

Design and Preliminary PM_{2.5} Characterization of a Low-Cost Zeolite–Titanium Dioxide Air Filtration Device

Anshuman Roy¹, Santiago Gonzalez Silva², Bhumija Grandhe³,
Sydney Guillaume⁴, Jailyn Agard⁵

¹Bridgewater-Raritan Regional High School, Bridgewater, NJ, USA

²Wayne Hills High School, Wayne, NJ, USA

³Academy for Health and Medical Sciences, Somerset County
Vocational & Technical High School, Bridgewater, NJ, USA

⁴Bard High School Early College Newark, Newark, NJ, USA

⁵Ramapo College of New Jersey, Mahwah, NJ, USA

anroy2209@gmail.com • Santiago.gonzalezsilva@yale.edu • bhumijagb@gmail.com
sydneyguillaume2009@gmail.com • mragard13@gmail.com

Corresponding author: Anshuman Roy, anroy2209@gmail.com

ORCID: <https://orcid.org/0009-0008-1271-2730>

This is a non-peer-reviewed preprint submitted to engrXiv. The manuscript has not been submitted to a peer-reviewed journal at this time.

Design and Preliminary PM_{2.5} Characterization of a Low-Cost Zeolite–Titanium Dioxide Air Filtration Device

Anshuman Roy¹, Santiago Gonzalez Silva², Bhumija Grandhe³, Sydney Guillaume⁴, Jailyn Agard⁵

¹Bridgewater-Raritan Regional High School, Bridgewater, NJ, USA

²Wayne Hills High School, Wayne, NJ, USA

³Academy for Health and Medical Sciences, Somerset County Vocational & Technical High School, Bridgewater, NJ, USA

⁴Bard High School Early College Newark, Newark, NJ, USA

⁵Ramapo College of New Jersey, Mahwah, NJ, USA

anroy2209@gmail.com; Santiago.gonzalezsilva@yale.edu; bhumijagb@gmail.com;

sydneyguillaume2009@gmail.com; mragard13@gmail.com

Abstract—This study presents the design and preliminary fine particulate matter (PM_{2.5}) characterization of a low-cost air-filtration device intended to reduce localized exposure to air pollution in densely populated and high-traffic communities. The fan-driven device combines two minimum efficiency reporting value (MERV) 13 filters, a clinoptilolite zeolite bed, and an exterior anatase titanium dioxide (TiO₂) coating for particulate filtration and potential gas-phase adsorption and photocatalysis. Quantitative analysis focused on PM_{2.5} because the AirGradient Open Air monitor reported nitrogen oxides (NO_x) only as a relative index. Testing used a repeated-measures alternating OFF/ON crossover design at a residential site in Essex County, New Jersey, across four sessions using controlled particulate loading; two sessions met a prespecified concentration gate for pooled analysis. Paired OFF–ON differences were evaluated using a two-sided Wilcoxon signed-rank test with a prespecified significance level of 0.05. Across 29 pooled block pairs, mean PM_{2.5} was 1.10 $\mu\text{g m}^{-3}$ (9.6%) lower during ON than OFF blocks; 17 of 29 paired differences were positive ($W = 135.5$, $p = 0.076$), and the result did not reach the prespecified significance threshold. Larger-scale testing with paired sensors is needed to determine whether the observed difference is reproducible and to evaluate quantitative NO_x performance.

Index Terms—PM_{2.5}, air filtration, zeolite, titanium dioxide, environmental justice

I. INTRODUCTION

Fine particulate matter (PM_{2.5}), consisting of particles with aerodynamic diameters of 2.5 μm or less, can penetrate deep into the lungs and has been associated with aggravated asthma, reduced lung function, cardiovascular complications, respiratory symptoms, and premature death [1]. Traffic-related nitrogen oxides (NO_x), including nitrogen dioxide (NO₂), are produced during fuel combustion and can adversely affect the respiratory system [2]. Although the device incorporates zeolite and titanium dioxide for potential gas-phase pollutant removal, this study evaluates PM_{2.5} because the available monitor provided quantitative PM_{2.5} measurements.

Newark contains major highways, Newark Liberty International Airport, and the Port Newark–Elizabeth Marine Terminal, creating substantial transportation-related emission

sources. The New Jersey Department of Environmental Protection (NJDEP) identifies urban environmental justice communities near major roads and ports as disproportionately affected by transportation emissions [3], while national research has found higher-than-average PM_{2.5} exposure among people of color across most major emission sources [4]. Research in Newark has examined associations between PM_{2.5} and pediatric asthma emergency department visits [5].

Current mitigation strategies include emissions regulation, transportation electrification, industrial controls, green infrastructure, and filtration, but large-scale implementation requires substantial funding, infrastructure, and maintenance. New Jersey’s 2023–2025 Regional Greenhouse Gas Initiative Strategic Funding Plan reported transportation electrification below the level needed to meet long-term emission-reduction goals [3], while filtration systems require filter replacement, eventual adsorbent replacement, and continuous fan power [6]. These constraints motivate affordable systems for high-exposure community spaces. This study therefore developed a low-cost, fan-driven device combining minimum efficiency reporting value (MERV) 13 filtration, a clinoptilolite zeolite bed, and a titanium dioxide photocatalytic coating, and reports its preliminary PM_{2.5} characterization under an alternating OFF/ON crossover protocol in a residential New Jersey microenvironment.

II. BACKGROUND

Zeolites are crystalline, microporous materials composed primarily of interconnected silicon, aluminum, and oxygen atoms. Natural zeolites often form when volcanic ash or rock reacts with alkaline water, although zeolites can also be synthesized with structures designed for specific applications. Their three-dimensional frameworks contain uniformly sized channels and cavities that create a large internal surface area [7]. Because only molecules of appropriate sizes and shapes can enter these pores, zeolites can function as molecular sieves and selective adsorbents [7], [8]. Their adsorption capacity, ion-exchange ability, structural stability, and molecular selec-

TABLE I
MATERIAL COST BREAKDOWN FOR FILTRATION DEVICE CONSTRUCTION

Name of Item	Cost
Box Fan	\$30
MERV 13 pleated air filters (2)	\$45
Mesh with Zeolite	\$25
Titanium Dioxide	\$1
Base Structure	\$30
Miscellaneous Items	\$20
Total Cost	\$151

tivity have made them useful in gas separation and catalysis [7], [8].

Titanium dioxide (TiO_2) is a chemically stable semiconductor commonly used in environmental photocatalysis. When the anatase phase of TiO_2 absorbs ultraviolet light, electrons are excited from the valence band to the conduction band, leaving positively charged holes. These charge carriers participate in oxidation and reduction reactions and can generate reactive oxygen species (ROS) that chemically degrade pollutants [9]. Combining zeolite and TiO_2 may improve performance, as zeolite concentrates pollutants near photocatalytically active TiO_2 surfaces. Prior work on $\text{TiO}_2/\text{HZSM-5}$ composites reported higher nitric oxide conversion than pure TiO_2 , although humidity affected performance [10]. The present device uses physically separate clinoptilolite and exterior TiO_2 rather than a TiO_2 /zeolite composite.

In the proposed system, the zeolite bed is intended primarily as a gas-phase adsorbent for molecules compatible with its micropore channels. Any contribution to particulate capture was not separately evaluated. Ultraviolet radiation in ambient sunlight may activate the exterior TiO_2 coating, potentially enabling passive photocatalytic degradation of gas-phase pollutants at exposed device surfaces during daytime operation [9].

III. DEVICE DESIGN

To construct the air filter, the main materials included two MERV 13 pleated air filters, clinoptilolite zeolite, titanium dioxide, the base structure, and the box fan.

The filtration device is a multistage air-filtration unit housed in a wooden box frame with 20×20 in filter faces and a total materials cost of approximately \$151 (Table I). On the intake side, an external Utilitech 20-inch 3-speed box fan rated at 2300 Cubic Feet per Minute (CFM) free-air on high, used throughout testing, drives air through the device. This active configuration was adopted to provide forced airflow rather than rely solely on ambient wind. The completed device and airflow pathway are shown in Fig. 1.

A. Filtration Sequence

The device contains a three-stage filtration sequence supplemented by an exterior titanium dioxide coating. The first stage is a 20×20 in MERV 13 pleated filter (Filterbuy, electrostatically charged synthetic media) on the intake side, serving as a pre-filter that captures coarse particulate matter such as dust, pollen, and debris. The second stage is

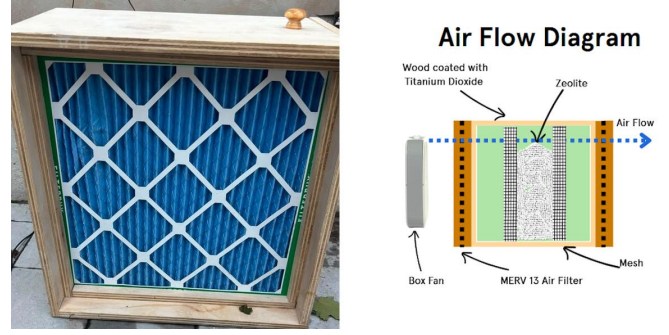


Fig. 1. Filtration device and airflow pathway. Left: completed device with MERV 13 intake filter. Right: airflow through the MERV 13 pre-filter, clinoptilolite zeolite bed, and MERV 13 exhaust filter; exterior wooden surfaces are coated with TiO_2 .

a clinoptilolite zeolite bed (US Sieve Mesh 3–7, sourced from Purified Air) contained within a dual-layer fiberglass screen mesh panel (Saint-Gobain ADFORS, 18×16 mesh, ~ 1.0 mm openings). Three horizontal seams formed with hot-melt adhesive divide the panel into four sealed channels to maintain uniform granule distribution when the device is oriented vertically. An anatase-phase titanium dioxide coating is applied to the exterior wooden surfaces to provide a surface potentially photocatalytically active under ambient ultraviolet exposure. The final filtration stage is a second MERV 13 filter on the exhaust side, which captures any residual zeolite dust or fine particulates before filtered air exits the device. The properties and filtration mechanisms of both zeolite and titanium dioxide are discussed in Section II.

B. Design Rationale and Material Selection

The selection of materials and device geometry was based on prior research on air filtration optimization. Prior work has demonstrated nitric oxide adsorption on zeolitic materials [11]. The box filter geometry was selected over a flat panel configuration to accommodate the multistage filtration sequence within a single enclosed structure. Prior testing of fan-driven do-it-yourself air cleaners using MERV 13 filters has demonstrated measurable $\text{PM}_{2.5}$ clean air delivery rates [12].

IV. METHODS

A. Site Description

Testing was conducted across four sessions from 31 July to 6 August 2026 in a residential microenvironment in Essex County, New Jersey, USA (approximate masked coordinates: 40.75° N, 74.20° W). Exact coordinates were rounded to two decimal places to protect private-property confidentiality. The device and monitor were positioned on an asphalt driveway outside a residence in a suburban-urban neighborhood. Potential background sources included vehicular traffic on nearby municipal roadways.

B. Instrumentation

PM_{2.5} concentrations were measured using an AirGradient Open Air O-1PST monitor, which contains a Plantower PMS5003T particle sensor and a Sensirion SGP41 gas sensor [13]. The SGP41 reports a relative NO_x index rather than quantitative NO_x concentration, so quantitative analysis focused on PM_{2.5}. A South Coast Air Quality Management District (AQMD) field evaluation of PurpleAir PA-II monitors, which use PMS5003 sensors related to the PMS5003T, reported strong PM_{2.5} correlations with Federal Equivalent Method (FEM) GRIMM measurements ($R^2 > 0.93$ for most sensor channels) [14]. Raw PMS5003T PM_{2.5} values were used for all analyses. The monitor was configured to log at 5-min intervals.

C. Experimental Setup

The filtration device was placed on the asphalt driveway with its intake oriented toward the nearby roadway. A box fan was positioned 15–20 cm in front of the device intake and directed toward the device. The fan was either OFF or ON according to the assigned block, defining the experimental state. The O-1PST was positioned approximately 30 cm downstream of the device exhaust, at approximately the height of the device centerline and within the directed exhaust airflow. Equipment positions of the filtration device base, box fan, and sensor were marked on the ground with chalk at the first session to ensure positional consistency.

Preliminary ambient measurements conducted before the four formal sessions showed that PM_{2.5} at the site could fall to approximately 1 $\mu\text{g m}^{-3}$, preventing resolution of a device-related difference under ambient conditions alone. Controlled particulate loading was therefore used in all four formal sessions: 3–4 incense sticks were placed in a holder approximately 1 m upwind of the device intake, with loading initiated approximately 30 min before the crossover protocol and replenished as needed to sustain elevated concentrations.

D. Experimental Protocol

A repeated-measures crossover design was used to characterize PM_{2.5} differences between device OFF and ON states using a single sensor. Because only one monitor was available, the device alternated between states at a fixed sensor location rather than using simultaneous upstream/downstream sensors.

The field campaign consisted of four testing sessions from 31 July to 6 August 2026. Each session comprised one or more consecutive 2-h testing periods. Each period contained eight 15-min blocks alternating between OFF and ON, yielding four adjacent block pairs, each containing one OFF and one ON block. The first 5 min of each block were discarded as equilibration time, leaving 10 min of usable data per block. The starting state for each session was randomized by coin flip, in which A denotes OFF and B denotes ON, and alternation continued throughout the session. The device remained in place regardless of fan state.

A block pair was excluded if either constituent block contained a documented anomalous event, such as a vehicle idling

adjacent to the device, or if sensor-recorded relative humidity (RH) exceeded 80%. Plantower-based low-cost monitors have demonstrated humidity-dependent PM_{2.5} bias [15]. The 80% threshold and all other exclusion criteria were prespecified before analysis.

Sessions were retained for pooled analysis only if they met a prespecified concentration gate: session mean PM_{2.5} > 5 $\mu\text{g m}^{-3}$ and $\geq 30\%$ of blocks with mean PM_{2.5} > 5 $\mu\text{g m}^{-3}$. Sessions failing this gate were reported as low-loading cases and were not pooled. The gate was based solely on PM_{2.5} concentration and was independent of the direction or magnitude of the OFF–ON difference.

For each block pair, mean PM_{2.5} concentration during the usable 10-min window was computed separately for the OFF block ($C_{\text{OFF},i}$) and ON block ($C_{\text{ON},i}$), and the paired difference was defined as $\Delta_i = C_{\text{OFF},i} - C_{\text{ON},i}$. Session-level and pooled relative differences reported in Table II were calculated from the corresponding aggregate OFF and ON means:

$$\% \text{ Difference} = \left(\frac{\bar{C}_{\text{OFF}} - \bar{C}_{\text{ON}}}{\bar{C}_{\text{OFF}}} \right) \times 100. \quad (1)$$

E. Statistical Analysis

Statistical inference on the pooled dataset used a two-sided Wilcoxon signed-rank test on the paired differences Δ_i , with a prespecified significance level of $\alpha = 0.05$. The Wilcoxon test was selected because the distribution of paired differences could not be assumed normal and the pooled sample was modest.

V. RESULTS

A. Session Inclusion

Four testing sessions were conducted from 31 July to 6 August 2026. Two sessions (Sessions 2 and 3) failed to meet the prespecified pooling criteria because controlled particulate loading did not sustain PM_{2.5} concentrations above the required threshold. PM_{2.5} during both remained at approximately 1 $\mu\text{g m}^{-3}$, such that no device-related difference could be resolved with the available sensor. These sessions are reported as low-loading cases and were not pooled. Sessions 1 ($N = 17$ block pairs) and 4 ($N = 12$ block pairs) both achieved sufficiently elevated PM_{2.5} concentrations under controlled particulate loading and cleared the prespecified gate, yielding $N = 29$ pooled block pairs.

B. Session-Level Results

Session 1 yielded a mean within-pair OFF–ON difference of $\Delta = 1.41 \mu\text{g m}^{-3}$ (18.3% relative difference), with 11 of 17 block pairs having positive differences (Wilcoxon signed-rank $W = 42.5$, $p = 0.107$). Session 4 yielded $\Delta = 0.65 \mu\text{g m}^{-3}$ (3.9% relative difference), with 6 of 12 block pairs having positive differences ($W = 30.0$, $p = 0.519$). Session-level and pooled summary statistics are reported in Table II, and the retained-session time series are shown in Fig. 2.

TABLE II

SESSION-LEVEL AND POOLED RESULTS FOR SESSIONS MEETING THE PRESPECIFIED POOLING GATE. Δ DENOTES THE MEAN WITHIN-PAIR DIFFERENCE (OFF – ON); OFF > ON GIVES THE NUMBER OF BLOCK PAIRS WITH LOWER PM_{2.5} DURING ON BLOCKS. WILCOXON SIGNED-RANK TESTS ARE TWO-SIDED.

Session	<i>N</i>	Mean OFF ($\mu\text{g m}^{-3}$)	Mean ON ($\mu\text{g m}^{-3}$)	Δ ($\mu\text{g m}^{-3}$)	Diff. (%)	OFF > ON	<i>W</i>	<i>p</i>
Session 1	17	7.74	6.33	1.41	18.3	11/17	42.5	0.107
Session 4	12	16.73	16.07	0.65	3.9	6/12	30.0	0.519
Pooled (S1 + S4)	29	11.46	10.36	1.10	9.6	17/29	135.5	0.076

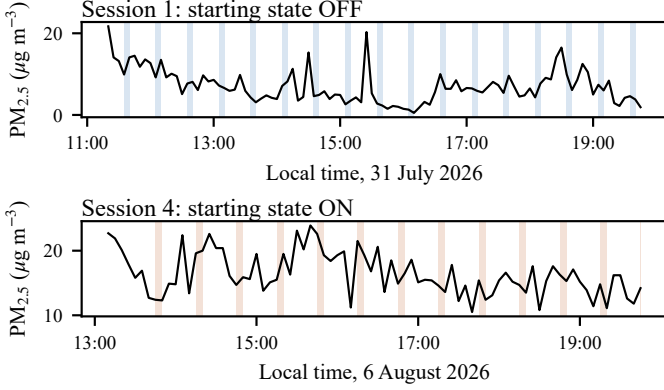


Fig. 2. PM_{2.5} time series at 5-min logging intervals for the two sessions retained for pooled analysis. Session 1 (top, 31 July 2026) reflects controlled particulate loading with mean PM_{2.5} = 7.04 $\mu\text{g m}^{-3}$; Session 4 (bottom, 6 August 2026) reflects controlled particulate loading with mean PM_{2.5} = 16.4 $\mu\text{g m}^{-3}$. Shaded bands indicate device-ON intervals; the first 5 min of each block are excluded as equilibration time.

C. Pooled Analysis

Across both retained sessions, mean PM_{2.5} was 11.46 $\mu\text{g m}^{-3}$ during OFF blocks and 10.36 $\mu\text{g m}^{-3}$ during ON blocks, yielding a mean paired OFF–ON difference of $\Delta = 1.10 \mu\text{g m}^{-3}$ and an aggregate relative difference of 9.6%. Of the 29 pooled block pairs, 17 (58.6%) had positive OFF–ON differences. A two-sided Wilcoxon signed-rank test returned $W = 135.5$, $p = 0.076$ at the prespecified $\alpha = 0.05$ level; therefore, the null hypothesis was not rejected. The mean paired difference was positive in both retained sessions, but the pooled test did not reach the prespecified significance threshold. Individual paired differences are shown in Fig. 3.

VI. DISCUSSION AND LIMITATIONS

The pooled analysis showed a small positive OFF–ON PM_{2.5} difference that did not reach the prespecified significance threshold. A larger campaign is needed to determine whether this pattern reflects a reproducible device-related difference rather than residual variability from the single-sensor design.

Sessions 2 and 3 failed the pooling gate because controlled particulate loading did not sustain sufficiently elevated PM_{2.5} concentrations for the optical counter to resolve a device-related difference. This supports adequate and stable particulate loading as a requirement for future testing of similarly scaled devices. Because all four formal sessions used

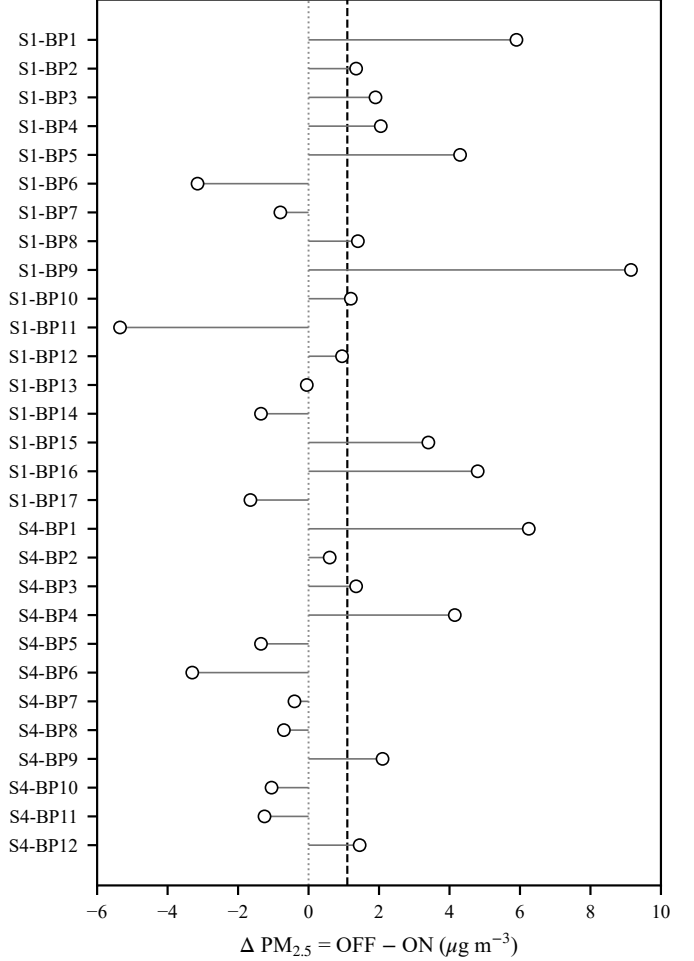


Fig. 3. Within-pair PM_{2.5} differences (OFF – ON) for the 29 pooled block pairs. Positive values indicate lower PM_{2.5} during ON blocks. The dashed vertical line marks the pooled mean difference ($\Delta = 1.10 \mu\text{g m}^{-3}$); the dotted line marks zero. Labels identify session (S1 or S4) and block pair (BP).

controlled incense loading rather than naturally occurring ambient pollution, the pooled estimate should not be interpreted as direct performance under typical ambient Newark PM_{2.5} conditions.

Because multiple block pairs were obtained within each retained session, temporal autocorrelation may reduce the effective number of independent observations. The pooled Wilcoxon result should therefore be interpreted as exploratory.

The single-sensor temporal crossover design could not elim-

inate ambient $\text{PM}_{2.5}$ variation between ON and OFF blocks, although OFF/ON alternation mitigated this risk. No fan-only sham or component-ablation controls were included, so fan-induced air mixing and the individual contributions of the MERV 13 filters, zeolite bed, and TiO_2 coating could not be separated. Testing at one residential site over approximately one week also limits generalizability and excludes seasonal effects and long-term zeolite saturation. The PMS5003T is a low-cost optical particle counter; the manufacturer specifies an absolute $\text{PM}_{2.5}$ accuracy of $\pm 10 \mu\text{g m}^{-3}$ below $100 \mu\text{g m}^{-3}$, and related PMS5003-based systems exhibit humidity-dependent bias [13], [15]. Although the within-sensor crossover design may reduce fixed calibration bias, short-term sensor variability remains important relative to the observed $1.10 \mu\text{g m}^{-3}$ mean difference. Under American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 52.2-2025, MERV 13 requires a minimum composite efficiency of 50% in the 0.3–1.0 μm size range [16]. Because airflow through the prototype was not measured, the nominal MERV 13 rating does not directly establish the filters’ in-device efficiency.

Outdoor wind variability and changing solar conditions could alter pollutant delivery and TiO_2 photocatalytic activity. Airflow rate, pressure drop, and clean air delivery rate (CADR) were not measured, limiting comparison with conventional air cleaners. The AirGradient O-1PST provided quantitative $\text{PM}_{2.5}$ measurements but only relative volatile organic compound (VOC) and NO_x indices, so gas-phase removal by the zeolite bed or TiO_2 coating was not evaluated.

Future work should employ simultaneous upstream/downstream $\text{PM}_{2.5}$ sensors, a fan-only sham and component-ablation controls, quantitative NO_x instrumentation, airflow and pressure-drop measurements, and testing across multiple sites and seasons. These changes would permit independent validation of particulate removal and evaluation of gas-phase contributions from the zeolite bed and TiO_2 coating. Partnerships with Newark agencies and community organizations could support longer-term deployments and datasets, while source-control measures should complement community-scale filtration, targeting emissions at their source.

VII. CONCLUSION

This work contributes a documented low-cost air-filtration platform (\$151 in materials), a prespecified crossover characterization protocol, and an observed mean OFF–ON $\text{PM}_{2.5}$ difference of $1.10 \mu\text{g m}^{-3}$ (9.6%) under adequately loaded conditions. The pooled Wilcoxon result did not reach the prespecified significance threshold, so the observed difference should be interpreted as exploratory. The documented design, protocol, and analysis framework can be replicated by other research groups or community organizations evaluating low-cost interventions in high-exposure microenvironments. Overall, this work is offered as an incremental step toward community-deployable air-quality infrastructure as part of a

broader effort to address disproportionate pollution burdens in New Jersey environmental justice communities.

ACKNOWLEDGMENT

We thank the Governor’s STEM Scholars program for mentorship and project support; Rutgers Makerspace and its engineering students for fabrication access and prototyping assistance; Jess Munyan of the New Jersey Department of Environmental Protection for loaning the AirGradient monitor; and the New Jersey Environmental Justice Alliance, particularly Quiya Harris, for her mentorship and support throughout the project.

REFERENCES

- [1] U.S. Environmental Protection Agency, “Health and environmental effects of particulate matter (PM),” <https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm>, 2026, accessed: Aug. 7, 2026.
- [2] World Health Organization, “WHO global air quality guidelines: Particulate matter, ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide,” World Health Organization, Geneva, Switzerland, Tech. Rep., 2021.
- [3] New Jersey Department of Environmental Protection, “RGGI strategic funding plan: Years 2023 through 2025,” New Jersey Department of Environmental Protection, Tech. Rep., 2023.
- [4] C. W. Tessum, D. A. Paoletta, S. E. Chambliss, J. S. Apte, J. D. Hill, and J. D. Marshall, “ $\text{PM}_{2.5}$ pollutants disproportionately and systemically affect people of color in the United States,” *Sci. Adv.*, vol. 7, no. 18, p. eabf4491, 2021.
- [5] J. A. Gleason and J. A. Fagliano, “Associations of daily pediatric asthma emergency department visits with air pollution in Newark, NJ: Utilizing time-series and case-crossover study designs,” *J. Asthma*, vol. 52, no. 8, pp. 815–822, 2015.
- [6] G. Liu, M. Xiao, X. Zhang, C. Gal, X. Chen, L. Liu, S. Pan, J. Wu, L. Tang, and D. Clements-Croome, “A review of air filtration technologies for sustainable and healthy building ventilation,” *Sustain. Cities Soc.*, vol. 32, pp. 375–396, 2017.
- [7] M. Król, “Natural vs. synthetic zeolites,” *Crystals*, vol. 10, no. 7, p. 622, 2020.
- [8] N. Kordala and M. Wyszowski, “Zeolite properties, methods of synthesis, and selected applications,” *Molecules*, vol. 29, no. 5, p. 1069, 2024.
- [9] A. Fujishima, X. Zhang, and D. A. Tryk, “ TiO_2 photocatalysis and related surface phenomena,” *Surf. Sci. Rep.*, vol. 63, no. 12, pp. 515–582, 2008.
- [10] G. Guo, Y. Hu, S. Jiang, and C. Wei, “Photocatalytic oxidation of NO_x over $\text{TiO}_2/\text{HZSM-5}$ catalysts in the presence of water vapor: Effect of hydrophobicity of zeolites,” *J. Hazard. Mater.*, vol. 223–224, pp. 39–45, 2012.
- [11] T. H. Nguyen, P. L. Nguyen, V. D. Le, M. T. Le, T. T. Do, and N. T. Vu, “NO adsorption on zeolites and active carbon toward the application for the treatment of highly concentrated NO_x in industry,” *Engineering and Technology for Sustainable Development*, vol. 35, no. 4, pp. 1–8, 2025.
- [12] S. Sankhyan, N. Clements, A. Heckman, A. K. Hollo, D. Gonzalez-Beltran, J. Aumann, C. Morency, L. Leiden, and S. L. Miller, “Optimization of a do-it-yourself air cleaner design to reduce residential air pollution exposure for a community experiencing environmental injustices,” *Atmosphere*, vol. 14, no. 12, p. 1734, 2023.
- [13] AirGradient, “Open Air outdoor air quality monitor: Technical data,” 2026, accessed: Aug. 8, 2026. [Online]. Available: <https://www.airgradient.com/outdoor/>.
- [14] South Coast Air Quality Management District, “Field evaluation: PurpleAir PA-II PM sensor,” South Coast Air Quality Management District, AQ-SPEC Program, Tech. Rep., 2017.
- [15] K. K. Barkjohn, B. Gantt, and A. L. Clements, “Development and application of a United States-wide correction for $\text{PM}_{2.5}$ data collected with the PurpleAir sensor,” *Atmos. Meas. Tech.*, vol. 14, no. 6, pp. 4617–4637, 2021.

- [16] National Air Filtration Association, "Understanding MERV: NAFA user's guide for ANSI/ASHRAE standard 52.2-2025," Jan. 2026, accessed: Aug. 8, 2026. [Online]. Available: <https://www.nafahq.org/assets/pdf/522BrochureJanuary2026/>.