinas et al., "A Review of Fabrication Methods, Properties and Applications of Superhydrophobic Metals," *Processes*, vol. 9, no. 4, pp. 1-29, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[15] Francesco Anglani, John Barry, and Willem Dekkers, "A Numerical Study on High-Pressure Water-Spray Cleaning for CSP Reflectors," *AIP Conference Proceedings*, Cape Town, South Africa, vol. 1734, no. 1, pp. 1-11, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[16] Werner V. Brandt, "Cleaning of Photomask Substrates using CO_2 Snow," *21st Annual BACUS Symposium on Photomask Technology,* Monterey, CA, United States, vol. 4562, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[17] Doopyo Yoon et al., "Empirical Optimization and Evaluation for Multi-Nozzle Cleaning Device," *International Journal of Precision Engineering and Manufacturing*, vol. 22, no. 7, pp. 1229-1236, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[18] Zhang Haidong et al., "Stability Research of Quadcopter UAV under Unstable Wind," *2021 IEEE 7th International Conference on Control Science and Systems Engineering (ICCSSE)*, Qingdao, China, pp. 114-118, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[19] Juan Wang et al., "Drift Potential Characteristics of a Flat Fan Nozzle: A Numerical and Experimental Study," *Applied Sciences*, vol. 12, no. 12, pp. 1-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[20] Tony Huang, RPLIDAR-A2 Solid Industrial 360° Lidar Sensor, SLAMTEC, 2016. [Online]. Available: https://www.slamtec.com/en/Lidar/A2?gad_source=1&gad_campaignid=22714703255&gbraid=0AAAAA_rvLk2hGcWT0B-0BUvbWcHPonCp9&gclid=Cj0KCQjwmYzIBhC6ARIsAHA3IkRVrPOGfhVQuRnrvMmht5wpYsPMvo3rzrbgcU6mRpKY2OgqegFy-zwaArjGEALw_wcB

[21] Ernesto Ayala et al., "Image Segmentation by Agent-Based Pixel Homogenization," *IEEE Access*, vol. 11, pp. 54221-54239, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[22] Blake Hament, and Paul Oh, "A Pressure Washing Hosing-Drone - Mitigating Reaction Forces and Torques," *2022 International Conference on Unmanned Aircraft Systems (ICUAS)*, Dubrovnik, Croatia, pp. 468-477, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[23] Chunye Liu et al., "Different Irrigation Pressure and Filter on Emitter Clogging in Drip Phosphate Fertigation Systems," *Water*, vol. 14, no. 6, pp. 1-18, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[24] John Paul Arantes Rodrigues da Cunha, and Maria Rosa Rosa Alferes da Silva, "Spray Deposition from a Remotely Piloted Aircraft on the Corn Crop," *Agronomic Science Journal*, vol. 54, pp. 1-8, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[25] Manojkumara et al., "Development and Optimization of Operational Parameters for Tractor-Operated Boom Sprayer for Field Crops," *International Journal of Environment and Climate Change*, vol. 13, no. 10, pp. 1127-1134, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[26] Thijs de Goede et al., "Droplet Splashing on Rough Surfaces," *Physical Review Fluids*, vol. 6, no. 4, pp. 1-8, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[27] D.T. Yusupov, M. Rakhmatova, and Sh Tashmatova, "Study of Optimal Temperature during Adsorption Cleaning of Transformer Oil under Conditions of Long-Term Operation," *E3S Web of Conferences*, vol. 383, pp. 1-6, 2023. [CrossRef] [Google Scholar] [Publisher Link]