# Supplementary Material: Validation Matrices and Measurement Tables

**Table S1. Reference-use and evidence-tier mapping for literature roles and comparator relevance.**

| Source / source group | Literature role and physical topic | Relevance to this roadmap | Evidence tier supported here and boundary of use |
|---|---|---|---|
| PV/CSP soiling and water-context literature [1-7] | Application background: soiling mechanisms, performance loss, cleaning context and water constraints. | Motivates dry or low-water maintenance and helps define why residual fine-dust release is a relevant validation problem. | Supports application motivation and study framing. The validation implication is to use matched controls and predeclared endpoints for AIr-specific residual-response assessment. |
| Rotor, drone-downwash, impinging-jet and wall-jet literature [8,14-16] | Airflow mechanics: rotor/fan downwash, impingement, wall-jet transport and particle mobilisation by flow. | Provides vocabulary for standoff, shear footprint, wall-flow, redeposition and matched airflow-only controls. | Supports airflow and control-design context. AIr-specific ion-assisted increments remain a separate matched-control question. |
| Adhesion and PV-glass surface-state literature [9,12,29-33] | Contact mechanics and surface-state vocabulary: smooth-sphere limits, roughness, humidity, capillary effects, particle size and electrostatic adhesion. | Helps define why residual fine dust can persist and why dry/near-dry surface state, charge and humidity must be recorded. | Supports mechanism vocabulary and measurement planning, not absolute removal prediction for irregular field dust. |
| Electrostatics, image-charge and contact-electrification sources [12,34-36] | Charge generation, polarity dependence and idealised electrostatic boundary vocabulary. | Supports sign-conditional interpretation of particle charge, surface potential, image-charge attraction and polarity arms. | Supports polarity-aware design. A favourable ion effect remains surface-state and geometry specific and is tested by the matched-control programme. |
| Close-proximity corona, EHD and ionic-wind literature [17-24] | Electric body force, corona flow, ionic wind and electrostatic dust-motion comparators. | Informs EHD/corona controls, HV-on/HV-off sweeps, standoff sensitivity and separation of rotor-dominant, EHD-assisted and coupled regimes. | Supports comparator and diagnostic design. The roadmap tests rotor-carried ion delivery under matched airflow rather than importing performance from adjacent geometries. |
| Electrodynamic-screen and electrostatic dust-motion comparators [25-27] | Electrostatic dust mobilisation using integrated or surface-associated electrode architectures. | Provides comparator context for electrostatic dust-motion physics and surface/electrode distinctions. | Supports adjacent-art positioning. AIr is treated as an external co-delivery architecture rather than a surface-integrated electrode screen. |
| Stationary electrostatic/ionisation-based PV analogue [28] | Stationary electrostatic/ionisation-based PV comparison under a different architecture. | Useful as adjacent PV-relevant context and possible comparator logic, including reported site-specific values retained as context only. | Supports comparator selection and source-specific context. Rotor-entrained ion delivery, plume overlap and matched wall shear are handled by the proposed AIr validation programme. |
| Attractor/collector-electrode ionised-air systems [13] | Adjacent ionised-air/electrostatic collection architecture. | Helps distinguish non-collecting rotor-flow dust-fate logic from collection toward an opposite-polarity body. | Supports architectural boundary setting. The validation implication is to measure dust fate and redeposition rather than assuming collection. |
| Ion transport, ionisation measurement and safety sources [10,11,37-39] | Ion-aerosol interaction, recombination, measurement discipline and ozone/by-product safety context. | Supports delivered-dose caution, panel-plane collector/probe logic, recombination order-of-magnitude estimates and safety monitoring. | Supports measurement and safety discipline. Emitter output is not treated as a substitute for panel-plane delivered ion evidence. |
| Public technical lineage [40] | Patent document cited for public technical lineage and architecture provenance for the surface-cleaning architecture. | Identifies the public technical lineage of the architecture while keeping empirical mechanism assessment in the validation roadmap. | Supports lineage/provenance only. Empirical residual-response increments are addressed through matched-control testing. |

**Table S2. Functional architecture, modes and primary attribution risks for a combined AIr pass.**

| Function / mode | Purpose | Positive response means | Primary attribution risk or control |
|---|---|---|---|
| Position and standoff control | Hold treatment in a repeatable envelope. | Surface receives consistent flow and ion exposure. | Standoff changes wall shear and delivered dose; record and hold constant. |
| Rotor-flow generation | Create incident jet, wall jet and clearance flow. | Airflow-only baseline is defined. | Coarse dust removal by airflow alone can be mistaken for ion-assisted fine-film removal. |
| Ion entrainment | Capture generated ions into useful rotor wake. | Panel-plane collector proxy indicates delivered ion flux. | Emitter current may not equal surface dose due to recombination or frame loss. |
| Flow/ion overlap | Co-locate useful shear footprint with delivered ion footprint. | Same surface patch receives both functions. | Poor overlap can produce false negatives even with strong emitter output. |
| Combined ionised airflow | Default architecture test. | More residual fine dust removed than matched airflow-only. | Wrong polarity, insufficient dose, capillary/cemented state or shear mismatch. |
| Bipolar mode | Neutralise mixed/unknown particle charge. | Charge-dependent adhesion or redeposition is reducible. | Delivered bipolar balance may be altered by recombination or frame interception. |
| Positive / negative unipolar modes | Test polarity sensitivity and possible Coulomb assist. | Different responses support polarity-dependent mechanism. | Favourable sign depends on particle, surface, water film and field state. |
| Ioniser-on/motors-off weak-flow control | Mechanism isolation for charge-state change while allowing for weak corona/EHD flow. | Adhesion/potential changes without rotor/fan removal flow. | Can be a lab control; not necessarily a product mode. Any weak EHD flow should be noted. |
| Airflow-only matched control | Mechanical baseline. | Defines added value of ionised airflow. | Must match geometry, standoff, traverse and dust state. |
| Sham ioniser, high-voltage (HV) off | Geometry/wake disturbance control. | Identifies hardware effects without ionisation. | If sham changes removal, attribution to ions is unsafe. |
| Redeposition management | Reduce residual charge and track particle fate. | Target-zone cleaning is not offset downstream. | Use witness zones and downstream imaging. |

**Table S3. Model terms and optional organising metrics retained for interpretation, not as confirmed predictors.**

| Term / quantity | Role | How AIr may affect it | First check |
|---|---|---|---|
| $F_{adhesion,before}$ / $F_{adhesion,after}$ | Threshold logic for particle mobilisation before and after ion exposure. | Ion delivery may reduce charge-sensitive components or contact pinning. | Compare matched airflow-only and ionised-airflow response. |
| Faero / Faero,t | Useful aerodynamic mobilisation capacity from rotor/fan flow; in the schematic, primarily the tangential wall-jet drag/shear term acting on rolling or sliding thresholds. | Estimated from surface-plane velocity, wall-jet/shear proxy, standoff, rotor/fan state and footprint; normal impingement or stagnation-pressure loading should be treated as a separate contribution. | Surface velocity map, wall-shear proxy or matched flow proxy; report any separate normal loading interpretation where relevant. |
| $F_{vdW}$ | Dry molecular adhesion baseline. | Not directly neutralised; remains after charge reduction. | Infer from residual threshold and dust/surface state. |
| $F_{img}$ / q / surface potential | Idealised image-charge or particle/surface charge contribution; not a literal conductor-plane model of the PV module stack. | Bipolar or selected unipolar ions may reduce, redirect or increase charge-dependent adhesion depending on sign, surface potential, field geometry and water state. | Particle/surface charge proxy, Kelvin/electrostatic probe, polarity comparison and boundary-state record. |
| $F_{cap}$ / salt state | Capillary and brine/cementation boundary. | Often limits electrostatic benefit after wetting/deliquescence. | Dew-point margin, surface wetness, salt/deliquescence state, humidity ramp. |
| Πremove = Faero,t / Fadhesion,after | Proposed threshold-crossing index using the same test-specific mobilisation proxy in both matched arms. | AIr aims to increase the ratio by reducing effective adhesion. | Use as interpretation after matched-control data exist. |
| $\Pi_{ion}$ = delivered dose / neutralisation need | Proposed ion-sufficiency index. | Requires delivered ion flux at the panel plane, not emitter current alone. | Panel-plane collector or Faraday-style proxy. |
| $\Pi_{dwell} = t_{dwell} / t_{charge}$ response | Proposed dwell adequacy ratio. | Longer local dwell or repeated passes may compensate for short response time. | Record traverse, pass count and charge/mobility decay. |
| $\Pi_{EHD}$ | Proposed comparison of EHD forcing and a rotor-induced aerodynamic force-density scale. ρqE is the classical electric body-force-density scale used in EHD/corona-flow descriptions; see main text Section 4.4 and main manuscript references [23], [24]. The ratio ΠEHD is used here only as a proposed comparison organiser, not as a standard named EHD dimensionless group. | Classifies rotor-dominant, EHD-assisted and coupled operation. | HV-on/HV-off near-surface velocity and particle response. Select and report $L_c$ as a consistent near-surface comparison scale across the sweep; for example, a measured boundary-layer or near-wall velocity-gradient thickness may be used where supported by the fixed-rig data, this is one possible choice and sensitivity to reasonable $L_c$ choices should be stated. |
| $\Pi_{rec,turb}$ | Qualitative ion-transport/recombination organiser, not a fixed scalar definition. | Turbulence, aerosol loading, polarity balance, recombination and frame/wall losses may alter delivered ion balance. | Polarity-resolved current maps and turbulence/flow proxies; report as a study-design organiser unless a formal definition is introduced. |
| $F_{pull,JKR}$ / $F_{pull,DMT}$ | Ideal smooth-sphere contact-mechanics limits for pull-off scaling; used to ground contact-area and work-of-adhesion sensitivity. | Ion exposure may change effective work of adhesion, active asperity contact or contact geometry; real mineral dust remains irregular and multi-contact. | Use only as interpretation support; test by atomic force microscopy (AFM)/lateral-force or particle-mobility response, not as absolute prediction. |
| $t_{tr}$, $\tau_{rec}$ and $S_{rec}$ | Transit and bipolar/mixed-polarity recombination plausibility check: ttr = L/ud; τrec ≈ 1/(α $n_0$); Srec ≈ 1/(1 + α $n_0$ ttr) for bipolar/mixed-polarity estimates. This is a lumped plug-flow/order-of-magnitude recombination warning, not a plume-resolved transport solution. Unipolar plumes require separate treatment of space-charge drift/expansion, field geometry and boundary losses rather than same-sign ion-ion recombination. | Standoff, downwash velocity, ion mode, ion density, aerosol attachment and frame/wall losses determine whether emitted ions survive to the panel plane. If $S_{tot}$ is used, it should be treated as a heuristic survival organiser with ad hoc geometry-specific first-order loss rates, not a derived transport solution. | Use α ~ 1.6 × 10^-12 m^3 s^-1 only as an order-of-magnitude representative small-ion recombination coefficient for bipolar/mixed-polarity estimates; reported values vary with ion composition, temperature, pressure and humidity. Verify all ion modes by panel-plane delivered-current mapping and state sensitivity to reasonable α, attachment and boundary-loss assumptions. |

**Table S4. Operating regimes, expected response and interpretation priority.**

| Regime / surface state | Dominant physics | If ionised airflow improves over matched airflow-only | If no improvement is observed |
|---|---|---|---|
| Coarse loose dust | Aerodynamic drag, rolling/sliding and gravity dominate. | May reflect extra turbulence or EHD, not necessarily charge-sensitive fine-dust release. | Expected if airflow already dominates; not a decisive negative for fine residual dust. |
| Fresh fine mineral dust | Van der Waals plus possible image-charge/triboelectric adhesion. | Strong early mechanism signal if delivered ion dose and matched airflow are documented. | Check ion dose, polarity, particle size, charge state and surface history. |
| Mixed-size residual film after airflow-only pass | Fine particles remain after coarse dust is cleared. | High-value target: supports ion-assisted residual-fine mobilisation. | Check redeposition, imaging threshold and baseline non-uniformity. |
| Humid near-dew surface | Adsorbed water increases conductivity and capillary risk. | A response may indicate a narrow pre-capillary window. | No response may reflect capillary or screening dominance rather than failure of dry-dust mechanism. |
| Salt-containing / deliquescent dust | Brine, ionic screening and capillary adhesion. | Only interpretable if salt and wetness state are measured. | Delay, classify as boundary regime, or treat as future preventive-maintenance study. |
| Organic / oily / biological deposits | Binder/film adhesion rather than charge-sensitive mineral dust. | Possible secondary reactive oxygen species (ROS) or airflow effect but not core proof. | Use as boundary/extension case after dry mineral dust validation. |
| Live or recently-live PV glass | Surface field and electrical memory may influence ion landing and dust charge. | Supports PV-specific surface-state importance if controlled. | Compare grounded, floating/off and live/recent states where safe. |
| Coated glass / anti-soiling surface | Altered wettability, surface energy, charge relaxation and durability. | May show complementarity with passive coatings. | Run coating-specific optical, wettability and material-response checks. |

**Table S5. Surface-state variables, sensors and decision rules for first validation.**

| Variable / decision point | Why it matters | Recommended record or choice | Avoid as first proof case |
|---|---|---|---|
| Dust state | Determines whether charge-sensitive fine adhesion is plausible. | Fresh or moderately adhered fine mineral dust; residual film after airflow-only; document source, size and wet/dry history. | Loose coarse sand only, mature crust, wet mud, oily films. |
| Humidity / dew-point margin | Controls adsorbed water, capillary onset and charge mobility. | Ambient RH, ambient temperature, panel temperature, dew point and dew-point margin. | Unlogged near-dew or condensation conditions. |
| Temperature and irradiance / illuminance | PV output and local drying depend on heat and light exposure. | Panel/surface temperature, ambient temperature, irradiance where possible; lux as practical proxy if no irradiance sensor. | Electrical comparisons without irradiance/temperature normalisation. |
| Surface conductivity / wetness | Indicates ionic screening, brine and charge-relaxation boundary. | Surface wetness proxy, conductivity/leakage where feasible, salt state. | Treating brine/cemented states as direct dry-dust evidence. |
| Electrical state | Panel fields and grounding can alter particle and surface charge. | Record live/off/open/grounded/floating and time since operation. | Uncontrolled electrical state across replicates. |
| Particle-size evidence | Response differs by size and agglomeration. | Microscopy/image analysis; scanning electron microscopy (SEM) or size classifier subset where feasible. | No particle-size information. |
| Treatment endpoint | Defines what "cleaning" means. | Primary: particle coverage/removal map; secondary: transmittance/haze; PV tests normalised to irradiance and temperature. | Qualitative visual cleanliness alone. |
| Reverse/top-down triage | Prevents over-investing in mechanism detail before a measurable increment exists. | First compare matched airflow-only and ionised rotor airflow under controlled dust/loading/surface state. | Proceeding to fine mechanism studies without a measurable ion-assisted increment. |
| Panel-proximity / ground-effect electrical boundary | Close rotor operation modifies wall-jet flow and may intensify frame-to-panel or emitter-to-panel electric fields. | Record standoff relative to rotor diameter, frame/panel electrical state and delivered-ion footprint; compare across standoffs. | Treating close-standoff results as purely aerodynamic without electrical-boundary checks. |
| Pass-to-pass charge history | Residual charge or contact-state change from one pass may influence the next pass. | Record pass number, delay, polarity history and mobility/charge decay; avoid assuming a neutral initial state after prior treatment. | Pooling first-pass and later-pass data without sequence metadata. |
| Field attribution factors: light and vibration | Irradiance, hot surfaces, blade-passage forcing and panel vibration may assist particle mobilisation and require separate interpretation. | Record irradiance/surface temperature and bound rotor acoustic or structural vibration where feasible. | Attributing sunlit or vibration-assisted release solely to ion delivery. |

**Table S6. First validation matrix: conditions, measurements and interpretation.**

| Condition | Isolates / controls | Primary measurements | Candidate response / negative interpretation |
|---|---|---|---|
| Untreated control | Natural change, imaging repeatability and dust stability. | Before/after images, particle coverage, surface state. | Large uncontrolled loss/gain invalidates paired comparison. |
| Matched airflow-only | Mechanical removal baseline. | Rotor/fan state, standoff, surface velocity, dust map. | If equal to ionised case, ion increment is not established in that regime. |
| Combined ionised rotor airflow | Core AIr condition. | Same flow metrics plus ion voltage/current and delivered-ion proxy. | Improvement over matched airflow-only supports integrated architecture signal. |
| Bipolar ionised airflow | Neutralisation response for mixed/unknown charge. | Removal map, potential proxy, redeposition map. | No response may imply weak charge adhesion or delivered-dose failure. |
| Positive and negative unipolar modes | Polarity sensitivity and sign dependence. | Matched dose/flow; mobility and redeposition. | No polarity difference may favour neutralisation, airflow dominance or dose insufficiency. |
| Sham ioniser, high-voltage (HV) off | Hardware/wake distortion from emitter body. | Airflow map and removal relative to airflow-only. | If sham changes removal, separate geometric effect before claiming ion effect. |
| Ioniser-on/motors-off weak-flow exposure | Charge-state or contact-state response without rotor/fan removal flow; weak EHD flow remains possible. | Surface potential, delayed mobility, microscopy, and any weak-flow/EHD observation. | No response may still be consistent with co-delivery if ions act only during shear. |
| Stationary bipolar ionised-air comparator | Dust/surface ion responsiveness under an adjacent, non-rotor comparator technique. | Ion dose, removal/optical response. | Negative result suggests deposit is not charge-responsive or dose is inadequate. |
| Manual or wet reference clean | Recoverable endpoint and optical/electrical ceiling. | Transmittance/haze or PV electrical reference. | Needed to avoid overstating partial recovery. |
| Redeposition witness zones | Dust fate and downstream contamination. | Witness slides/zones, downstream/edge imaging. | Target-zone improvement with redeposition must be reported as redistribution. |
| Delayed or second-pass comparison | Pass-to-pass charge history and separate-conditioning possibility. | Delay between ion exposure and airflow, charge/mobility decay, repeated-pass order. | Positive response indicates persistence or sequencing effect; negative result supports co-delivery-only interpretation in that state. |
| Vibration / acoustic bounded run | Rotor blade-passage and panel vibration independent of ion delivery. | Panel accelerometer or vibration proxy; acoustic or rotor speed, revolutions per minute (RPM), blade-passing frequency (BPF) record where feasible. | If vibration correlates with removal, separate mechanical excitation from ion effect. |

**Table S7. Endpoint hierarchy and first-stage outcome decision ladder.**

| Endpoint / outcome | What it measures | Interpretation | Next action |
|---|---|---|---|
| Particle-level removal map | Pre/post particle coverage, size bins and residual fine fraction. | Primary laboratory evidence for surface cleaning. | Repeat by zone/day; stratify by particle size and surface state. |
| Optical recovery | Transmittance, haze, reflectance or spectral attenuation. | Links particle removal to optical function. | Normalise to reference-clean endpoint. |
| PV electrical recovery | current-voltage (I-V) curve, power, current or soiling ratio normalised to irradiance and module temperature. | Field/module-level relevance; not a substitute for particle evidence. | Use clean reference cell/module or expected-clean baseline. |
| Redeposition map | Whether dust leaves target region or redistributes. | Distinguishes true clearance from local displacement. | Adjust pass direction, neutralisation or follow-up clearance. |
| Candidate positive signal | Ionised airflow improves over matched airflow-only after sham/surface controls. | Supports integrated ion-assisted mobilisation. | Repeat and proceed to polarity, EHD and surface-state resolution. |
| Positive but sham-sensitive | Emitter geometry/HV-off hardware changes removal. | Flow disturbance should be separated from ion attribution. | Redesign geometry or quantify wake effect. |
| Positive but redeposition-sensitive | Target zone improves but adjacent zones worsen. | Cleaning and dust fate are separated. | Add neutralise-before-clearance and witness-zone controls. |
| No increment over airflow-only | No ion-assisted benefit in tested condition. | Could be true null or boundary/delivery failure. | Check delivered dose, humidity/salt, polarity, surface state, particle charge and EHD isolation. |
| Ambiguous / high variance | Controls or replicates are unstable. | Experiment not yet interpretable. | Improve randomisation, sample preparation and imaging threshold. |
| Bounce / rebound / re-adhesion signature | Whether displaced particles re-contact and re-adhere or saltate onward. | Connects neutralisation-before-clearance to dust fate, not only initial release. | Analyse witness zones and post-pass residual charge/spatial redeposition pattern. |

**Table S8. UAV translation, hardware safety and staged deployment checkpoints for the first mechanism-isolation campaign and later staged translation.**

| Translation item | Risk / question | Control, measurement or progression check |
|---|---|---|
| Surface velocity and wall shear | Hover thrust does not establish useful near-surface shear. | Map velocity, standoff, stagnation region and radial wall-jet; compare with fixed rig and separate tangential mobilisation from any normal impingement loading. |
| Delivered ion current density | Emitter current may be lost to airframe or recombination. | Measure panel-plane collector proxy and frame-intercepted current. |
| Flow/ion overlap | Ion plume and useful shear footprint may not coincide. | Map both footprints; report thresholded overlap area. |
| Standoff, traverse and dwell | Coverage rate changes dose and removal opportunity. | Record speed, swath, pass count, exposure time and dose per pass. Candidate standoff ranges must be determined by measured airflow/ion-footprint overlap and delivered dose; no hopt or validated operating window is implied at the roadmap stage. |
| Frame charge / HV routing | Apparatus may act as unintended ion sink or electrode. | Audit frame potential, referenced/grounded/floating states, leakage and arcing. Treat carbon-fibre-reinforced polymer (CFRP) arms or guards as geometry-specific electrical structures because anisotropic conductivity and lay-up can change their effective ion-capture cross-section relative to aluminium. |
| Mass, power and endurance | Payload may reduce coverage or safety margin. | Record take-off mass, thrust margin, hover/traverse current and HV-on/off endurance. |
| EMI and controls | High voltage (HV) may affect flight controller, sensors or communications. | Test shielded/isolated HV; log anomalies; maintain safe standoff. |
| Material safety | Ozone/reactive species or leakage may affect coatings. | Monitor ozone/leakage where feasible; compare with applicable occupational exposure limits, e.g., OSHA 0.1 ppm 8-hour TWA PEL and NIOSH 0.1 ppm ceiling REL for ozone, as applicable; perform optical/wettability/coating checks after exposure. |
| Fixed rig to rotor stand | First translation stage. | Progression evidence: ionised airflow increment persists using actual rotor/fan hardware. |
| Tethered/controlled UAV | Flight integration stage. | Progression evidence: standoff, overlap, dose and safety controls reproduce rig conditions. |
| Field block trial | Operational stage. | Progression evidence: repeated treatments improve normalised particle/optical/PV endpoints without unacceptable redeposition or material response. |

**Table S9. Evidence-tier boundaries and statement scope.**

| Statement class / adjacent field | Safe statement now | Avoid overstating | Evidence needed for stronger statement |
|---|---|---|---|
| Architecture | AIr proposes a rotor-flow ion-delivery architecture for dry, non-contact fine-dust release and validation. | Claiming field performance or universal cleaning from architecture alone. | None for architecture statement, if not phrased as performance. |
| Mechanism plausibility | Ion delivery may modify charge/contact state and reduce some adhesion barriers. | Stating dominant mechanism without isolation data. | Surface dose, charge/potential response, matched removal and particle tracking. |
| UAV downwash cleaning | Rotor flow can interact with surfaces and remove some deposits. | Treating airflow-only results as proof of ion assistance. | Matched airflow-only and ionised-airflow comparison. |
| Stationary electrostatic/ionisation-based PV analogues | Stationary electrostatic/ionisation-based PV studies provide adjacent-art context. | Assuming direct transfer to rotor-wake/UAV conditions. | Positive-control bridge plus rotor-specific integration test. |
| Close corona/EHD systems | EHD devices can move dust in close geometries. | Claiming generic corona novelty. | Regime separation and standoff-dependent HV-on/HV-off comparisons. |
| Attractor/collector systems | Ionised airflow plus electrode collection exists in adjacent art. | Implying AIr uses collector electrodes or solved dust fate without proof. | Non-collection framing, redeposition mapping and frame/plume audit. |
| Surface-state/dew maintenance | Preventive timing is a plausible future/extension use. | Presenting dew-front conditioning as established efficacy. | Humidity-ramp, delay-to-adhesion and field weather-window tests. |
| Specific percentage recovery values | No AIr-specific percentage recovery should be stated without data. | Quoting removal/output gains before controlled data. | Statistical experiments with reference-clean normalisation. |

**Table S10. Priority notation and measurement roles for first-stage validation.**

| Symbol / quantity | Meaning | Measurement or interpretation role |
|---|---|---|
| $F_{adhesion}$ | Total resistance to initial particle mobilisation. | Inferred from removal threshold and before/after response; not directly measured in first study. |
| $F_{adhesion,before}$/after | Adhesion budget before and after useful ion exposure. | Threshold-crossing logic for comparing airflow-only and ionised airflow. |
| Faero / Faero,t | Useful aerodynamic mobilisation capacity from rotor/fan flow; in the schematic, primarily the tangential wall-jet drag/shear term acting on rolling or sliding thresholds. | Estimated from surface-plane velocity, wall-jet/shear proxy, standoff, rotor/fan state and footprint; normal impingement or stagnation-pressure loading should be treated as a separate contribution. |
| $F_{vdW}$ | Baseline dry molecular adhesion. | Literature/inference term; remains after charge reduction. |
| $F_{img}$ / $q_p$ | Idealised image-charge or particle-charge contribution; image-charge language is a limiting electrostatic vocabulary, not a literal PV-module conductor-plane model. | Charge proxy, surface potential, polarity response and boundary-state interpretation. |
| $F_{cap}$ | Capillary bridge adhesion. | Boundary term; diagnose with RH/dew/wetness and humidity ramp. |
| σ_s / τ_relax | Surface conductivity and charge-relaxation time. | Recommended pre-campaign mechanism screen where delayed conditioning, pass-interval scheduling or polarity-persistence interpretation is in scope; not a per-run minimum unless such claims are tested. |
| D_i / J_i | Delivered ion dose or current density at surface. | Panel-plane collector/Faraday proxy; not emitter current alone. |
| η_co | Overlap of delivered ion footprint and useful shear footprint. | Map velocity and ion dose footprints separately; use thresholded overlap. |
| $u_{surf}$ / $\tau_w$ | Surface velocity or wall-shear proxy. | Matched airflow baseline; can use hot-wire/vane/particle image velocimetry (PIV) or laser Doppler anemometry (LDA) depending on rig. |
| h / standoff | Distance between rotor/ion source and surface. | Record and control; affects flow, delivered ion dose and EHD. Candidate standoff ranges must be determined by measured airflow/ion-footprint overlap and delivered dose; no validated hopt or operating window is implied at the roadmap stage. |
| v_traverse / $t_{dwell}$ | Traverse speed and local dwell time. | Controls exposure dose and mobilisation opportunity. |
| RH, Tambient, Tpanel, dew margin | Humidity and thermal boundary variables. | Record for surface-state and PV electrical normalisation. |
| Irradiance / illuminance | Light/heat exposure and PV output normalisation. | Prefer irradiance for PV; lux may be practical proxy when irradiance unavailable. |
| Δ_particle / Δ_optical / Δ_electrical | Particle, optical and electrical recovery or residual-reduction endpoints. | Use particle maps, transmittance/haze and irradiance/temperature-normalised PV response. |
| Redeposition | Dust fate and downstream deposition. | Witness zones, downstream/edge imaging and optional particle counters. |
| N_pass / pass sequence | Repeated exposure and maintenance logic. | Record pass number, sequence, dose and airflow for each pass. |
| $\Pi_{remove}$, $\Pi_{ion}$, $\Pi_{dwell}$, $\Pi_{EHD}$ | Optional dimensionless or comparison metrics. | Use for organising data; not prerequisites or confirmed predictors. |

| Symbol / quantity | Meaning | Measurement or interpretation role |
| --- | --- | --- |
| $F_{pull,JKR}$ / $F_{pull,DMT}$ | Ideal JKR/DMT pull-off scaling terms for smooth-sphere contact limits. | Interpret contact-area/work-of-adhesion sensitivity; not absolute prediction for irregular mineral dust. |
| $t_{tr}$ / $\tau_{rec}$ / $S_{rec}$ | Transit time, recombination time and recombination survival scale. | Order-of-magnitude ion-survival plausibility check; verify with panel-plane ion current; $S_{rec}$ applies to bipolar/mixed-polarity plumes only, while unipolar operation requires space-charge drift, field-geometry and boundary-loss treatment. |
| $\alpha$ / $n_0$ | Ion-ion recombination coefficient and local ion-density scale. | Use α ≈ 1.6 × 10^-12 m^3 s^-1 as scale; $n_0$ should be measured or bounded. |
| Fn,flow | Normal impingement or stagnation-pressure loading from incident flow. | Separate surface-normal contribution; not the mobilising drag/shear term and not, by itself, evidence of particle release. |

$\Delta_{res}$ denotes the normalised residual-response metric used for primary comparisons; $\Delta_{particle}$, $\Delta_{optical}$ and $\Delta_{electrical}$ denote endpoint-specific implementations.

**Table S11. Minimum measurement package and per-run data record for the first mechanism-isolation validation campaign.**

| Category | Minimum data to record | Purpose / interpretation |
|---|---|---|
| Run identity | Date/time, operator, sample ID, zone ID, condition, order, replicate number. | Supports randomisation, blocking and traceability. |
| Substrate state | Glass/panel type, coating, tilt/orientation, electrical state, time since live operation. | Controls surface field, coating and contact mechanics. |
| Deposit state | Dust source, natural/artificial label, approximate size class, loading/residual-film status, ageing/wet-dry history. | Defines applicability to intended fine-dust regime. |
| Surface/environment | Ambient RH/temperature, panel temperature, dew point/margin, surface wetness, wind, recent rain/dew, irradiance/illuminance. | Turns weather and solar exposure into interpretable surface state. |
| Airflow module | Rotor/fan type, modular/removable/foldable configuration, rotor speed, standoff, traverse, airflow map/proxy. | Verifies that matched airflow-only, ioniser-on/motors-off weak-flow/EHD-permitted, and ionised-airflow states share geometry. |
| Ion source | Emitter type, voltage, current, polarity/mode, duty cycle, on/off timing. | Links treatment to generated ion conditions. |
| Delivered ions | Panel-plane delivered-current or collector proxy, polarity balance where feasible, frame-intercepted current if measured. | Distinguishes emitter output from useful delivered dose. |
| Treatment layout | Zone map, pass direction, swath, overlap, number of passes, treatment window and order. | Supports dose/dwell and redeposition analysis. |
| Primary endpoint | Pre/post imaging, particle coverage, residual fine-particle fraction, removal map. | Minimum evidence for surface cleaning beyond visual impression. |
| Secondary endpoints | Transmittance, haze, reflectance or spectral attenuation; PV electrical response normalised to irradiance and temperature. | Connects particle removal to optical or electrical function. |
| Attribution factors and exclusions | Arcing, wind gusts, condensation, imaging failure, non-uniform loading, HV anomaly. | Prevents retrospective overinterpretation. |
| Interpretation fields | Comparison to airflow-only, reference clean, redeposition, inclusion/exclusion and notes. | Makes the analysis auditable. |
| Transit and proximity check | Standoff L, representative downwash velocity ud, estimated ttr, frame/panel electrical state, proximity condition. | Links emitted ions to delivered-dose plausibility and panel-proximity electric-field effects. |
| Mechanical / field attribution factors | Rotor rotor speed, revolutions per minute (RPM), blade-passing frequency (BPF) proxy, panel vibration where feasible, irradiance/surface temperature, photophoretic/thermophoretic risk note. | Separates ion effect from sunlit, vibration-assisted or thermally assisted particle release. |
| Pre-campaign charge-relaxation screen (recommended where relevant) | Kelvin/electrostatic decay on bare and dust-loaded coupons after a calibrated ion pulse, where delayed-conditioning, pass-interval or polarity-persistence interpretations are in scope. | Defines charge-modification observation window; not a per-run minimum unless such claims are tested. |
| Mechanism-resolution measurements (where pathway resolution is in scope) | Polarity-resolved ion-footprint mapping; dust-charge characterisation by size class where feasible; bare/dust-loaded surface-potential relaxation; sub-rotor-diameter removal maps; pre/post agglomerate imaging. | Supports polarity-arm, EHD/rotor contribution, cluster-fragmentation and delayed-conditioning interpretation; not required for the primary matched-control comparison unless such pathway claims are being made. |

**Table S12. Condensed first-pass validation checklist for the first mechanism-isolation campaign.**

| Question | Minimum acceptable evidence for first mechanism-isolation campaign | If not satisfied |
|---|---|---|
| Does ionised rotor airflow outperform matched airflow-only? | Same dust/surface state, same standoff, same rotor/fan state, same exposure; primary particle endpoint improves. | Do not claim mechanism signal; diagnose flow match, dose and surface state. |
| Did useful ions reach the surface? | Panel-plane delivered-current or dose proxy and emitter state logged. | Treat result as delivery-limited or uninterpretable. |
| Was the surface in the intended regime? | Dust type/size, wet/dry history, RH/dew, temperature and wetness recorded. | Classify as boundary test rather than core dry-fine-dust validation. |
| Was the result not just geometry or turbulence? | Sham HV-off or equivalent geometry control included. | Separate hardware/wake contribution. |
| Was redeposition controlled? | Witness zones/downstream imaging and particle fate considered. | Report redistribution and revise clearance/neutralisation logic. |
| Can it translate beyond the fixed rig? | Rotor stand/UAV hardware reproduces overlap, dose, dwell and safety controls. | Do not generalise to flight deployment yet. |

**Table S13. Minimum first-study reporting specification for the first mechanism-isolation campaign.**

| Required item | Minimum required specification |
|---|---|
| Primary endpoint | Predeclare one primary residual-response metric, preferably normalised residual-film coverage change. |
| Dust preparation | Report dust composition/source, particle-size bins, deposition method, areal loading or coverage, preconditioning and uniformity rule. |
| Particle-size scope | State the intended residual-fine-dust fraction. An indicative core validation regime is approximately 1-50 µm equivalent diameter; coarser loose particles and submicrometre residues should be analysed separately. |
| Rotor/fan source | Report rotor/fan diameter or outlet geometry, blade/impeller type where relevant, speed/command, standoff, traverse speed, footprint and measured panel-plane airflow/shear proxy. |
| Ioniser hardware | Report electrode type, geometry, spacing, polarity mode, voltage/current setting, mounting position and HV-on/HV-off state. |
| Airflow matching | Match by panel-plane airflow/shear proxy, not rotor command alone. |
| Ion delivery | Report panel-plane delivered ion proxy, such as collector current, Faraday-style current, field/probe response or time-integrated delivered-current proxy. |
| Charge state | Report particle charge state, surface potential, frame/grounding state and charge-relaxation history before and after treatment where measurable; if not measured, state as a limitation on mechanism attribution. |
| Exposure/dwell | Predeclare exposure time, dwell time, number of passes, traverse speed and treatment order. |
| Environmental/electrical boundary | Report RH, temperature, dew-point margin, wetness state, tilt angle, glass/coating state and grounding/electrical boundary condition. |
| Control arms | Define airflow-only, ionised airflow, ioniser-on/motors-off weak-flow, sham geometry, stationary comparator, polarity arms and charge-audit conditions. |
| Sham geometry | Use the same aerodynamic obstruction/mounting as the ioniser hardware, but with ion production disabled. |
| Stationary comparator | Report source type, standoff, exposure time, carrier airflow if any, polarity mode and delivered panel-plane ion proxy; treat as a comparator, not as AIr-equivalent. |
| Redeposition | Report target-zone residual response plus off-target/witness-zone deposition maps. |
| Statistics | Report blocking, randomisation, replicate count, baseline values and paired/block-normalised or baseline-adjusted comparison. |
| Safety/by-products | Report ozone/by-product monitoring where relevant; compare with applicable occupational exposure limits without implying product-safety validation. |

*These tables support mechanism attribution, reproducibility and study design. They are research-support materials for validation planning rather than product requirements or architectural limits.*

Abbreviations used in this supplement:

AIr, airflow with ion-assisted release; PV, photovoltaic; CSP, concentrating solar power; UAV, unmanned aerial vehicle; EHD, electrohydrodynamic; RH, relative humidity; HV, high-voltage; EMI/EMC, electromagnetic interference and electromagnetic compatibility; AFM, atomic force microscopy; SEM, scanning electron microscopy; PIV, particle image velocimetry; LDA, laser Doppler anemometry; CFRP, carbon-fibre-reinforced polymer; OSHA, Occupational Safety and Health Administration; NIOSH, National Institute for Occupational Safety and Health; ROS, reactive oxygen species; RPM, revolutions per minute; BPF, blade-passing frequency; I-V, current-voltage.