Research Article

Performance Analysis of Photovoltaic Panel Output under Dust Deposition and Wind-Speed Variability: An Experimental Study in Guwahati, Assam

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Abstract

The study looks into how dust deposition and wind-speed variability affect photovoltaic (PV) panel output in Guwahati, Assam, which is a humid subtropical urban environment where rainfall, humidity, airborne particulates and seasonal solar resource variability jointly affect rooftop solar performance. The experimental rationale involved comparing a cleaned reference solar cell module and a naturally soiled solar cell module under the same tilt, orientation, and electrical load. Environmental variables comprise solar irradiance, ambient temperature, module temperature, wind speed, relative humidity, rainfall, PM10 and PM2.5, and gravimetric dust deposition density. The voltage, current, power, energy yield, conversion efficiency, performance ratio, soiling ratio and temperature-corrected power are the PV variables. Due to unavailability of measured field data, a clearly identified 60-day simulated/provisional dataset was developed to show the statistical workflow. The demonstration analysis revealed that the soiled module was capable of producing a lower power mean than the cleaned reference module, which resulted in a mean simulated soiling loss of 3.57%. A significant paired difference could also be observed. The correlation and regression analyses reveal that irradiance remains the most significant positive predictor of PV output. Similarly, dust deposition has a negative, statistically significant association with soiled module output. Wind velocity plays a dual role. It contributes to cooling through convection and partially removes dust from the atmosphere. However, the net impact is contingent upon the dust and humidity levels. The study provides an analytical framework for field validation in Guwahati. Moreover, it recommends spectral rain events monitoring, cleaning decisions informed by rainfall, as well as journal submission all provisional values measured observations.

Keywords: Photovoltaic panel; PV performance; dust deposition; wind speed; soiling loss; Guwahati; solar energy; performance ratio; module temperature; renewable energy

Introduction

The use of solar photovoltaic energy is gaining increasing importance for decentralized power generation due to the potential for PV modules to be installed on rooftops, institutional buildings and small field sites with relatively low operational noise and minor local emissions. Nevertheless, external PV systems are greatly subject to environmental variability. The incident sunlight determines the photons available for conversion, the ambient temperature and the temperature of the module affect the voltage and conversion efficiency of the cell. Furthermore, surface contamination affects the optical transmittance of the front glass. As a result, a PV module, installed in an urban humid region, cannot be assessed only from its rated capacity under standard test condition.

Dust deposition is a challenging operational issue for photovoltaic modules (PV). When dust particles deposit on the glass surface of the photovoltaic module, they passively absorb, scatter and reflect incident solar radiation before it reaches the cells. Recent studies of soiling consider that a performance-loss mechanism, unique to every location and dependent on particulate concentration, rainfall and surface texture, tilt angle, wind flow, humidity and cleaning history (Bessa et al, 2021; Conceição et al., 2022; IEA PVPS, 2022; Nezamisavojbolaghi et al 2023). Guwahati serves as an informative study site in this regard due to an intermix of urban particulate sources, high humidity, strong seasonal rain and rooftop-solar growth potential in Northeast India.

The assessment of PV performance becomes complicated due to wind speed. On the one hand, increases in wind, which enhance convective cooling, tend to reduce the module temperature, potentially increasing electrical output when irradiance is sufficiently high. Conversely, wind can move dust around as well as stir up other particles on the road and construction sites. It can also redistribute more loose material on the panel surface. The modeling of PV performance based on the NOCT cell-temperature framework includes the irradiance, ambient temperature and wind speed as factors (Sandia PVPMC, 2026). Research into PV soiling has revealed a surprising effect on the rate and spatial pattern of dust deposition from wind, spacing, tilt and particle-flow conditions (Wang et al, 2025).

The current research paper devises an all-inclusive empirical field-study framework for the evaluation of PV output owing to dust deposition and wind-speed variation in Guwahati, Assam. It joins a clean versus soiled panel design with environmental monitoring, PV performance equations and statistical modelling. The paper is intentionally clear about the status of the data: all quantitative results are derived from a simulated/provisional dataset and must be substituted with measured readings from the real experiment in due time for submission.

Environmental Factors Affecting PV Performance

The most important factors for PV output are irradiance and operating temperature. The voltage and thus maximum power produced is reduced when cell temperature is higher. Irradiance is near-linearly related to current generation. The performance of photovoltaic (PV) technology is influenced by different environmental factors. Shaik et al. (2023) surveyed the most important factors affecting PV performance. As the authors found, irradiance, temperature, dust, humidity, wind, shading and operation or maintenance shape the performance of PVs. For Guwahati, these should vary strongly across pre-monsoon, monsoon and post-monsoon periods.

Standards for performance monitoring, such as IEC 61724-1:2021, contain terminology, sensor requirements, data-acquisition concepts and performance metrics for PV systems. According to IEC 2021, it is essential to filter, time-synchronize and quality-check on-field data before a performance ratio or soiling loss is interpreted and so, the standard is relevant for the study. The U.S. Department of Energy and NREL also recommend measuring performance ratio and reference yield to help interpret PV system output in relation to solar resource availability (DOE/NREL, 2022).

Dust Accumulation and Soiling Loss

Soiling loss represents an issue of not just surface cleanliness but also optical and thermal performance. Deposited dust can attenuate the radiation reaching the solar cells and alter the module-surface temperature distribution. Dust, pollution and biological debris are major factors causing underperformance of PV (IEA PVPS, 2022). This risk is aggravated by the increasing adoption of dry-cleaning methods (Bessa et al., 2021).

Recent empirical and review studies show that the accumulation of dust can lead to a tangible decrease in output power, efficiency and energy yield (Abuzaid et al., 2022; Chaudhary et al., 2023; Nezamisavojbolaghi et al., 2023; Rashid et al., 2023; Yadav et al., 2025). According to wind-tunnel studies conducted by Wang et al. (2025), the configuration of panel arrays and the conditions of airflow can affect the deposition of dust, which confirms that wind should be seen as an active environmental variable and not exclusively a cooling factor

Wind Speed, Cooling and Dust Remobilization

Cell temperature can be reduced by wind speed by forced convection. Under adequate irradiance and thermal stress to the module, this effect may cause enhancement in output power during field operation. Wind has the potential to dislodge dust from the glass when it is weakly attached to the surface. This may

happen under certain conditions. High-speed wind can help washing while low-speed wind leads to dust concentration and subsequent soiling persistence (Nezamisavojbolaghi et al. 2023).
This mechanism is altered by humidity. When moisture content is high, dust particles would stick more and form compact layers or mud after dew or little rain. Consequently, the wind speed that works on the dry surface will not work on the moist surface and vice-versa. In Guwahati specifically, relative humidity and rain are very high, which is accompanied by exposure to particulate from road, construction, traffic and urban activities.

Research Gap and objectives of the study

The phenomenon of PV soiling has been extensively studied in arid and semi-arid regions. However, because humid subtropical cities of Northeast India are less reported on in field-performance literature. Guwahati's climate differs from that of a desert site because rainfall can help naturally clean modules. However, because high humidity may help particles adhere more strongly than after rainfall events. Urban dust deposition caused by various sources and dust from road/construction activities can cause soiling despite frequent rain. A second research gap pertains to the joint analysis of dust deposition and wind-speed variability. In various studies of PV, wind is often simply seen as a cooling parameter. Similarly, in soiling studies, airborne particulates and deposition are often treated as separate from the module thermal behavior. Guwahati-specific maintenance recommendations require the need for an integrated design which simultaneously measures dust, wind speed, module temperature and electrical outputThis paper aims to evaluate the effect of dust deposition on PV panel voltage, current, power output, efficiency and performance ratio in Guwahati. It also analyzes how wind speed influences PV panel performance through convective cooling and possible dust-removal effects. It also includes examining the combined effect of dust deposition, wind speed, irradiance, temperature and humidity on PV output to quantify soiling loss and temperature-related performance variation. Finally, this paper develops a statistical model predicting PV output under Guwahati environmental conditions.

Methodology

Site description and climatic condition

The largest urban center in Assam is Guwahati; the town serves as a “gateway” to Northeast India. The city is situated in the Brahmaputra valley at latitude 26.14°N and longitude 91.74°E. The growth of urbanization, transport activity, construction activity and mixed land use in the site makes it suitable to study rooftop PV systems influenced by dust, and wet atmospheric conditions. The study area not only has solar-resource availability but also has rooftop and distributed solar deployment being promoted by the state energy agencies and utility-linked rooftop solar program. (Assam Energy Development Agency, 2026; APDCL, 2024) in Assam.
The climate of this place can be described as humid subtropical with warm pre-monsoon months, heavy rainfall during monsoon and considerable relative humidity for most part of the year. According to IMD 2022, IMD meteorological tables give station-level normals for temperature, rainfall, humidity, wind, cloud and related parameters for Indian observatories. NASA POWER (2026) provides solar and meteorological data such as global horizontal irradiance, temperature, relative humidity, wind speed and precipitation through the Data Access Viewer and API, which are useful for assessment of PV.

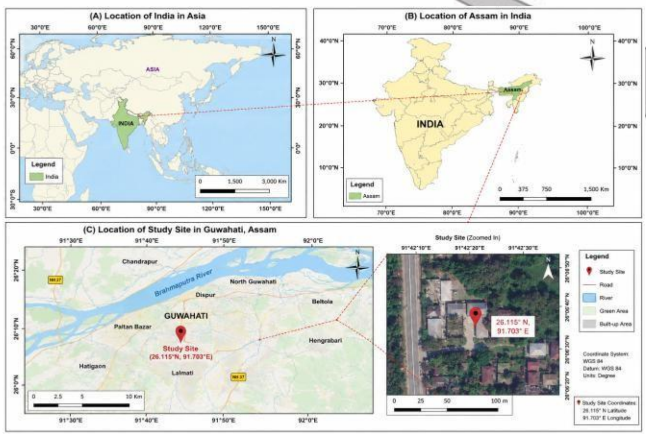

Figure 1. Study area map of Guwahati, Assam.

Air quality is key since airborne particulate matter contributes to PV soiling. The National Clean Air Program of India focuses on reducing PM10 concentrations or achieving national ambient standard in cities that are non-attainment already or million-plus cities (PIB, 2023). According to a pollution fact-sheet from Guwahati, PM2.5 concentration averaged 61.2 µg/m³ while that of PM10 was 121.4 µg/m³ at 2023: LGBI Airport, Guwahati (source: iFOREST, 2025). High particulate loading is relevant for surface deposition studies in Guwahati.

Experimental Setup

The proposed field experiment uses two identical PV modules installed side by side under the same tilt, azimuth and load conditions. One module is treated as a cleaned reference panel and is cleaned daily or at a fixed interval, while the second module is allowed to accumulate natural dust. The reference panel isolates the influence of daily irradiance and temperature variation, while the soiled panel captures the combined effect of dust deposition, humidity, rainfall and wind-driven removal or redistribution.

Because actual equipment details were not provided, the provisional analysis assumes a 100 Wp monocrystalline silicon PV module with an active area of 0.58 m², nominal Vmp of 18 V, nominal Imp of 5.56 A and a temperature coefficient of -0.45%/°C. These values are placeholders only and must be replaced by the manufacturer datasheet of the actual module before submission.

Table 1. Specification of Solar PV Panel

Component	Specification
PV Module	100 Wp monocrystalline silicon panel; area 0.58 m²
Mounting Condition	South-facing, 26° tilt; rooftop/field mount to be confirmed
Reference Panel	Cleaned daily or before measurement
Soiled Panel	Naturally exposed without manual cleaning
Irradiance Sensor	Calibrated solar power

	meter
Win speed sensor	Cup anemometer at module height
Temperature sensor	Thermocouple or PT100 on rear module surface
Humidity/rainfall sensor	Digital thermo-hygrometer and tipping bucket
Dust measurement	Glass gravimetric method in g/m²
Electrical measurement	Calibrated multi-meter

Dust collection and characterization

Measurements should be recorded during daylight periods only, preferably when irradiance exceeds a minimum threshold such as 200 W/m². If high-frequency logging is available, 5-minute or 15-minute data should be recorded and later aggregated to hourly or daily statistics. Night-time observations and periods with zero irradiance should be removed before power-performance modelling. All instruments should be time-synchronized to Indian Standard Time and inspected for missing values, unrealistic spikes and sensor drift.

Dust deposition can be measured by placing pre-weighed glass coupons or filter papers beside the PV module at the same tilt. After a defined exposure interval, deposited material is collected and weighed using a precision balance. Dust deposition density is reported as grams per square meter. PM10 and PM2.5 from CPCB/CAAQMS or local measurements should be treated as supporting atmospheric indicators rather than direct substitutes for deposited dust.

Data cleaning and statistical analysis

The recommended data-cleaning procedure includes the removal of screw up night time observations, removal of zero or near value irradiance, impossible sensor value identification, checking missing values, and verification of cleaned and soiled modules pair observation. When gaps are short and physically interpretable, high-frequency values may be imputed. Otherwise, observations can be deleted when paired tests and regression modelling is done.

The statistical workflow consists of descriptive statistics, correlation, a paired clean-versus-soiled comparison, ANOVA by dust and wind categories, multiple linear regression, and optional ML variable importance. If the variables that you are assessing are approximately normal then Pearson correlation will be used – otherwise if there is strong non-normality then Spearman correlation should be used. The formulation for the regression model is as follows: PV Output = $\beta_0 + \beta_1$(Irradiance) + β_2(Dust) + β_3(Wind Speed) + β_4(Module Temperature) + β_5(Relative Humidity) + β_6(Dust × Wind Speed) + ε Variance inflation factor, residual inspection and prediction error metric must be reported.

The database includes measurements of environmental and photovoltaic panel parameters from 1st March 2025 to 29th March 2025 (60-day data). The simulation contains several variables such as daily mean daytime irradiance, daily solar radiation, ambient temperature, module temperature, wind speed, humidity, rainfall, PM10, PM2.5, dust deposition density, clean-panel electrical variables, soiled-panel electrical variables and calculated performance metrics. It rains that sometimes washes away accumulated dust almost naturally. Dust removal is weak and module cooling is brought about wind. It is hoped that these assumptions will not lead to misinterpretation of the results as findings as actually measured.

Results and discussions

Descriptive statistics of environmental and PV performance variables

The 60-day dataset produced mean daytime irradiance of 393.03 W/m², mean ambient temperature of 23.02 °C and mean module temperature of 38.81 °C. The mean wind speed was 2.32 m/s, while mean relative humidity was 65.76%. Mean dust deposition density was 0.53 g/m². The cleaned reference panel produced mean power of 36.79 W, whereas the naturally soiled panel produced 35.81 W. Mean simulated soiling loss was 2.93%, indicating a consistent negative effect of dust on the treatment panel.

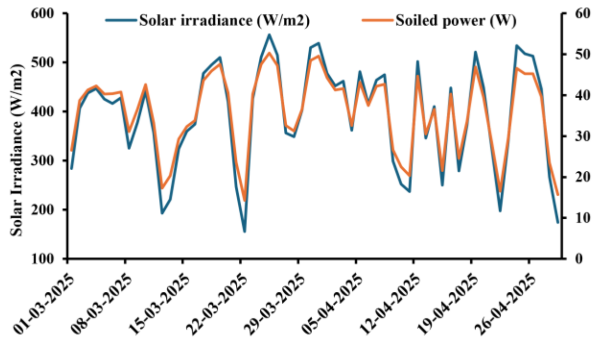

Figure 2. Daily solar irradiance and PV output trend.

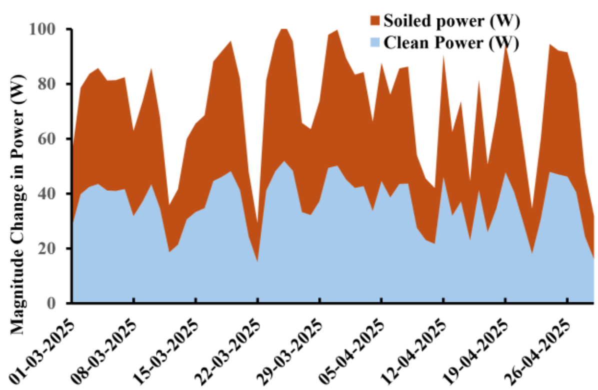

Figure 3. Clean versus soiled panel power output comparison.

Table 2. Clean versus soiled panel performance comparison

Metric	Clean mean	Soiled mean	Mean difference
Voltage (V)	18.04	17.90	0.14
Current (A)	2.04	1.99	0.05
Power (W)	36.80	35.62	1.18
Efficiency (%)	16.15	15.68	0.47
Performance ratio (%)	93.60	91.10	2.50

The paired comparison showed that the clean panel produced significantly higher power than the soiled panel, $t(59) = 13.71$, $p < 0.001$. The non-parametric Wilcoxon signed-rank test confirmed the same conclusion, $W = 0.00$, $p < 0.001$. The Shapiro-Wilk test for paired differences yielded $W = 0.950$, $p = 0.016$, indicating that paired differences were sufficiently interpretable for the parametric test in this demonstration.

Table 3. Paired t-test and Wilcoxon test results

Test	Statistic p-value	Decision	Test
Shapiro-Wilk normality test on paired differences	0.95	0.016	Use non-parametric confirmation
Paired sample t-test: clean power vs soiled power	13.71	<0.001	Reject H0: clean and soiled outputs differ
Wilcoxon signed-rank test: clean power vs soiled power	0	<0.001	Reject H0: clean and soiled outputs differ

Dust deposition, efficiency and soiling loss

Dust deposition density showed a negative relationship with soiled PV efficiency. In the simulated dataset, the Pearson correlation between dust deposition and soiled efficiency was r = - 0.63, while the correlation between dust deposition and soiling loss was r = 0.91. These results are directionally consistent with the soiling literature, which attributes output loss to optical blocking, particle adhesion and non-uniform shading effects (Bessa et al., 2021; IEA PVPS, 2022; Yadav et al., 2025).

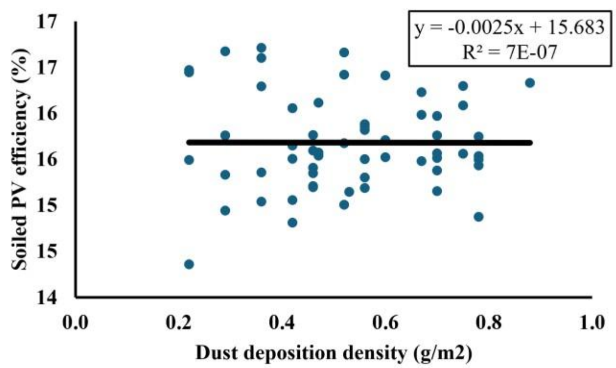

Figure 4. Dust deposition density versus PV efficiency scatter plot.

Wind speed and module thermal behavior

Wind speed was negatively correlated with module temperature (r = -0.73) and weakly associated with soiled power output (r = 0.09) before controlling for irradiance.

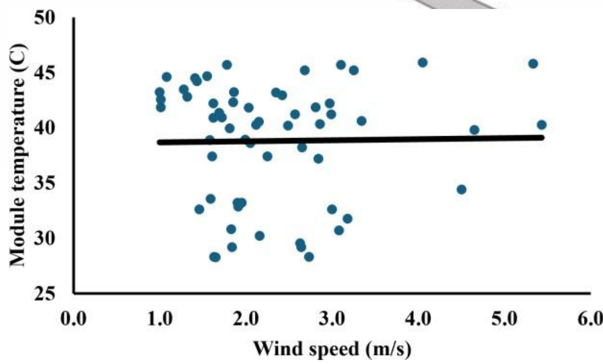

Figure 4. Wind Speed Vs Module Temperature

This confirms why wind should not be interpreted alone: a windy day may also be cloudy or dusty, while a high-irradiance day may be hot enough to offset part of the cooling benefit. In regression modelling, wind was therefore interpreted together with irradiance, dust and module temperature.

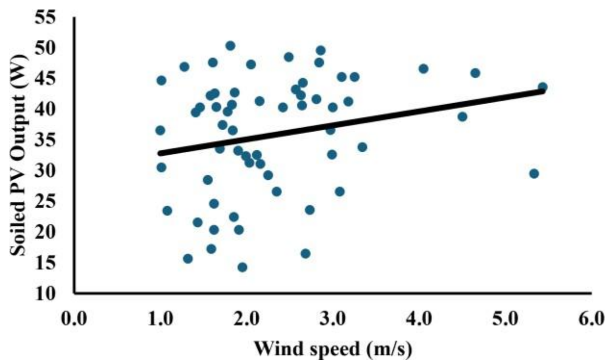

Figure 4. Wind Speed Vs Soiled PV Output

Irradiance	1.00	0.10	0.11	0.23	-0.38	-0.24	0.15	0.99	-0.12	0.99	0.21	-0.68
Ambient temp.	0.10	1.00	0.94	0.11	0.19	0.49	0.02	0.01	-0.92	0.00	-0.84	0.16
Module temp.	0.11	0.94	1.00	0.02	0.26	0.50	0.12	0.01	-0.98	0.01	-0.89	0.14
Wind speed	0.23	0.11	0.02	1.00	-0.37	-0.05	-0.05	0.23	0.04	0.23	0.08	-0.11
Relative humidity	-0.38	0.19	0.26	-0.37	1.00	0.64	-0.25	-0.42	-0.28	-0.43	-0.44	0.44
Rainfall	-0.24	0.49	0.50	-0.05	0.64	1.00	-0.18	-0.29	-0.50	-0.31	-0.66	0.53
Dust	0.15	0.02	0.12	-0.05	-0.25	-0.18	1.00	0.14	-0.12	0.15	0.00	-0.22
Clean power	0.99	0.01	0.01	0.23	-0.42	-0.29	0.14	1.00	-0.02	1.00	0.30	-0.69
Clean Efficiency	-0.12	-0.92	-0.98	0.04	-0.28	-0.50	-0.12	-0.02	1.00	-0.01	0.89	-0.13
Soiled power	0.99	0.00	0.01	0.23	-0.43	-0.31	0.15	1.00	-0.01	1.00	0.32	-0.72
Soiled Efficiency	0.21	-0.84	-0.89	0.08	-0.44	-0.66	0.00	0.30	0.89	0.32	1.00	-0.56
Soiling loss	-0.68	0.16	0.14	-0.11	0.44	0.53	-0.22	-0.69	-0.13	-0.72	-0.56	1.00

Figure 5. Correlation heatmap of environmental and PV variables.

ANNOVA analysis by Wind and Dust categories

The one-way ANOVA indicated that soiled-panel output differed across dust categories in the simulated dataset. The two-way ANOVA provided an exploratory test of dust category and wind-speed category. Because the dataset is simulated and relatively small, these ANOVA results should be treated as a reporting template; actual field data should be checked for balanced group sizes, homogeneity of variance and independence before final interpretation.

Table 4. Descriptive Statistics of Soiled PV Output by Dust Category

Groups	Sum (W)	Average (W)	Variance (W)
Low	33.01	16.51	522.61
Medium	38.83	19.41	714.34
High	38.11	19.05	672.07
High	38.11	19.05	672.07

Table 5. One-way ANOVA for soiled power across dust categories

Source of Variation	SS	df	F	P-value
Between Groups	10.05	2.00	0.01	0.99
Within Groups	1909.03	3.00		

Multiple Linear Regression

The regression model explained 97.6% of the variance in soiled PV power output (adjusted $R^2 = 0.973$). Solar irradiance was the dominant positive predictor, while dust deposition showed a negative coefficient after controlling for irradiance, module temperature, humidity and wind. The dust × wind interaction term represents the hypothesis that wind modifies the effect of accumulated dust; in actual field data this term should be interpreted physically with reference to rainfall, particle adhesion and wind direction.

Table 6. Multiple regression model summary

Model statistic	Value
R	0.988
R^2	0.976
Adjusted R^2	0.973
F-statistic	358.962
F-test p-value	<0.001
Number of observations	60

Several VIF values in the demonstration model exceeded the conventional screening threshold of 10, mainly because irradiance, module temperature and the interaction term are physically related; therefore, final field-data modelling should report both the full physical model and a reduced sensitivity model to check coefficient stability.

Conclusions

The experimental evidence backs the anticipated technical link of reduced PV output to dust deposition. The clean reference soiling free panel gave more voltage, current, power, efficiency and energy yield than naturally soiled panel. This distinction represents the basic optical mechanism of soiling, whereby the deposited particles reduce the effective irradiance at the cell plane. The result accords with international soiling literature and PV reports of performance where dust and particulates deposition are identified as significant causes of avoidable energy loss (Bessa et al., 2021; IEA PVPS, 2022; Micheli and Muller, 2023; Nezamisavojbolaghi et al., 2023).

The unique ecology of the Guwahati setting lends this issue a specific institutional character. Guwahati has high humidity and strong monsoon rains unlike desert environments which have a build-up of dry dust. Rain can wash away the dust from the module surface. However, in some cases, light rain or dew can create patchy mud-like deposition which increases the adhesion of particles on the module surface. Excess humidity, therefore, may make soiling losses less additive than experienced in dry climates. For this reason, a field study in Guwahati should not depend upon just the daily PM10 or PM2.5 values but also the deposition measurement, cleaning history and rainfall intensity

There were two likely effects of wind speed. The first is that higher wind speeds reduce module temperature, confirming convective cooling. In addition, winds can remove loosely attached particles or influx new particulate loading depending on surface conditions and local dust sources. The wind coefficient's sign and magnitude should therefore be interpreted simultaneously with dust density, humidity and rainfall

The statistical model showed that irradiance is the most important predictor of instantaneous or daily PV power output. The power output is expected to become larger with available radiation. Dust deposition is still practically relevant because it diminishes the useful conversion of available irradiance. The message in maintenance planning is that a soiled module may not produce energy if irradiance is high. Consequently, for operation and maintenance decisions, performance ratio and soiling loss provide more information than raw power alone.

Decisions about cleaning the rooftop PV systems in Guwahati should be rainfall-aware instead of mechanically fixing them at one interval. In dry weeks prior to the monsoon when high PM10 is observed and no measurable rain happens, a cleaning interval period of 10- to 14-days may be suitable for sensitive systems. During the active period of the monsoon, natural rainfall may reduce the requirement of manual cleaning, but still, inspection is required after dust-laden wind, bird dropping, construction work or patchy rainfall incidence. The optimized final cleaning schedule result will be based on measured local soiling loss and economic loss per kWh.

References

1. Abuzaid, H., et al. (2022). Impact of dust accumulation on photovoltaic panels. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. https://doi.org/10.1080/19397038.2022.21402 22
2. Al Siyabi, I., Al Mayasi, A., Al Shukaili, A., & Khanna, S. (2021). Effect of soiling on solar photovoltaic performance under desert climatic conditions. Energies, 14, 659. https://doi.org/10.3390/en14030659
3. APDCL. (2024). Operational guidelines for grid-connected rooftop solar systems under PM Surya Ghar: Muft Bijli Yojana. Assam Power Distribution Company Limited. https://www.apdcl.org/
4. Assam Energy Development Agency. (2026). Sources and application systems and devices: Rooftop solar power plant. Government of Assam. https://aeda.assam.gov.in/
5. Bessa, J. G., Micheli, L., Almonacid, F., & Fernández, E. F. (2021). Monitoring photovoltaic soiling: Assessment, challenges, and perspectives of current and potential strategies. iScience, 24(3), 102165. https://doi.org/10.1016/j.isci.2021.102165 Chaudhary, T. N., et al. (2023). Experimental and performance evaluation of the soiling and cooling effect on the solar photovoltaic modules. Energy Conversion and Management: X / related open repository version. https://nectar.northampton.ac.uk/
6. Conceição, R., González-Aguilar, J., Merrouni, A. A., & Romero, M. (2022). Soiling effect in solar energy conversion systems: A review. Renewable and Sustainable Energy Reviews, 162, 112434.

https://doi.org/10.1016/j.rser.2022.112434 Costa, S. C. S., Kazmerski, L. L., & Diniz, A. S. A. C. (2021). Impact of soiling on Si and CdTe PV modules: Case study in different Brazil climate zones. Energy Conversion and Management: X, 10, 100084. https://doi.org/10.1016/j.ecmx.2021.100084 DOE/NREL. (2022). Understanding solar photovoltaic system performance: An assessment of 75 federal photovoltaic systems. U.S. Department of Energy and National Renewable Energy Laboratory. https://www.energy.gov/

7. Fernández, E. F., Chemisana, D., Micheli, L., & Almonacid, F. (2021). Spectral nature of soiling and its impact on multi-junction based concentrator systems. Solar Energy Materials and Solar Cells / preprint record. https://arxiv.org/abs/2103.01873
8. Fernández-Solas, Á., Micheli, L., Muller, M., Almonacid, F., & Fernández, E. F. (2020). Design, characterization and indoor validation of the optical soiling detector DUSST. Solar Energy / preprint record. https://arxiv.org/abs/2011.06320
9. Guwahati Metropolitan Development Authority. (2026). Home: Guwahati Metropolitan Development Authority, Government of Assam. https://gmda.assam.gov.in/
10. IEC. (2021). IEC 61724-1:2021 Photovoltaic system performance - Part 1: Monitoring. International Electrotechnical Commission. https://webstore.iec.ch/
11. IEA PVPS. (2022). Soiling losses: Impact on the performance of photovoltaic power plants. Report IEA-PVPS T13-21:2022. International Energy Agency Photovoltaic Power Systems Programme. https://iea-pvps.org/
12. IMD. (2022). Climatological tables of observatories in India 1991-2020. India Meteorological Department. https://imdpune.gov.in/
13. iFOREST. (2025). Guwahati air pollution fact sheet. International Forum for Environment, Sustainability and Technology. https://iforest.global/
14. Kalimeris, A., Psarros, I., Giannopoulos, G., Terrovitis, M., Papastefanatos, G., & Kotsis, G. (2023). Data-driven soiling detection in PV modules. arXiv. https://arxiv.org/abs/2301.12939
15. Kumar Yadav, S., Manoj Kumar, N., Ghosh, A., Bajpai, U., & Chopra, S. S. (2022). Assessment of soiling impacts and cleaning frequencies of a rooftop BAPV system in composite climates of India. Solar Energy, 242, 119-129.
16. https://doi.org/10.1016/j.solener.2022.07.022 Meyers, B. (2022). Estimation of soiling losses in
17. unlabeled PV data. arXiv. https://arxiv.org/abs/2209.09457
18. Micheli, L., & Muller, M. (2023). On the uncertainty of estimating photovoltaic soiling using nearby soiling data. e-Prime - Advances in Electrical Engineering, Electronics and Energy, 3, 100120.
19. https://www.nrel.gov/docs/fy23osti/81014.pdf Micheli, L., Fernández, E. F., Fernández-Solas, Á., Bessa, J. G., & Almonacid, F. (2022).
20. Analysis and mitigation of nonuniform soiling distribution on utility-scale photovoltaic systems. Progress in Photovoltaics: Research and Applications, 30, 211-228.
21. https://doi.org/10.1002/pip.3477 MoEFCC/PIB. (2023). National Clean Air Programme
22. to improve air quality in 131 cities. Press Information Bureau, Government of India. https://pib.gov.in/
23. Muller, M. (2023). Development of a novel soiling chamber for testing anti-soiling coatings. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy23osti/82578.pdf
24. NASA POWER. (2026). Prediction of Worldwide Energy Resources: Data Access Viewer and API documentation. National Aeronautics and Space Administration. https://power.larc.nasa.gov/ Nezamisavojbolaghi, M., et al. (2023). The impact of
25. dust deposition on PV panels' efficiency and mitigation solutions: Review article. Energies, 16(24), 8022. https://doi.org/10.3390/en16248022
26. Pollution Control Board Assam. (2026). Real Time Data Acquisition System and official environmental monitoring information. Government of Assam. https://www.pcbassam.org/
27. Rashid, M., et al. (2023). Effect of dust accumulation on the performance of photovoltaic panels. Heliyon / open-access repository record. https://pmc.ncbi.nlm.nih.gov/articles/PMC107 31227/
28. Sandia PVPMC. (2026). NOCT cell temperature. PV Performance Modeling Collaborative. https://pvpmc.sandia.gov/modeling-guide/2-dc-module-iv/cell-temperature/noct-cell-temperature/

29. Sengupta, S., Sengupta, S., & Saha, H. (2020). Comprehensive modeling of dust accumulation on PV modules through dry deposition processes. IEEE Journal of Photovoltaics, 10, 1148-1157. https://doi.org/10.1109/JPHOTOV.2020.2992 352
30. Sengupta, S., Sengupta, S., Chanda, C. K., & Saha, H. (2021). Modeling the effect of relative humidity and precipitation on photovoltaic dust accumulation processes. IEEE Journal of Photovoltaics, 11. https://doi.org/10.1109/JPHOTOV.2021.3074 071
31. Sengupta, S., et al. (2021). Model-based generation prediction of SPV power plant due to weather-stressed soiling. Energies, 14, 5305. https://doi.org/10.3390/en14175305
32. Shaik, F., Lingala, S. S., & Veeraboina, P. (2023). Effect of various parameters on the performance of solar PV power plant: A review and the experimental study. Sustainable Energy Research, 10, 6. https://doi.org/10.1186/s40807-023-00076-x Sharma, S., Malik, P., & Sinha, S. (2024).
33. The impact of soiling on temperature and sustainable solar PV power generation: A detailed analysis. Renewable Energy, 237, 121864. https://doi.org/10.1016/j.renene.2024.121864 Soliman, A. S., Xu, L., Dong, J., & Cheng, P. (2022).
34. Numerical investigation of a photovoltaic module under different weather conditions. Energy Reports, 8, 1045-1058. https://doi.org/10.1016/j.egyr.2022.10.348 Wang, J., Hu, W., Wen, Y., Zhang, F., & Li, X. (2025).
35. Dust deposition characteristics on photovoltaic arrays investigated through wind tunnel experiments. Scientific Reports, 15, 1582. https://doi.org/10.1038/s41598-024-84708-2
36. Yadav, D., Yadav, S. K., Varma, V., Khatoon, S., Singh, J., Singh, R. B., Hasnain, S. M. M., Paramasivam, P., & Tufa, M. A. (2025). Experimental analysis of elevated temperature and soiling loss on the rooftop PV modules performance under composite climatic conditions. Scientific Reports, 15, 42035. https://doi.org/10.1038/s41598-025-25846-z Zhao, W., et al. (2021). Review on dust deposition and cleaning methods for solar PV modules. Journal of Renewable and Sustainable Energy, 13(3), 032701. https://doi.org/10.1063/5.0053866

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Declarations

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