

Electrostatic and Surfactant-Enhanced Cellulose Nanocrystal Cloud Seeding With Machine Learning-Based Spatiotemporal Targeting

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Electrostatic and Surfactant-Enhanced Cellulose Nanocrystal Cloud Seeding With Machine Learning-Based Spatiotemporal Targeting

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Abstract

Cloud seeding success depends on both the seeding material and atmospheric conditions during deployment. This study developed a more environmentally friendly cloud-seeding formulation and a machine-learning method for identifying favorable deployment windows. Six conditions were tested in a cloud chamber: distilled water, sodium chloride, cellulose nanocrystals (CNCs), CNCs passed through polytetrafluoroethylene (PTFE) tubing, CNCs with saponin, and CNCs with both modifications. A 650 nm laser and light sensor measured cloud formation onset, minimum transmitted illuminance, and persistence across five trials per condition. Compared with unmodified CNCs, the combined formulation reduced mean onset time by 61% (27.0 to 10.6 s), reduced minimum transmitted illuminance by 93.5% (3818 to 248 lux), and increased persistence by 85% (90.8 to 168.0 s). Welch’s tests produced $p = 0.021$, $p = 0.008$, and $p < 0.001$, respectively. Saponin produced most of the improvement, while PTFE routing provided a smaller additional benefit. In parallel, an Extreme Gradient Boosting (XGBoost) classifier was trained on approximately 41 million records from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) and Integrated Multi-satellite Retrievals for Global Precipitation Measurement (IMERG). Using precipitation during the following six hours to identify favorable windows, the model achieved a receiver operating characteristic area under the curve of 0.802 on a 2023 holdout set. Location and season emerged as important predictors, demonstrating the spatiotemporal dependence of cloud-seeding opportunities. Together, these results support direct testing of the combined formulation and provide a practical method for identifying favorable deployment windows.

Keywords: Cellulose nanocrystals, cloud condensation nuclei, cloud seeding, electrostatic charging, hygroscopic seeding, machine learning, meteorological targeting, precipitation forecasting, saponin, XGBoost.

1 Introduction

Cloud seeding begins with a simple idea: if a cloud already contains water, adding the right particles may help more of that water grow into precipitation. Seeding does not create clouds or add water vapor. It only has a chance to work when the cloud already has suitable temperature, liquid water, upward motion, background aerosol, and enough time for droplets to grow. For this reason, major reviews and international guidance do not support one universal claim that cloud seeding works under every condition [1–4]. In cold-cloud seeding, silver iodide is commonly released into supercooled clouds to promote ice formation. Recent winter experiments have tracked released silver iodide through ice formation and snowfall [5–7]. This study instead tests an environmentally friendly hygroscopic seeding material designed to help liquid droplets grow in warm clouds.

Warm rain begins when water vapor condenses onto small airborne particles called cloud condensation nuclei (CCN). As moist air rises and cools, some of these particles take up enough water to become cloud droplets. This process is called activation. The droplets must then grow through condensation and collisions before they can become drizzle or rain. Particle size and amount are important. Too many small particles can force the droplets to compete for the available water, while a smaller number of larger particles may help create the first large drops that collect smaller ones [8–11].

Köhler theory explains when an aerosol particle can activate into a cloud droplet. For a solution droplet with wet diameter D , the equilibrium saturation ratio is

$$S_{eq}(D) = a_w(D) \exp \left[\frac{4\sigma_{s/a}(D)M_w}{RT\rho_w D} \right], \quad (1)$$

where a_w is water activity, $\sigma_{s/a}$ is the solution–air surface tension, M_w and ρ_w are the molar mass and density of water, R is the universal gas constant, and T is absolute temperature [12, 13]. Two effects compete. Dissolved material helps water condense by lowering water activity, while the curved surface of a very small droplet makes growth more difficult. The highest point on the resulting Köhler curve gives the critical diameter and

supersaturation required for activation and continued growth.

The κ -Köhler form summarizes a particle’s ability to take up water using a dimensionless hygroscopicity value, κ [14]. If D_d is the dry-particle diameter and $s_c = S_c - 1$ is the fractional critical supersaturation, a common approximation is

$$s_c \simeq \left(\frac{4A^3}{27\kappa D_d^3} \right)^{1/2}, \quad (2)$$

$$A = \frac{4\sigma_{s/a} M_w}{RT\rho_w}.$$

Equation (2) shows why larger and more hygroscopic particles usually activate at lower supersaturation. Lower surface tension may also reduce the supersaturation required for activation. However, surfactant molecules move between the droplet interior and its surface as the droplet grows. A surface-tension value measured in a large container may therefore give an inaccurate prediction for a microscopic droplet [15–18]. Köhler theory supports testing the formulation developed in this study, but direct CCN measurements are still needed to confirm how it affects droplet activation.

Cellulose nanocrystals (CNCs) are plant-derived, rod-shaped particles with modifiable surface chemistry [19, 20]. Their surface hydroxyl groups allow them to interact with water, making them promising materials for cloud condensation nuclei (CCN) research. However, CCN activity can vary with surface chemistry, particle structure, and the size and shape of the CNC clusters produced during aerosolization [21, 22]. Recent studies have found moderate water uptake and cloud-droplet activation for unmodified cellulose aerosols [23, 24]. These findings suggest that modifying CNCs may improve their performance. They also show that the aerosol leaving the delivery system, rather than only the suspension stored in the container, determines the material’s practical behavior.

This study tested two modifications intended to improve CNC aerosol performance. The first was Quillaja saponin, a plant-derived surfactant that collects at air–water interfaces and can form stable surface layers [25, 26]. Saponin may influence droplet formation, stability, and activation by changing interfacial properties. It may also affect the amount and size distribution of aerosol produced by an ultrasonic nebulizer [27]. The second modification routed the aerosol through polytetrafluoroethylene (PTFE) tubing. Contact with PTFE may produce electrostatic charge, which can influence aerosol behavior, particle capture, and droplet collisions [28, 29]. The tubing may also alter the delivered aerosol through particle loss or size-dependent transport [30, 31]. The experiment therefore evaluates the overall effect of the PTFE delivery pathway, while later work can separately measure its electrostatic and transport effects.

Figure 1 summarizes the proposed activation mech-

anism behind the combined formulation. Saponin is expected to modify the droplet interface, while PTFE routing may provide an additional benefit through electrostatic charging or changes in the delivered aerosol. Together, these effects may allow the CNC-based formulation to reach activation at a lower critical supersaturation. The curves are conceptual and show the study hypothesis rather than measured Köhler curves.

Köhler Theory: Droplet Activation Behavior

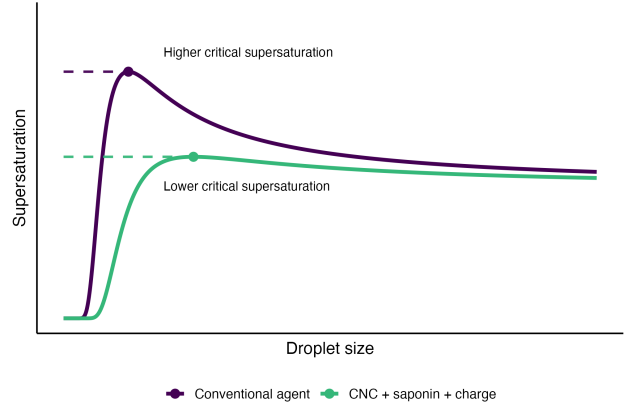


Figure 1: Conceptual Köhler curves comparing a conventional seeding agent with the proposed CNC–saponin formulation using electrostatic charging. The proposed formulation is expected to reach its critical point at a lower supersaturation. The curves illustrate the study hypothesis and are not derived from the chamber measurements.

A useful material can still fail if it is released into the wrong cloud. Temperature, cloud water, upward motion, and remaining cloud lifetime all affect whether droplets can grow. Choosing a deployment window is therefore also a forecasting problem. Recent studies have used models and rapid observations to rank possible cloud conditions [32, 33]. A model trained on natural rainfall can learn when rain is likely to follow a weather pattern, but it cannot directly calculate how much additional rain cloud seeding would produce.

This study combines two complementary approaches. First, six formulation and delivery conditions were compared in the same cloud chamber. Second, an Extreme Gradient Boosting (XGBoost) classifier used weather fields from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) and precipitation labels from the Global Precipitation Measurement (GPM) mission’s Integrated Multi-satellitE Retrievals for GPM (IMERG) Final Run Version 07B product to rank six-hour deployment windows in a later year. The cloud chamber experiment compares how the formulations affect transmitted light and cloud persistence under controlled conditions, while the model ranks atmospheric conditions according to the likelihood of subsequent natural precipitation. Together, these approaches help iden-

tify both a promising formulation and favorable weather periods for further testing.

Two research questions define the study. **RQ1** asks: does adding saponin and a PTFE delivery pathway change the onset, minimum transmitted illuminance, and persistence of chamber cloudiness compared with unmodified CNCs and the tested controls? **RQ2** asks: can an XGBoost model trained on historical weather conditions rank six-hour precipitation-supportive windows in a future year? RQ1 selects a formulation for direct aerosol and CCN testing. RQ2 tests whether the weather data provide useful predictions across time.

The remainder of the paper is structured as follows. Section II reviews earlier cloud-seeding research, warm-cloud particle design, CNC and saponin behavior, PTFE routing, optical measurement, and weather-based targeting. Section III describes the chamber experiment, statistical analysis, atmospheric data, and machine-learning workflow. Section IV reports the results. Section V discusses their meaning and the next tests needed before field deployment. Section VI concludes the paper.

2 Literature Review

2.1 Evaluating Evidence for Cloud-Seeding Effects

Cloud seeding includes two main approaches. Glaciogenic seeding adds ice-forming material to cold clouds that contain supercooled water. Hygroscopic seeding adds soluble, water-attracting particles to influence liquid droplets. Evidence for one approach does not automatically support the other. Reviews therefore look for a chain of evidence: the cloud must be suitable, the material must reach the target region, the intended particle process must occur, and that change must last long enough to affect precipitation [1, 2, 4, 34].

Recent winter mountain-cloud experiments show why this chain matters. The SNOWIE project combined known aircraft release paths with radar and in-cloud measurements [5]. French et al. followed the formation and growth of seeded ice, while Friedrich et al. used radar and ground gauges to measure snowfall in selected cases [6, 7]. Other case studies have also combined aircraft, radar, satellite, or drop-size observations [35, 36]. Their strength comes from measuring several steps between release and precipitation instead of relying on rainfall alone.

Warm-cloud results are harder to separate from natural weather changes. Silverman reviewed four randomized hygroscopic-seeding experiments and found that positive rainfall estimates had not yet met both the statistical and physical standards needed to prove the proposed mechanism [37]. Later reviews continue to call for random assignment, objective cloud selection, analysis that does not depend on whether a case was seeded, and in-cloud

measurements [2, 3, 38]. Two clouds that look similar can still differ in liquid water, lifetime, upward motion, mixing with dry air, and background aerosol. A chamber removes much of this weather variability, but it measures only an early step. Its purpose here is to identify which formulations should advance to direct CCN testing.

2.2 Warm-Cloud Seeding Depends on Particle Size, Amount, and Cloud Conditions

Hygroscopic seeding has followed two related strategies: releasing many smaller particles to change the initial droplet-size distribution, or releasing fewer very large particles that can become the first drizzle drops. Early calculations and a South African field program supported the first approach [39, 40]. Later models showed that more particles are not always better. Very large particles may form useful drops but settle quickly, while too many small particles can divide the available water among too many droplets. The most effective size also changes with released mass, updraft speed, and the cloud’s natural population of large particles [41, 42].

Studies of sea salt and giant CCN show this dependence more clearly. In models, the effect on precipitation can grow or disappear when the background CCN concentration changes. Large salt particles can also keep the droplet-size distribution wider than simple small-particle models predict [43–45]. Satellite observations have linked coarse sea aerosol with larger cloud droplets after accounting for meteorological conditions, although this relationship does not prove a seeding effect [46]. Field studies found more large drops or drizzle after salt release in some cases, but the result still depended on the initial cloud conditions [11, 47]. Overall, the literature indicates that effective particle sizes and concentrations depend on the cloud and delivery conditions. Particles can be too small and numerous, while very large particles may settle before reaching much of the cloud. A new material should therefore be described by the size and number of particles that actually leave the device, not only by the liquid concentration in the reservoir.

Delivery can weaken a promising material. Strong dilution may leave too few particles to affect the cloud, and complex terrain can make it difficult to determine where the material traveled [10, 48]. Models show that particle size, release height, injection method, and cloud structure can change both the magnitude and direction of the precipitation response [49–51]. Higher-resolution simulations also show that hygroscopicity, particle number, and turbulence work together [52]. Particle size, count, and released amount must therefore be measured together.

CCN measurements lead to the same conclusion at the activation scale. Dry-particle size often explains more variation in activation than detailed chemistry, although soluble material, internal mixing, and surface

properties still matter [8, 9, 53, 54]. A CCN counter exposes particles to a known supersaturation and measures how many activate [55]. A recent Korean cloud-chamber study combined controlled saturation with particle and droplet sizing for NaCl and CaCl₂ [56]. The two salts produced different formation rates and droplet sizes. This work supports NaCl as a useful comparison material in the present study while demonstrating how direct CCN measurements can extend the chamber-based optical measurements reported here.

2.3 CNC and Saponin Properties Affect Droplet Activation

CNC properties change with their source and processing. Samples can differ in particle dimensions, surface sulfate or carboxyl groups, counterions, crystallinity, and stability in water [57, 58]. Their hydroxyl groups interact with water, but vapor uptake also depends on surface treatment, structure, porosity, and humidity history [21, 59, 60]. Bulk water absorption therefore does not prove that every dry CNC aerosol will activate at cloud-level supersaturation. Reproducible studies should report the CNC source, production chemistry, counterion, solids content, mixing method, and storage history.

The CNC in the reservoir may also differ from the particle in the chamber. Drying and changes in salt concentration can form clusters whose shape and ability to redisperse depend on how the suspension was prepared [61, 62]. Warnes et al. directly showed that suspension stability and surface groups affect the size and shape of CNC particles formed during aerosolization [22]. Direct cloud evidence is still limited. In one CCN study, cellulose nanoparticles activated less easily than several nanoplastics, and a CNC-focused thesis found only moderate hygroscopicity for unmodified CNCs [23, 24]. These findings do not determine the performance of the modified formulation tested here, but they show why CNC alone must be included as a comparison.

A modified CNC formulation could behave differently by changing dry-particle size, soluble content, or droplet-surface properties. Larger clusters may scatter more light but produce fewer particles per unit mass, while soluble material or surface-active additives could alter activation and droplet coalescence. The chamber cannot separate these mechanisms, but it can identify formulations for direct particle-sizing and CCN measurements.

Saponin introduces an additional interfacial effect. Atmospheric organic material can lower surface tension and sometimes change activation in ways that a uniform bulk-solution model does not predict [63–65]. Surfactant molecules move from the droplet interior to its surface, changing both the amount of dissolved material within the droplet and its surface tension [15, 16, 66, 67]. Surface tension can also change with droplet size and the time allowed for adsorption [68, 69].

Experiments have produced mixed results. Organic

surface films can lower surface tension and sometimes produce larger-than-expected droplets at activation [18, 70, 71]. Phase separation and the small volume of aerosol droplets can make surface effects especially important [72, 73]. In other studies, fatty-acid coatings greatly lowered surface tension but changed critical supersaturation only when the organic fraction was high; a solid film sometimes slowed water uptake [17]. Mixed aerosols have also differed from predictions based on bulk surface tension [74, 75]. Therefore, lower surface tension in the prepared solution is a reason to test activation, not proof that activation improves. Dynamic surface-tension measurements and a controlled CCN activation curve would provide more direct evidence.

Research on Quillaja helps define this question. Saponins are a broad group of molecules, and commercial extracts can have different compositions [76, 77]. Quillaja saponin collects at the air–water interface, but pH, salt, temperature, and product source affect its micelles, adsorption, and surface tension [25, 78–80]. Its surface layers can be highly elastic [26, 81, 82]. This property may stabilize droplets rather than promote their coalescence, so good foam stability does not necessarily indicate faster rain formation. No published study identified in the literature directly measured the activation of Quillaja-modified CNC aerosols across controlled supersaturations. This gap motivates testing the combined formulation while leaving its activation mechanism open for direct investigation.

One concentration comparison is especially useful. Mitra and Dungan reported a Quillaja critical micelle concentration of approximately 0.5–0.8 g L^{−1} at 298 K, although pH, salt, temperature, and product source affected the value [79]. The saponin concentration prepared in this study, 0.5 mg mL^{−1}, is equivalent to 0.5 g L^{−1} and therefore lies near the lower end of that range. However, the concentration and composition of the aerosol leaving the nebulizer may differ from those of the reservoir solution. This comparison does not establish that micelles formed in the tested product, but it suggests that small changes in concentration or formulation could affect its interfacial behavior.

2.4 Interpreting PTFE Routing and Optical Measurements

Electric charge may influence several stages of aerosol and droplet development. Atmospheric ions can charge aerosols, and charge can change how particles or droplets approach one another [28, 83]. However, collisions still depend strongly on droplet size and speed even without charge [84–86]. Calculations predict the largest electrical effects at specified charge or field strengths and for small droplet pairs [29]. A strong electrical claim therefore requires measurements of charge magnitude, charge sign, particle or droplet size, and the surrounding electric field. Charge should also be distinguished from Köhler activa-

tion: surface tension and water activity affect activation, whereas electrical attraction may influence particle capture and droplet collisions after aerosol generation or activation.

Liquid contact with PTFE can produce charge, but its magnitude and sign depend on pH, salt concentration, dissolved carbon dioxide, humidity, prior use, and surface condition [30, 87]. Other studies also show that both the liquid and polymer influence contact electrification [88, 89]. The nebulizer or even a pipette can charge droplets before they reach the tube [90, 91]. PTFE tubing may also deposit particles selectively on its walls, changing the size distribution and amount of aerosol reaching the chamber [31]. A direct-versus-PTFE comparison therefore tests the entire delivery path, not charge alone. Future charge measurements should be paired with measurements of airflow, aerosol mass, and particle size.

The light sensor also measures several effects at once. Light loss depends on particle number, size, shape, refractive index, laser wavelength, and sensor geometry [92, 93]. When the chamber becomes very cloudy, repeated scattering makes it even harder to convert transmitted light directly into particle concentration [94–96]. Low-cost sensor studies also show that geometry and the assumed particle-size distribution can change the response [97, 98]. Keeping the setup fixed supports relative comparisons between formulations, but uncalibrated illuminance should not be interpreted as a direct measurement of particle concentration or liquid-water content.

Changes in nebulizer output provide an important alternative explanation for the saponin result. Ultrasonic droplet size depends on the device and liquid properties such as viscosity and surface tension [99–101]. Particle size in the suspension and nebulizer type also affect how much material becomes airborne [102, 103]. Most importantly, surface-active compounds have increased ultrasonic-nebulizer output in a concentration-dependent manner [27]. The greater reduction in transmitted illuminance after adding saponin could therefore result from increased aerosol output or a different particle-size distribution. Measuring reservoir mass loss and the size and number of particles entering the chamber would help determine whether saponin primarily changed the amount of aerosol produced or the properties of that aerosol.

2.5 Predicting Favorable Weather Windows from ERA5 and IMERG

Weather-targeting research uses cloud physics and forecasts to identify where and when seeding material might be released. Models have used cloud water, temperature, vertical motion, and particle transport to identify possible release regions [48, 51, 104]. Roy et al. grouped weather and aerosol states according to their potential suitability for seeding, while Kotsuki et al. used rapid satellite and radar updates to guide an aircraft toward a short-lived cloud [32, 33]. These studies show that atmospheric data

can narrow short deployment windows, but they do not provide a general label for additional rainfall caused by seeding.

The model in this study combines predictors derived from ERA5 with precipitation labels derived from GPM IMERG. ERA5 combines observations with a numerical weather model to produce spatially and temporally continuous hourly estimates, but its grid cannot resolve every individual cloud or updraft [105, 106]. IMERG combines satellite microwave and infrared observations and, in the Final product, rain-gauge information [107, 108]. Its error varies with region, season, terrain, precipitation type, and time scale [109]. Studies using IMERG V06 have shown that interpolation and daily timing can affect precipitation estimates at short time scales [110, 111]. However, those findings do not directly validate the V07B labels used here. Version 07 changed several parts of the IMERG algorithm and improved upon V06 in at least one regional comparison, although geographically varying errors remained [108, 112].

A natural-precipitation target has a clear limitation. A window labeled positive using IMERG may contain a storm that would have produced precipitation without intervention, while a negatively labeled window may still contain a cloud capable of responding to seeding. Because the training data do not compare seeded and otherwise similar unseeded clouds, the model predicts subsequent natural precipitation rather than additional rainfall attributable to seeding. Its output should therefore be interpreted as a ranking of atmospheric windows for further evaluation, not as a prediction of seeding effectiveness.

XGBoost can provide a useful ranking because it handles large tabular datasets and nonlinear relationships effectively [113]. Other precipitation studies have also improved prediction by incorporating radar, numerical weather-model, or spatiotemporal data [114–116]. The main validation concern is that nearby grid cells, adjacent hours, and observations from the same storm are not independent. A time-based split can test performance on a future period, but it may still overstate the model’s ability to transfer to unfamiliar locations [117, 118]. Additional validation using held-out geographic regions and models trained without latitude, longitude, or month would help determine how strongly performance depends on location and season.

The receiver operating characteristic area under the curve measures how well the model ranks positive cases across classification thresholds, while precision–recall curves are especially informative when precipitation events are uncommon [119–121]. Reliability plots and the Brier score could additionally test whether predicted probabilities correspond to observed precipitation frequencies [122]. Feature-attribution methods can help describe how variables contribute to model predictions, but they do not establish that those variables cause precipitation [123].

2.6 Research Gap

Earlier studies address the main parts of this problem separately. Warm-cloud research shows that particle size, released amount, background aerosol, cloud conditions, and release location can all influence seeding outcomes. CNC research shows that water uptake and aerosol properties can be modified, but it provides limited evidence for strong cloud-level activation of unmodified CNCs. Surfactant research suggests that interfacial effects may alter activation while demonstrating that bulk surface tension alone cannot predict aerosol behavior. Electrical studies support a possible influence of charge on particle capture and droplet collisions, but they also show that PTFE routing may change the amount and size distribution of aerosol reaching the chamber. Optical and nebulizer studies further demonstrate that a formulation can affect both aerosol production and the resulting light-sensor response. Weather models can rank atmospheric windows associated with subsequent precipitation, but labels based on natural rainfall cannot measure the additional precipitation caused by seeding.

No published study identified in this review combined aerosolized CNC with Quillaja saponin, a separate PTFE-routing condition, controlled optical chamber comparisons, and a weather model for prioritizing later test windows. The present study brings these components together in a single workflow. The chamber experiment compares formulations and delivery conditions to identify candidates for direct particle-sizing and CCN measurements, while the classifier ranks atmospheric windows for further meteorological evaluation. Together, these complementary stages can direct later experiments toward the most promising material formulations and atmospheric conditions without treating either the optical response or predicted natural precipitation as direct evidence of cloud-seeding effectiveness.

3 Materials and Methods

3.1 Study Design

The study consisted of two separate analyses. For RQ1, six formulation–delivery conditions were tested in the same chamber using a standardized aerosol pulse and optical measurement procedure. The conditions were distilled water, sodium chloride, unmodified CNCs, CNCs with saponin, CNCs routed through PTFE tubing, and CNCs with saponin routed through PTFE tubing. Five trials were conducted for each condition. The principal comparison was between unmodified CNCs and CNCs with both saponin and PTFE routing. Distilled water and sodium chloride served as reference conditions, while the CNC–saponin and CNC–PTFE conditions helped determine whether observed differences were associated with the formulation, the delivery pathway, or their combination.

For RQ2, a classifier was trained using historical atmospheric conditions and evaluated on a later year that was excluded from model fitting and selection. The response variable indicated whether natural precipitation occurred after each atmospheric observation. Chamber outcomes and model predictions were analyzed separately rather than being used as inputs to one another. They contribute to the proposed workflow as sequential stages: the chamber analysis identifies formulations for more direct particle-sizing and CCN testing, while the classifier ranks meteorological windows for further evaluation.

3.2 Physical Basis and Experimental Expectations

The formulation hypotheses follow the Köhler relationships introduced in (1) and (2). Those equations identify dry-particle diameter, hygroscopicity, water activity, and finite-droplet surface tension as quantities that can affect activation. They were not fitted to the chamber results. Particle diameter, κ , finite-droplet surface tension, and critical supersaturation were not measured, so no theoretical Köhler curve was calculated for the tested CNCs.

The saponin-containing conditions were expected to change the optical response if saponin’s interfacial behavior altered droplet formation or persistence. The PTFE-routed conditions were expected to change the response only if passage through the tubing altered the emitted aerosol. Because charge was not measured, the latter expectation concerns the delivery pathway as a whole rather than electrostatic charge alone. For the computational analysis, the working expectation was that a model trained on pre-event meteorology would rank the occurrence of natural precipitation within the following six hours better than chance in the future-year holdout.

3.3 Cloud-Chamber Apparatus and Formulations

A sealed acrylic chamber was designed and assembled for repeated optical-scattering measurements (Fig. 2). An ultrasonic nebulizer generated the aerosol. A cooled upper surface promoted condensation, while a DHT22 sensor recorded temperature and relative humidity. A 650 nm laser traversed the chamber toward a BH1750 digital light sensor. As suspended droplets scattered the beam, the sensor reported a decrease in transmitted illuminance. An Arduino Uno coordinated sensing and logging at 1 Hz.

All working suspensions were prepared in distilled water. CNC and NaCl concentrations were 1.0 mg mL^{-1} , and saponin was used at 0.5 mg mL^{-1} . Distilled water served as a negative control and sodium chloride as a conventional hygroscopic comparison. The six conditions

Table 1: Cloud-chamber conditions used to answer RQ1.

Condition	Aqueous composition	Delivery path	Experimental role
Distilled water	Distilled water	Direct	Negative control
NaCl	1.0 mg mL ⁻¹ NaCl	Direct	Hygroscopic comparison
CNC only	1.0 mg mL ⁻¹ CNC	Direct	Base formulation
CNC + PTFE path	1.0 mg mL ⁻¹ CNC	PTFE	Pathway condition
CNC + saponin	1.0 mg mL ⁻¹ CNC + 0.5 mg mL ⁻¹ saponin	Direct	Surfactant condition
CNC + saponin + PTFE path	1.0 mg mL ⁻¹ CNC + 0.5 mg mL ⁻¹ saponin	PTFE	Combined condition

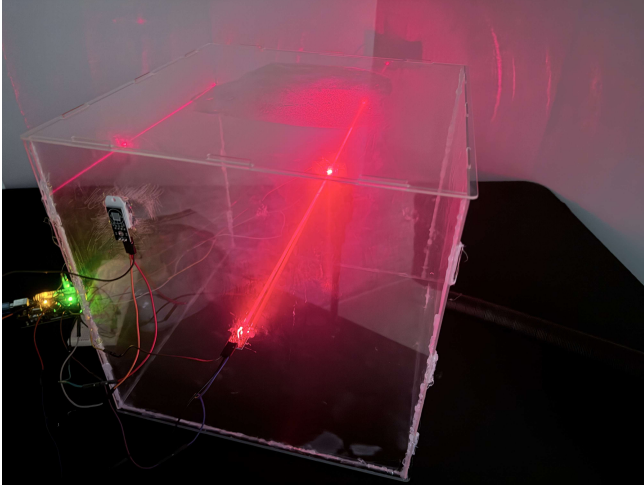


Figure 2: Custom acrylic cloud chamber during an optical-scattering trial. The visible red beam marks the laser path through the aerosol volume. The apparatus supports relative comparisons among formulations but is not a scale model of a natural convective cloud.

are shown in Table 1. Direct and PTFE-path conditions entered through the same chamber inlet.

3.4 Trial Protocol and Optical Response Measures

Before each trial, the selected suspension was prepared, chamber humidity was allowed to stabilize, and the laser baseline was checked. Aerosol delivery began at $t = 0$ and continued for 60 s. In PTFE-path trials, the aerosol passed through the tubing immediately before entering the chamber; all other trials used the direct inlet. Illuminance, temperature, and relative humidity were sampled at 1 Hz. After 60 s, the nebulizer was stopped, and recording continued while the optical signal recovered. The chamber was then cleaned and reset before the next trial. Five trials were completed for each condition.

Let $I(t)$ denote the sensor-reported illuminance and I_0 the mean illuminance during the pre-delivery baseline

period. Normalized transmission was calculated as

$$T(t) = \frac{I(t)}{I_0}. \quad (3)$$

Three response measures were extracted from each trace during post-processing. Onset time was defined as the first time after aerosol delivery began that illuminance fell below 95% of the pre-delivery baseline and remained below that threshold for at least five consecutive samples, corresponding to 5 s at the 1-Hz sampling rate. Minimum illuminance was the lowest observed value of $I(t)$ and represented the greatest measured attenuation. Recovery was identified as the first time after the minimum that illuminance returned to at least 95% of the pre-delivery baseline and remained at or above that threshold for at least 10 consecutive samples, corresponding to 10 s. Persistence was calculated as the elapsed time from onset to the beginning of this sustained recovery period. Requiring consecutive samples prevented isolated sensor spikes from being classified as onset or recovery. The same post-processing code and thresholds were applied to every trial and condition.

Lux is a photometric sensor output rather than a direct measurement of droplet number concentration or liquid-water content. Minimum illuminance is therefore reported as an optical proxy. Ratios between minimum-illuminance values cannot be interpreted as equivalent ratios of physical cloud density without calibration for droplet size, number concentration, and extinction efficiency.

3.5 Statistical Analysis

Means and standard deviations were calculated for each condition and response measure. The primary comparison contrasted CNC only with CNC + saponin + PTFE path for onset time, minimum illuminance, and persistence. Welch two-sample t tests were used because equal population variances were not assumed. Each condition contained five trials. Two-sided p values and 95% confidence intervals are reported for mean differences, calculated as CNC + saponin + PTFE path minus CNC only.

Table 2: Atmospheric data sources and processing used to answer RQ2.

Product	Period used	Native sampling	Processing and role
ERA5 hourly single levels	2001–2023	Hourly atmospheric fields	Aligned to a 1.0-degree grid; supplied thermodynamic, cloud, wind, and pressure predictors
GPM IMERG Final V07B	2001–2023	0.1-degree, half-hourly precipitation	Aggregated spatially and temporally; supplied the six-hour future-precipitation target

Three comparisons were conducted. The reported p values are unadjusted, and the corresponding Bonferroni-adjusted significance threshold is $0.05/3 = 0.0167$. These tests compare the two complete conditions and do not estimate the separate effects of saponin, PTFE routing, or their interaction. The small sample size limits the precision of the estimated differences.

3.6 Atmospheric Data, Predictors, and Target

The computational pipeline joined ERA5 hourly single-level reanalysis data with the GPM IMERG Final half-hourly precipitation product [106–108]. IMERG V07B precipitation was spatially aggregated to the 1.0-degree analysis grid and temporally aggregated to hourly intervals. The resulting table contained approximately 41 million hourly grid-cell observations spanning 2001–2023. Data sources and processing roles are summarized in Table 2.

For each time-location record, the binary target indicated whether accumulated precipitation during the following six hours exceeded 0.1 mm. This target provided a reproducible label for the subsequent occurrence of natural precipitation. It was not derived from cloud-seeding operations and therefore cannot identify precipitation caused by seeding. The temporal split used 2001–2018 for training, 2019–2021 for validation, and 2023 as the future-year holdout test set. Records from 2022 were excluded from these partitions.

The 16 predictors are listed in Table 3. Raw ERA5 fields were supplemented with derived moisture, air-density, and wind terms. Latitude, longitude, and sine and cosine encodings of month supplied spatial and seasonal context.

3.7 Classifier and Evaluation

Tree-based classifiers were compared during model development, and XGBoost was selected as the final model for the precipitation-ranking task [113]. The final configuration used 10,000 trees, a learning rate of 0.005, and a maximum tree depth of 10. Model performance was evaluated on the 2023 holdout set using receiver operating characteristic area under the curve (ROC AUC), which measures how consistently the model ranks observations followed by precipitation above those not followed by precipitation across possible thresholds. Feature importance

Table 3: Predictors supplied to the XGBoost classifier for each hourly 1.0-degree grid cell.

Group	Predictors
Thermodynamic state	2 m air temperature; 2 m dewpoint temperature; surface pressure; derived air density
Moisture and cloud	water-vapor mixing ratio; vapor-pressure deficit; dewpoint depression; total cloud cover
Wind field	10 m zonal wind; 10 m meridional wind; wind-speed magnitude; moisture-flux proxy
Spatial and seasonal context	latitude; longitude; sine of month; cosine of month

was summarized using model gain. Gain measures the improvement in the model objective attributed to splits involving each predictor; it does not show the direction of an association or establish causality.

The temporal holdout prevented observations from the test year from being used during model training, but it did not test geographic transfer. Because latitude and longitude were included as predictors, the model could learn regional climatological patterns in addition to relationships with the atmospheric variables. This design supports ranking within represented locations, but spatially blocked evaluation would be necessary before claiming that the model transfers to new regions.

4 Results

4.1 Research Question 1: Modified Formulations Changed Chamber Timing and Attenuation

Every condition produced a decrease and subsequent recovery in transmitted illuminance after aerosol delivery (Fig. 4). The representative CNC-only trace declined later and remained well above the lowest values reached by the saponin-containing conditions. The CNC + saponin and combined traces both approached the lower end of the plotted sensor range and remained near those values before recovery. The six panels have different durations because recording continued until each trial met the recovery criterion.

The representative traces also show a measurement constraint. Several conditions drove the signal close to zero, compressing differences among the strongest attenu-

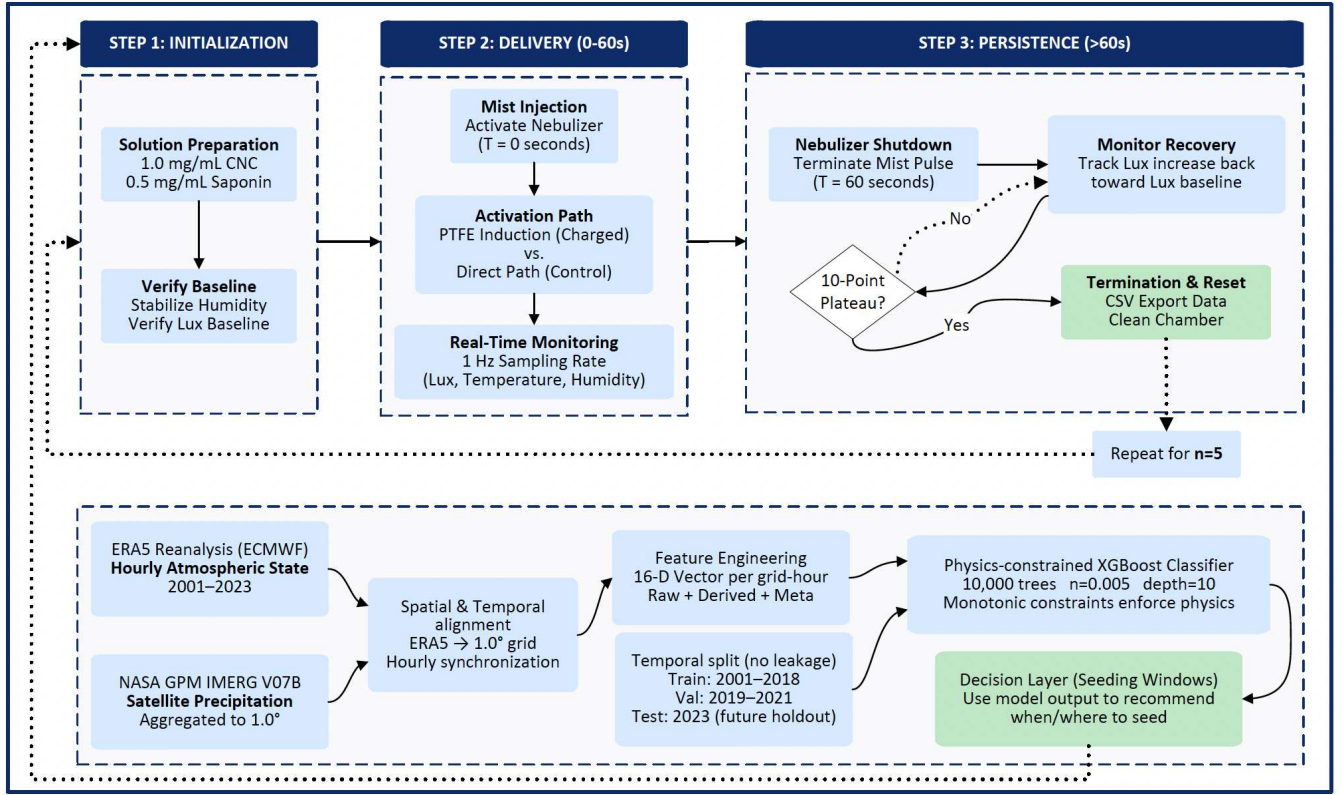


Figure 3: Experimental and computational workflow. The upper sequence shows preparation, 60-s aerosol delivery, optical monitoring, recovery, and repetition. The lower sequence shows ERA5 and GPM IMERG V07B alignment, feature construction, temporal partitioning, XGBoost fitting, and scoring. Labels in the source graphic that refer to “charged” particles or “physics-constrained” learning describe the intended design; particle charge was not measured, and the monotonic constraints do not constitute a complete physical model.

ation responses. Minimum illuminance remains useful for separating the CNC-only and CNC + PTFE-path conditions from the saponin-containing conditions, but values near the lower bound should not be treated as proportional measurements of droplet number or liquid-water content.

The combined CNC + saponin + PTFE-path condition had the fastest mean onset at 10.6 s (Fig. 5). CNC + saponin followed at 12.4 s, sodium chloride at 13.0 s, distilled water at 15.8 s, CNC + PTFE path at 17.0 s, and CNC only at 27.0 s. Relative to CNC only, onset occurred 16.4 s earlier with the combined condition, corresponding to a 60.7% reduction. The CNC + saponin condition was 14.6 s earlier than CNC only, a 54.1% reduction, while the CNC + PTFE-path condition was 10.0 s earlier, a 37.0% reduction.

The combined condition was 1.8 s faster than CNC + saponin, a further 14.5% reduction relative to the CNC + saponin mean. It was also 2.4 s faster than sodium chloride and 5.2 s faster than distilled water. These pairwise differences were not included in the planned inferential comparison and are therefore reported descriptively. Across the six condition means, CNC only had the latest onset, while both distilled water and sodium

chloride reached the onset criterion earlier than CNC only.

Minimum illuminance showed a clear descriptive separation among the four CNC-based formulations (Fig. 6). The combined CNC + saponin + PTFE-path and CNC + saponin conditions reached mean minimum illuminances of 248 and 326 lux, respectively. CNC + PTFE path reached 2079 lux, while CNC only reached 3818 lux. Relative to CNC only, the minimum signal was 91.5% lower for CNC + saponin, 45.5% lower for CNC + PTFE path, and 93.5% lower for the combined condition. Adding the PTFE pathway to the CNC + saponin formulation lowered the mean by a further 78 lux, although no planned test directly compared those two modified conditions.

Mean persistence increased from 90.8 s for CNC only to 168.0 s for the combined condition, an absolute increase of 77.2 s and a relative increase of 85.0%. The combined mean was also 35.0 s, or 26.3%, longer than the 133.0 s mean for distilled water. Together, these comparisons show that the combined formulation produced both an earlier optical response and longer-lasting attenuation than CNC alone.

The planned Welch comparisons between CNC only and the combined condition are reported in Table 4.

Laser Intensity Time-Series (One Representative Trial per Condition)

Each panel shows cloud formation and recovery behavior for a representative trial.

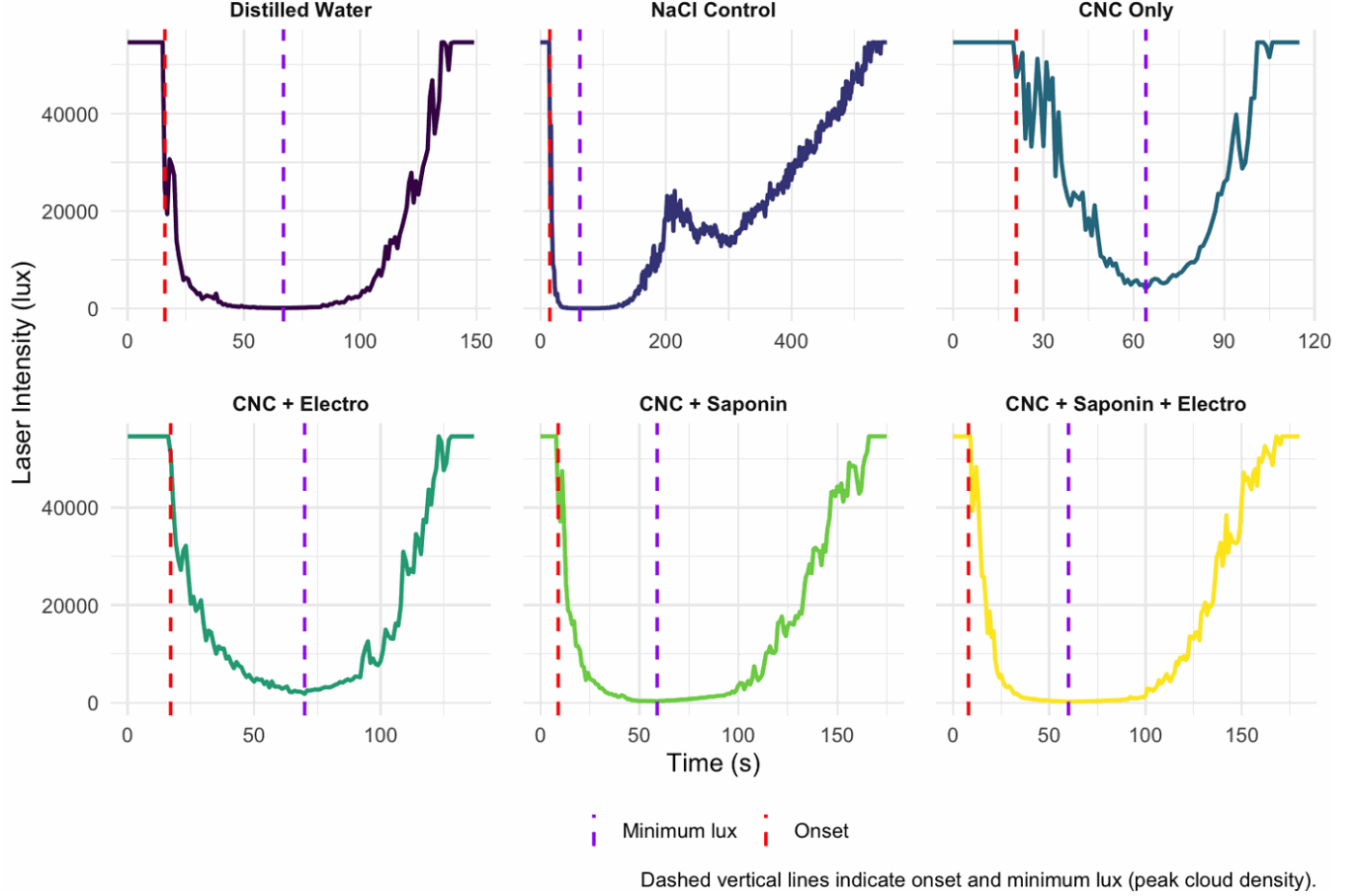


Figure 4: One representative illuminance trace per condition. Red dashed lines mark onset and purple dashed lines mark minimum illuminance. The panels show the shape of a single trial and are not substitutes for the five-trial summaries. “Electro” in the source graphic denotes the PTFE-path condition.

Table 4: Planned Welch comparisons between CNC only and the combined condition.

Measure	CNC only, mean $\pm$ SD	Combined, mean $\pm$ SD	Mean difference (95% CI)	p
Onset (s)	27.00 $\pm$ 10.10	10.60 $\pm$ 1.52	16.4 earlier (3.9, 28.9)	0.021
Minimum illuminance (lux)	3817.67 $\pm$ 1655.21	248.33 $\pm$ 202.76	3569 lower (1522, 5616)	0.008
Persistence (s)	90.80 $\pm$ 6.38	168.00 $\pm$ 8.22	77.2 longer (66.4, 88.0)	< 0.001

Note. $n = 5$ per condition. Differences are expressed in the direction favoring the combined condition. Reported p values are two-sided and unadjusted.

Mean onset was 16.4 s earlier for the combined condition (95% CI: 3.9 to 28.9 s; $p = 0.021$), minimum illuminance was 3569 lux lower (95% CI: 1522 to 5616 lux; $p = 0.008$), and persistence was 77.2 s longer (95% CI: 66.4 to 88.0 s; $p < 0.001$). All three unadjusted p values were below 0.05. Using the Bonferroni reference threshold of 0.0167, the attenuation and persistence comparisons remained below the threshold, whereas the onset comparison did not.

4.2 Research Question 2: Future-Year Ranking Was Informative but Strongly Climatological

The XGBoost classifier achieved a ROC AUC of 0.802 on the 2023 holdout set (Fig. 7). A randomly selected precipitation-positive observation received a higher score than a randomly selected negative observation 80.2% of the time. The ROC curve remained above the random-ranking diagonal, indicating that the model preserved useful ordering across classification thresholds.

Cloud Activation Onset Time by Seeding Condition

Onset defined as first sustained drop below baseline after mist activation (LOWER IS BETTER; error bars represent $\pm$ SEM)

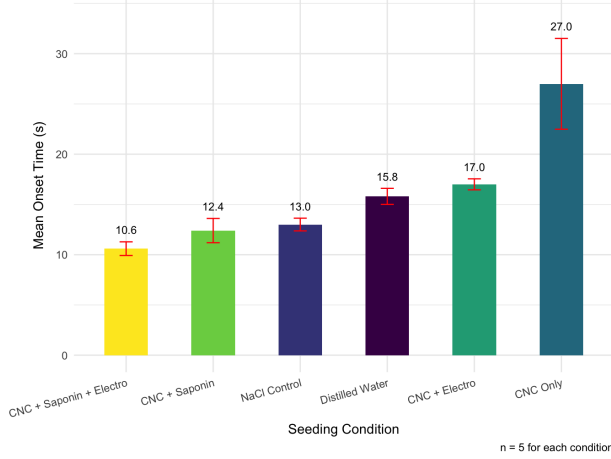


Figure 5: Mean onset time across all six conditions. Lower values indicate earlier optical response. Error bars show $\pm$ SEM; $n = 5$ trials per condition. “Electro” in the source graphic denotes the PTFE-path condition.

Peak Cloud Density Within CNC Formulations

Cloud density quantified by minimum measured laser intensity (LOWER IS BETTER; error bars represent $\pm$ SEM)

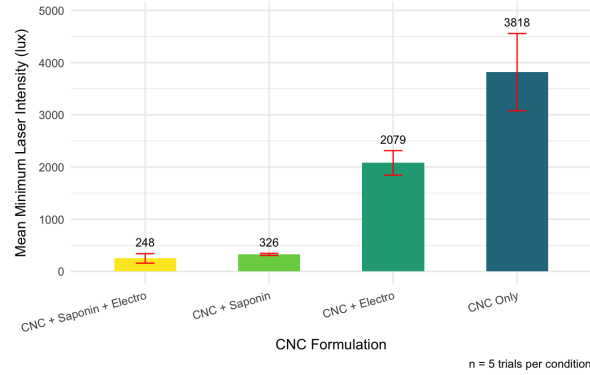


Figure 6: Mean minimum illuminance for the four CNC-based formulations. Lower values indicate stronger measured attenuation rather than directly measured cloud density. Error bars show $\pm$ SEM; $n = 5$ trials per condition. “Electro” in the source graphic denotes the PTFE-path condition.

At the selected operating threshold, sensitivity was 83.9%, meaning that the model identified 83.9% of the precipitation-positive observations in the 2023 holdout set. This value represents recall among positive cases rather than overall classification accuracy.

Model gain was concentrated in location, season, and temperature (Fig. 8). Latitude was the largest contributor by a wide margin, with twice the plotted gain of 2-m temperature and more than three times that of longitude. Longitude and the two month encodings also appeared among the five highest-ranked predictors. Among the remaining physical variables, mixing ratio, air density, and dewpoint contributed more gain than pressure, wind,

Model Discrimination Performance (ROC Curve)

AUC = 0.802 (dashed line indicates random classification)

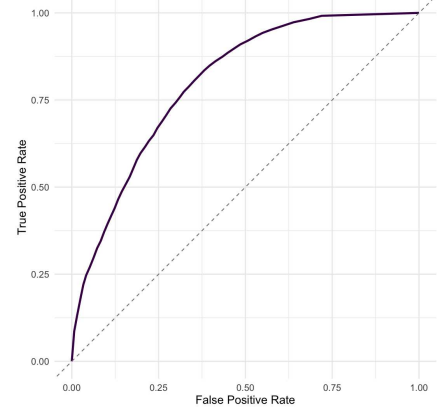


Figure 7: Receiver operating characteristic curve for the 2023 holdout set. The area under the curve was 0.802; the dashed diagonal denotes random ranking.

Relative Feature Importance (XGBoost Model)

Scores reflect each variable's contribution to reducing prediction error

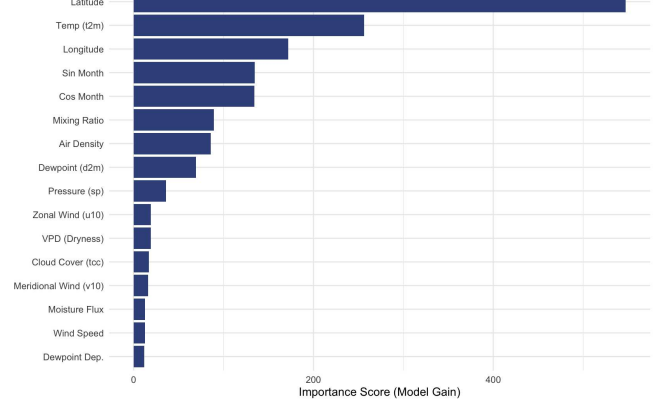


Figure 8: Gain-based XGBoost feature importance. Gain measures the improvement in the model objective attributed to splits involving each predictor. It does not show whether a predictor increased or decreased the score and should not be interpreted causally.

moisture flux, or total cloud cover.

This feature ordering indicates that the holdout AUC reflected both local atmospheric information and broad climatological structure. The evaluation does not isolate how effectively the model distinguishes favorable and unfavorable hours within the same location and season. Establishing that narrower capability would require spatially blocked and within-region evaluation.

5 Discussion

5.1 Saponin Produced the Clearest Improvement Among CNC Formulations

The ordering of the six conditions provides information beyond the combined-versus-CNC percentages alone. CNC only was the slowest condition to reach the optical onset point, at 27.0 s. Distilled water and NaCl reached it at 15.8 and 13.0 s, respectively. The combined condition was fastest at 10.6 s, while CNC + saponin followed closely at 12.4 s. Among the four CNC formulations, minimum illuminance showed a similar separation. CNC only reached 3818 lux, CNC + PTFE reached 2079 lux, and the two saponin-containing conditions reached 326 and 248 lux. These results identify the saponin-containing formulations as the clearest candidates for follow-up testing. They also agree with research showing moderate water uptake by unmodified cellulose aerosol and strong effects of suspension preparation on airborne CNC shape [22–24].

All three planned Welch comparisons favored the combined formulation. Compared with CNC only, it reached onset 16.4 s earlier, produced a minimum illuminance that was 3569 lux lower, and remained optically detectable 77.2 s longer. The attenuation and persistence comparisons remained below the Bonferroni reference threshold of 0.0167, whereas the onset comparison ($p = 0.021$) did not. Although each condition included five trials, the consistent improvements across onset, attenuation, and persistence provide strong evidence of the combined formulation’s potential and support further investigation through larger-scale validation.

The tested saponin concentration also creates a useful follow-up question. The 0.5 mg mL^{-1} formulation equals 0.5 g L^{-1} , near the lower end of the $0.5\text{--}0.8 \text{ g L}^{-1}$ critical micelle concentration reported for one Quillaja product at 298 K [79]. The exact value varies with product, pH, salt concentration, and temperature, so the published range cannot be applied directly to the present material. Nevertheless, it suggests that testing concentrations above and below the current value could reveal how saponin concentration and surface organization influence the optical response.

Several mechanisms could explain the saponin-associated improvement. Quillaja layers can lower surface tension and become highly elastic [25, 26]. At the same time, molecular transport to the surface, dilution, and film formation can reduce the activation benefit predicted from bulk surface-tension measurements [16, 17, 69]. Surface-active compounds can also increase aerosol output from an ultrasonic nebulizer [27]. Saponin may therefore have altered the emitted aerosol amount or size before any CCN activation occurred. Measuring reservoir mass loss and downstream particle-size distributions would help separate this delivery effect from an

activation effect.

Together, the three measures show that the combined condition outperformed CNC only, although further testing is needed to identify the processes responsible for these improvements. Follow-up experiments should independently measure aerosol output, particle-size distribution, and surface tension across a saponin concentration series. These measurements would clarify whether the stronger optical response arose primarily from increased aerosol delivery, altered droplet activation, or a combination of both processes.

5.2 PTFE Routing Produced a Smaller Secondary Improvement

PTFE routing produced a smaller improvement than saponin. CNC + PTFE reached onset 10.0 s earlier than CNC only and lowered mean minimum illuminance from 3818 to 2079 lux. After saponin was already present, adding the PTFE pathway changed onset by 1.8 s and minimum illuminance by 78 lux. However, the study did not include a planned comparison between the two saponin-containing conditions or a full factorial analysis. The results therefore associate PTFE routing with an additional change in optical response, but they do not establish that saponin and PTFE produced additive or synergistic effects.

Contact electrification is one possible explanation, although its direction and magnitude depend on the formulation. Charge generated when water passes through PTFE can change sign with liquid composition and surface condition, and its magnitude can decrease as salt concentration or humidity increases [30, 87]. The nebulizer itself may also generate charged aerosol [90]. In addition, PTFE tubing can cause particles to deposit on the tube wall or alter the particle-size distribution reaching the chamber [31]. The observed response could therefore reflect charging, particle loss, size selection, or a combination of these effects.

Charge should also be considered at the appropriate stage of cloud development. Köhler activation primarily depends on water activity, curvature, dry-particle size, and surface tension. Electrical forces are more likely to influence particle capture and droplet collisions when charge and electric-field strength are sufficiently high [28, 29, 124]. Follow-up experiments should measure aerosol charge and particle-size distribution immediately after each pathway. Comparing PTFE with tubing of similar length and geometry but a lower charging tendency would help separate effects caused by the PTFE material from those caused by airflow, particle loss, and travel through the tube.

5.3 Optical Attenuation Provided a Practical Comparison

Under the same laser path and sensor geometry, the saponin formulations attenuated substantially more light than CNC only, producing a strong and repeatable apparatus-level difference. Lux measurements alone cannot determine whether this difference resulted from particle concentration, particle size, refractive index, or aerosol distribution within the chamber. Multiple scattering and detector geometry also become more influential at high aerosol concentrations [92–94]. Because several traces approached the lower limit of the sensor range, minimum illuminance reliably distinguished high- and low-attenuation conditions but was less suitable for ranking responses near the sensor floor.

Despite these limitations, the chamber provided a low-cost and effective method for comparing formulations under consistent conditions. The large optical differences identify the formulations that should next be evaluated for emitted mass, particle size, humidified growth, and CCN activation. More advanced chamber experiments combine controlled saturation with aerosol and droplet measurements [56]. A calibrated Cloud Droplet Probe or similar instrument could provide direct particle-size and concentration measurements, although careful calibration would be required [125].

5.4 Location and Season Explain Part of the Model’s Skill

The 2023 holdout ROC AUC of 0.802 demonstrates useful ranking on future-year data. A randomly selected positive six-hour window received a higher score than a randomly selected negative window 80.2% of the time. The feature ranking adds an important detail. Latitude contributed the most gain, followed by temperature, longitude, and month. Cloud cover, wind, and moisture flux contributed less. The model therefore learned from both current atmospheric conditions and the locations and seasons in which precipitation is more common. This information can help rank windows at known locations, but the present evaluation does not isolate how much predictive skill remains after broad regional and seasonal patterns are removed.

Three additional tests could help identify the sources of this skill. A model using only latitude, longitude, and month would estimate the predictive value of regional and seasonal patterns. A model excluding those features would test how effectively the remaining atmospheric variables rank precipitation windows. Finally, a spatially blocked evaluation would measure performance in previously unseen regions. Studies of spatial data show that ordinary validation can overestimate transfer when nearby or environmentally similar samples appear in both the training and testing sets [117, 118].

The labels were derived from GPM IMERG Final V07B

[107, 108]. The two V06 studies explain why interpolation and daily timing matter at short timescales, but they do not directly validate the V07B data used here [110, 111]. Version 07 changed several parts of the algorithm and improved upon V06 in some regional evaluations, although errors continued to vary by location and precipitation type [112]. The reported AUC therefore measures agreement with the V07B labels used by the model, not perfect agreement with ground measurements in every region.

The reported 83.9% sensitivity should be interpreted alongside the selected decision threshold, event frequency, false-positive rate, precision, and precision–recall area. ROC AUC summarizes ranking across thresholds, whereas precision–recall results are especially informative when positive events are uncommon [119–121]. A reliability plot and Brier score would further show whether predicted probabilities match observed precipitation frequencies [122]. Feature gain and SHAP can explain how the model used individual predictors, but they cannot establish that any variable caused precipitation [123].

Most importantly, natural future precipitation is an indirect indicator of seeding suitability rather than a direct measure of seeding response. A high score may identify a system that would already produce precipitation, while a cloud capable of responding to seeding could receive a low score. A stronger future target could incorporate cloud phase, liquid-water content, vertical motion, cloud depth, background aerosol, and operational access limits. Estimating added rainfall will ultimately require carefully controlled comparisons between seeded and unseeded clouds.

5.5 The Combined Workflow Helps Focus Future Testing

The chamber and model address different parts of the same problem. The chamber identifies promising formulations for direct testing, while the model identifies weather windows for closer evaluation. Used together, these tools can reduce the time and cost spent testing weaker formulations or unsuitable atmospheric conditions. This integration is the main systems-level contribution of the study. The next stage is to connect both parts through direct particle measurements, stronger weather-model validation, and eventually controlled field experiments.

Environmental evaluation is also essential for field readiness. CNCs are cellulose-based and renewable, but inhalation responses can vary with particle length, shape, dose, and preparation [126–130]. EPA’s Quillaja assessment applies to specific registered pesticide uses and exposure controls, not to an aerosolized CNC–saponin formulation [131]. Research on potential silver-iodide impacts supports the development of alternative materials, but every new formulation still requires its own safety evaluation [132, 133]. The formulation is therefore best described as a promising biobased candidate. Its renewable components and strong chamber perfor-

mance support continued study, while dose, inhalation, and environmental-fate testing would establish conditions for responsible field use.

5.6 Next Steps

The next chamber experiment should include more trials and independently vary CNC concentration, saponin concentration, and tubing material in a randomized factorial design. Reservoir mass loss would quantify nebulizer output. An optical particle sizer and microscopy could measure downstream particle concentration, size distribution, and CNC aggregate shape. A Faraday cup or electrometer could measure aerosol charge after each matched pathway. Dynamic surface tension should also be measured across the tested saponin concentrations.

The central cloud-physics test is a size-resolved CCN activation curve under controlled supersaturations. This would measure activated fraction and allow effective κ to be estimated for CNC only, CNC + saponin, and each routed condition. Droplet imaging or calibrated optical extinction could then connect direct activation measurements with the current chamber traces. Together, these measurements would distinguish whether the strong saponin response resulted primarily from greater aerosol output, particle growth, CCN activation, or multiple effects.

For the model, the reason for excluding 2022 and all preprocessing steps should be fully documented. Performance should be compared with a location-and-month baseline and a model excluding coordinates. Spatial and temporal holdouts, calibration, precision–recall area, event frequency, and threshold-specific false-positive rates should be reported alongside ROC AUC. These evaluations would determine how much predictive value comes from current atmospheric conditions before the target is expanded to include cloud properties and potential treatment response.

6 Conclusion

This study developed a combined material-and-model approach to two challenges in cloud seeding: identifying a promising biobased formulation and selecting atmospheric conditions for its use. Across all six chamber conditions, CNC + saponin + PTFE routing produced the earliest mean optical onset. Among the four CNC-based formulations, it also produced the lowest mean transmitted illuminance, indicating the greatest measured attenuation. Compared with CNC only, onset time decreased by 61%, minimum transmitted illuminance decreased by 93.5%, and persistence increased by 85%. Because lower illuminance indicated greater obstruction of the laser by the chamber aerosol, these results show a substantially stronger and longer-lasting optical response. Most of the improvement was already present after saponin was

added, identifying the saponin-containing CNC formulation as the leading candidate for direct particle and cloud-condensation-nuclei (CCN) testing. The smaller change associated with PTFE routing motivates follow-up measurements of aerosol charge and particle transmission.

The XGBoost weather model achieved a ROC AUC of 0.802 on the independent 2023 holdout set and detected 83.9% of precipitation-positive observations at the selected threshold. Using ERA5 atmospheric variables, it successfully ranked six-hour weather windows associated with later precipitation in GPM IMERG Final V07B. However, location, temperature, and season were its strongest predictors. Future evaluation should therefore compare the model with a location-and-month baseline, remove coordinate and calendar features, and hold out complete geographic regions. Calibration, precision, and false-positive rates would further determine whether its scores can support practical deployment decisions.

The main contribution is an integrated workflow connecting formulation development with atmospheric-window selection. The chamber identifies which material combinations should advance to more detailed cloud-physics testing, while the model focuses evaluation on the most promising weather conditions. Together, these tools could reduce ineffective trials and unnecessary material release while directing resources toward stronger candidates. The next stage is to measure emitted aerosol, particle size, charge, dynamic surface tension, and CCN activation; repeat the chamber study using a larger randomized factorial design; and validate the weather model with stricter baselines and geographic holdouts. These steps provide a practical path from the current chamber and modeling results toward a carefully validated field system.

Data and Code Availability

All data, code, and supporting materials are available from the author upon reasonable request.

Author Contributions

Aahan Sachdeva independently designed and conducted the entire study, including constructing the chamber, preparing the formulations, performing the experiments, collecting and analyzing the data, developing and evaluating the machine-learning pipeline, preparing the figures, and writing the manuscript.

Competing Interests

The author declares no competing interests.

References

- [1] Roelof T. Bruintjes. A Review of Cloud Seeding Experiments to Enhance Precipitation and Some New Prospects. *Bulletin of the American Meteorological Society*, May 1999. doi: 10.1175/1520-0477(1999)080<0805:AROCSE>2.0.CO;2. URL https://journals.ametsoc.org/view/journals/bams/80/5/1520-0477_1999_080_0805_arocse_2_0_co_2.xml.
- [2] Andrea I. Flossmann, Michael Manton, Ali Abshaev, Roelof Bruintjes, Masataka Murakami, Thara Prabhakaran, and Zhanyu Yao. Review of Advances in Precipitation Enhancement Research. *Bulletin of the American Meteorological Society*, August 2019. doi: 10.1175/BAMS-D-18-0160.1. URL <https://journals.ametsoc.org/view/journals/bams/100/8/bams-d-18-0160.1.xml>.
- [3] Karen Howard. Cloud Seeding Technology: Assessing Effectiveness and Other Challenges | U.S. GAO. Technical Report GAO-25-107328, U.S. Government Accountability Office, December 2024. URL <https://www.gao.gov/products/gao-25-107328>.
- [4] WMO Statement on Weather Modification, June 2025. URL <https://wmo.int/content/wmo-statement-weather-modification>.
- [5] Sarah A. Tessendorf, Jeffrey R. French, Katja Friedrich, Bart Geerts, Robert M. Rauber, Roy M. Rasmussen, Lulin Xue, Kyoko Ikeda, Derek R. Blestrud, Melvin L. Kunkel, Shaun Parkinson, Jefferson R. Snider, Joshua Aikins, Spencer Faber, Adam Majewski, Coltin Grasmick, Philip T. Bergmaier, Andrew Janiszewski, Adam Springer, Courtney Weeks, David J. Serke, and Roelof Bruintjes. A Transformational Approach to Winter Orographic Weather Modification Research: The SNOWIE Project. *Bulletin of the American Meteorological Society*, January 2019. doi: 10.1175/BAMS-D-17-0152.1. URL <https://journals.ametsoc.org/view/journals/bams/100/1/bams-d-17-0152.1.xml>.
- [6] Jeffrey R. French, Katja Friedrich, Sarah A. Tessendorf, Robert M. Rauber, Bart Geerts, Roy M. Rasmussen, Lulin Xue, Melvin L. Kunkel, and Derek R. Blestrud. Precipitation formation from orographic cloud seeding. *Proceedings of the National Academy of Sciences*, 115(6):1168–1173, February 2018. doi: 10.1073/pnas.1716995115. URL <https://www.pnas.org/doi/full/10.1073/pnas.1716995115>.
- [7] Katja Friedrich, Kyoko Ikeda, Sarah A. Tessendorf, Jeffrey R. French, Robert M. Rauber, Bart Geerts, Lulin Xue, Roy M. Rasmussen, Derek R. Blestrud, Melvin L. Kunkel, Nicholas Dawson, and Shaun Parkinson. Quantifying snowfall from orographic cloud seeding. *Proceedings of the National Academy of Sciences*, 117(10):5190–5195, March 2020. doi: 10.1073/pnas.1917204117. URL <https://www.pnas.org/doi/full/10.1073/pnas.1917204117>.
- [8] U. Dusek, G. P. Frank, L. Hildebrandt, J. Curtius, J. Schneider, S. Walter, D. Chand, F. Drewnick, S. Hings, D. Jung, S. Borrmann, and M. O. Andreae. Size Matters More Than Chemistry for Cloud-Nucleating Ability of Aerosol Particles. *Science*, 312(5778):1375–1378, June 2006. doi: 10.1126/science.1125261. URL <https://www.science.org/doi/10.1126/science.1125261>.
- [9] M. O. Andreae and D. Rosenfeld. Aerosol–cloud–precipitation interactions. Part 1. The nature and sources of cloud-active aerosols. *Earth-Science Reviews*, 89(1):13–41, July 2008. doi: 10.1016/j.earscirev.2008.03.001. URL <https://www.sciencedirect.com/science/article/pii/S0012825208000317>.
- [10] Daniel Rosenfeld, Duncan Axisa, William L. Woodley, and Ronen Lahav. A Quest for Effective Hygroscopic Cloud Seeding. *Journal of Applied Meteorology and Climatology*, July 2010. doi: 10.1175/2010JAMC2307.1. URL <https://journals.ametsoc.org/view/journals/apme/49/7/2010jamc2307.1.xml>.
- [11] Sarah A. Tessendorf, Sisi Chen, Courtney Weeks, Roelof Bruintjes, Roy M. Rasmussen, and Lulin Xue. The Influence of Hygroscopic Flare Seeding on Drop Size Distribution Over Southeast Queensland. *Journal of Geophysical Research: Atmospheres*, 126(6):e2020JD033771, 2021. doi: 10.1029/2020JD033771. URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2020JD033771>.
- [12] Hilding Köhler. The nucleus in and the growth of hygroscopic droplets. *Transactions of the Faraday Society*, 32:1152–1161, January 1936. doi: 10.1039/TF9363201152. URL <https://doi.org/10.1039/TF9363201152>.
- [13] Ernie R. Lewis. An examination of Köhler theory resulting in an accurate expression for the equilibrium radius ratio of a hygroscopic aerosol particle valid up to and including relative humidity 100%. *Journal of Geophysical Research: Atmospheres*, 113(D3), 2008. doi: 10.1029/2007JD008590. URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2007JD008590>.
- [14] M. D. Petters and S. M. Kreidenweis. A single parameter representation of hygroscopic growth and cloud condensation nucleus activity. *Atmospheric*

- Chemistry and Physics*, 7(8):1961–1971, April 2007. doi: 10.5194/acp-7-1961-2007. URL <https://acp.copernicus.org/articles/7/1961/2007/>.
- [15] R. Sorjamaa, B. Svenningsson, T. Raatikainen, S. Henning, M. Bilde, and A. Laaksonen. The role of surfactants in Köhler theory reconsidered. *Atmospheric Chemistry and Physics*, 4(8):2107–2117, October 2004. doi: 10.5194/acp-4-2107-2004. URL <https://acp.copernicus.org/articles/4/2107/2004/>.
- [16] M. D. Petters and S. M. Kreidenweis. A single parameter representation of hygroscopic growth and cloud condensation nucleus activity – Part 3: Including surfactant partitioning. *Atmospheric Chemistry and Physics*, 13(2):1081–1091, January 2013. doi: 10.5194/acp-13-1081-2013. URL <https://acp.copernicus.org/articles/13/1081/2013/>.
- [17] Sara D. Forestieri, Sean M. Staudt, Thomas M. Kuborn, Katharine Faber, Christopher R. Ruehl, Timothy H. Bertram, and Christopher D. Cappa. Establishing the impact of model surfactants on cloud condensation nuclei activity of sea spray aerosol mimics. *Atmospheric Chemistry and Physics*, 18(15):10985–11005, August 2018. doi: 10.5194/acp-18-10985-2018. URL <https://acp.copernicus.org/articles/18/10985/2018/>.
- [18] Bryan R. Bzdek, Jonathan P. Reid, Jussi Malila, and Nønne L. Prisle. The surface tension of surfactant-containing, finite volume droplets. *Proceedings of the National Academy of Sciences*, 117(15):8335–8343, April 2020. doi: 10.1073/pnas.1915660117. URL <https://www.pnas.org/doi/full/10.1073/pnas.1915660117>.
- [19] Robert J. Moon, Ashlie Martini, John Nairn, John Simonsen, and Jeff Youngblood. Cellulose nanomaterials review: structure, properties and nanocomposites. *Chemical Society Reviews*, 40(7):3941–3994, July 2011. doi: 10.1039/c0cs00108b. URL <https://doi.org/10.1039/c0cs00108b>.
- [20] Youssef Habibi, Lucian A. Lucia, and Orlando J. Rojas. Cellulose Nanocrystals: Chemistry, Self-Assembly, and Applications. *Chemical Reviews*, 110(6):3479–3500, June 2010. doi: 10.1021/cr900339w. URL <https://dx.doi.org/10.1021/cr900339w>.
- [21] Laleh Solhi, Valentina Guccini, Katja Heise, Iina Solala, Elina Niinivaara, Wenyang Xu, Karl Mihels, Marcel Kröger, Zhuojun Meng, Jakob Wohler, Han Tao, Emily D. Cranston, and Eero Kontturi. Understanding Nanocellulose–Water Interactions: Turning a Detriment into an Asset. *Chemical Reviews*, 123(5):1925–2015, February 2023. doi: 10.1021/acs.chemrev.2c00611. URL <https://doi.org/10.1021/acs.chemrev.2c00611>.
- [22] Daniel Warnes, Wenyang Xu, Jia Hui Lim, Richard M. Parker, Bruno Frka-Petesic, Ray Freshwater, Camila Honorato-Rios, Yu Ogawa, Chiara Giorio, and Silvia Vignolini. Tuning the morphology of aerosolised cellulose nanocrystal particulates via controlled aggregation. *Carbohydrate Polymers*, 373:124592, February 2026. doi: 10.1016/j.carbpol.2025.124592. URL <https://www.sciencedirect.com/science/article/pii/S0144861725013761>.
- [23] Chun-Ning Mao, Kanishk Gohil, Dewansh Rastogi, and Akua Asa-Awuku. The hygroscopicity of nano-plastic particles and implications for cloud formation and climate. *Aerosol Science and Technology*, 58(9):1024–1032, September 2024. doi: 10.1080/02786826.2024.2361041. URL <https://doi.org/10.1080/02786826.2024.2361041>.
- [24] Daniel Warnes. *Cellulose nanocrystals as a candidate for solar geoengineering*. PhD thesis, University of Cambridge, June 2025. URL <https://www.repository.cam.ac.uk/handle/1810/385986>.
- [25] Kamil Wojciechowski. Surface activity of saponin from *Quillaja* bark at the air/water and oil/water interfaces. *Colloids and Surfaces B: Biointerfaces*, 108:95–102, August 2013. doi: 10.1016/j.colsurfb.2013.02.008. URL <https://www.sciencedirect.com/science/article/pii/S0927776513001288>.
- [26] Konstantin Golemanov, Slavka Tcholakova, Nikolai Denkov, Edward Pelan, and Simeon D. Stoyanov. Remarkably high surface visco-elasticity of adsorption layers of triterpenoid saponins. *Soft Matter*, 9(24):5738–5752, June 2013. doi: 10.1039/c3sm27950b. URL <https://doi.org/10.1039/c3sm27950b>.
- [27] A. Arzhavitina and H. Steckel. Surface active drugs significantly alter the drug output rate from medical nebulizers. *International Journal of Pharmaceutics*, 384(1):128–136, January 2010. doi: 10.1016/j.ijpharm.2009.10.012. URL <https://www.sciencedirect.com/science/article/pii/S0378517309007212>.
- [28] R. G. Harrison and K. S. Carslaw. Ion-aerosol-cloud processes in the lower atmosphere. *Reviews of Geophysics*, 41(3), 2003. doi: 10.1029/2002RG000114. URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2002RG000114>.
- [29] Shian Guo and Huiwen Xue. The enhancement of droplet collision by electric charges and atmospheric electric fields. *Atmospheric Chemistry and Physics*, 21(1):69–85, January 2021. doi: 10.5194/acp-21-69-2021. URL <https://acp.copernicus.org/articles/21/69/2021/>.

- [30] Jamilya Nauruzbayeva, Zhonghao Sun, Adair Gallo, Mahmoud Ibrahim, J. Carlos Santamarina, and Himanshu Mishra. Electrification at water–hydrophobe interfaces. *Nature Communications*, 11(1):5285, October 2020. doi: 10.1038/s41467-020-19054-8. URL <https://www.nature.com/articles/s41467-020-19054-8>.
- [31] B. Y. H. LIU, D. Y. H. PUI, K. L. RUBOW, and W. W. SZYMANSKI. ELECTROSTATIC EFFECTS IN AEROSOL SAMPLING AND FILTRATION. *The Annals of Occupational Hygiene*, 29(2):251–269, January 1985. doi: 10.1093/annhyg/29.2.251. URL <https://doi.org/10.1093/annhyg/29.2.251>.
- [32] Rupam Kumar Roy, Amartya Bhattacharya, Anupam Priamvada, and Bipasha Paul Shukla. Seedable Conditions of Clouds Using Machine Learning Techniques. In *2023 International Conference on Machine Intelligence for GeoAnalytics and Remote Sensing (MIGARS)*, volume 1, pages 1–4, January 2023. doi: 10.1109/MIGARS57353.2023.10064525. URL <https://ieeexplore.ieee.org/document/10064525>.
- [33] Shunji Kotsuki, Kazuaki Yasunaga, Atsushi Hamada, Kazuhiro Yoshimi, Kenta Shiraishi, Akira Takeshima, Yoshiki Terashima, Kaya Kanemaru, Yusuke Hiraga, Takuya Funatomi, Hiroyuki Kubo, Kohei Suzuki, Masanao Ohashi, and Tadashi Tsuyuki. A Real-Time Remote-Sensing-Guided Decision-Support Framework for Cloud-Seeding Operations: A Field Demonstration Using Himawari-9 and C-band Phased Array Weather Radar, July 2026. URL <http://arxiv.org/abs/2607.05050>. arXiv:2607.05050 [physics.ao-ph].
- [34] Robert M. Rauber, Bart Geerts, Lulin Xue, Jeffrey French, Katja Friedrich, Roy M. Rasmussen, Sarah A. Tessendorf, Derek R. Blestrud, Melvin L. Kunkel, and Shaun Parkinson. Wintertime Orographic Cloud Seeding—A Review. *Journal of Applied Meteorology and Climatology*, 58(10):2117–2140, October 2019. doi: 10.1175/JAMC-D-18-0341.1. URL <https://journals.ametsoc.org/view/journals/apme/58/10/jamc-d-18-0341.1.xml>.
- [35] Jin Wang, Zhiguo Yue, Daniel Rosenfeld, Lei Zhang, Yannian Zhu, Jin Dai, Xing Yu, and Jinhui Li. The Evolution of an AgI Cloud-Seeding Track in Central China as Seen by a Combination of Radar, Satellite, and Disdrometer Observations. *Journal of Geophysical Research: Atmospheres*, 126(11):e2020JD033914, 2021. doi: 10.1029/2020JD033914. URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2020JD033914>.
- [36] Xiaobo Dong, Chuanfeng Zhao, Zhaochu Huang, Rong Mai, Feng Lv, Xuewu Xue, Xiaorui Zhang, Shaoyu Hou, Yang Yang, Yikun Yang, and Yue Sun. Increase of precipitation by cloud seeding observed from a case study in November 2020 over Shijiazhuang, China. *Atmospheric Research*, 262:105766, November 2021. doi: 10.1016/j.atmosres.2021.105766. URL <https://www.sciencedirect.com/science/article/pii/S0169809521003227>.
- [37] Bernard A. Silverman. A Critical Assessment of Hygroscopic Seeding of Convective Clouds for Rainfall Enhancement. *Bulletin of the American Meteorological Society*, September 2003. doi: 10.1175/BAMS-84-9-1219. URL <https://journals.ametsoc.org/view/journals/bams/84/9/bams-84-9-1219.xml>.
- [38] Xianghua Wu, Ni Yan, Huaying Yu, Shengjie Niu, Fangxiu Meng, Weiqi Liu, and Haiyan Sun. Advances in the Evaluation of Cloud Seeding: Statistical Evidence for the Enhancement of Precipitation. *Earth and Space Science*, 5(9):425–439, 2018. doi: 10.1029/2018EA000424. URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2018EA000424>.
- [39] William A. Cooper, Roelof T. Brientjes, and Graeme K. Mather. Calculations Pertaining to Hygroscopic Seeding with Flares. *Journal of Applied Meteorology and Climatology*, November 1997. URL https://journals.ametsoc.org/view/journals/apme/36/11/1520-0450_1997_036_1449_cpthsw_2.0.co_2.xml.
- [40] G. K. Mather, D. E. Terblanche, F. E. Steffens, and L. Fletcher. Results of the South African Cloud-Seeding Experiments Using Hygroscopic Flares. *Journal of Applied Meteorology and Climatology*, November 1997. doi: 10.1175/1520-0450(1997)036<1433:ROTSAC>2.0.CO;2. URL https://journals.ametsoc.org/view/journals/apme/36/11/1520-0450_1997_036_1433_rotsac_2.0.co_2.xml.
- [41] Dimitri Caro, Wolfram Wobrock, and Andrea I. Flossmann. A Numerical Study on the Impact of Hygroscopic Seeding on the Development of Cloud Particle Spectra. *Journal of Applied Meteorology and Climatology*, March 2002. URL https://journals.ametsoc.org/view/journals/apme/41/3/1520-0450_2002_041_0333_ansoti_2.0.co_2.xml.
- [42] Y Segal, A Khain, M Pinsky, and D Rosenfeld. Effects of hygroscopic seeding on raindrop formation as seen from simulations using a 2000-bin spectral cloud parcel model. *Atmospheric Research*, 71(1):3–34, July 2004. doi: 10.1016/j.atmosres.2004.03.003. URL <https://www.sciencedirect.com/science/article/pii/S0169809504000304>.

- [43] Graham Feingold, William R. Cotton, Sonia M. Kreidenweis, and Janel T. Davis. The Impact of Giant Cloud Condensation Nuclei on Drizzle Formation in Stratocumulus: Implications for Cloud Radiative Properties. *Journal of the Atmospheric Sciences*, December 1999. URL https://journals.ametsoc.org/view/journals/atsc/56/24/1520-0469_1999_056_4100_tiogcc_2.0.co_2.xml.
- [44] Jørgen B. Jensen and Sunhee Lee. Giant Sea-Salt Aerosols and Warm Rain Formation in Marine Stratocumulus. *Journal of the Atmospheric Sciences*, December 2008. doi: 10.1175/2008JAS2617.1. URL <https://journals.ametsoc.org/view/journals/atsc/65/12/2008jas2617.1.xml>.
- [45] Jørgen B. Jensen and Alison D. Nugent. Condensation Growth of Drops Formed on Giant Sea-Salt Aerosol Particles. *Journal of the Atmospheric Sciences*, March 2017. doi: 10.1175/JAS-D-15-0370.1. URL <https://journals.ametsoc.org/view/journals/atsc/74/3/jas-d-15-0370.1.xml>.
- [46] Yoav Lehahn, Ilan Koren, Orit Altaratz, and Alexander B. Kostinski. Effect of coarse marine aerosols on stratocumulus clouds. *Geophysical Research Letters*, 38(20), 2011. doi: 10.1029/2011GL048504. URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2011GL048504>.
- [47] E. Jung, B. A. Albrecht, H. H. Jonsson, Y.-C. Chen, J. H. Seinfeld, A. Sorooshian, A. R. Metcalf, S. Song, M. Fang, and L. M. Russell. Precipitation effects of giant cloud condensation nuclei artificially introduced into stratocumulus clouds. *Atmospheric Chemistry and Physics*, 15(10):5645–5658, May 2015. doi: 10.5194/acp-15-5645-2015. URL <https://acp.copernicus.org/articles/15/5645/2015/>.
- [48] Lulin Xue, Xia Chu, Roy Rasmussen, Daniel Breed, Bruce Boe, and Bart Geerts. The Dispersion of Silver Iodide Particles from Ground-Based Generators over Complex Terrain. Part II: WRF Large-Eddy Simulations versus Observations. *Journal of Applied Meteorology and Climatology*, June 2014. doi: 10.1175/JAMC-D-13-0241.1. URL <https://journals.ametsoc.org/view/journals/apme/53/6/jamc-d-13-0241.1.xml>.
- [49] István Geresdi, Lulin Xue, and Roy Rasmussen. Evaluation of Orographic Cloud Seeding Using a Bin Microphysics Scheme: Two-Dimensional Approach. *Journal of Applied Meteorology and Climatology*, May 2017. doi: 10.1175/JAMC-D-16-0045.1. URL <https://journals.ametsoc.org/view/journals/apme/56/5/jamc-d-16-0045.1.xml>.
- [50] Juha Tonttila, Ali Afzalifar, Harri Kokkola, Tomi Raatikainen, Hannele Korhonen, and Sami Romakkaniemi. Precipitation enhancement in stratocumulus clouds through airborne seeding: sensitivity analysis by UCLALES-SALSA. *Atmospheric Chemistry and Physics*, 21(2):1035–1048, January 2021. doi: 10.5194/acp-21-1035-2021. URL <https://acp.copernicus.org/articles/21/1035/2021/>.
- [51] Kai-I. Lin, Kao-Shen Chung, Sheng-Hsiang Wang, Li-Hsin Chen, Yu-Chieng Liou, Pay-Liam Lin, Wei-Yu Chang, Hsien-Jung Chiu, and Yi-Hui Chang. Evaluation of hygroscopic cloud seeding in warm-rain processes by a hybrid microphysics scheme using a Weather Research and Forecasting (WRF) model: a real case study. *Atmospheric Chemistry and Physics*, 23(18):10423–10438, September 2023. doi: 10.5194/acp-23-10423-2023. URL <https://acp.copernicus.org/articles/23/10423/2023/>.
- [52] Sisi Chen, Lulin Xue, and Man-Kong Yau. Impact of aerosols and turbulence on cloud droplet growth: an in-cloud seeding case study using a parcel-DNS (direct numerical simulation) approach. *Atmospheric Chemistry and Physics*, 20(17):10111–10124, August 2020. doi: 10.5194/acp-20-10111-2020. URL <https://acp.copernicus.org/articles/20/10111/2020/>.
- [53] G. McFiggans, P. Artaxo, U. Baltensperger, H. Coe, M. C. Facchini, G. Feingold, S. Fuzzi, M. Gysel, A. Laaksonen, U. Lohmann, T. F. Mentel, D. M. Murphy, C. D. O’Dowd, J. R. Snider, and E. Weingartner. The effect of physical and chemical aerosol properties on warm cloud droplet activation. *Atmospheric Chemistry and Physics*, 6(9):2593–2649, July 2006. doi: 10.5194/acp-6-2593-2006. URL <https://acp.copernicus.org/articles/6/2593/2006/>.
- [54] Delphine K. Farmer, Christopher D. Cappa, and Sonia M. Kreidenweis. Atmospheric Processes and Their Controlling Influence on Cloud Condensation Nuclei Activity. *Chemical Reviews*, 115(10):4199–4217, March 2015. doi: 10.1021/cr5006292. URL <https://dx.doi.org/10.1021/cr5006292>.
- [55] G. C. Roberts and A. Nenes. A Continuous-Flow Streamwise Thermal-Gradient CCN Chamber for Atmospheric Measurements. *Aerosol Science and Technology*, 39(3):206–221, March 2005. doi: 10.1080/027868290913988. URL <https://doi.org/10.1080/027868290913988>.
- [56] Bu-Yo Kim, Miloslav Belorid, Joo Wan Cha, Youngmi Kim, and Seungbum Kim. Analysis of hygroscopic cloud seeding materials using the Korea Cloud Physics Experimental Chamber (KCPEC): a case study for powder-type sodium chloride and calcium chloride. *Atmospheric Measurement Techniques*, 18(15):3781–3797, August 2025.

- doi: 10.5194/amt-18-3781-2025. URL <https://amt.copernicus.org/articles/18/3781/2025/>.
- [57] Michael S. Reid, Marco Villalobos, and Emily D. Cranston. Benchmarking Cellulose Nanocrystals: From the Laboratory to Industrial Production. *Langmuir*, 33(7):1583–1598, February 2017. doi: 10.1021/acs.langmuir.6b03765. URL <https://dx.doi.org/10.1021/acs.langmuir.6b03765>.
- [58] Gwendoline Delepierre, Oriana M. Vanderfleet, Elina Niinivaara, Behzad Zakani, and Emily D. Cranston. Benchmarking Cellulose Nanocrystals Part II: New Industrially Produced Materials. *Langmuir*, 37(28):8393–8409, July 2021. doi: 10.1021/acs.langmuir.1c00550. URL <https://doi.org/10.1021/acs.langmuir.1c00550>.
- [59] Xin Guo, Yiqiang Wu, and Xinfeng Xie. Water vapor sorption properties of cellulose nanocrystals and nanofibers using dynamic vapor sorption apparatus. *Scientific Reports*, 7(1):14207, October 2017. doi: 10.1038/s41598-017-14664-7. URL <https://www.nature.com/articles/s41598-017-14664-7>.
- [60] Minna Hakalahti, Marco Faustini, Cédric Boissière, Eero Kontturi, and Tekla Tammelin. Interfacial Mechanisms of Water Vapor Sorption into Cellulose Nanofibril Films as Revealed by Quantitative Models. *Biomacromolecules*, 18(9):2951–2958, August 2017. doi: 10.1021/acs.biomac.7b00890. URL <https://doi.org/10.1021/acs.biomac.7b00890>.
- [61] Yussef Esparza, Tri-Dung Ngo, Carole Fraschini, and Yaman Boluk. Aggregate Morphology and Aqueous Dispersibility of Spray-Dried Powders of Cellulose Nanocrystals. *Industrial & Engineering Chemistry Research*, 58(43):19926–19936, October 2019. doi: 10.1021/acs.iecr.9b03951. URL <https://dx.doi.org/10.1021/acs.iecr.9b03951>.
- [62] Kévin Ballu, Jia-Hui Lim, Thomas G. Parton, Richard M. Parker, Bruno Frka-Petesic, Alexei A. Lapkin, Yu Ogawa, and Silvia Vignolini. Tailoring the Morphology of Cellulose Nanocrystals via Controlled Aggregation. *ACS Nano*, 19(27):25228–25242, July 2025. doi: 10.1021/acsnano.5c05548. URL <https://doi.org/10.1021/acsnano.5c05548>.
- [63] Maria Cristina Facchini, Mihaela Mircea, Sandro Fuzzi, and Robert J. Charlson. Cloud albedo enhancement by surface-active organic solutes in growing droplets. *Nature*, 401(6750):257–259, September 1999. doi: 10.1038/45758. URL <https://www.nature.com/articles/45758>.
- [64] Jurgita Ovadnevaite, Darius Ceburnis, Giovanni Martucci, Jakub Bialek, Ciaran Monahan, Matteo Rinaldi, Maria Cristina Facchini, Harald Berresheim, Douglas R. Worsnop, and Colin O’Dowd. Primary marine organic aerosol: A dichotomy of low hygroscopicity and high CCN activity. *Geophysical Research Letters*, 38(21), 2011. doi: 10.1029/2011GL048869. URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2011GL048869>.
- [65] Christopher R. Ruehl, James F. Davies, and Kevin R. Wilson. An interfacial mechanism for cloud droplet formation on organic aerosols. *Science*, 351(6280):1447–1450, March 2016. doi: 10.1126/science.aad4889. URL <https://www.science.org/doi/10.1126/science.aad4889>.
- [66] N. L. Prisle, T. Raatikainen, A. Laaksonen, and M. Bilde. Surfactants in cloud droplet activation: mixed organic-inorganic particles. *Atmospheric Chemistry and Physics*, 10(12):5663–5683, June 2010. doi: 10.5194/acp-10-5663-2010. URL <https://acp.copernicus.org/articles/10/5663/2010/>.
- [67] N. L. Prisle, M. Dal Maso, and H. Kokkola. A simple representation of surface active organic aerosol in cloud droplet formation. *Atmospheric Chemistry and Physics*, 11(9):4073–4083, May 2011. doi: 10.5194/acp-11-4073-2011. URL <https://acp.copernicus.org/articles/11/4073/2011/>.
- [68] Barbara Nozière, Christine Baduel, and Jean-Luc Jaffrezo. The dynamic surface tension of atmospheric aerosol surfactants reveals new aspects of cloud activation. *Nature Communications*, 5(1):3335, February 2014. doi: 10.1038/ncomms4335. URL <https://www.nature.com/articles/ncomms4335>.
- [69] Jack J. Lin, Thomas B. Kristensen, Silvia M. Calderón, Jussi Malila, and Nønne L. Prisle. Effects of surface tension time-evolution for CCN activation of a complex organic surfactant. *Environmental Science: Processes & Impacts*, 22(2):271–284, February 2020. doi: 10.1039/c9em00426b. URL <https://doi.org/10.1039/c9em00426b>.
- [70] C. R. Ruehl, P. Y. Chuang, A. Nenes, C. D. Cappa, K. R. Kolesar, and A. H. Goldstein. Strong evidence of surface tension reduction in microscopic aqueous droplets. *Geophysical Research Letters*, 39(23), 2012. doi: 10.1029/2012GL053706. URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2012GL053706>.
- [71] Christopher R. Ruehl and Kevin R. Wilson. Surface Organic Monolayers Control the Hygroscopic Growth of Submicrometer Particles at High Relative Humidity. *The Journal of Physical Chemistry A*, 118(22):3952–3966, June 2014. doi: 10.1021/jp

- 502844g. URL <https://dx.doi.org/10.1021/jp502844g>.
- [72] Jurgita Ovadnevaite, Andreas Zuend, Ari Laaksonen, Kevin J. Sanchez, Greg Roberts, Darius Ceburnis, Stefano Decesari, Matteo Rinaldi, Natasha Hodas, Maria Cristina Facchini, John H. Seinfeld, and Colin O' Dowd. Surface tension prevails over solute effect in organic-influenced cloud droplet activation. *Nature*, 546(7660):637–641, June 2017. doi: 10.1038/nature22806. URL <https://www.nature.com/articles/nature22806>.
- [73] Chun Xiong, Xueyan Chen, Xiaolei Ding, Binyu Kuang, Xiangyu Pei, Zhengning Xu, Shikuan Yang, Huan Hu, and Zhibin Wang. Reconsideration of surface tension and phase state effects on cloud condensation nuclei activity based on the atomic force microscopy measurement. *Atmospheric Chemistry and Physics*, 22(24):16123–16135, December 2022. doi: 10.5194/acp-22-16123-2022. URL <https://acp.copernicus.org/articles/22/16123/2022/>.
- [74] Sarah Suda Petters and Markus Dirk Petters. Surfactant effect on cloud condensation nuclei for two-component internally mixed aerosols. *Journal of Geophysical Research: Atmospheres*, 121(4):1878–1895, 2016. doi: 10.1002/2015JD024090. URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/2015JD024090>.
- [75] James F. Davies, Andreas Zuend, and Kevin R. Wilson. Technical note: The role of evolving surface tension in the formation of cloud droplets. *Atmospheric Chemistry and Physics*, 19(5):2933–2946, March 2019. doi: 10.5194/acp-19-2933-2019. URL <https://acp.copernicus.org/articles/19/2933/2019/>.
- [76] Juliane Deise Fleck, Andresa Heemann Betti, Francini Pereira Da Silva, Eduardo Artur Troian, Cristina Olivaro, Fernando Ferreira, and Simone Gasparin Verza. Saponins from Quillaja saponaria and Quillaja brasiliensis: Particular Chemical Characteristics and Biological Activities. *Molecules*, 24(1):171, January 2019. doi: 10.3390/molecules24010171. URL <https://www.mdpi.com/1420-3049/24/1/171>.
- [77] Summaia Fordos, Sana Amin, Namrah Abid, Imran Pasha, Muhammad Kashif Iqbal Khan, Amina Amin, Muhammad Gulzar, Muhammad Subtain, and Gholamreza Abdi. Saponins: Advances in extraction techniques, functional properties, and industrial applications. *Applied Food Research*, 5(2):101146, December 2025. doi: 10.1016/j.afres.2025.101146. URL <https://www.sciencedirect.com/science/article/pii/S2772502225004512>.
- [78] J. Penfold, R. K. Thomas, I. Tucker, J. T. Petkov, S. D. Stoyanov, N. Denkov, K. Golemanov, S. Tcholakova, and J. R. P. Webster. Saponin Adsorption at the Air–Water Interface–Neutron Reflectivity and Surface Tension Study. *Langmuir*, 34(32):9540–9547, August 2018. doi: 10.1021/acs.langmuir.8b02158. URL <https://dx.doi.org/10.1021/acs.langmuir.8b02158>.
- [79] Shuman Mitra and Stephanie R. Dungan. Micellar Properties of Quillaja Saponin. 1. Effects of Temperature, Salt, and pH on Solution Properties. *Journal of Agricultural and Food Chemistry*, 45(5):1587–1595, May 1997. doi: 10.1021/jf960349z. URL <https://doi.org/10.1021/jf960349z>.
- [80] Vamseekrishna Ulaganathan, Lorena Del Castillo, Jessie L. Webber, Tracey T. M. Ho, James K. Ferri, Marta Krasowska, and David A. Beattie. The influence of pH on the interfacial behaviour of *Quillaja* bark saponin at the air-solution interface. *Colloids and Surfaces B: Biointerfaces*, 176:412–419, April 2019. doi: 10.1016/j.colsurfb.2019.01.017. URL <https://www.sciencedirect.com/science/article/pii/S0927776519300177>.
- [81] R. Stanimirova, K. Marinova, S. Tcholakova, N. D. Denkov, S. Stoyanov, and E. Pelan. Surface Rheology of Saponin Adsorption Layers. *Langmuir*, 27(20):12486–12498, October 2011. doi: 10.1021/la202860u. URL <https://dx.doi.org/10.1021/la202860u>.
- [82] Konstantin Golemanov, Slavka Tcholakova, Nikolai Denkov, Edward Pelan, and Simeon D. Stoyanov. Surface Shear Rheology of Saponin Adsorption Layers. *Langmuir*, 28(33):12071–12084, August 2012. doi: 10.1021/la302150j. URL <https://dx.doi.org/10.1021/la302150j>.
- [83] Brian A. Tinsley, Limin Zhou, and Abigail Plemmons. Changes in scavenging of particles by droplets due to weak electrification in clouds. *Atmospheric Research*, 79(3):266–295, March 2006. doi: 10.1016/j.atmosres.2005.06.004. URL <https://www.sciencedirect.com/science/article/pii/S0169809505001602>.
- [84] Kenneth V. Beard and Harry T. Ochs III. Collection and coalescence efficiencies for accretion. *Journal of Geophysical Research: Atmospheres*, 89(D5):7165–7169, 1984. doi: 10.1029/JD089iD05p07165. URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/JD089iD05p07165>.
- [85] O. W. Jayaratne and Basil John Mason. The coalescence and bouncing of water drops at an air/water interface. *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*, 280(1383):545–565, August 1964. doi:

- 10.1098/rspa.1964.0161. URL <https://doi.org/10.1098/rspa.1964.0161>.
- [86] Kenneth V. Beard, Russell I. Durkee, and Harry T. Ochs III. Coalescence Efficiency Measurements for Minimally Charged Cloud Drops. *Journal of the Atmospheric Sciences*, January 2002. doi: 10.1175/1520-0469(2002)059<0233:CEMFMC>2.0.CO;2. URL https://journals.ametsoc.org/view/journals/atmsc/59/2/1520-0469_2002_059_0233_cemfmc_2.0.co_2.xml.
- [87] Mariana D. Sosa, M. Luz Martínez Ricci, Leandro L. Missoni, Daniel H. Murgida, Antonela Cánneva, Norma B. D’Accorso, and R. Martín Negri. Liquid–polymer triboelectricity: chemical mechanisms in the contact electrification process. *Soft Matter*, 16(30):7040–7051, August 2020. doi: 10.1039/d0sm00738b. URL <https://doi.org/10.1039/d0sm00738b>.
- [88] Shiquan Lin, Xiangyu Chen, and Zhong Lin Wang. Contact Electrification at the Liquid–Solid Interface. *Chemical Reviews*, 122(5):5209–5232, March 2022. doi: 10.1021/acs.chemrev.1c00176. URL <https://dx.doi.org/10.1021/acs.chemrev.1c00176>.
- [89] Mingzi Sun, Qiuyang Lu, Zhong Lin Wang, and Bolong Huang. Understanding contact electrification at liquid–solid interfaces from surface electronic structure. *Nature Communications*, 12(1):1752, March 2021. doi: 10.1038/s41467-021-22005-6. URL <https://www.nature.com/articles/s41467-021-22005-6>.
- [90] Philip Chi Lip Kwok, Sebastiaan J. Trietsch, Michiko Kumon, and Hak-Kim Chan. Electrostatic Charge Characteristics of Jet Nebulized Aerosols. *Journal of Aerosol Medicine and Pulmonary Drug Delivery*, 23(3):149–159, June 2010. doi: 10.1089/jamp.2009.0795. URL <https://doi.org/10.1089/jamp.2009.0795>.
- [91] Dongwhi Choi, Horim Lee, Do Jin Im, In Seok Kang, Geunbae Lim, Dong Sung Kim, and Kwan Hyoung Kang. Spontaneous electrical charging of droplets by conventional pipetting. *Scientific Reports*, 3(1):2037, June 2013. doi: 10.1038/srep02037. URL <https://www.nature.com/articles/srep02037>.
- [92] Romain Ceolato and Matthew J. Berg. Aerosol light extinction and backscattering: A review with a lidar perspective. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 262:107492, March 2021. doi: 10.1016/j.jqsrt.2020.107492. URL <https://www.sciencedirect.com/science/article/pii/S0022407320310207>.
- [93] Marilena Teri, Thomas Müller, Josef Gasteiger, Sara Valentini, Helmuth Horvath, Roberta Vecchi, Paulus Bauer, Adrian Walser, and Bernadett Weinzierl. Impact of particle size, refractive index, and shape on the determination of the particle scattering coefficient – an optical closure study evaluating different nephelometer angular truncation and illumination corrections. *Atmospheric Measurement Techniques*, 15(10):3161–3187, May 2022. doi: 10.5194/amt-15-3161-2022. URL <https://amt.copernicus.org/articles/15/3161/2022/>.
- [94] Wladyslaw W Szymanski. Multiple scattering enhancement of transmitted radiation in water droplet aerosols. *Journal of Aerosol Science*, 23(5):425–435, July 1992. doi: 10.1016/0021-8502(92)90014-M. URL <https://www.sciencedirect.com/science/article/pii/002185029290014M>.
- [95] Avishai Ben-David. Multiple-scattering effects on differential absorption for the transmission of a plane-parallel beam in a homogeneous medium. *Applied Optics*, 36(6):1386–1398, February 1997. doi: 10.1364/AO.36.001386. URL <https://opg.optica.org/ao/abstract.cfm?uri=ao-36-6-1386>.
- [96] L. Wind and W. W. Szymanski. Quantification of scattering corrections to the Beer-Lambert law for transmittance measurements in turbid media. *Measurement Science and Technology*, 13(3):270, February 2002. doi: 10.1088/0957-0233/13/3/306. URL <https://doi.org/10.1088/0957-0233/13/3/306>.
- [97] David H. Hagan and Jesse H. Kroll. Assessing the accuracy of low-cost optical particle sensors using a physics-based approach. *Atmospheric Measurement Techniques*, 13(11):6343–6355, November 2020. doi: 10.5194/amt-13-6343-2020. URL <https://amt.copernicus.org/articles/13/6343/2020/>.
- [98] James Ouimette, W. Patrick Arnott, Philip Laven, Richard Whitwell, Nagarajan Radhakrishnan, Suresh Dhaniyala, Michael Sandink, Jessica Tryner, and John Volckens. Fundamentals of low-cost aerosol sensor design and operation. *Aerosol Science and Technology*, 58(1):1–15, January 2024. doi: 10.1080/02786826.2023.2285935. URL <https://doi.org/10.1080/02786826.2023.2285935>.
- [99] Paul R. Phipps, B. Pharm, and Igor Gonda. Droplets Produced by Medical Nebulizers: Some Factors Affecting Their Size and Solute Concentration. *CHEST*, 97(6):1327–1332, June 1990. doi: 10.1378/chest.97.6.1327. URL [https://journal.chestnet.org/article/S0012-3692\(16\)32013-X/abstract](https://journal.chestnet.org/article/S0012-3692(16)32013-X/abstract).

- [100] Orla N. M. McCallion, Kevin M. G. Taylor, Marian Thomas, and Anthony J. Taylor. Nebulization of Fluids of Different Physicochemical Properties with Air-Jet and Ultrasonic Nebulizers. *Pharmaceutical Research*, 12(11):1682–1688, November 1995. doi: 10.1023/A:1016205520044. URL <https://doi.org/10.1023/A:1016205520044>.
- [101] Stefan Kooij, Alina Astefanei, Garry L. Corthals, and Daniel Bonn. Size distributions of droplets produced by ultrasonic nebulizers. *Scientific Reports*, 9(1):6128, April 2019. doi: 10.1038/s41598-019-42599-8. URL <https://www.nature.com/articles/s41598-019-42599-8>.
- [102] Mohammad Najlah, Ishrat Parveen, Mohamed Albed Alhnan, Waqar Ahmed, Ahmed Faheem, David A. Phoenix, Kevin M. G. Taylor, and Abdelbary Elhissi. The effects of suspension particle size on the performance of air-jet, ultrasonic and vibrating-mesh nebulisers. *International Journal of Pharmaceutics*, 461(1):234–241, January 2014. doi: 10.1016/j.ijpharm.2013.11.022. URL <https://www.sciencedirect.com/science/article/pii/S0378517313010156>.
- [103] Ralph W. Niven, Anna Y. Ip, S. Mittelman, S. J. Prestrelski, and T. Arakawa. Some Factors Associated with the Ultrasonic Nebulization of Proteins. *Pharmaceutical Research*, 12(1):53–59, January 1995. doi: 10.1023/A:1016282502954. URL <https://doi.org/10.1023/A:1016282502954>.
- [104] Megbar Wondie. Modeling cloud seeding technology for rain enhancement over the arid and semiarid areas of Ethiopia. *Heliyon*, 9(4), April 2023. doi: 10.1016/j.heliyon.2023.e14974. URL [https://www.cell.com/heliyon/abstract/S2405-8440\(23\)02181-3](https://www.cell.com/heliyon/abstract/S2405-8440(23)02181-3).
- [105] Hans Hersbach, Bill Bell, Paul Berrisford, Shoji Hiraehara, András Horányi, Joaquín Muñoz-Sabater, Julien Nicolas, Carole Peubey, Raluca Radu, Dinand Schepers, Adrian Simmons, Cornel Soci, Saleh Abdalla, Xavier Abellan, Gianpaolo Balsamo, Peter Bechtold, Gionata Biavati, Jean Bidlot, Massimo Bonavita, Giovanna De Chiara, Per Dahlgren, Dick Dee, Michail Diamantakis, Rossana Dragani, Johannes Flemming, Richard Forbes, Manuel Fuentes, Alan Geer, Leo Haimberger, Sean Healy, Robin J. Hogan, Elías Hólm, Marta Janisková, Sarah Keeley, Patrick Laloyaux, Philippe Lopez, Cristina Lupu, Gabor Radnoti, Patricia de Rosnay, Iryna Rozum, Freja Vamborg, Sebastien Villaume, and Jean-Noël Thépaut. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730):1999–2049, 2020. doi: 10.1002/qj.3803. URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/qj.3803>.
- [106] ERA5 hourly data on single levels from 1940 to present, 2023.
- [107] G.J. Huffman, E.F. Stocker, D.T. Bolvin, E.J. Nelkin, and J. Tan. GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V07, 2023. URL https://cmr.earthdata.nasa.gov/search/concepts/C2723754847-GES_DISC.
- [108] George J. Huffman, David T. Bolvin, Robert Joyce, Eric J. Nelkin, Jackson Tan, Dan Braithwaite, Kuolin Hsu, Owen A. Kelley, Phu Nguyen, Soroosh Sorooshian, Daniel C. Watters, B. Jason West, and Pingping Xie. IMERG V07 ATBD. Technical report, National Aeronautics and Space Administration (NASA), July 2023. URL <https://gpm.nasa.gov/resources/documents/imerg-v07-atbd>.
- [109] Rajani K. Pradhan, Yannis Markonis, Mijael Rodrigo Vargas Godoy, Anahí Villalba-Pradas, Konstantinos M. Andreadis, Efthymios I. Nikolopoulos, Simon Michael Papalexiou, Akif Rahim, Francisco J. Tapiador, and Martin Hanel. Review of GPM IMERG performance: A global perspective. *Remote Sensing of Environment*, 268:112754, January 2022. doi: 10.1016/j.rse.2021.112754. URL <https://www.sciencedirect.com/science/article/pii/S0034425721004740>.
- [110] Jackson Tan, George J. Huffman, David T. Bolvin, and Eric J. Nelkin. IMERG V06: Changes to the Morphing Algorithm. *Journal of Atmospheric and Oceanic Technology*, December 2019. doi: 10.1175/JTECH-D-19-0114.1. URL <https://journals.ametsoc.org/view/journals/atot/36/12/jtech-d-19-0114.1.xml>.
- [111] Jackson Tan, George J. Huffman, David T. Bolvin, and Eric J. Nelkin. Diurnal Cycle of IMERG V06 Precipitation. *Geophysical Research Letters*, 46(22): 13584–13592, 2019. doi: 10.1029/2019GL085395. URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2019GL085395>.
- [112] Hakan Aksu and Sait Genar Yaldiz. Performance comparison of GPM IMERG V07 with its predecessor V06 and its application in extreme precipitation clustering over Türkiye. *Atmospheric Research*, 315: 107840, April 2025. doi: 10.1016/j.atmosres.2024.107840. URL <https://www.sciencedirect.com/science/article/pii/S0169809524006227>.
- [113] Tianqi Chen and Carlos Guestrin. XGBoost: A Scalable Tree Boosting System. In *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, KDD ’16, pages 785–794, New York, NY, USA, August 2016. Association for Computing Machinery. ISBN 978-1-4503-4232-2. doi: 10.1145/2939672.2939785.

URL <https://dl.acm.org/doi/10.1145/2939672.2939785>.

<https://www.sciencedirect.com/science/article/pii/S016786550500303X>.

- [114] Yiwen Mao and Asgeir Sorteberg. Improving Radar-Based Precipitation Nowcasts with Machine Learning Using an Approach Based on Random Forest. *Weather and Forecasting*, November 2020. doi: 10.1175/WAF-D-20-0080.1. URL <https://journals.ametsoc.org/view/journals/wef/35/6/waf-d-20-0080.1.xml>.
- [115] Suman Ravuri, Karel Lenc, Matthew Willson, Dmitry Kangin, Remi Lam, Piotr Mirowski, Megan Fitzsimons, Maria Athanassiadou, Sheleem Kashem, Sam Madge, Rachel Prudden, Amol Mandhane, Aidan Clark, Andrew Brock, Karen Simonyan, Raia Hadsell, Niall Robinson, Ellen Clancy, Alberto Arribas, and Shakir Mohamed. Skilful precipitation nowcasting using deep generative models of radar. *Nature*, 597(7878):672–677, September 2021. doi: 10.1038/s41586-021-03854-z. URL <https://www.nature.com/articles/s41586-021-03854-z>.
- [116] Lasse Espeholt, Shreya Agrawal, Casper Sønderby, Manoj Kumar, Jonathan Heek, Carla Bromberg, Cenk Gizen, Rob Carver, Marcin Andrychowicz, Jason Hickey, Aaron Bell, and Nal Kalchbrenner. Deep learning for twelve hour precipitation forecasts. *Nature Communications*, 13(1):5145, September 2022. doi: 10.1038/s41467-022-32483-x. URL <https://www.nature.com/articles/s41467-022-32483-x>.
- [117] David R. Roberts, Volker Bahn, Simone Ciuti, Mark S. Boyce, Jane Elith, Gurutzeta Guillera-Arroita, Severin Hauenstein, José J. Lahoz-Monfort, Boris Schröder, Wilfried Thuiller, David I. Warton, Brendan A. Wintle, Florian Hartig, and Carsten F. Dormann. Cross-validation strategies for data with temporal, spatial, hierarchical, or phylogenetic structure. *Ecography*, 40(8):913–929, 2017. doi: 10.1111/ecog.02881. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/ecog.02881>.
- [118] Pierre Ploton, Frédéric Mortier, Maxime Réjou-Méchain, Nicolas Barbier, Nicolas Picard, Vivien Rossi, Carsten Dormann, Guillaume Cornu, Gaëlle Viennois, Nicolas Bayol, Alexei Lyapustin, Sylvie Gourlet-Fleury, and Raphaël Pélissier. Spatial validation reveals poor predictive performance of large-scale ecological mapping models. *Nature Communications*, 11(1):4540, September 2020. doi: 10.1038/s41467-020-18321-y. URL <https://www.nature.com/articles/s41467-020-18321-y>.
- [119] Tom Fawcett. An introduction to ROC analysis. *Pattern Recognition Letters*, 27(8):861–874, June 2006. doi: 10.1016/j.patrec.2005.10.010. URL <https://www.sciencedirect.com/science/article/pii/S016786550500303X>.
- [120] Jesse Davis and Mark Goadrich. The relationship between Precision-Recall and ROC curves. In *Proceedings of the 23rd international conference on Machine learning*, ICML ’06, pages 233–240, New York, NY, USA, June 2006. Association for Computing Machinery. ISBN 978-1-59593-383-6. doi: 10.1145/1143844.1143874. URL <https://dl.acm.org/doi/10.1145/1143844.1143874>.
- [121] Takaya Saito and Marc Rehmsmeier. The Precision-Recall Plot Is More Informative than the ROC Plot When Evaluating Binary Classifiers on Imbalanced Datasets. *PLOS ONE*, 10(3):e0118432, March 2015. doi: 10.1371/journal.pone.0118432. URL <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0118432>.
- [122] Glenn W. Brier. VERIFICATION OF FORECASTS EXPRESSED IN TERMS OF PROBABILITY. *Monthly Weather Review*, January 1950. doi: 10.1175/1520-0493(1950)078<0001:VOFEIT>2.0.CO;2. URL https://journals.ametsoc.org/view/journals/mwre/78/1/1520-0493_1950_078_0001_vofeit_2_0_co_2.xml.
- [123] Scott M. Lundberg, Gabriel Erion, Hugh Chen, Alex DeGrave, Jordan M. Prutkin, Bala Nair, Ronit Katz, Jonathan Himmelfarb, Nisha Bansal, and Su-In Lee. From local explanations to global understanding with explainable AI for trees. *Nature Machine Intelligence*, 2(1):56–67, January 2020. doi: 10.1038/s42256-019-0138-9. URL <https://www.nature.com/articles/s42256-019-0138-9>.
- [124] R. G. Harrison, K. A. Nicoll, and M. H. P. Ambaum. On the microphysical effects of observed cloud edge charging. *Quarterly Journal of the Royal Meteorological Society*, 141(692):2690–2699, 2015. doi: 10.1002/qj.2554. URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/qj.2554>.
- [125] Spencer Faber, Jeffrey R. French, and Robert Jackson. Laboratory and in-flight evaluation of measurement uncertainties from a commercial Cloud Droplet Probe (CDP). *Atmospheric Measurement Techniques*, 11(6):3645–3659, June 2018. doi: 10.5194/amt-11-3645-2018. URL <https://amt.copernicus.org/articles/11/3645/2018/>.
- [126] Maren Roman. Toxicity of Cellulose Nanocrystals: A Review. *Industrial Biotechnology*, 11(1):25–33, February 2015. doi: 10.1089/ind.2014.0024. URL <https://doi.org/10.1089/ind.2014.0024>.
- [127] James D. Ede, Kimberly J. Ong, Michael Gørgen, Alan Rudie, Cassidy A. Pomeroy-Carter, and Jo Anne Shatkin. Risk Analysis of Cellulose

Nanomaterials by Inhalation: Current State of Science. *Nanomaterials*, 9(3):337, March 2019. doi: 10.3390/nano9030337. URL <https://www.mdpi.com/2079-4991/9/3/337>.

- [128] Natasha Stoudmann, Mélanie Schmutz, Cordula Hirsch, Bernd Nowack, and Claudia Som. Human hazard potential of nanocellulose: quantitative insights from the literature. *Nanotoxicology*, 14(9):1241–1257, October 2020. doi: 10.1080/17435390.2020.1814440. URL <https://doi.org/10.1080/17435390.2020.1814440>.
- [129] Carola Endes, Silvana Mueller, Calum Kinnear, Dimitri Vanhecke, E. Johan Foster, Alke Petri-Fink, Christoph Weder, Martin J. D. Clift, and Barbara Rothen-Rutishauser. Fate of Cellulose Nanocrystal Aerosols Deposited on the Lung Cell Surface In Vitro. *Biomacromolecules*, 16(4):1267–1275, March 2015. doi: 10.1021/acs.biomac.5b00055. URL <https://doi.org/10.1021/acs.biomac.5b00055>.
- [130] Naveena Yanamala, Mariana T. Farcas, Meghan K. Hatfield, Elena R. Kisin, Valerian E. Kagan, Charles L. Geraci, and Anna A. Shvedova. In Vivo Evaluation of the Pulmonary Toxicity of Cellulose Nanocrystals: A Renewable and Sustainable Nanomaterial of the Future. *ACS Sustainable Chemistry & Engineering*, 2(7):1691–1698, April 2014. doi: 10.1021/sc500153k. URL <https://doi.org/10.1021/sc500153k>.
- [131] U.S. Environmental Protection Agency. Biopesticides Registration Action Document: Saponins of *Quillaja saponaria*. Technical Report 097095, Office of Pesticide Programs, Biopesticides and Pollution Prevention Division, September 2009. URL https://www3.epa.gov/pesticides/chem_search/reg_actions/registration/decision_PC-097095_11-Sep-09.pdf.
- [132] C. Fajardo, G. Costa, L. T. Ortiz, M. Nande, M. L. Rodríguez-Membibre, M. Martín, and S. Sánchez-Fortún. Potential risk of acute toxicity induced by AgI cloud seeding on soil and freshwater biota. *Ecotoxicology and Environmental Safety*, 133:433–441, November 2016. doi: 10.1016/j.ecoenv.2016.06.028. URL <https://www.sciencedirect.com/science/article/pii/S0147651316302342>.
- [133] Akshi Kunwar Singh, B. Abhijith, and Leelakant Dewangan. Safety Concerns and Consequences of Cloud Seeding Implications—A Systematic Review. In N. A. Siddiqui, Akmalov Shamshodbek Baxtiyarovich, Abhishek Nandan, and Prasenjit Mondal, editors, *Advances in Waste Management*, pages 11–27, Singapore, 2023. Springer Nature. ISBN 978-981-19-7506-6. doi: 10.1007/978-981-19-7506-6_2.