

Field Evaluation of a Drone-Based High-Pressure Cleaning System for Residential Rooftop Photovoltaics in Tropical Malaysia

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Abstract

Residential rooftop photovoltaic (PV) systems in tropical environments are susceptible to surface soiling, while conventional cleaning may require direct work at height or elevated-access equipment. This study evaluates a ground-fed, non-contact drone-based high-pressure cleaning system for residential rooftop PV in Malaysia. Engineering trials considered spray-lance lengths of 600, 900 and 1200 mm; operating pressures of 1800, 2500 and 3000 psi; and zig-zag, circular and hybrid flight strategies. The selected field configuration used a 900 mm customised lance, 1800 psi, a fan-shaped spray, a nominal flow rate of 13 L/min, an approximately 3 m stand-off distance and a hybrid flight strategy. The field programme covered 150 residential PV systems across Johor, Negeri Sembilan, Melaka, Selangor and Kuala Lumpur. Mean daily energy yield was 21.706 kWh/day during the pre-cleaning observation period and 32.571 kWh/day during the post-cleaning period, with a mean within-system difference of 10.864 kWh/day. The mean system-level percentage change was 49.82% (paired $t(149) = 30.582$, $p < 0.001$; Cohen's $d_z = 2.50$). This is an observed pre-post operational response, not an irradiance-normalised cleaning gain: simultaneous uncleaned controls and uniform plane-of-array irradiance measurements were unavailable. In the access-constrained cost scenarios assessed, estimated drone operating costs were lower than manual-cleaning costs when a skylift was required; the comparison was sensitive to roof access, location, mobilisation, labour and local rates. The findings support the technical feasibility of the integrated aerial-nozzle hose system and indicate the need for controlled, irradiance-normalised studies and broader economic evaluation.

Keywords: photovoltaic cleaning; unmanned aerial vehicle; drone cleaning; solar PV maintenance; soiling; residential rooftop PV; tropical climate; energy yield; cost-effectiveness



Figure 1: Field Deployment

1. Introduction

Residential rooftop photovoltaic (PV) deployment has expanded in Malaysia alongside growing interest in distributed renewable generation. Maintaining these systems matters because the long-term value of a PV installation depends on both equipment condition and the amount of sunlight transmitted through the exposed module surface. Malaysian measurements have linked surface soiling to changes in PV performance, although the magnitude varies by site and measurement period [1].

Soiling is not a single, uniform contaminant. Airborne mineral dust, traffic-related particles, pollen, bird deposits, leaves and moisture-assisted biological material can differ in size, composition and adhesion. These properties influence how much light reaches the cells and how readily deposits are removed. Weather and rainfall affect both accumulation and natural removal; urban exposure studies also show that soiling losses vary over time and across surfaces [11]. Field measurements in a high-density urban environment have examined changes in optical and electrical performance over a 108-day exposure, illustrating why location and exposure duration should be described when interpreting PV soiling [12].

Rain can remove some deposits, but the effect depends on rainfall characteristics and the accumulated material; rain therefore cannot be treated as a consistent cleaning intervention [13]. Soiling models likewise use environmental and operational data to estimate losses and cleaning schedules, but model performance depends on site conditions and available measurements [16]. Together, these findings support reporting cleaning outcomes alongside measurement windows and environmental limitations rather than treating a single pre-post percentage as a universal soiling-loss factor.

Manual rooftop cleaning is familiar and can remove visible contaminants, but it may require access to inclined or wet roofs, hoses and elevated-access equipment. These conditions create safety and productivity constraints that vary with roof geometry and array layout. Reviews of PV cleaning methods describe trade-offs among cleaning effectiveness, labour, water use, cost and the risk of surface damage [3].



Figure 2: Conventional manual rooftop solar PV cleaning at height during maintenance operations.

Unmanned aerial vehicles (UAVs) have been studied for both PV inspection and cleaning. Earlier work examined drone retrofit methods and rotor-downwash cleaning [5,6]. More recent work has assessed drone-based spraying over PV installations under operational conditions [15]. Other studies use aerial imaging to detect soiling or optimise inspection parameters; these address monitoring and decision support rather than the active cleaning intervention evaluated here [8].

Prior field studies have used environmental measurements, statistical analysis and time-series or exposure-based comparisons to study soiling effects [11,12]. However, the studies identified here do not jointly assess a ground-fed drone cleaning system, multi-site residential rooftop operations, pre-post energy response and access-sensitive operating costs in Malaysia. This study therefore evaluates the system's technical feasibility, the observed pre-post change in PV energy yield and estimated direct operating costs under defined access assumptions. Because matched uncleaned controls and uniform irradiance measurements were unavailable, the energy result is interpreted as an operational pre-post response rather than a causal estimate of the cleaning effect.



Figure 2: Type of residential rooftop

Table 1. Positioning of this study relative to related PV-soiling and UAV research.

Research stream	Example setting or approach	Primary contribution	Relation to this study
PV soiling field data [11,12]	Environmental monitoring and exposure studies	Characterise environmental and performance changes	This study examines a cleaning intervention across residential sites

Research stream	Example setting or approach	Primary contribution	Relation to this study
Rain-driven cleaning [13]	Field observations and modelling	Assess natural removal by rainfall	Rain history was not uniformly available for this study
Drone cleaning [5,6,15]	Rotor downwash or UAV spray configurations	Explore aerial cleaning mechanisms and operation	This study evaluates a ground-fed, non-contact hose-and-nozzle system
UAV inspection [8–10]	Aerial imaging, detection and inspection	Identify contamination or optimise monitoring	This study uses the UAV as a cleaning-positioning platform
Present study	150 residential rooftops in five Malaysian locations	Engineering trials, pre–post yield and access-sensitive costs	Integrated field evaluation under tropical residential conditions

2. Materials and Methods

2.1. Research design and field sites

A one-group field pre–post design was used. Each residential PV installation served as its own comparison unit, with performance observed before and after the drone-based cleaning intervention. The sample comprised 150 residential rooftop PV systems in Johor (n = 33), Negeri Sembilan (n = 33), Melaka (n = 31), Selangor (n = 29) and Kuala Lumpur (n = 24). Installed capacity ranged from 3.96 to 14.08 kWp (mean 7.97 kWp), and system age ranged from 3 to 5 years (mean 3.95 years). The sites included single-, double- and three-storey houses with variation in roof height, array geometry, obstacles and flight access. The field variables included cleaning condition (pre- or post-cleaning), spray-lance length (600, 900 or 1200 mm), pump pressure (1800, 2500 or 3000 psi) and flight strategy (zig-zag, circular or hybrid). The UAV platform, ground water supply, pump, nominal flow, hose arrangement, cleaning procedure and measurement schedule were kept consistent where practicable. Site-specific roof and obstacle conditions remained part of the operating environment.



Figure 3: Comparison of the customised spray nozzle configurations evaluated during the experimental programme.

2.2. Drone-based cleaning system and engineering trials

The system integrated a commercial multirotor UAV with a ground-based high-pressure pump and a customised spray-nozzle assembly. Water was supplied from a 150 L ground tank through a 60 m tethered hose. The ground-fed arrangement avoided carrying a water tank on the UAV and allowed continuous water supply. A certified remote pilot operated the system from ground level.

Spray-lance lengths of 600, 900 and 1200 mm were fabricated and compared in preliminary engineering trials. The 900 mm lance was selected for the field programme based on operational judgement of spray coverage, structural stability and manoeuvrability. The 1800 psi pressure setting was likewise selected following preliminary trials as the operating setting used for the field programme. Although 2500 and 3000 psi were included in engineering trials, comparative pressure measurements are not reported here; therefore, the manuscript does not claim that 1800 psi was statistically superior to the other settings.

A fan-shaped spray was used at a nominal flow rate of 13 L/min. The UAV was operated at an average stand-off distance of approximately 3 m above the modules. The system's performance depended on the interaction among lance geometry, hose drag, stand-off distance, rotor downwash, spray coverage and flight trajectory; the present study evaluates this integrated configuration rather than the UAV in isolation.

2.3. Flight strategies and operating procedure

Zig-zag, circular and hybrid flight patterns were compared under the selected operating configuration: 1800 psi, a 900 mm lance, 13 L/min nominal flow, fan-shaped spray, approximately 3 m stand-off distance and ground-based water supply. The hybrid pattern combined systematic linear coverage with targeted circular treatment and was selected for the main field programme.

At each site, the operator assessed the roof, obstacles and ground operating area; inspected the UAV, pump, hose and nozzle; completed pre-flight checks; established a safety perimeter; and monitored battery condition, flight stability, hose tension and pump operation during cleaning. Visual line of sight was maintained. Weather, surrounding structures and high-pressure water were treated as operational hazards requiring site assessment and controlled procedures.



2.4. Performance measurements

Baseline PV performance was observed for seven consecutive days before cleaning. The recorded outcome was daily energy yield, supplemented by inverter and environmental parameters where available. Cleaning duration, water use and operational observations were recorded during the intervention. Post-cleaning performance was observed for seven consecutive days using the same measurement approach. Thermal images were acquired under comparable daytime conditions to support assessment of surface condition and thermal uniformity.

The system-level percentage change was calculated from the pre- and post-cleaning daily yields for each site. It is not an irradiance-normalised soiling ratio because plane-of-array irradiance, matched uncleaned control arrays, rainfall history and direct soiling measurements were not uniformly available for all site.

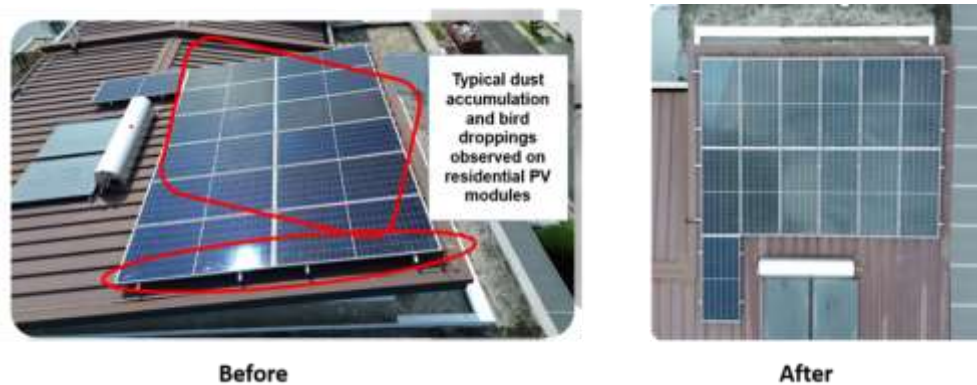


Figure 4: Residential rooftop photovoltaic module before and after cleaning

Equation (1). System-level pre–post percentage change.

$$\text{Percentage change}_i (\%) = 100 \times (E_{\text{post},i} - E_{\text{pre},i}) / E_{\text{pre},i}$$

where $E_{\text{pre},i}$ and $E_{\text{post},i}$ are the mean daily energy yields for site i during the seven-day pre-cleaning and post-cleaning observation periods, respectively.

Cleaning completion was assessed through post-cleaning visual inspection and infrared thermal inspection. The operational assessment considered visible contaminant removal from active glass surfaces, spray coverage, untreated areas or dry patches, and the general thermal distribution. Thermal imaging was used as complementary condition evidence and not as a standalone measure of contaminant removal.

2.5. Statistical analysis

Data were screened for completeness and abnormal operating conditions. Descriptive statistics were calculated for capacity, system age, pre-cleaning yield, post-cleaning yield, absolute change and system-level percentage change. Because the same systems were measured before and after cleaning, paired-samples analysis was used. The distribution of paired differences was assessed using the Shapiro–Wilk

test. A paired-samples t-test quantified the mean difference; the Wilcoxon signed-rank test was used as a non-parametric sensitivity analysis. Effect size was expressed as Cohen's d_z . Associations of capacity with absolute change and system age with percentage change were assessed using Pearson and Spearman correlations, respectively. Statistical significance was set at $p < 0.05$.

Equation (2). Shapiro–Wilk statistic.

$$W = [\sum_{i=1}^n a_i x(i)]^2 / \sum_{i=1}^n (x_i - \bar{x})^2$$

where $x(i)$ denotes the ordered observations, $\bar{x}$ is their mean and a_i are the coefficients determined from the expected order statistics of a normal distribution.

Equation (3). Paired-samples t statistic.

$$t = (\bar{d} \times \text{sqr}(n)) / s^d$$

where $\bar{d}$ and s^d are the mean and standard deviation of the paired differences, and n is the number of paired systems.

Equation (4). Wilcoxon signed-rank statistic.

$$W = \min(W^+, W^-); W^+ = \sum (d_i > 0) R_i; W^- = \sum (d_i < 0) R_i$$

where R_i is the rank of $|d_i|$ after zero differences are omitted. The two-sided test compares the smaller positive- or negative-rank sum with its null distribution.

Equation (5). Paired-samples effect size.

$$\text{Cohen's } d^z = \bar{d} / s^d$$

where $\bar{d}$ and s^d are the mean and standard deviation of paired differences.

Equation (6). Pearson product–moment correlation.

$$r = \sum [(x_i - \bar{x})(y_i - \bar{y})] / \text{sqr} \{ \sum (x_i - \bar{x})^2 \times \sum (y_i - \bar{y})^2 \}$$

Pearson correlation was used for installed capacity and absolute energy-yield change.

Equation (7). Spearman rank correlation.

$$\rho = \text{corr}(\text{rank}(x_i), \text{rank}(y_i))$$

Spearman correlation was used for system age and system-level percentage change; it is the Pearson correlation calculated on ranked observations.

The inferential tests assess whether the observed within-system pre–post differences were distinguishable from zero. They do not remove time-varying irradiance or weather effects. Statistical significance is therefore not interpreted as proof that soiling removal alone caused the full observed change.

2.6. Cost-effectiveness assessment

The economic assessment compared estimated direct operating costs for residential PV systems from 4 to 15 kWp. The reported drone-system capital investment was RM41,900: UAV platform (RM32,000), high-pressure pump (RM3,900) and customised spray-nozzle payload (RM6,000). Per-session drone estimates included pilot, operational permit, ground assistant, pump operation, transportation, battery charging or depreciation, maintenance allocation and water. Manual-cleaning estimates included labour, equipment, personal protective equipment and transportation.

The primary comparison assumes that elevated-access equipment (a skylift) is required for manual cleaning. A separate sensitivity scenario excludes RM1,500 for the skylift to show how access assumptions change the comparison. These are case-based cost estimates, not a universal market-price survey or a full life-cycle cost analysis.

3. Results

3.1. Engineering optimisation and operational performance

The 900 mm spray lance and 1800 psi operating pressure were selected for the field programme following preliminary engineering trials and operational assessment. The main field configuration also used fan-shaped spray, 13 L/min nominal flow, approximately 3 m stand-off distance and the hybrid flight strategy. Comparative pressure measurements were not available for reporting; conclusions about the pressure selection are therefore limited to the operational setting used in the field evaluation.

Table 2. Operational comparison of flight strategies under the selected cleaning configuration.

PV capacity	Pattern	Flight time (min)	Water used (L)	Completion (%)
4 kWp	Zig-zag	13.8	22	97.1
4 kWp	Circular	16.5	27	98.4
4 kWp	Hybrid	11.6	19	98.9
10 kWp	Zig-zag	33.7	53	96.8
10 kWp	Circular	40.5	63	98.3
10 kWp	Hybrid	28.9	44	99.2
15 kWp	Zig-zag	49.6	78	96.7
15 kWp	Circular	58.8	91	98.1
15 kWp	Hybrid	42.1	66	99.1

In the representative comparisons in Table 2, cleaning completion ranged from 96.7% to 99.2%. Water use increased from 19 L at 4 kWp to 66 L at 15 kWp, while cleaning duration increased from 11.6 to 42.1 min for the hybrid pattern. The hybrid pattern had the shortest flight time and lowest water use in the representative 4, 10 and 15 kWp comparisons shown in Table 2.

3.2. Observed pre–post PV energy–yield response

Table 3. Descriptive statistics for residential PV performance (N = 150).

Variable	Mean	SD	Median	Minimum	Maximum
Installed capacity (kWp)	7.97	2.98	7.04	3.96	14.08
System age (years)	3.95	0.82	4.00	3.00	5.00
Before cleaning (kWh/day)	21.706	8.139	19.665	9.283	42.357
After cleaning (kWh/day)	32.571	12.359	30.011	13.277	62.485
Increase (kWh/day)	10.864	4.351	9.858	3.809	21.840

System-level percentage change (%)	49.82	5.71	49.18	40.07	59.93
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Mean daily yield was 21.706 kWh/day during the pre-cleaning period and 32.571 kWh/day during the post-cleaning period. The mean within-system difference was 10.864 kWh/day. The mean of the site-level percentage changes was 49.82%; this is distinct from the percentage calculated from the ratio of the group mean yields. All 150 systems in the analysed dataset showed a positive pre–post difference.

Paired differences departed from normality (Shapiro–Wilk $W = 0.936$, $p < 0.001$). The paired-samples t-test showed a significant increase, $t(149) = 30.582$, $p < 0.001$, with a mean difference of 10.864 kWh/day (95% CI: 10.162–11.566). The Wilcoxon signed-rank sensitivity test also indicated a positive change ($W = 0.000$, $p < 0.001$). Cohen’s d_z was 2.50. These tests demonstrate a strong within-system pre–post difference but do not isolate the share attributable exclusively to cleaning.

Installed capacity was strongly associated with absolute pre–post energy-yield change ($r = 0.924$, $p < 0.001$; $R^2 = 0.854$). This association is expected in part because larger systems have greater baseline production. System age was not significantly associated with percentage change within the restricted 3–5-year range (Spearman $\rho = 0.051$, $p = 0.538$). Mean percentage change was similar across Johor (50.09%), Negeri Sembilan (49.21%), Melaka (49.52%), Selangor (49.60%) and Kuala Lumpur (50.94%).

3.3. Case-based cost comparison and access sensitivity

Table 4. Estimated direct operating-cost comparison when manual cleaning requires a skylift.

PV capacity (kWp)	Manual (RM)	Drone (RM)	Estimated saving (RM)	Reduction (%)
4	1,900	690	1,210	63.7
5	1,940	695	1,245	64.2
6.6	2,000	700	1,300	65.0
8	2,150	710	1,440	67.0
10	2,240	720	1,520	67.9
12	2,400	735	1,665	69.4
15	2,500	750	1,750	70.0

Table 5. Sensitivity scenario excluding the RM1,500 skylift estimate from manual cleaning.

PV capacity (kWp)	Manual without skylift (RM)	Drone (RM)	Drone minus manual (RM)	Lower estimate
4	400	690	+290	Drone cost higher
5	440	695	+255	Drone cost higher
6.6	500	700	+200	Drone cost higher
8	650	710	+60	Drone cost higher
10	740	720	–20	Drone cost lower
12	900	735	–165	Drone cost lower
15	1,000	750	–250	Drone cost lower

When a skylift was included, the estimated drone-service cost was lower for all seven capacity scenarios, with estimated reductions of 63.7% to 70.0%. When the skylift estimate was excluded, the drone estimate was higher at 4–8 kWp and lower at 10–15 kWp. Figure 1 displays this access sensitivity. These estimates depend on the cost assumptions, roof access, location, mobilisation, labour and prevailing local rates.

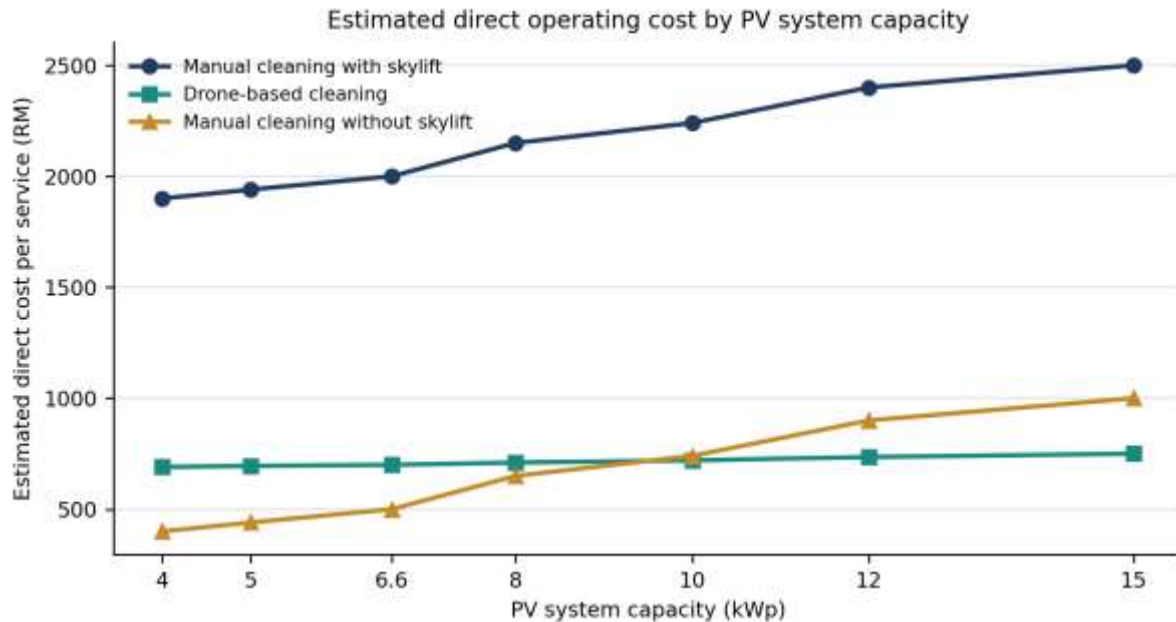


Figure 1. Estimated direct cost per service under three access scenarios. Values are the case estimates reported in Tables 4 and 5.

4. Discussion

The field evaluation indicates that a drone-based cleaning operation depends on integrating the aerial platform with the nozzle, hose and operating procedure. The 900 mm lance, fan-shaped spray and approximately 3 m stand-off distance formed the configuration used in the field programme. Because comparative pressure measurements are not reported, the study supports the feasibility of the selected operating configuration but does not establish an optimum pressure across all residential systems.

The hybrid flight pattern had shorter completion time and lower water use than the zig-zag and circular patterns in the representative comparisons. This result is consistent with the operational value of combining broad array coverage with localised treatment, although the reported comparisons are limited to the listed capacity examples and should not be generalised beyond them without additional trials.

The observed mean within-system increase of 10.864 kWh/day and mean site-level percentage change of 49.82% are substantial, but the design cannot attribute the entire change to cleaning. The study did not include simultaneous uncleaned controls or uniform plane-of-array irradiance, and it did not consistently measure rainfall, direct soiling mass, optical transmittance or time since previous cleaning. Weather and temporal effects may therefore have contributed to the pre–post difference. Future work should use matched control arrays or reference modules, measure irradiance and meteorological conditions, and calculate an irradiance-normalised performance ratio or soiling ratio.

The cost comparison suggests a potential operating-cost advantage where manual cleaning requires elevated-access equipment. The sensitivity analysis shows that this advantage changes when the skylift estimate is removed. The result is therefore an access-specific comparison, not evidence that drone

cleaning is always cheaper. A larger economic study should use verified local quotations, recurring maintenance costs, mobilisation by region, equipment life and different roof-access conditions. From a safety perspective, keeping the pilot and assistant at ground level reduces direct work-at-height exposure during routine cleaning, but it does not eliminate operational risk. UAV flight, hose management, high-pressure water, weather and nearby structures require competent operators, site assessment, exclusion zones and appropriate regulatory compliance.

5. Limitations

This study used a one-group pre–post field design without simultaneous uncleaned controls. Plane-of-array irradiance and irradiance-normalised performance ratio were not measured uniformly, and environmental factors including rainfall, humidity, particulate concentration, roof tilt and orientation were not consistently recorded. The sample covered five locations in Peninsular Malaysia and systems aged 3–5 years; it is not a national sample. Cleaning completion was assessed visually and thermally rather than through laboratory optical transmittance or gravimetric soiling ratio. Finally, the cost comparison is case-based and sensitive to roof access, system size, mobilisation, labour, location and the need for elevated-access equipment. Results should be interpreted within these boundaries.

6. Conclusions

A ground-fed, non-contact drone-based high-pressure cleaning system was evaluated on 150 residential rooftop PV systems across five Malaysian locations. The field configuration used a 900 mm customised lance, 1800 psi pressure, fan-shaped spray, nominal flow of 13 L/min, approximately 3 m stand-off distance and a hybrid flight strategy. The hybrid strategy had the shortest flight time and lowest water use in the representative capacity comparisons reported.

Mean daily energy yield increased from 21.706 to 32.571 kWh/day between the pre- and post-cleaning observation periods. The mean within-system difference was 10.864 kWh/day, and the mean of the site-level percentage changes was 49.82%. Because the study lacked simultaneous uncleaned controls and uniform irradiance-normalised measurements, this is an observed operational response, not a causal estimate or universal soiling-loss factor.

Estimated drone-service costs were lower than the manual-cleaning estimates in scenarios requiring a skylift, but the comparison changed when the skylift estimate was excluded. The findings support technical feasibility under the studied operating conditions and motivate controlled, irradiance-normalised trials and broader life-cycle cost analysis.

Intellectual Property and Innovation Recognition

The customised water-jet nozzle associated with the system is linked to Malaysian copyright notification CRAR2024W07925, titled “Drone Cleaning Water Jet Nozzle”, with Wan Energy Solution (M) Sdn. Bhd. as the copyright owner and Wan Nor Hami bin Wan Isa among the registered creators. The LavDr.One® brand is registered in Malaysia under Trademark No. TM2024020709, Class 37, with Wan Energy Solution (M) Sdn. Bhd. as the registered proprietor. The technology has also received Malaysia Science, Technology and Innovation (MySTI) recognition through the Malaysian Research Accelerator for Technology and Innovation (MRANTI), Certificate No. MOSTI2025STI202501073, valid from 30 September 2025 to 30 September 2028. These credentials identify the technology and its commercial context; they are not independent validation of the scientific findings.

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