air2

An Ultra Low-Cost Bioaerosol Analyzer for Pandemic Prevention

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1. ABSTRACT

We have rigorous standards for tap water but accept invisible pathogens in our air because we lack continuous bioaerosol monitoring to see and enforce clean air. Commercial analyzers cost over $50,000, restricting deployment to research labs. This project develops air2, a novel bioaerosol detection system costing $300 that integrates three validated techniques: electrostatic precipitation for efficient particle collection, smartphone-based visible fluorescence spectroscopy for low-cost metabolic fingerprinting, and machine learning classification trained on large bioaerosol datasets.

The system concentrates airborne particles into liquid using a 3D-printed electrostatic precipitator (ESP), then analyzes intrinsic fluorescence from metabolic molecules (NADH, flavins) via a smartphone spectrometer with DVD-grating optics. The ESP design, validated by Priyamvada et al. (2020), achieves >50% collection efficiency for particles 0.01-10 μm—including bacteria and viruses that conventional low-cost cyclones miss. Lock-in detection on an Arduino achieves sensitivity approaching PMT-based systems at a fraction of the cost. A CNN pretrained on public WIBS datasets and fine-tuned classifies particles as biological or non-biological based on NADH/flavin fluorescence ratios.

Validation uses safe proxies: nebulized NADH and riboflavin as fluorescence standards, baker's yeast as a cellular bioaerosol, and sodium chloride as a negative control. Success criteria include detection limit below 1 μM NADH equivalent and classification accuracy exceeding 80%. By demonstrating that ESP collection, visible fluorescence, and ML classification can achieve useful bioaerosol discrimination at 1/150th the cost of commercial instruments, air2 addresses the critical bottleneck preventing clean air standards from becoming as rigorous as those for water.

2. IDEA

Problem

Clean water is now a fundamental right, achieved through infrastructure and rigorous verification. We do not accept cholera in our tap, but we accept influenza and COVID-19 in the air we breathe and assume a few days off each year to recover from cold. This is because unlike muddy water, microscopic pathogens in the air are invisible.

The bottleneck of the clean air revolution is in detection. We have safe sterilization technology (HEPA filters, Far-UVC), but a regulation would need an affordable way to enforce it. Unlike particles (PM2.5) or CO2, bioaerosols are not easily proxied. Without a scalable way to make pathogens visible, businesses lack cost-benefit data to invest in safety, and the public can't see the need to demand it. Detection is the fulcrum.

However, current monitoring is reactive. Respiratory pathogens, including the flu, coronavirus, and tuberculosis, spread mainly through aerosols (particles <5μm that stay in air for extended periods) (Fennelly, 2020). The COVID-19 pandemic showed just how fast airborne pathogens can spread through indoor environments, but by the time outbreaks are detected through symptoms, exponential transmission has already occurred (Lipsitch et al., 2020). Mathematical modeling shows that for a pathogen with basic reproduction number R_0=2.5, each day of delayed detection results in ~2.5x more infections (Fraser et al., 2004). A bioaerosol system could monitor spikes and alert building managers, schools, or public health officials before visible outbreaks merge.

The scientific basis for detection relies on intrinsic fluorescence. Biological particles contain molecules that absorb UV and re-emit longer wavelengths. The main fluorophores are: **NADH**: 340 nm excitation, 450 nm emission (metabolic indicator); **Flavins**: 450 nm excitation,

520nm emission (cellular cofactors); and **Tryptophan**: 280nm excitation, 340-350nm emission (present in all proteins). Critically, NADH and flavins emit in the visible spectrum, making them detectable by smartphone cameras. Commercial WIBS instruments use the Tryptophan/NADH fluorescence ratio to distinguish bacteria from fungi and pollen (Pöhlker et al., 2012).

Current Work

1. Commercial UV-LIF instruments like **WIBS** fire lasers and read with PMTs for real-time classification. They have excellent specificity but cost $55k-$77k, restricting deployment to research settings (Savage & Huffman, 2018; Niederberger, 2022). Several research groups have developed reduced-cost alternatives. **Optical Particle Counters** like Alphasense ($650) use laser to scatter and size airborne particles: real-time and low maintenance but can't distinguish a pollen or virus carrier (Crilley et al., 2018). They're plagued by false alarms. **Sampling only methods** like wet-cyclone sampling, ABLE's nucleation condensation (~$200), and electrostatic precipitators (ESP) can capture airborne biomarkers, but they only collect, needing transport to a lab for PCR/analysis (Ma et al., 2025). Lastly, **smartphone microscopy** (optics attachments) can image settled spores/pollen and are cheap, but struggle on the relevant airborne and small particles (Schaefer et al., 2023). These limitations explain why rapid bioaerosol monitoring are still absent from schools, offices, and public buildings where it could provide truly remarkable public health benefit.

Solution:

air2 addresses the barrier to low-cost bioaerosol detection by synergizing four innovations:

1. Electrostatic Precipitation (ESP) for Sub-Micron Particle Collection

air2 uses ESP, a proven method of cheap bioaerosol capture, to condense particles for higher sensitivity in detection. Then, unlike current methods that require lab tests, we will merge

it with continuous monitoring. Instead of cyclone collectors (which rely on powerful pumps and large particles), ESP is static. A high-voltage (HV) needle ionizes passing air, charging bioaerosol particles. The charged particles are then attracted (by Coulomb's force) to a grounded liquid collector. This approach, validated by Priyamvada et al. (2020) in TracB bioaerosol sampler, achieves >50% collection efficiency for particles 0.01-10μm using only a low-power fan. Note: corona discharge produces ozone, which can degrade biological molecules. We mitigate this by collecting into an antioxidant buffer (dilute ascorbic acid or sodium thiosulfate), a technique recently validated for virus collection in ESPs (Piri et al., 2024).

2. Visible-Wavelength Fluorescence Detection with Smartphones

air2 uses smartphones, not to image tiny pathogens (as was proven inaccurate) but to analyze fluorescence. Commercial sensors use tryptophan/NADH fluorescence for detection. air2 targets NADH and flavins, molecules that emit visible light and present in all living cells. NADH/flavin fluorescence ratio varies by organism type (e.g. between bacteria, fungi, and pollen), allowing discrimination without UV detectors. This lowers production cost without degrading accuracy.

3. Lock-In Amplification for Signal Extraction

Biological fluorescence is weak. Standard photodiodes generate substantial thermal and electronic noise that can overwhelm the signal. air2 implements lock-in detection: the excitation LED is modulated at 1 kHz, and the Arduino multiplies the photodiode signal by a reference waveform at the same frequency. Noise at other frequencies is rejected by lowpass filtering. This technique, standard in research spectroscopy but absent from low-cost bioaerosol sensors, improves SNR by 100-1000x (Stanford Research Systems, 2016).

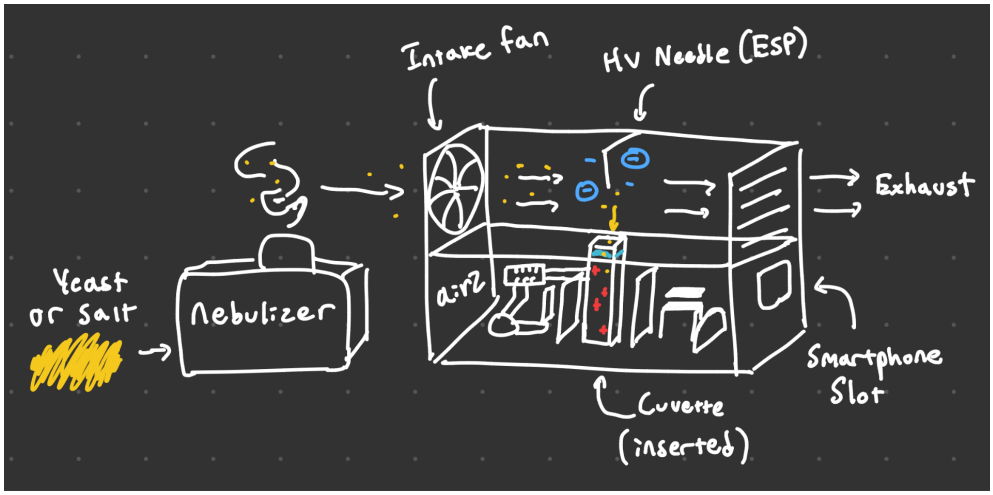
4. Machine Learning Classification

Finally, air2 overcomes Alphasense's false-alarms with recent ML advancements. We DVD-diffract fluorescent emissions to obtain full-spectra information. Then, we pretrain a CNN on public datasets from commercial WIBS instruments that contain thousands of labeled bioaerosol measurements. With tuning from air2's own sensor spectra, our model will learn to distinguish biological from non-biological particles based on fluorescence patterns. This leverages expensive commercial instrumentation to achieve useful bioaerosol discrimination at 1/150th the cost of commercial instruments.

3. PLAN

Approach:

Module 1: Electrostatic Precipitator (ESP)

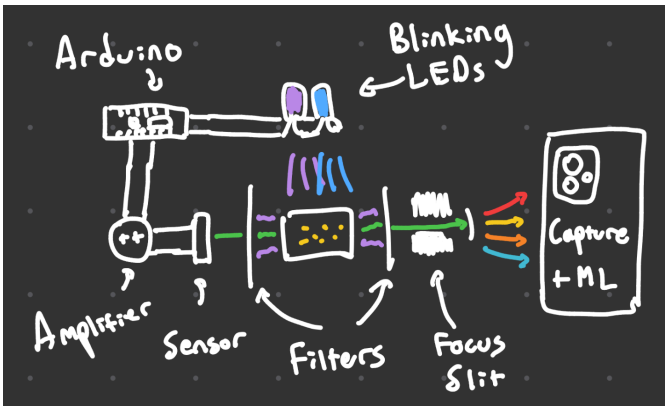


Yeast (proxy for bioaerosol) or salt (control) is nebulized. A 3D-printed vertical chamber houses the collection system. A 40mm PC fan draws air through the chamber at approximately 5 CFM (140 L/min). At the top, a stainless steel needle connected to a high-voltage DC module (-8 to -15 kV) creates a corona discharge, ionizing the air and charging passing bioaerosol particles. The charged particles are repelled from the needle and attracted to the grounded liquid collector (a UV-transparent cuvette) at the chamber base.

Collection efficiency scales with electric field strength. At 8 kV/cm, Priyamvada et al. (2020) report >50% efficiency for particles 0.01-10 µm. Our design targets 10 kV with a 1 cm needle-to-liquid gap, yielding comparable field strength.

The collection liquid is an *antioxidant buffer*: 1) distilled water base, 2) 10mM NaCl (conductive), and 3) 10mM ascorbic acid (scavenges ozone). After 30 minutes at 140 L/min, the system processes 4200 liters of air into 3 mL of liquid-a 700,000x effective concentration factor, far exceeding low-cost cyclones. **Safety note**: the 15 kV supply operates at <100µA, delivering less energy than a static shock; the HV line will include a series Gigohm current-limiting resistor near needle to limit output current <50µA even in the event of a direct short. A magnetic kill-switch will cut power to the HV module immediately if the case is opened.

Module 2: Dual-Channel Lock-In Fluorescence Detection (Continuous Monitoring)



Channel 1 UV LED fires 365nm at 1kHz, NADH absorbs and reemits 450nm; emission passes through a 400 nm longpass filter to a silicon photodiode. Then, system switches. *Channel 2 Blue LED* fires 450nm at 1kHz, Flavins absorbs and reemits 520nm (green); 500nm longpass filter blocks blue and lets green glow through.

During both channels, silicon photodiode sensor captures and sends signal through amplifier to Arduino ESP32. Arduino implements lock-in detection: (1) Generates 1 kHz PWM to modulate the excitation LED, (2) samples photodiode at 10 kHz, (3) multiplies by reference waveform (in-phase and quadrature components), (4) lowpass filters (10 Hz cutoff) to extract DC magnitude, (5) reports NADH and flavin intensities; computes ratio.

Based on learned ratio, if it senses high signal, trigger **Module 3** for verification.

Module 3: Smartphone Spectrometer + ML Classification (Prevent False-Alarm)

For full-spectra analysis, the Arduino stops blinking and turns the LED Solid ON. Emitted light is focused via slit and fluorescence is dispersed using a 3D-printed smartphone spectrometer (McGonigle et al., 2018). A DVD diffraction grating separates wavelengths across the camera sensor; custom software converts the image to a calibrated spectrum spanning 400-700 nm.

The ML pipeline: (1) download BIOARC WIBS dataset (publicly available), (2) extract NADH-channel and flavin-channel intensity ratios, (3) train CNN classifier (MobileNet backbone, fine-tuned), (4) validate on held-out test set; report accuracy and confusion matrix, (5) collect and fine-tune with custom data from air2 (6) combine trained model to air2 spectra.

Resources

Materials and Acquisition (details in table below): $302 total covering ESP components (HV module, fan, needle), optics (LEDs, filters, photodiode), electronics (Arduino, amplifier), fabrication (filament, cuvettes), and testing supplies (NADH, riboflavin, nebulizer). Components will be acquired from DigiKey, Amazon, Sigma-Aldrich, and school/local makerspace. BIOARC dataset is freely available from CEDA archive.

Mentorship Needs: ESP and optical system design, HV safety review, ML data collection/architecture guidance, potential access to biosafety facilities for biological validation.

Goals and Milestones

Milestone	Week	Success Criterion
M1: ESP prototype	3	Smoke test: visible smoke captured in liquid with HV on
M2: ESP efficiency validated	4	Fluorescein tracer test: >30% collection efficiency
M3: Lock-in detection functional	6	SNR >100:1 for 10 μM NADH solution

M4: Smartphone spectrometer calibrated	8	Spectrum matches reference within ±5 nm
M5: ML model trained	10	>80% accuracy on WIBS test set
M6: Full validation complete	14	Classification accuracy >75% on yeast vs. salt aerosols

Performance Specifications: Detection limit <1 μM NADH; classification accuracy >75% bio vs. non-bio; lock-in SNR improvement >100x; collection efficiency >30% for 1 μm particles; spectral resolution <5 nm.

Evaluation: (1) ESP efficiency measured via fluorescein tracer test, (2) NADH/riboflavin standard curves for sensitivity, (3) nebulize yeast vs salt for specificity comparison, (4) lock-in SNR with/without modulation, (5) ML cross-validated confusion matrix.

Risks

Risk 1: Lock-in SNR insufficient: Arduino ADC noise may limit performance. Mitigations: external ADC ($15), higher LED modulation frequency, or dedicated lock-in IC (AD630, ~$20).

Risk 2: Emission too dim for smartphone: Intrinsic bio-fluorescence is faint. Mitigations: long 30-second exposure images and software-side pixel binning too boost SNR by >10x. If loss still too high, pivot to 11-channel AS7341 spectral sensor ($20) which eliminates the need for diffraction optics and provides direct, calibrated spectral data for the ML classifier..

Risk 3: ML transfer fails: WIBS may use different wavelengths. Mitigations: curate larger air2 dataset, use simpler algorithms (Random Forest), test tryptophan approach below in Risk 4.

Risk 4: NADH/flavins are bad proxies in production: Respiratory droplets may be better mimicked by tryptophan/NADH (as with commercial use). Mitigation: alternative realtime approach: High-static-pressure 40mm fan pulls air in, nozzle diverts/concentrates air to dark 3mmx3mm sensing chamber, UV-LED illuminates *tryptophan*, SiPM (~$20) with filter sees UV flash and photodiode sizes particle, and algorithm discriminates pollen/dust.

Project Budget $302: Unlinked are estimates.

Item	Qty	Unit Cost	Total	Supplier
ESP Collection				
HV DC module (12V->15kV)	1	$12.00	$12.00	Amazon
40mm PC fan (12V)	1	$15.00	$15.00	Amazon
Stainless steel needle	2	$1.00	$2.00	Amazon
Optics				
UV LED 365nm, 3W	1	$12.00	$12.00	DigiKey
Blue LED 450nm, 3W	1	$8.00	$8.00	DigiKey
Longpass filter 400nm	1	$17.24	$17.24	Amazon
Longpass filter 500nm	1	$12.95	$12.95	Amazon
Cuvettes (UV-transparent, pack)	1	$15.00	$15.00	Amazon/School
Electronics				
Arduino Nano/ESP32	1	$20.00	$20.00	Amazon
Silicon photodiode (BPW34)	1	$6.89	$6.89	Amazon
Op-amp (OPA380) for TIA	2	$5.00	$10.00	DigiKey
Resistors, capacitors (kit)	1	$15.00	$15.00	Amazon
MOSFET, LED driver components	1	$10.00	$10.00	DigiKey
Fabrication				
PLA filament (1 kg, black)	1	$20.00	$20.00	Amazon/School
Tubing, connectors, enclosure	1	$15.00	$15.00	Hardware store
Testing supplies				
NADH (100 mg)	if needed	$178.00		Sigma-Aldrich
Riboflavin (25g)	1	$42.10	$15.00	Sigma-Aldrich
Fluorescein (for ESP test)	1	$13.99	$13.99	Amazon
Ascorbic acid (antioxidant buffer)	1	$22.00	$22.00	Amazon
Ultrasonic nebulizer	1	$34.99	$34.99	Amazon
Sodium chloride (4lb)	1	$10.00	$10.00	Amazon
Baker's yeast	1	$5.00	$5.00	Grocery
Isopropyl alcohol (cleaning)	1	$8.00	$8.00	Amazon
DVD (diffraction grating source)	1	$2.00	$2.00	Any store

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