# Enhancing Efficacy and Cost Effectiveness of Air Filtration Systems by Optimized Nanoparticle Deposition

Ishika Nag

*Abstract*— **Every year, seven million people die from severe cardiovascular and respiratory diseases, caused by ambient and household air pollution. An increase in air pollution from particulate matter less than 2.5 microns in diameter ($PM_{2.5}$) has shown to be a significant contributor of cardiovascular and respiratory diseases. The goal of this study was to develop an efficient and cost-effective air-filtration system by the impregnation of selected nanoparticles, utilizing their high surface-to-volume ratio to entrap $PM_{2.5}$. The experimental set-up consisted of a wind tunnel with incense sticks as the particulate matter source, measured by laser particle detectors upstream and downstream of the filters. Results found that a mixture of zinc oxide, titanium dioxide & graphene improved filtration efficiency of a baseline filter by 206%. There was also a 70% improvement in the cost of the filters. The versatility and cost-effectiveness of this design makes it applicable for personal masks & filters, air-conditioning filters, car-cabin filters, and fire-fighting equipment. The correlation between air pollution and fatalities from viral infections suggests that abatement technologies with innovative filtration systems are critical in saving human lives.**

## I. INTRODUCTION

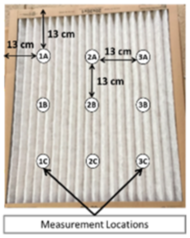
Seven million people die every year because of air pollution [1]. The majority (91%) of the world's population lives in locations exceeding the World Health Organization's air quality guidelines. Due to its small size, $PM_{2.5}$, particulate matter less than 2.5 microns in diameter, is capable of penetrating deep into lung passageways and entering the bloodstream, causing and aggravating cardio-vascular, cerebro-vascular, and other respiratory diseases [2]. Furthermore, long-term exposure to air pollution has been found to increase the vulnerability of contracting COVID-19 [3]. An increase of only 1 $\mu g/m^3$ in $PM_{2.5}$ is associated with an 8% increase in the COVID-19 death rate in the United States [3]. Abatement technologies such as ionic and High Efficiency Particulate Air (HEPA) air filtration systems [4] have been developed to filter $PM_{2.5}$ particles,but remain quite expensive and hence unaffordable to communities with limited resources [5, 6]. Therefore, a cost-effective and efficient abatement system is essential to help resolve the issue.

Nanoparticles have a high surface-to-volume ratio, which enhances the entrapment of particulate matter by adsorption. The surface adsorption energy is unique to the small size of nanoparticles with extremely high surface to volume ratios, where the unsaturated surface chemical bonds tend to adsorb other chemicals or biomolecules to reduce their surface energy [7]. The three nanoparticles used for this study were graphene, titanium dioxide ($TiO_2$), and zinc oxide (ZnO), which have been known to have filtration properties due to their high adsorption capabilities [8, 9, 10]. Graphene, an allotrope of carbon consisting of a single layer of carbon atoms arranged in a hexagonal lattice structure, has high adsorption capacities mainly due to these unique nanostructures, and hence have been proven to be efficient in the capture of particulate matter [11, 12].

The current work is aimed to develop an efficient and cost-effective air-filtration system by an optimized deposition of nanoparticles, based on their air filtration capabilities, clinical safety, and non-toxicity. The filtration system needs to be versatile and effective at different pollution levels in different parts of the world. The goal of this work is to also develop a simple application technique of the nanoparticles such that it can be easily applied to various filtration systems, thus providing an affordable alternative to expensive high quality air filtration devices with comparable air filtration capabilities.

## II. METHOD

The nanoparticles (NPs) used for this study were titanium oxide ($TiO_2$), zinc oxide (ZnO) and graphene. The combination of NPs was mixed with ethanol to create a suspension. This was then aerosolized and sprayed on to the air filters, using the pressurized sprayer system. A 'high-quality' air filter (MERV-14, FPR-10, HEPA) was used for comparison and benchmarking the filtration efficiency in order to validate the results from this experiment, compared to previously performed studies [13]. The deposition method of NPs onto the filtration media was also varied and tested for uniform spatial distribution. Different spray mechanisms were tested using pipettes, spray bottles and pressurized sprayers. Different zones of the air filter, in 9 locations, were tested for spatial consistency in filtration efficiency (Fig. 1). The pressurized spray application resulted in the most uniform spatial distribution of the NPs, and it was chosen as the preferred application method for its simplicity and effectiveness.



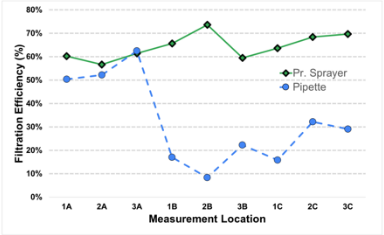


Figure 1. The pressurized sprayer system demonstrated better nanoparticle deposition uniformity, verified with the spatial consistency test.

The surface morphology of the filters was characterized using the scanning electron microscope (SEM) imaging technique, confirming the adhesion of nanoparticles to the filters in the 'before' images and the entrapment of particulate matter onto the nanoparticle surfaces in the 'after' images of the different nanoparticle coated filters (Fig. 2).

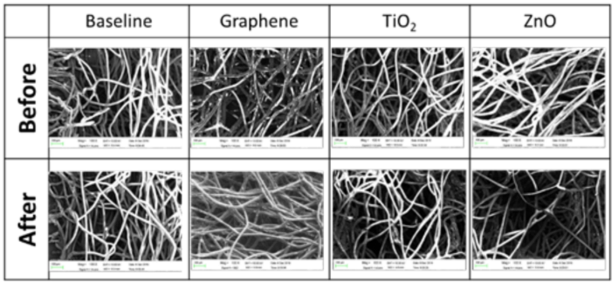


Figure 2. Scanning Electron Microscope (SEM) images of uncoated and coated filters before and after exposure to PM$_{2.5}$ particles, confirm the adhesion of NPs and entrapment of PM$_{2.5}$.

A full-factorial Design of Experiments (DOE) statistical analysis model was used to randomize the run order of the experiment, minimize bias, and aid with the Analysis of Variance (ANOVA) study. A statistical repeatability and reproducibility study (Gage R&R) was used to determine the measurement uncertainty of the experiment. The tests were repeated for 10 trials each. As seen in Fig. 3, 95% of the contribution was from 'part-to-part variation' and 5% from the process variation.

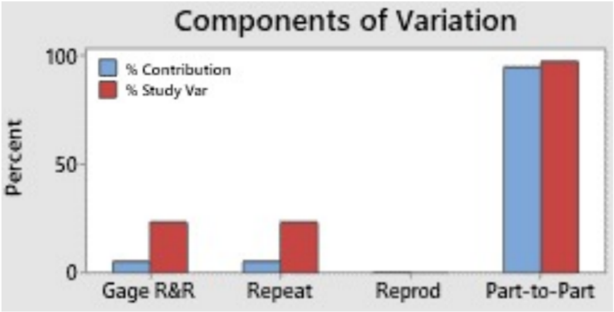


Figure 3. The Gage Repeatability and Reproducibility analysis of the experimental set-up indicating acceptable levels of measurement uncertainty

## III. EXPERIMENTAL DESIGN

A wind tunnel was designed and created to test for the efficiency of the filters (Fig. 4). Incense sticks were used as the source of PM$_{2.5}$ and laser particle detectors measured the PM$_{2.5}$ at the inlet and outlet sections of the wind tunnel. A manometer was used to measure pressure drop, and a lamp was used on the TiO$_2$-coated filters for photocatalysis testing.

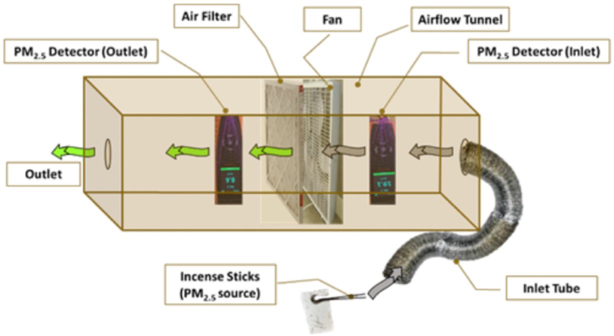


Figure. 4. The experimental set-up included a wind tunnel with a fan, incense sticks to simulate the PM$_{2.5}$ and laser particle detectors to measure filtration efficiency.

## IV. RESULTS AND DISCUSSION

The results showed (Fig. 5) that the concentration of NPs has a direct correlation to the filtration efficiency (1). The correlation between nanoparticle type and filtration efficiency was also observed, with TiO$_2$ coated filters demonstrating the highest efficiency.

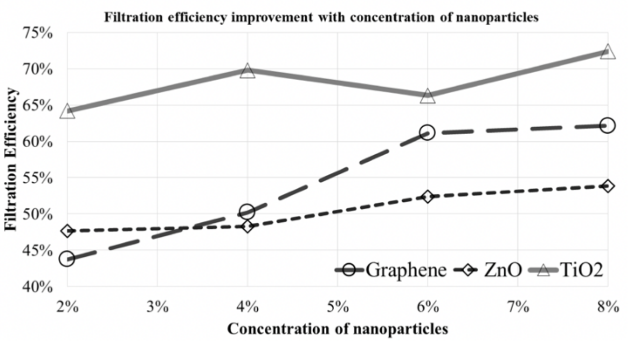


Figure. 5. Increase in nanoparticle concentration on coatings improves filtration efficiency

The TiO$_2$ coated filters had a 7% increase in filtration efficiency when placed under light. TiO$_2$, with its photocatalytic properties, absorbs the ultraviolet component of sunlight which excites the electrons from its valence band to the conduction band. They act as a catalyst to form the superoxide anion ($O^{\bullet -}_2$) and reactive hydroxyl (OH•) radicals from atmospheric moisture and oxygen. They are then able to react with the PM$_{2.5}$ particles converting them into $CO_2$ and $H_2O$ [14].

A significant parameter that affects the filtration system's energy consumption is its pressure drop. Pressure drop was calculated by using the Bernoulli equation, which is given by (Eq. 1):

$$Filtration\ Efficiency\ (\%) = \frac{PM_{2.5_{inlet}} - PM_{2.5_{outlet}}}{PM_{2.5_{inlet}}} \times 100$$

. Assuming a steady, incompressible, and frictionless flow along a streamline, with the same horizontal height; this can be simplified to the pressure drop equation (2):

$$\Delta P = \frac{1}{2}\rho(v_1^2 - v_2^2)$$

A quantitative test of airflow, conducted by measuring the pressure drop (Δp) across the filter, determined that the application of NPs to air filters does not affect their energy consumption in a measurable way.

The NP coatings consistently demonstrated the ability to improve the filtration efficiency of a baseline filter (Fig. 6). The filter, coated with a mixture of the three-NPs, had the highest filtration efficiency which was 206% higher than a baseline filter. The filtration efficiency of this filter, at 77%, was quite comparable to the more expensive 'high-quality' FPR10 filters. The filter coated with $TiO_2$ alone was also quite effective, but less versatile due to its dependence on light for activation of its photocatalytic properties.

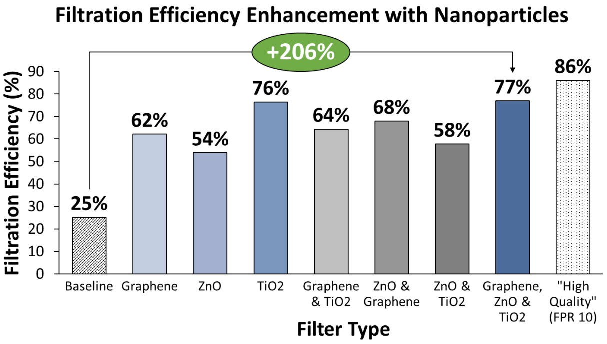


Fig. 6 The Gr/ZnO/TiO2 combination is 206% more effective than a baseline uncoated filter and is almost similar to a 'high-quality' HEPA filter

An accelerated durability testing was also performed to test the effectiveness of the filters over longer usage periods. 90% of the filter's effectiveness was maintained after 50 equivalent days of operation.

Considering the baseline cost of a commercially available filter and the additional cost of NPs and processing, the nanoparticle coated filters were 70% cheaper than the HEPA filters, and 99% cheaper than ionic filters (Fig. 7).

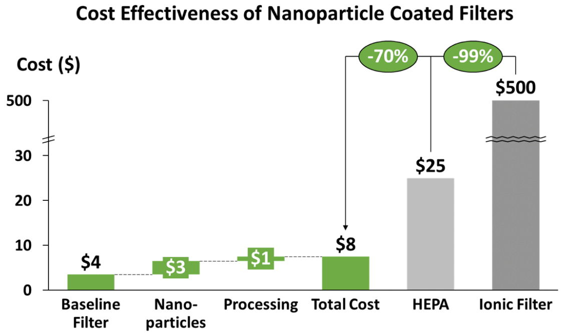


Fig. 7. NP coated filters are significantly less expensive than HEPA or ionic filtration systems, while having comparable filtration efficiency.

## V. CONCLUSION

The nanoparticle coatings consistently demonstrated the ability to improve the filtration efficiency of a baseline filter. The mixture of the three nanoparticles - graphene, $TiO_2$ and ZnO - improved the efficiency of a baseline filter by 206%. The $TiO_2$ coated filter was also quite effective and demonstrated its photocatalytic effectivity, but less versatile due to its dependence on light. Cost-effectiveness was one of the main objectives of this experiment in order to make this technology available to societies with limited resources. Considering the baseline cost of a commercially available filter and the additional cost of nanoparticles and processing, the nanoparticle coated filters were 70% cheaper than the HEPA filters, and 99% cheaper than ionic filters. The safety of nanoparticle usage is of utmost importance and continues to be a subject of research worldwide[15, 16]. The nanoparticles chosen for this study are known for their clinical safety and non-toxicity and are extensively used in cosmetic and biomedical applications, e.g., pill coatings, sunscreens[17]. These NP coatings can be used in several applications including face masks, air-conditioning and car cabin filters, fire-fighting masks, and industrial pollution control systems. The versatility and effectiveness of this nanoparticle coated filtration system makes it applicable for varying pollution levels in different parts of the world. There is a significant correlation between air pollution and deaths from respiratory diseases and virus infections like COVID-19 [3]. Such novel and cost-effective filtration systems may help in abating the life-threatening impacts of air pollution.

## VI. ACKNOWLEDGEMENTS

The author thanks Mr. William J. Furiosi II (Oviedo High School) for his mentorship, Dr. Yang Yang (University of Central Florida) for his guidance, and Guanzhi Wang for her support with coating filters in Dr. Yang's laboratory.

# VII. REFERENCES

[1] World Health Organization. (2020). *https://www.who.int/health-topics/air-pollution*

[2]Xing, Y., Xu, Y., Shi, M., Lian, Y., “The impact of PM2.5 on the human respiratory system,” in *J Thorac Dis*. 2016 Jan; 8(1): E69–E74.

[3]Wu et al., “Air pollution and COVID-19 mortality in the United States: Strengths and limitations of an ecological regression analysis,” *in Sci. Adv*. 2020; 6 : eabd4049 4 November 2020.

[4]“Abatement Technologies. Facts about true HEPA filtration”, *https://www.abatement.com/learning-center/patient-isolation/facts-about-hepa-filtration/*, 2018.

[5] Brook, D., “What is an air ionizer? Are air ionizers good for you?”, *https://breathequality.com/ionizer/* (2019).

[6] Vyas, S., Srivastav, N., Spears, D., “An experiment with Air Purifiers in Delhi during Winter 2015-2016”, *PLoS ONE* 11(12): e0167999. doi: 10.1371/journal.pone.0167999

[7] Xia, X., Riviere, N., Mathur, S., Song, X., Xiao, L., Oldenberg, S., Fadeel, B., Riviere, J., “Mapping the surface adsorption forces of nanomaterials in biological systems”, *National Institute of Health,* 5(11), 9074-9081, 2011. doi: 10.1021/nn203303c

[8] Zhong, Z., Xu, Z., Sheng, T., Yao, J., Xing, W., Wang, Y., “Unusual Air Filters with Ultrahigh Efficiency and Antibacterial Functionality Enabled by ZnO Nanorods”, *ACS Applied Materials & Interfaces*, 7 (38), 21538-21544. doi:10.1021/acsami.5b06810

[9]Wongwatcharapaiboon, J., Gan, G., Riffat, S., “A new air PM2.5 filtrative lamp with a combination of fabric filter and TiO2 coating mop”, *International Journal of Low-Carbon Technologies*, 14 (3), 394–399, https://doi.org/10.1093/ijlct/ctz027, 2019.

[10]Ruan, D., Qin, L., Chen, R. et al., “Transparent PAN:TiO2 and PAN-co-PMA:TiO2 Nanofiber Composite Membranes with High Efficiency in Particulate Matter Pollutants Filtration”, *Nanoscale Res Lett.*, 15, 7. doi: 10.1186/s11671-019-3225-2.

[11]Szczęśniak, B., Choma, J., & Jaroniec, M., “Gas adsorption properties of graphene-based materials”, Advances in Colloid and Interface Science, 243(1), 46-59, 2017. doi: 10.1016/j.cis.2017.03.007

[12] Zhang, S., Sun, J., Hu, D., Xiao, C., Zhuo, Q., Wang, J., Qin, C., Dai, L., “Large-sized graphene oxide/modified tourmaline nanoparticle aerogel with stable honeycomb-like structure for high-efficiency PM2.5 capture”, *J. Mater. Chem. A*, 2018, 6, 16139-16148. doi: 10.1021/acsami.8b22382

[13]Zhao. D., Parham. A., Stephens. B. (2015). Evaluating the long-term health and economic impacts of central residential air filtration for reducing premature mortality associated with indoor fine particulate matter (PM2.5) of outdoor origin. *Int. J. Environ. Res. Public Health*, 12(7), 8448-8479.

[14] Giovanetti et al., “Recent advances in graphene based TiO2 nanocomposites (GTiO2Ns) for photocatalytic degradation of synthetic dyes”, *Catalysts*, 7(10), 305, 2017. doi:10.3390/catal7100305

[15]Weiss, C. et al. (2020). Toward Nanotechnology-Enabled Approaches against the COVID-19 Pandemic, *ACS Nano* 2020 14 (6), 6383-6406, doi: 10.1021/acsnano.0c03697

[16] Mitra, P. et. al. (2018). Antibacterial and Photocatalytic Properties of ZnO–9-Aminoacridine Hydrochloride Hydrate Drug Nanoconjugates. *ACS Omega* 2018 3 (7), 7962-7970, doi: 10.1021/acsomega.8b00568

[17] Xiong, H.-M. (2013). ZnO Nanoparticles Applied to Bioimaging and Drug Delivery. *Adv. Mater.* 25, 5329-5335. doi: 10.1002/adma.201301732