# “Soiling, Antireflective Coatings, Antisoiling Coatings, and Cleaning in Different Locations”

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# Motivation

- In PV: insolation, temperature, and ***soiling*** are the 3 primary natural factors limiting electricity production.

-1%·day$^{-1}$ loss from soiling, *e.g.*, MENA.

-80%·storm$^{-1}$ loss, *e.g.*, haboob sand storms.

> $\Delta[\eta_{TOPCon}, \eta_{PERC}, \dots \eta_{prior}]$

**A Texas sized sand storm.**

**https://en.wikipedia.org/wiki/Haboob#/media/File:Haboob_in_Big_Spring,_TX.jpg**

<u>Goals of the field soiling coupon study</u>:

- **Characterize soiling** and its effect.
- **Compare** efficacy of **AR and AS coatings**.
- **Compare** common **cleaning strategies**.

  *-Relative to IEC 62788-7-3 machine brush tests*.

**Field soiling experiment in Kuwait (this study).**

# Today's Topics

5 year outdoor field coupon study :

- The range of **morphology**, **particle size distributions** observed from soiling.
- **Area concentration**, **object size**, **cementation**, and organic **composition** are location specific.

- A preferred **cleaning method**, possibly requiring contact, notably reduces soiling.
- **AR** gave performance **benefit**; **AS** coating cleanliness not readily distinguished from glass.
- **Impact from- and pH of-rain** may degrade PS coatings in precipitation prone locations.

- Much of **quantifiable optical loss** from absorptance (PAC), then forward scattering.

*Location (climate) specific results observed*

# Details of the Field Coupon Study (Specimens, Locations, …)


**Original specimen set deployed at Sacramento.**
*Einhorn et. al., J PV 2019, 233-239.*
*Toth et. al., SOLMAT, 185, 2018, 375-384.*

Samples:
- 7.5 cm x 7.5 cm coupons.
- Includes AR, AS (-phobic & -philic), reference glass.
- Black backpane (similar temperature to PV).

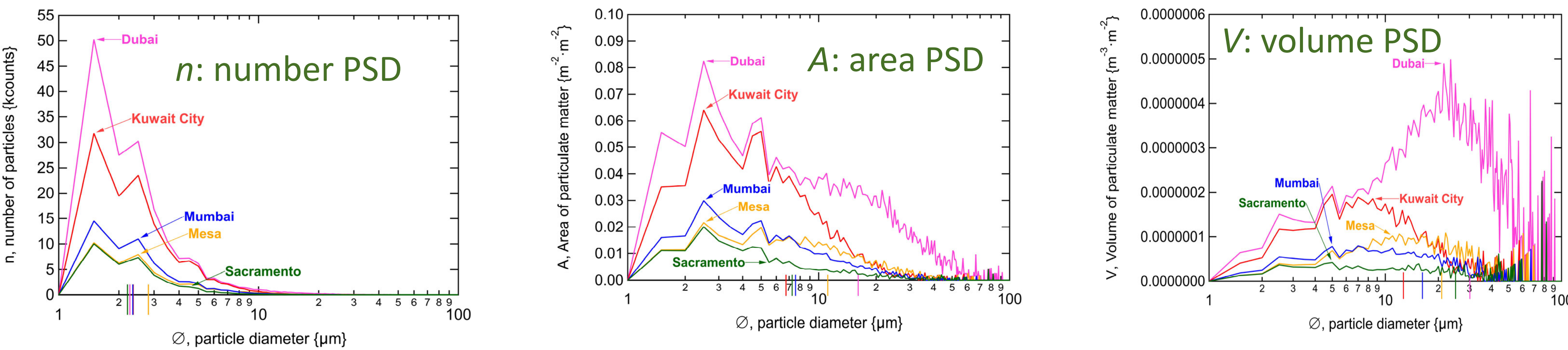
Test sites:
- Contamination and abrasion prone locations.
- **Mesa**, Arizona; **Sacramento**, California; **Mumbai**, India; **Kuwait City**, Kuwait; **Dubai**, United Arab Emirates.

Cleaning methods:
- No clean (NC); dry brush (DB); low-pressure water spray (WS); wet sponge and squeegee (WSS).
- Clean 1x/month. Kuwait only: clean 1x/day.
- Examine 2 replicates·material$^{-1}$, each year for 5 years.

Characterize:
- Particulate contamination (particle-size distribution, -area coverage, and -mass concentration).
- Optical performance (hemispherical transmittance).
- Damage morphology (scratch-width & -depth).

# Particle Size Distribution Analysis Distinguishes Desert Locations

- Optical microscope images automatically thresholded, analyzed using ImageJ script.




- Median size ($p_{50}$): between 2 μm and 3 μm (*n*); 6 μm to 20 μm (*A*) and from 10 μm to 30 μm (*V*).
  - -No standardized method exists for analysis and reporting of PV surface contamination.
  - -16 μm size identified for modules surface contamination in literature review.
  - -*n* directly identifies size of contamination; *V* may be compared to atmospheric sciences.
  - -1 μm microscope resolution limits assessment to PM10 (0.5 < ∅ < 30 μm).

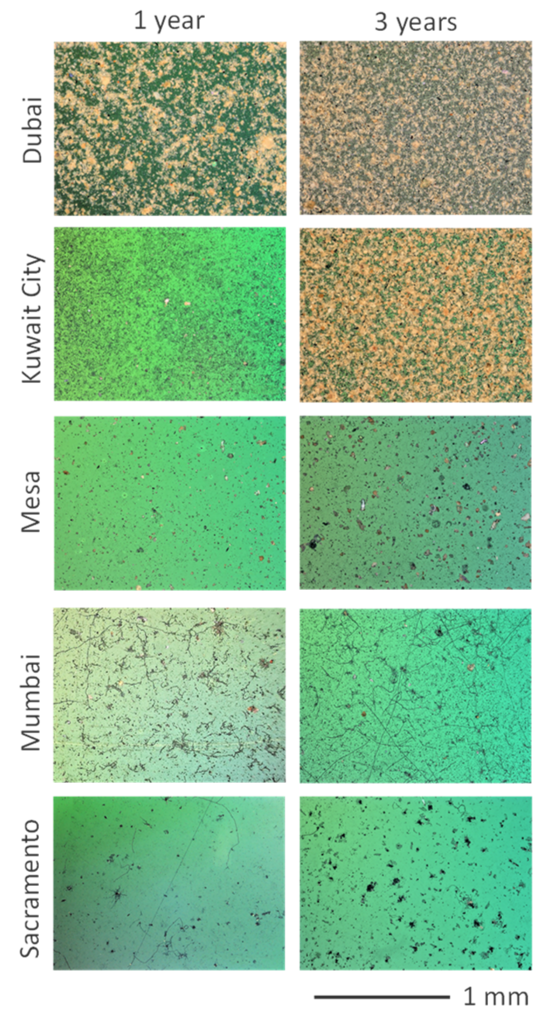
- $p_{50}$ > 30 μm (for Dubai) indicates cementation has occurred.

# Soiling Morphology is Complex Between the Five Locations

- **Most densely contaminated** locations: Dubai > Kuwait >> others.
  - -Dubai may accumulate multiple layers through study.
  - -Mesa has disparate object size.
  - (Green colorcast from cross polarization imaging).

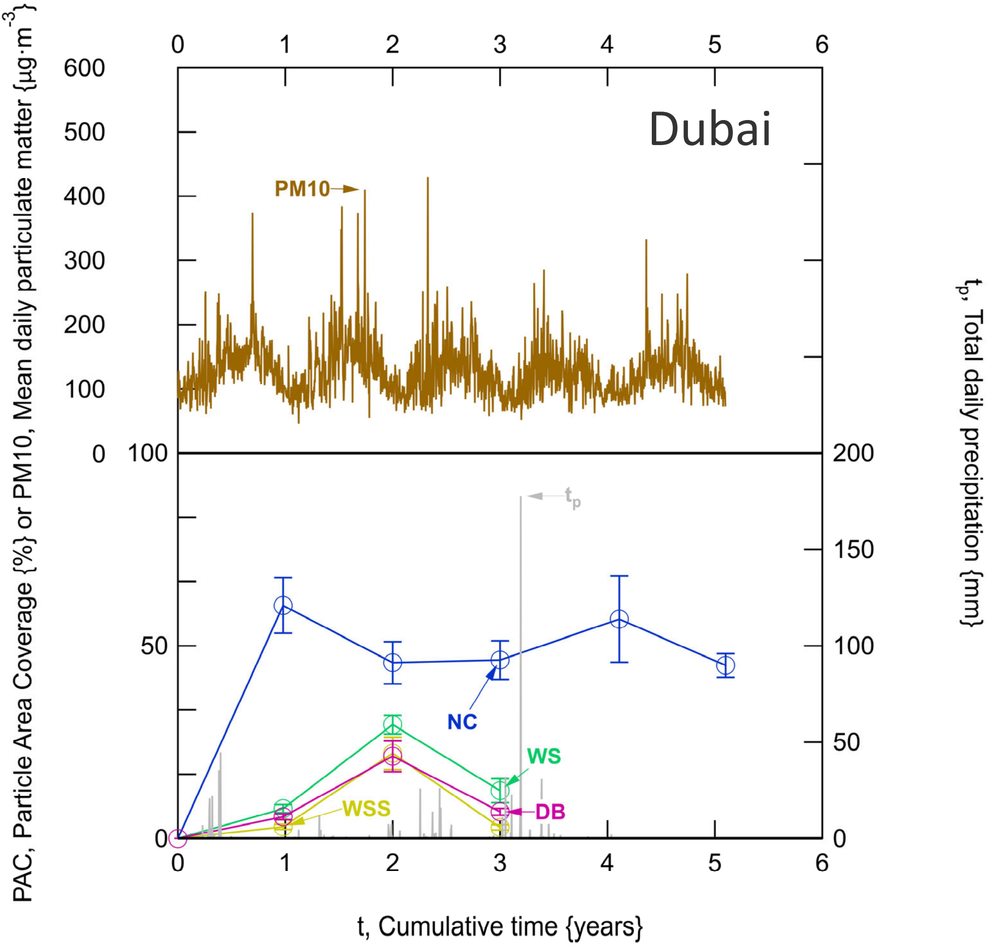
- **Cementation** (strong surface adhesion, from dew cycles):
  - -Dubai (evident), Kuwait (likely),
  - -Others (possible, depending on cleaning method).
  - -Palygorskite clay more prevalent in MENA than AZ, USA.

- **Organic contamination** (fungus is most robust):
  - -Mumbai (overt), Sacramento (heterogenous).
  - -Only observed at edges (under mounting frame) in desert locations.
  - -Fungus spore transport occurs intercontinentally, e.g., trade winds carry spores from Africa to Florida.




**Representative No Clean microscope images for all five sites.**

# To Reduce Soiling, Use a Cleaning Method!

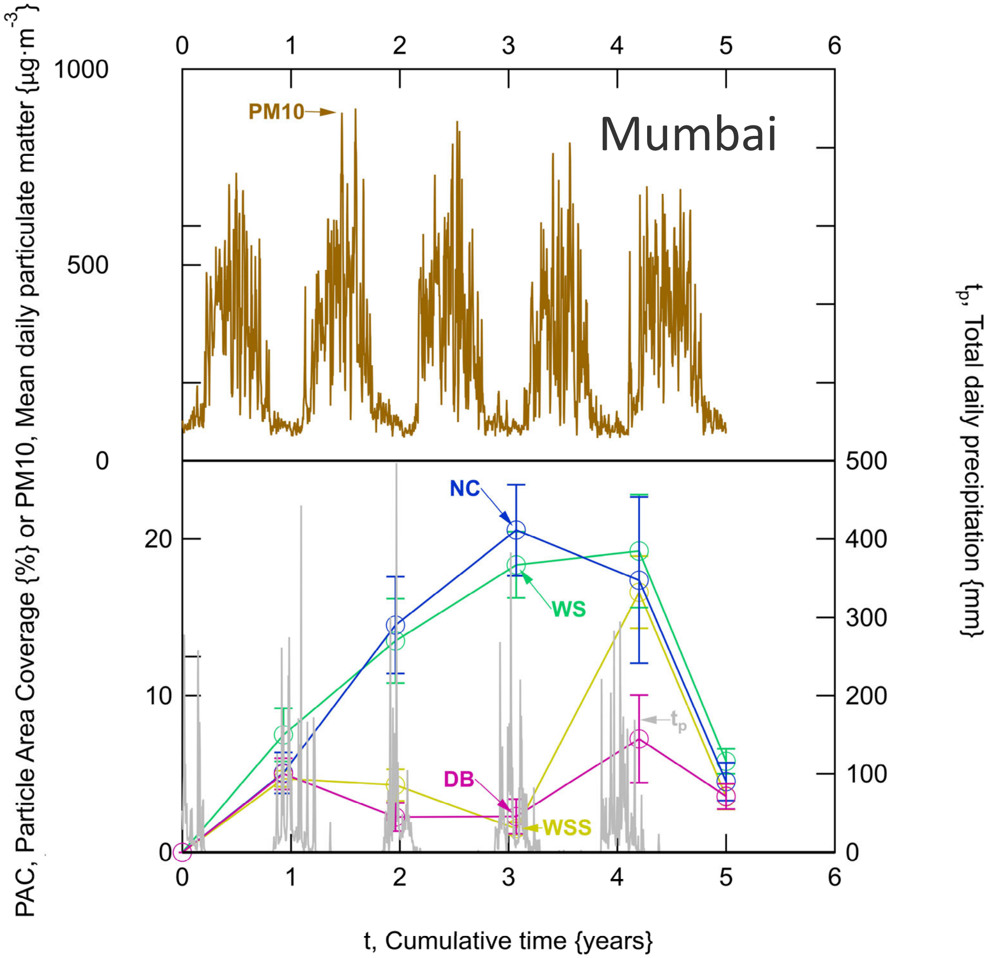



- Particle area coverage (% contamination) from ImageJ.
  - -Coupon cleaning eventually limited by CoVID.
- PM10, precipitation from web meteorological resource.
- In depth examination of 5/10 "materials".

- Cleaning can improve efficiency by 10's of percent! (NC: PAC 60% vs. WS, DB, WSS: 10<PAC<30%).
- Level of contamination asymptotes according to cleaning method.
  - -Cleaning more frequently than monthly warranted in Dubai (prevent cementation).
  - -Erratic PAC with time in may reflect timing of sample collection (relative to natural cleaning.)

**Data shown for all 4 cleaning methods for Dubai, AVG[B, D, G, J, U] coupons, when the history of cleaning was not affected by the CoViD pandemic.**

# To Reduce Soiling, Use a ***Preferred*** Cleaning Method!

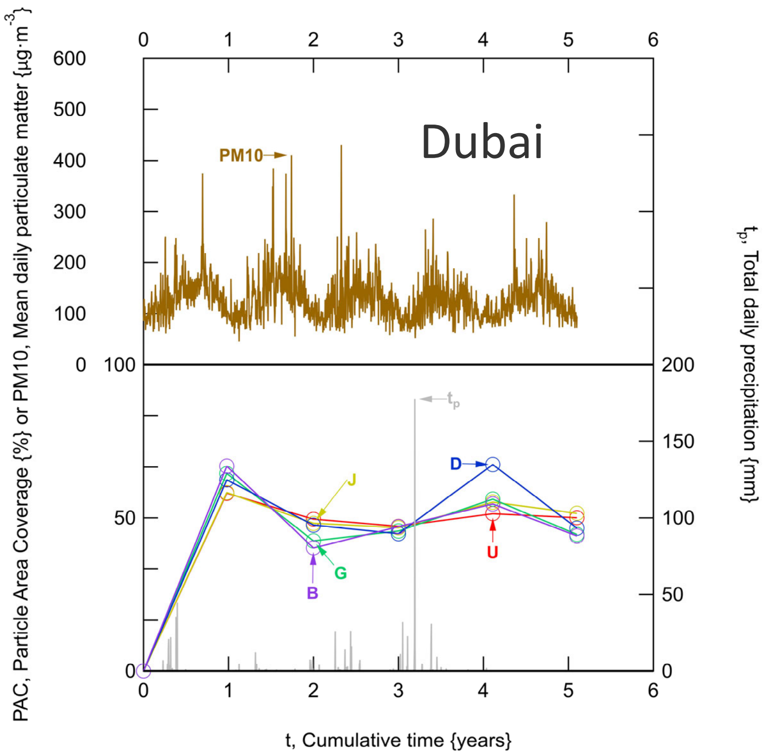



- Mumbai: Aw (tropical savannah), 2.3 m annual rain
- Dubai, Kuwait, Mesa: BWh (hot desert), 9-20 cm rain.
- Mumbai read points typically before rainy season.

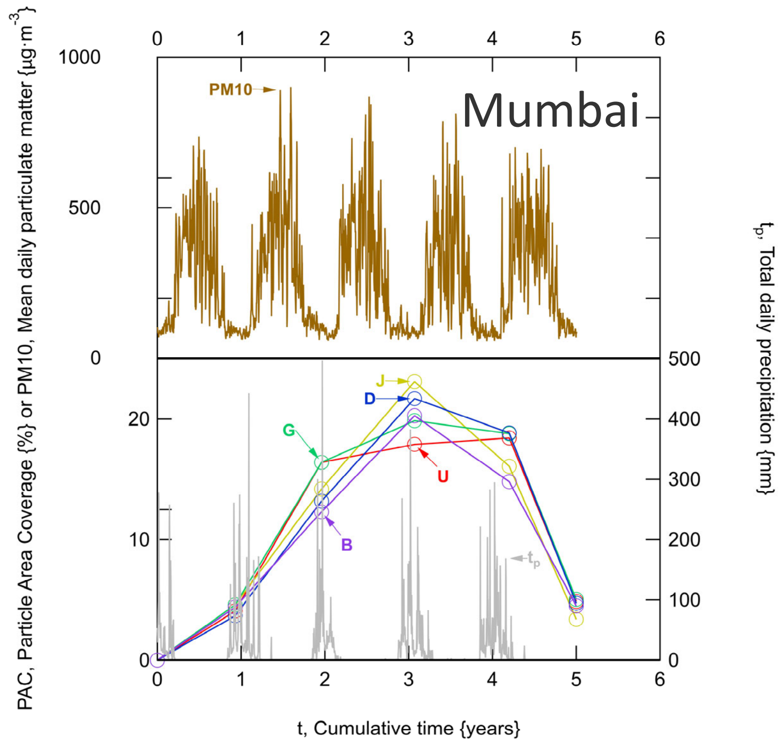
- No Clean still overtly distinguished from DB, WSS.
- Low pressure Water Spray not effective.
  - -Contact cleaning previously found to be required to remove fungus. https://doi.org/10.1016/j.solmat.2018.05.039.
  - -Fungus can trap inorganic contamination, magnifying its effect.
  - -Coarse annual read points; rain, organic species can vary through the day.

**Data shown for 4 cleaning methods for Mumbai, AVG[B, D, G, J, U] coupons.**

# AS Coating Cleanliness Is Not Readily Distinguished From Glass




- No overt effect of AS relative to glass substrate.




- ImageJ PAC analysis compares effectiveness of coatings.
- Examine No Clean coupons to avoid convoluting effect of cleaning.
- **AR, AS**: B, D, G. **AS** only: U. B, G, U are **hydrophobic**. D is **oleophobic** Uncoated glass: J.

**Data shown for No Clean coupons, including AR, AS, and uncoated specimens.**

# AR **Is**, But AS Coating Cleanliness **Is Not** Readily Distinguished From Glass

- Rank order analysis performed (for each site & read point) for all cleaning methods to quantify AR and AS efficacy.
- $\tau_{h,rsw}$ gives the optical performance (for 1J PV, from IEC 62788-1-4).
- PAC gives contamination remaining after shipping.

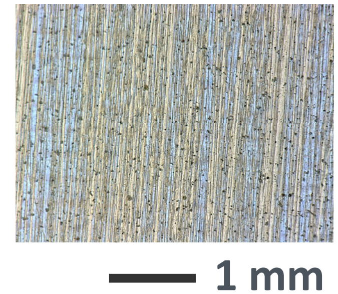
**The optical performance (average $\tau_{h,rsw}$ through the study and initial), obscuration (average PAC), and cumulative rank order are given for the five select coatings based on the transmittance or quantitative optical microscopy from each read point and at each location.**

| | | RAW DATA | | RANK ANALYSIS | | |
|---|---|---|---|---|---|---|
| | SPECIMEN INDEX | AVERAGE LEVEL SOILED (UNAGED) {%} | VARIATION IN LEVEL, 1 S.D. {%} | AVERAGE RANK {dimensionless} | VARIATION IN RANK, 1 S.D. {dimensionless} | OVERALL RANK {dimensionless} |
| $\tau_{h,rsw}$ | B | 87.9 (92.9) | 5.9 | 2.2 | 1.1 | 1 |
| | G | 87.5 (94.1) | 6.6 | 2.2 | 1.0 | 2 |
| | D | 87.4 (93.2) | 6.1 | 2.8 | 1.2 | 3 |
| | U | 86.8 (91.3) | 22.0 | 3.7 | 1.1 | 4 |
| | J | 86.7 (91.2) | 6.7 | 4.0 | 1.0 | 5 |
| PAC | unaged | 0 | N/A | N/A | N/A | unaged |
| | G | 12.0 | 11.0 | 2.6 | 1.3 | 1 |
| | J | 12.4 | 10.3 | 3.0 | 1.4 | 2 |
| | U | 12.4 | 10.1 | 3.0 | 1.4 | 3 |
| | B | 12.4 | 10.4 | 3.1 | 1.3 | 4 |
| | D | 12.6 | 10.4 | 3.1 | 1.3 | 5 |

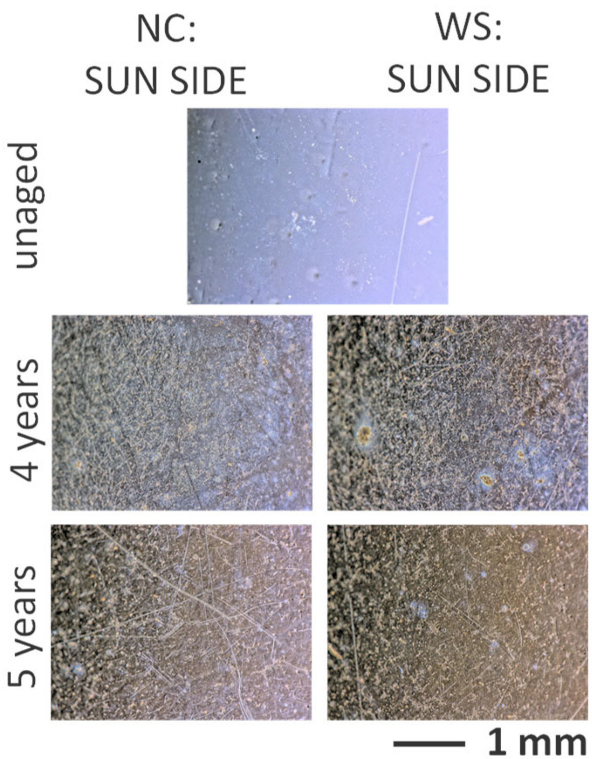
- On average, all coatings gave improved optical performance, relative to uncoated glass.
- **More electricity**! TEA not given here to identify critical coating cost.
- Material durability limited - PS ARs typically survive 50-200 cleanings. https://doi.org/10.1016/j.solmat.2020.110757
- Rank of AS's not readily distinguished. Uncoated glass may be cleaner than AS coatings.
- AS opportunity may still exist, relative to previous efforts (predominantly hydrophobic fluoro-coatings).

# Coating Damage Observed for Noncontact No Clean and Water Spray Cleaning

- Oblique (~11°) visualization method for qualitative integrity assessment, as in Karin et. al., IEEE J PV, 2021, https://doin.org/10.1109/JPHOTOV.2021.3053482.
- ~125 nm PS AR coating (present PV industry) appears blue.
  -Glass appears brown.

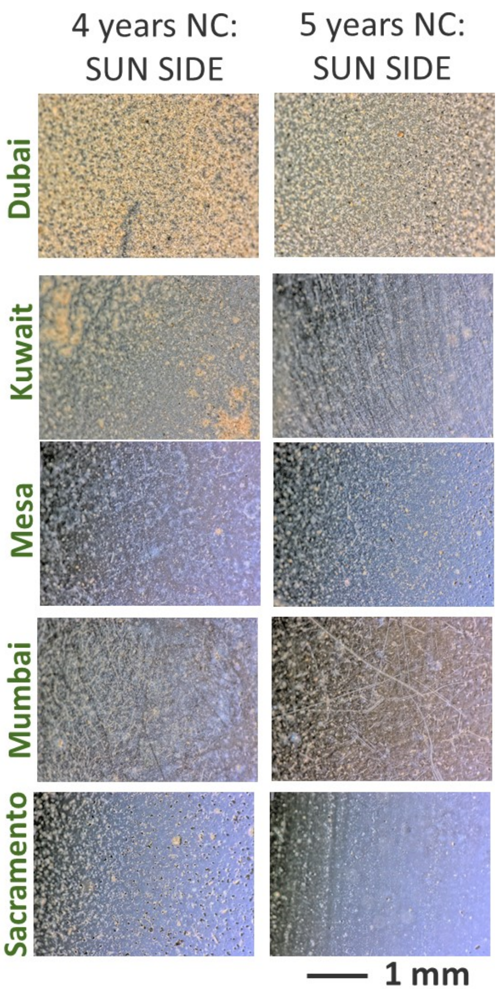

Oblique imaging to visualize coating integrity:
(left) microscope configuration, (right) representative image of Dry Brush sample.




- Coating integrity verified for:
  No Clean (natural cleaning & weathering) and Water Spray (noncontact cleaning).
- PS AR coatings (B and G) mostly absent at 4 and 5 years in Mumbai!!!
- Possible factors: rain (impact and pH), organic contamination (fungi secrete acid), hygrometric degradation.

Coating integrity for index B in Mumbai:
No Clean and Water Spray are shown relative to an unaged sample.

# Coating Damage Is Unique to Mumbai, Evident at 4 Years



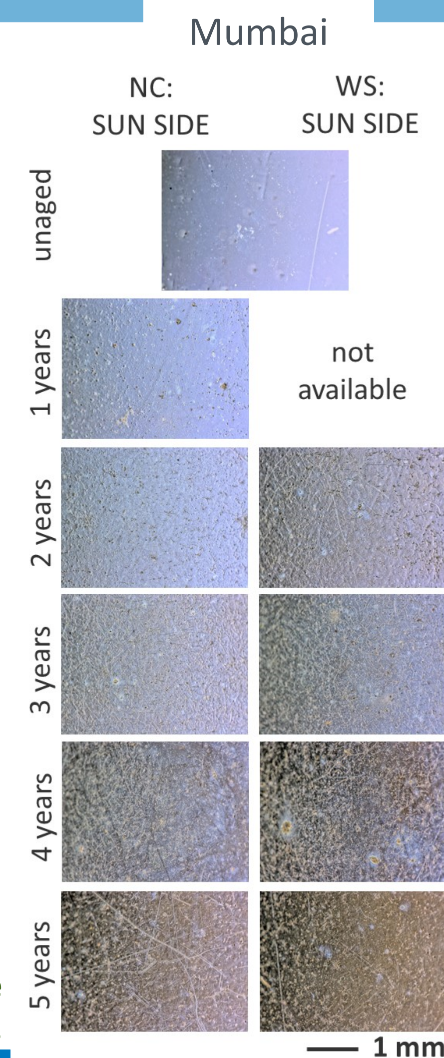

**Visualization of the presence and integrity of the final *No Clean (NC)* B coating (porous silica) between sites.**

- Damage to NC, WS coupons observed for Mumbai only. (Coating observed at surface perturbances for Dubai, Kuwait.)

- For Mumbai, glass substrate seen ≥ 4 years.
- Islands: trapped inorganic contamination may locally protect AR.

- The impact and pH of rain (~6.5-7) may degrade coating. (AS coatings in Bhaduri et. al, IEEE J PV, doi: 10.1109/JPHOTOV.2023.3273812)
- Accelerated test sequence should include: UV, “rain”, abrasion.

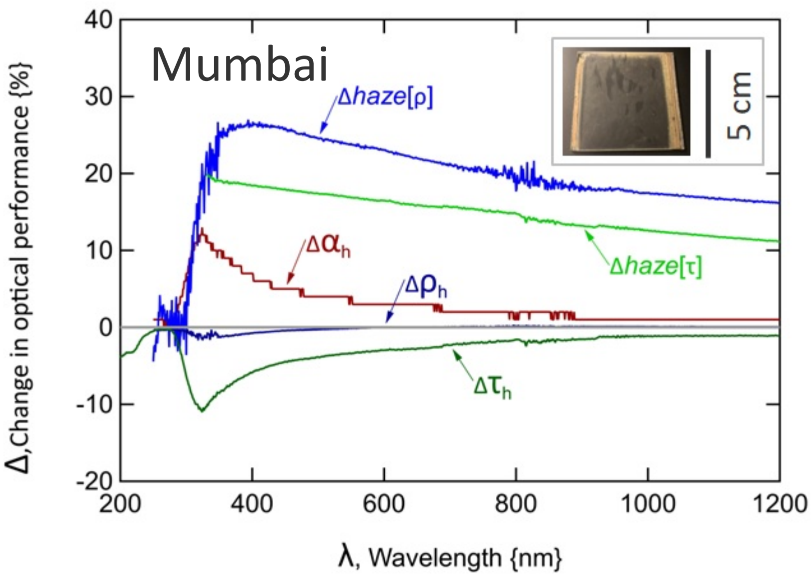
**Visualization of the presence and integrity of the B coating (porous silica) *No Clean (NC)* coupons late in the study.**



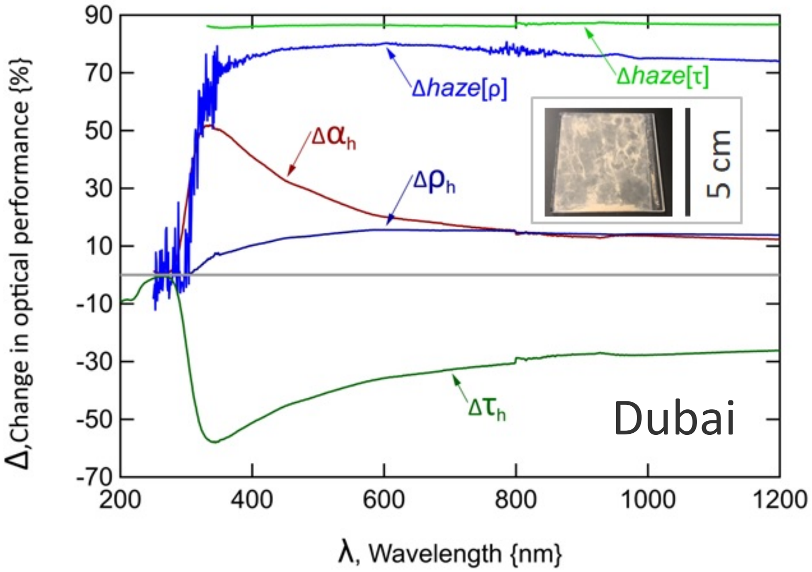
# Lessons From Comprehensive Optical Characterization

- Comprehensive optical characterization of No Clean coupons at all sites, at 3y.
  Compare transmittance, reflectance, absorptance, final-initial, including haze (scattering).

- Transmittance is reduced most in UV-VIS wavelengths, above $\lambda_{cUV}$. (greatest refractive index).
- Much of loss of transmittance results from optical absorptance (PAC), then forward scattering.
- Overall reflectance is often reduced … backscattering is often increased by soiling.
  -Reflectance instead overtly increased for Dubai, attributed to local calcite contamination.




**Comprehensive optical performance for Mumbai (left) and Dubai (right) at 3y, including hemispherical (integrating sphere): transmittance (τ), reflectance (ρ), and absorptance (α). The haze is evaluated from the difference between he hemispherical and direct (no integrating sphere) measurements.**



# Summary

5 year outdoor field coupon study:

•No standard analysis or reporting established for soiling in PV. Median size ($p_{50}$) ranged from 2 - 30 μm for number, area, and volume particle size distributions.

•Density (desert), object size, cementation (dew cycles), and organic composition (precipitation) are location (*climate*) specific.

•A preferred cleaning method, possibly requiring contact, notably reduces soiling.

•AR gave performance benefit; AS coating cleanliness not readily distinguished from glass.

•Impact from- and pH of-rain may degrade PS coatings in precipitation prone locations.

•Much of optical loss from absorptance (PAC), then forward scattering. Exceptions exist.

# For Further Information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## Soiling, cleaning, and abrasion: The results of the 5-year photovoltaic glass coating field study


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Particulate matter
Soiling
Surface coverage


ABSTRACT


External contamination ("soiling") of the incident surface is a major limiting factor for solar technologies. A 5-year field glass coupon study was conducted to better understand external contamination and its effects; compare cleaning methods and the use of preventative coatings; and explore the abrasion resulting from cleaning to advise on accelerated abrasion testing. Test sites included the cities of Dubai (UAE), Kuwait City (Kuwait), Mesa (AZ), Mumbai (India), and Sacramento (CA). Through the 5-year cumulative study, dry brush, water spray, and wet sponge and squeegee cleaning methods were compared to no cleaning. Optical microscopy was used to obtain images, including representative color images, grayscale images for object analysis, and oblique images for coating integrity assessment. A thresholding protocol was developed to analyze and distinguish specimens using the ImageJ software. Optical performance was quantified using a spectrophotometer, including comprehensive optical characterization (transmittance, reflectance, and absorptance in addition to forward- and back-scattering). Atomic force microscopy was used to verify the abrasion damage morphology, including the width and depth of surface scratches. Analysis of the results included correlation of optical performance and particle area coverage, rank order (by coating or location), and the acceleration factor for abrasion damage. The efficacy of external cleaning was more readily distinguished from the effectiveness of antisoiling coatings. The acceleration factor for dry brush cleaning of a porous silica coating was found to be on the order of unity.


### 1. Introduction

Natural factors limiting photovoltaic (PV) module performance include insolation, temperature, and external contamination ("soiling"). Insolation depends on the diurnal availability of the sun, which is further limited by meteorological factors (e.g., cloudiness or air mass [1]). The effectiveness of PV cells is reduced as the temperature increases, with most Si-based technologies being more adversely affected than thin-film technologies. Soiling can cause a gradually accumulated loss as well as an instantaneous, event-specific effect on the order of tens


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[1] https://www.nrel.gov/pv/accelerated-testing-analysis.html


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(supplementary information, 2024, slides) https://www.nrel.gov/docs/fy24osti/90174.pdf

*I have focused on some notable results of the study today, there is much more – including lessons from the methods!*

Bomber et. al., 2024, (paper): https://doi.org/10.1016/j.solmat.2024.113035

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