Research article

Air pollution abatement by selective nanoparticle deposition on filtration systems

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Abstract

Air pollution kills an estimated seven million people worldwide every year. The data from the World Health Organization (WHO) shows that almost all the global population (99%) breathe air that exceeds WHO guideline limits. The growing population and urbanization such as in Africa, which has the fastest growing population, may lead to substantial worsening of the air quality. Urbanization is also a powerful driver of the epidemiologic transition from traditional threats like infectious diseases and malnutrition to chronic, non-communicable diseases. Particulate matter less than 2.5 microns in size, $PM_{2.5}$, is the leading contributor to air pollution which results in such diseases like chronic obstructive pulmonary disease (COPD), bronchitis, and lung cancer. Recent studies have shown a strong correlation between ambient air pollution and COVID-19 cases, which has affected the lives of billions of people around the world. Abatement technologies such as ionic and other high efficiency filtration systems are quite expensive and hence unaffordable to communities with limited resources. The goal of this study was to develop an air pollution filtration method utilizing selective nanoparticle deposition in optimized concentrations, to maximize the entrapment of $PM_{2.5}$ particles. The experimental set-up consisted of a wind tunnel with incense sticks as the $PM_{2.5}$ source, measured by laser particle detectors upstream and downstream of the filters. Different nanoparticle coated filters were tested using the 'Design of Experiments' methodology and it was concluded that an optimized mixture of zinc oxide, titanium dioxide & graphene improved filtration efficiency of a baseline filter by 206% and was 70% cheaper than high efficiency filters. The versatility and cost-effectiveness of this design makes it applicable for personal masks & filters, air-conditioning and car-cabin filters, and fire-fighting equipment. The significant correlation between air pollution and fatalities from viral infections like COVID-19, makes such abatement technologies with innovative filtration systems critical to save human lives.

Keywords

Air Pollution, Filtration, Nanoparticle, Particulate Matter, $PM_{2.5}$

Introduction

Air pollution is the contamination of the air in the atmosphere by a physical, biological or chemical alteration. Particulate matter (PM) is one of the main contributors to air pollution, consisting of a mixture of solid and liquid particles suspended in the air. The most used health indicator related to PM refers to the mass concentration of particles with a diameter less than 2.5µm, $PM_{2.5}$ (Nolt-Helms et. al. 2018; Francesca et. al. 2006). Primary sources of $PM_{2.5}$ include anthropogenic sources such as automobile emissions, household fuel (Matawle et. al. 2017) and waste burning, energy production from fossil fuels (Kundu and Stone, 2014) and biomass, and industrial activities such as construction, mining, cement production, etc. 50% of the total PM emissions in urban areas is generated from traffic (Wrobel et. al. 2000). The most polluted areas around the world tend to be in developing countries in Africa, South-East Asia, India and China, due to their increased density of urban population, significant use of fossil fuels and relatively inadequate control measures and filtration systems (World Health Organization, WHO, 2022).

Africa has the fastest growing population in the world, predicted to surpass two billion by 2050 (UN 2011). Half of Africa's population is expected to live in urban areas by 2035, and Sub-Saharan Africa will host five of the world's 41 megacities by 2030 (Katoto et. al. 2019). Urbanization and increased industrialization, growing ownership of automobiles, and continued use of biomass as domestic energy source may lead to substantial worsening of air quality across the continent (Petkova et. al. 2013). Urbanization is also a powerful driver of the global demographic and epidemiologic transition, characterized by declining birth rates, increasing life expectancy, and a shift from traditional threats such as infectious diseases and malnutrition to chronic, non-communicable diseases like heart disease and diabetes (Omran 1971).

Almost all (99%) of the world's population lives in places exceeding WHO's air quality guidelines and 7 million people die every year because of air pollution (World Health Organization, WHO, 2022). The primary causes of such premature deaths are chronic obstructive pulmonary disease, heart disease, stroke, lung cancer and acute respiratory infections in children. $PM_{2.5}$, due to its small size, is capable of penetrating deep into lung passageways and entering the bloodstream causing cardio-vascular, cerebro-vascular, and respiratory impacts (Vijayan et. al. 2015; Xing et. al. 2016). Furthermore, long term exposure to air pollution has been found to increase the vulnerability to the most severe impacts of coronavirus outbreaks such as SARS in 2003 and COVID-19 in 2020 (Coker et. al. 2020; Comunian et. al. 2020; Zoran et. al. 2020; Wu et. al. 2020). 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 (Wu et. al. 2020).

Indirect effects of ambient air pollution include acid rain caused by excessive amounts of sulphur oxides in the air. This can impact aquatic ecosystems, as well as man-made landscapes (Bhargava and Bhargava 2013; Banerjee and Sarkar 2019). Photochemical smog caused by the combination of nitrogen oxides and $PM_{2.5}$ can harm the ozone layer which in turn results in global warming and its associated social, economic, and geopolitical consequences (Davidson 2015).

Abatement technologies such as ionic and High Efficiency Particulate Air (HEPA) air filtration systems (Abatement Technologies, 2018) have been developed that can filter $PM_{2.5}$ particles significantly but remain quite expensive and hence unaffordable to communities with limited resources (Vyas et. al. 2016; Brook 2019). Therefore, a cost-effective and efficient abatement system is essential in helping to 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 (Xia et. al. 2011). 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 (Zhong et. al. 2015; Wongwatcharapaiboon et. al. 2019; Ruan et. al. 2020). 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 has been proven to be efficient in the capture of particulate matter (Szczęśniak 2017; Zhang et. al. 2018). TiO_2 nanoparticles, with their photocatalytic properties, absorb the ultraviolet component of sunlight and act as a catalyst to form reactive hydroxyl (•OH) radicals and the superoxide anion (O_2•-) from atmospheric moisture and oxygen. These radicals react with the $PM_{2.5}$ particles due to their strong oxidizing capabilities converting them into CO_2 and H_2O (Giovanetti et. al. 2017), hence have been used for air purification (Thanh Son Le et. al. 2015).

The current work is aimed to develop an efficient and cost-effective air-filtration system by the deposition of nanoparticles on a readily available filtration media. The nanoparticles are selected 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 and from different pollutant sources, as described above. 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 in different parts of the world, thus providing an affordable alternative to expensive high quality air filtration devices with comparable air filtration capabilities.

Materials and methods

Experimental set-up

A wind tunnel was designed and created to test the efficiency of the filters (Fig. 1), as a continuation of a previous study (Nag, 2021-22). A cardboard box (142x50x50 cm) was used as the body of the tunnel. A washer-dryer exhaust tube (diameter 10 cm) was used to connect the PM source to the inlet section of the tunnel. Incense sticks were used as the source of $PM_{2.5}$ (Lui et. al. 2016; Jilla and Kura 2017). A fan (Lasko, 50x50 cm) was placed on the inside of the tunnel to blow the $PM_{2.5}$ through the filter, which was placed downstream of the fan. $PM_{2.5}$ detectors (Temtop LKC-1000S) were hung inside the inlet and outlet sections of the wind tunnel, and plexiglass windows were installed into the tunnel for visualization of the detector readings. A manometer (PerfectPrime AR1890P2) was used to measure pressure drop, with the tubes placed upstream and downstream of the fan and filter; and a lamp (Hyperikon, 15W, 5000K) was used to simulate the effect of daylight to enhance the photocatalytic properties of the TiO_2-coated filters.

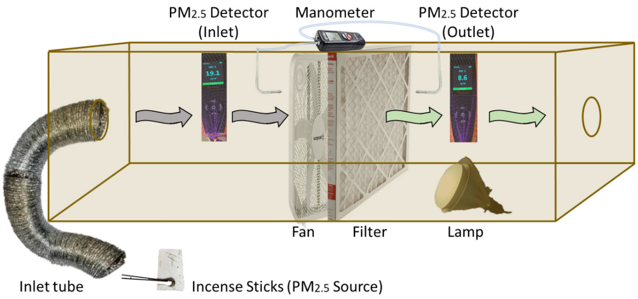


Figure 1: *A wind tunnel with a fan to create the draft, and incense sticks to simulate the $PM_{2.5}$, were used in this experimental set-up. Laser particle detectors at the inlet and outlet were used to measure the filtration efficiency and a manometer was used to measure the pressure drop.*

Nanoparticle deposition

The nanoparticles used for this study were Titanium Oxide (TiO_2 Anatase, 99.5% 40nm, US Research Nanomaterials, Inc.), Zinc Oxide (ZnO, 99+%, 35-45 nm, US Research Nanomaterials, Inc.) and Graphene (Alfa Aesar™ Graphene nanoplatelets aggregates, 500 m^2/g, Fisher-Scientific).

The combination of nanoparticles was mixed with ethanol (200 Proof (100%), USP/EP/ACS, Fisher-Scientific) to create a suspension which appears as a slurry. This suspension was then aerosolized using the pressurized sprayer system (Preval Airless Paint Sprayer, 70 psi, Home Depot), and the aerosolized spray was directed towards a typical Heating, Ventilation and Air Conditioning (HVAC) air filter (Rheem, 51x51x2.5 cm, wire-backed pleated fiberglass and paper media) with a Minimum Efficiency Reporting Value (MERV) rating of 8 (ASHRAE, 2020) while maintaining a spray-distance of about 15-18 cm. The filters were then air-dried for at least 8 hours and then tested for efficacy. A 'high quality' air filter (Rheem, 51x51x2.5 cm, MERV-14, Home Depot) was used for comparison and benchmarking the filtration efficiency.

Different combinations (Fig 4.) and concentrations (Fig. 7) of nanoparticles were experimented with, to determine the optimized mixture to maximize filtration efficiency. The nanoparticle loading was calculated at 2.33E-04 g/cm^2 for 2% coating with one nanoparticle, and at 4.65E-04 g/cm^2 for 2% coating with two nanoparticles. The maximum loading was 2.79E-03 g/cm^2 for the 8% coating with all three nanoparticles.

Spatial uniformity of nanoparticle deposition

The deposition method of nanoparticles onto the filtration media were also varied and tested for uniform spatial distribution as in the previous study by the same author (Nag, 2021-22). 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 variation in filtration efficiency (Fig. 2). The pressurized spray application resulted in the most uniform spatial distribution of the nanoparticles and was chosen as the preferred application method for its simplicity and effectiveness.

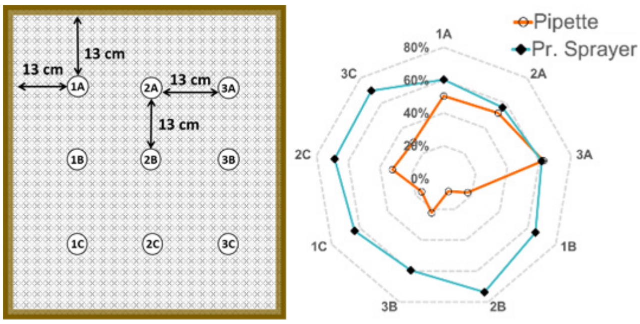


Figure 2: *Spatial variation test to verify and optimize nanoparticle deposition uniformity. The spider-chart depicts the uniformity of the pressurized sprayer over the pipette deposition.*

Surface morphology of coated filters

The surface morphology of the filters was characterized using the scanning electron microscope (SEM) imaging technique and confirmed the adhesion of the nanoparticles. A Zeiss Ultra-55 SEM with a Schottky field emission source and resolution of 1 nm @ 15 KV, 1.7 nm @ 1 KV was used. The images below are at 100X magnification. These SEM images (Fig. 3a) of the filters enabled the confirmation of the nanoparticle adhesion to the filters in the coated filters as compared to the baseline (uncoated). The

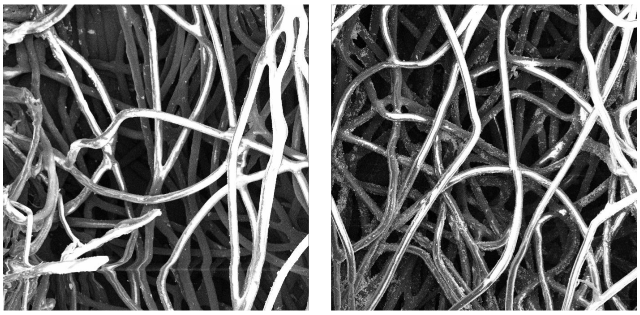


Figure 3a: *Scanning Electron Microscope (SEM) images of the baseline filter (left) and the TiO_2 coated one (right) confirm the adhesion of the nanoparticles to the fibres of the filtration media.*

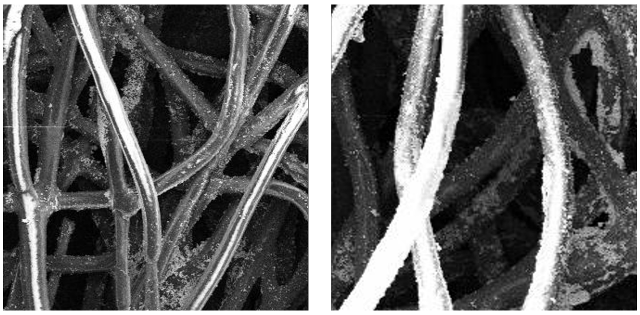
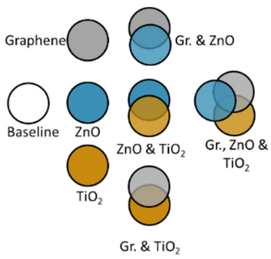


Figure 3b: *Scanning Electron Microscope (SEM) images of the TiO_2 coated filter before (left) and after (right) exposure to $PM_{2.5}$ particles, show the adsorption of the $PM_{2.5}$ particles to the nanoparticle adhesion areas of the filtration media.*

entrapment of particulate matter onto the nanoparticle surfaces in the 'after' images of the different nanoparticle coated filters are visualized in the SEM images (Fig. 3b), as previously reported (Nag, 2022). The embedded nanoparticles enhance the diffusion and electrostatic attraction mechanisms of filtration due to high surface to volume ratio and photocatalytic activation properties (N95 Respirators and Surgical Masks, CDC, 2009).

Design of experiments

A Design of Experiments (DOE) statistical analysis model helps with analysing and interpreting test results and the effects of multiple input variables and their interactions on an output variable (Minitab, 2020). A full factorial DOE design was used to collect and analyse the data to randomize the run order of the experiment, minimize bias and aid with the Analysis of Variance (ANOVA) study. Combinations of single nanoparticles (Graphene or ZnO or TiO_2), combination of two nanoparticles and finally all



StdOrder	RunOrder	Gr	ZnO	TiO2
2	1	1	-1	-1
3	2	-1	1	-1
8	3	1	1	1
1	4	-1	-1	-1
7	5	-1	1	1
4	6	1	1	-1
5	7	-1	-1	1
6	8	1	-1	1

-1: Absence, 1: Presence of nanoparticle

Figure 4: *Design of Experiments set-up using full-factorial design for ANOVA analysis. The table indicates the run order used to randomize the experimentation to avoid bias. The figure on the right illustrates the different combinations of the nanomaterials used for the experiment.*

three together were experimented in a random order, as shown in Fig. 4.

The $PM_{2.5}$ at the inlet was also varied significantly to test the versatility of the filters over different environmental conditions. The lower end of the inlet $PM_{2.5}$ at 80~100 µg/m³ represents pollution levels in typical polluted cities in India and China. The mid-level at 150~200 µg/m³ represents some polluted cities in Egypt and Niger, while the higher end at 250~300 µg/m³ represents forest fires, heavy vehicle exhausts and smoke.

Validation of experimental results

To validate the results from this experiment, commercially available 'high quality' filters were tested in this set-up and compared to previously performed studies. HVAC filters rated with a Minimum Efficiency Reporting Value (MERV) of 14 (ASHRAE, 2020) were tested using this wind tunnel experimental set-up over several days as shown in Fig. 5 and were found to be consistent and comparable to a previous study (Zhao et. al. 2015) using MERV 14 (equivalent to 'Filter Performance Rating' FPR 10) type filters, thus confirming the accuracy of the experimental set-up.

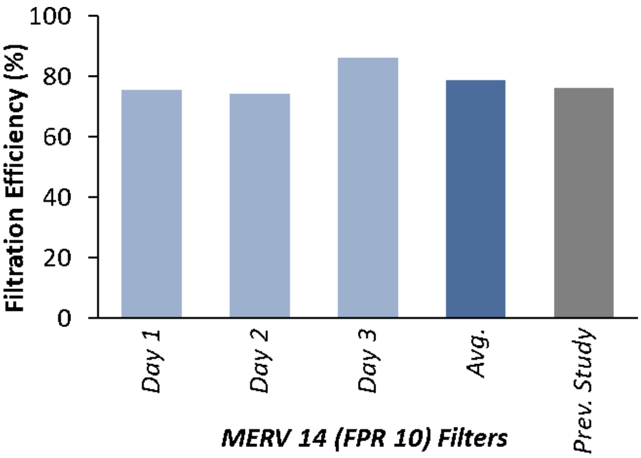


Figure 5: *Commercially available MERV14 filters' filtration efficiency was maintained over different days of testing and was found to be consistent to a previous study, thus confirming the validity of the experimental set-up.*

Measurement uncertainty

A statistical repeatability and reproducibility study (Gage R&R) was used using Minitab software (Minitab, 2020), to determine the measurement uncertainty of the experiment. The tests were repeated for 10 trials each and repeated over different days to measure repeatability and reproducibility. It was seen (Fig. 6) that 95% of the contribution was from 'part-to-part variation' (natural variability due to different parts) and 5% from the measurement process variation (variability due to measurement system uncertainties), which is deemed to be an acceptable measurement uncertainty, per statistical guidelines (Automotive Industry Action Group (AIAG), 2010). The reproducibility factor of this experiment (experiments conducted over different days) is very high since the uncertainty from the reproducibility is almost negligible.

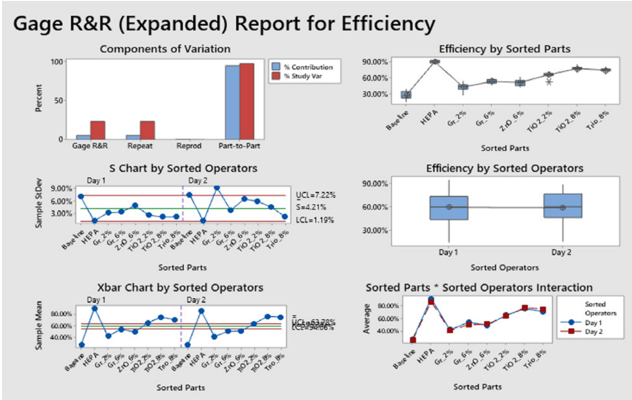


Figure 6: *The Gage Repeatability and Reproducibility analysis of the experimental set-up indicating acceptable levels (5% of total variation) of measurement uncertainty.*

Other sources of uncertainty

Sources of the remaining measurement uncertainty may include the calibration of the $PM_{2.5}$ detectors which may affect their absolute measurements, which can be improved by performing calibrations with mixtures of known $PM_{2.5}$ concentrations. The generation of $PM_{2.5}$ particles from incense sticks was inconsistent and may have also contributed to the measurement system uncertainty of the experiment. The sealing system (using insulation sealing materials) between the inlet and outlet sections of the wind-tunnel may have been another source of uncertainty.

Results and discussion

As explained in section 2.2, different concentrations and combinations of nanoparticles were evaluated for maximizing filtration efficiency. The results showed (Fig. 7) that the concentration of nanoparticles has a direct correlation to the filtration efficiency (1). The correlation between nanoparticle type and filtration efficiency was also observed, with titanium dioxide coated filters demonstrating the highest efficiency. The mixture of nanoparticles was more effective in reducing $PM_{2.5}$ as compared to the individual nanoparticles.

$$Filtration\ Efficiency\ (\%) = \frac{PM_{2.5_{inlet}} - PM_{2.5_{outlet}}}{PM_{2.5_{inlet}}} \times 100 \quad (1)$$

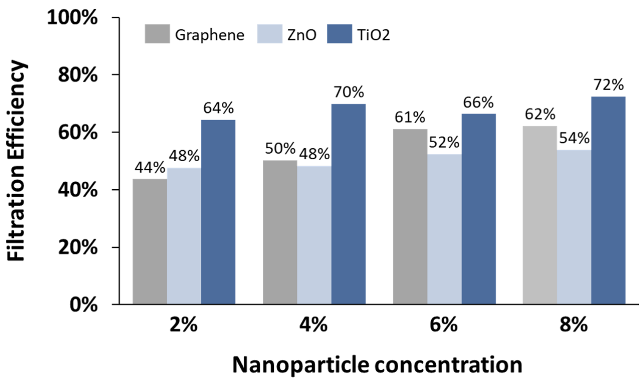


Figure 7: *Increase in nanoparticle concentration improves filtration efficiency. TiO_2 has the overall highest filtration efficiency, while Graphene demonstrates the strongest correlation in filtration efficiency and concentration.*

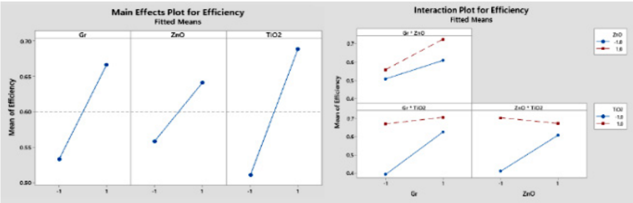


Figure 8: *Main and Interaction effect plots for nanoparticle coated filters indicating strong interaction effects of* TiO_2 *with Graphene and ZnO.*

The interaction plots from the ANOVA analysis (Fig. 8) indicate that although the main effects of the individual nanoparticles were significant, there was strong interaction between Graphene and TiO_2 and ZnO and TiO_2. However, the interaction between Graphene and ZnO was not as significant. Hence, it can be ascertained that TiO_2 has a key interaction effect and improves the efficiency of the other nanoparticles (ZnO and Graphene) in its presence.

The titanium dioxide coated filters had a 7% increase in filtration efficiency when placed under light, due to the activation of its photocatalytic properties. TiO_2 nanoparticles (NP), with their photocatalytic properties, absorb the ultraviolet component of sunlight which excites the electrons (e-) from Valence Band (VB) to Conduction Band (CB) and act as a catalyst to form the superoxide anion (O_2•-) and reactive hydroxyl (OH•) radicals from atmospheric moisture and oxygen (2). These radicals react with the $PM_{2.5}$ particles due to their strong oxidizing capabilities converting them into CO_2 and H_2O (Giovanetti et al. 2017).

a) NP(e-CB)+O_2 → (O_2•-)+NP *[The photo generated (e-) reacts with adsorbed* O_2 *to form superoxide radical(O2•-)]*

b) (O_2•-)+H_2O → HO_2• +OH-

c) HO_2•+H_2O → OH•+H_2O_2 (2)

d) H_2O_2 → 2OH• *[The (*O_2*•-) in turn reacts with moisture(*H_2O*) to form (OH•) hydroxyl radical]*

e) OH•+ air pollutant → CO_2+ H_2O *[The (OH•) degrades pollutants to* CO_2 *and* H_2O*]*

Although this mechanism is applicable to organic sources of $PM_{2.5}$, this author has also further evaluated the consistency of the filtration efficiency from different sources of $PM_{2.5}$ (Nag, 2022). Most of the $PM_{2.5}$ generated is from organic compounds such as fossil fuels and wood-burning (WHO, 2020).

A two-sample t-test (Fig. 9) with 95% confidence intervals, indicates the marked improvement of filtration efficiency with the application of light (p-value <0.05).

A significant parameter that affects the filtration system's energy consumption is its pressure drop. Pressure drop can be calculated by using the Bernoulli equation (3):

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \quad (3)$$

where P is the pressure, ρ is the density of the fluid, v is the velocity, g is the gravitational acceleration, h is the height, subscript[1] denotes upstream conditions and subscript[2] is for downstream conditions. Under steady, incompressible, and

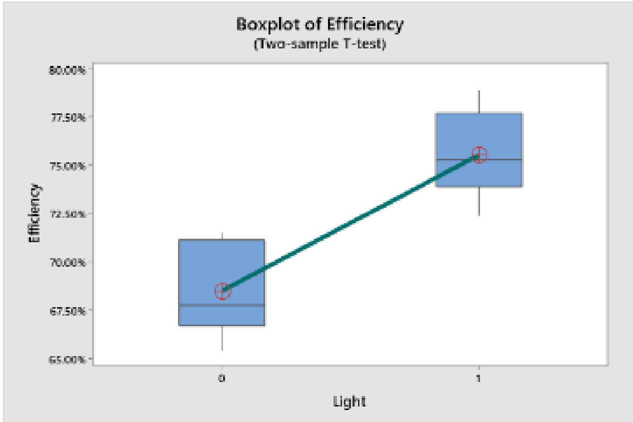


Figure 9: *A 2-sample t-test demonstrating impact of light on filtration efficiency of* TiO_2*.*

frictionless flow along a streamline assumption with the same horizontal height; (3) can be simplified to the pressure drop equation (4):

$$\Delta P = \frac{1}{2}\rho(v_1^2 - v_2^2) \quad (4)$$

A quantitative test of airflow was conducted by measuring the pressure drop (Δp) across the filter. As seen in Fig. 10, the pressure-drop (psi) was consistent across the baseline and the nanoparticle coated filters. This is because the size of these nanoparticles is considerably smaller (60-80 nm) than the size of the fibres in the filter (3-5 µm). This indicates that applying the nanoparticles to the air filters does not affect their energy consumption in a measurable way.

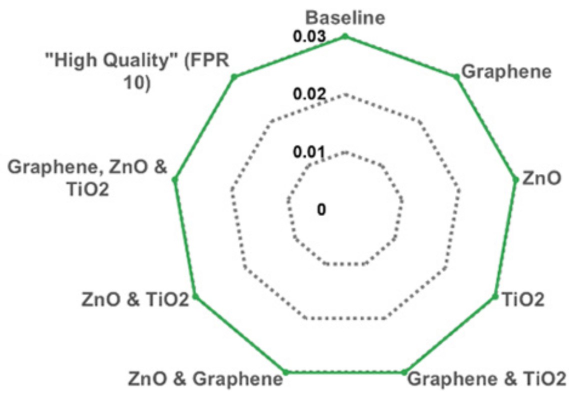


Figure 10: *Nanoparticle coated filters have no measurable impact on the pressure drop.*

An accelerated durability testing (5) was performed to test the effectiveness of the filters over longer usage periods. The durability testing was accelerated by increasing the volume flow rate of air by increasing the fan speed, and the mass flow rate of $PM_{2.5}$ was increased by increasing the incense stick count.

The samples were tested intermittently to monitor the decrease in filtration efficiency over time. It was seen that 90% of the filter's effectiveness was maintained after 50 equivalent operational days and 70% of its initial efficiency is maintained over 100 equivalent days of operation (Fig. 11).

$$\boldsymbol{H_{at}} = \frac{\mathrm{p \times a \times h \times FL}}{\mathrm{PM_i \times n \times a^+}} \tag{5}$$

$p = \mathrm{PM}_{2.5}@polluted\ city = 150\left[\frac{\mu g}{m^3}\right]$ $\mathrm{PM_i} = PM_{2.5_{per\ incense\ stick}} = 300\left[\frac{\mu g}{m^3}\right]$

$\mathrm{a} = Air\ flow\ rate_{nominal} = 1\left[\frac{m}{s}\right]$ $\mathrm{n} = \#\ incense\ sticks = 20$

$\mathrm{h} = Hours_{Per\ day} = 24$ $\mathrm{a^+} = Air\ flow\ rate_{increased}$

$\mathrm{FL} = Filter\ Life = 90[\mathrm{days}]$ $\boldsymbol{H_{at}} = Hours_{accelerated\ \ test} = 18$

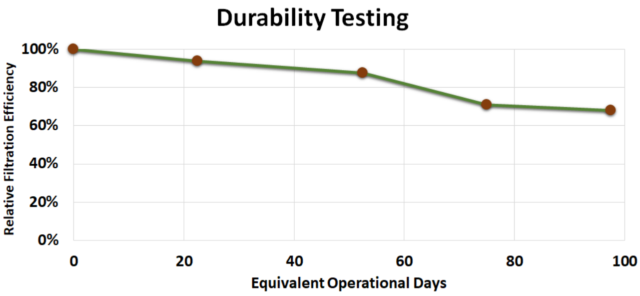


Figure 11: *Relative filtration efficiency maintained up to 90% of the initial efficiency during accelerated durability testing over 50 equivalent days.*

The nanoparticle coatings consistently demonstrated the ability to improve the filtration efficiency of a baseline filter (Fig. 12). The filters with single nanoparticle coatings (NP=1) with Graphene, ZnO or TiO_2, demonstrated an improvement of about 100% over the baseline uncoated filter. Coating the filters with two out of these three nanoparticles (NP=2) improved the efficiency further. However, the filter coated with a mixture of all three-nanoparticles (NP=3), had the highest filtration efficiency which was 3 times higher than the baseline filter. The filtration efficiency of this filter, at 77%, was quite comparable to the more expensive 'high-quality' MERV-14 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.

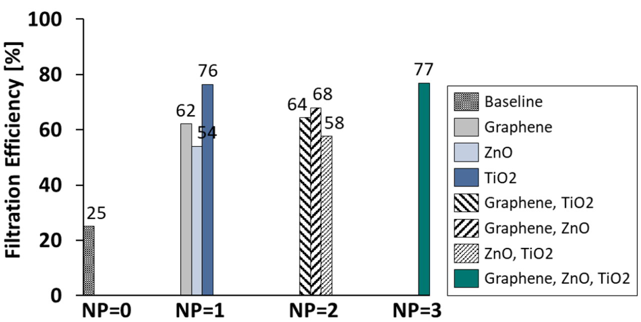


Figure 12: *Filtration efficiency of nanoparticle coated filters improved significantly relative to a baseline uncoated filter. The Graphene, ZnO, TiO_2 combination is 3 times more effective than a baseline uncoated filter.*

Cost-effectiveness was one of the main objectives of this experiment (Fig. 13) 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 cost assumptions behind this calculation are based on commercially available filters in a local hardware store. A regular air-conditioning filter with filter performance rating (FPR) 4 (equivalent to MERV 6/7) is considered as "baseline", priced at ~$4. The nanoparticle coating content in each filter is approximately 2.5 g (8% concentration wt./wt.) at an average cost of ~$400/kg thus a weighted total price of ~$3 for the 3 nanoparticles. The processing cost of $1 is assumed for consumables and labour. The FPR 10 (MERV equivalent 14) is the commercially available HEPA filter of the same size, priced at ~$25 and an ionic filtration system is commercially available for ~$500.

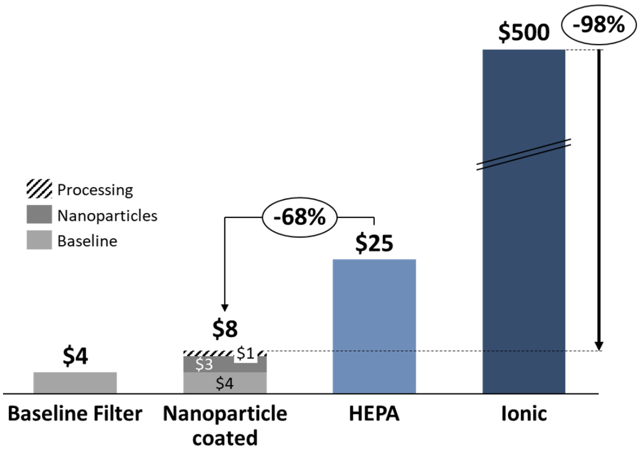


Figure 13: *Adding the costs of the nanoparticles and processing costs to a baseline filter, the coated filters are significantly less expensive than HEPA or ionic filtration systems.*

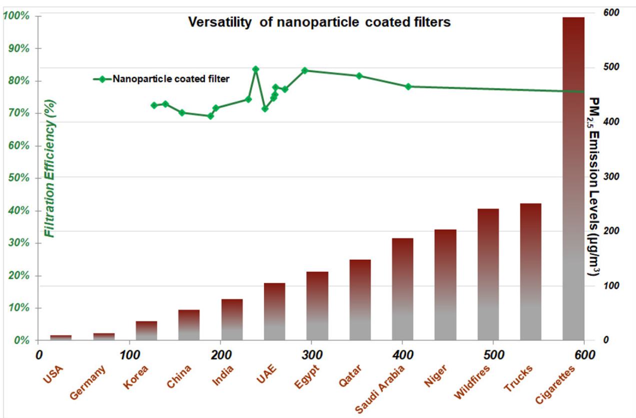


Figure 14: *Versatility of nanoparticle coated filters in different global pollution levels. The bar-chart indicates the different $PM_{2.5}$ levels in different countries and from different sources. The line graph indicates the filtration efficiency relative to the inlet $PM_{2.5}$ levels, indicating relatively consistent filtration efficiency over a wide range of $PM_{2.5}$ levels (100~600 µg/m³).*

The nanoparticle coated filters were also tested for their versatility at different inlet conditions and compared to the $PM_{2.5}$ pollution levels in different parts of the world and from different sources. In a further study, the filtration efficiency has been found to be consistent across different sources of $PM_{2.5}$, such as wood chips, paraffin and incense (Nag, 2022).

As illustrated in Fig. 14, the bar-chart indicates the $PM_{2.5}$ pollution levels found in different countries (2019 World Air Quality Report) like China, India, Niger etc. and from different pollutant sources (De Marco et. al. 2016) like wildfires, emissions from trucks etc. Typically, the $PM_{2.5}$ levels in countries like Niger are about 200 µg/m^3 or in India about 80 µg/m^3. The $PM_{2.5}$ levels from wildfires and emissions from trucks are in the range of 250-270 µg/m^3. The results of the filtration efficiency of the nanoparticle coated filters are plotted on the same graph relative to the inlet $PM_{2.5}$ conditions simulating the levels of pollution in different countries and from different sources. It can be seen in Fig. 14, that the filtration efficiency is relative consistent between 70-80% irrespective of the inlet levels of $PM_{2.5}$. This indicates that the nanoparticle coated filters are versatile in their usability – from different sources and levels of $PM_{2.5}$ pollution.

The safety of nanoparticle usage is of utmost importance and continues to be a subject of research worldwide. The nanoparticles chosen for this study are known for their clinical safety and non-toxicity. TiO_2, ZnO and Graphene are extensively used in commercial products like pill coatings, sunscreens, and biomedical applications (Shi et. al. 2015; Arvidsson 2018).

Conclusion

The results of this experiment can be used in several applications including personal protective equipment like air pollution masks, air-conditioning and car cabin filters, firefighting equipment, and industrial pollution control systems for power plants, incinerators, or automobiles. The versatility and effectiveness of this filtration system makes it applicable in different parts of the world with varying pollution levels. The simplicity of the application method and the cost-effectiveness make this process feasible to be used in low-income areas that have higher risks of air pollution and limited resources to combat their lethal effects. The nanoparticles selected for this application have been known for their non-toxicity and hence safe for human use. A significant correlation has been found between ambient air pollution and deaths caused by viral infections, such as COVID-19, which lead to respiratory diseases. This makes it essential for individuals to reduce their own pollution footprint, especially in rapidly urbanizing areas of the world, and adapt such novel, cost-effective and safe nanoparticle coated filtration technologies to reduce the deadly consequences of air pollution.

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