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High-Performance Nanomaterial's in Air Filtration and Purification

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Abstract:

Industrialization and urbanization are amongst the major sources of air pollution. Though high-performance nanomaterials offer compelling advances for air filtration and purification. In this work, several nanomaterials were tested for their ability to remove particulates (PM2.5 and PM10) and VOCs, while evaluating the wear and tear of each material. Pressure had no effect on PM2.5 capture efficiency which was 80% using activated carbon, while carbon nanotubes were more efficient in PM10 capture despite greater pressure drop. Graphene oxide was very effective in the abatement of volatile organic compounds, which was not the case for titanium dioxide which performed as good as activated carbon in the capture of PM2.5 particles but with a pressure drop of the same magnitude. Silver nanoparticles were the most effective in a percent capture of PM10 particles at low pressure drop. Yeoman's zinc was effective in re-absorbing volatile organic compounds from the dust. The PEI-coated and electro spun nanofibers are capable of capturing PM2.5 and PM10 particles respectively, and at relatively low-pressure reductions. Results from durability studies demonstrated that TiO2 and silver nanoparticles exhibited superior efficiency retention throughout numerous cycles, but PEI-coated nanofibers saw substantial efficiency degradation.

Key Words*: Air Filtration ,Carban nanotubes, Purification*

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Introduction:

Air pollution is a serious issue all over the world, one that is damaging to both human beings and the environment in general, which in turn induces numerous health problems and environmental degradation. Such a complete picture can include the awareness of particular substances called Particulate matter (PM): fine particulate matter (PM2.5) and coarse particulate matter (PM10) and Volatile organic compounds (monomeric form) as the harmful air contaminants causing adverse human health effects. Particles less than 2.5 micrometers find their way quite effectively into the lungs and the bloodstream, hence contributing to the development of respiratory and cardiovascular diseases (World Health Organization, 2022). Volatile Organic Compounds (VOCs), such as benzene and formaldehyde have also been

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implicated in various diseases throughout the world including cancer and neurological disease (U.S Environmental Protection Agency 2021). Most conventional air filtration approaches that deploy both mechanical filtration systems and electrostatic precipitators can handle big particles quite well but seem to have problems with ultrafine particles and gaseous contaminants. Mechanical filters, despite their benefits in controlling particulate clean air, are not ideal in the long run owing to saturation, pressure drops and the natural limits of particulate capturing surfaces requiring upkeep (Singh & Puri, 2020). Electrostatic precipitators are highly effective in the removal of particulate matter (PM), but are less efficient than desired in the control and removal of VOCs and often have high associated maintenance costs (Chen et al., 2021). Because of their different physicochemical properties, nanomaterials make great opportunities in overcoming these challenges. Nanomaterials have unique qualities of high surface area to volume ratio, controllable pore structures, and definite characteristics of the surface that make them more effective in the adsorption and decomposition of pollutants. Geometrical variants of nanomaterials such as carbon based, metal based and polymer based have all recorded positive impact in improving the quality of air filter and purification systems. Some nanomaterials with high specific areas such as activated carbon, carbon nanotubes (CNTs) and graphene oxide which are well known with high adsorbing surfaces have been used. Professor Liu et al (2021) report that carbon nanotubes and graphene oxide have high adsorptive and catalytic activity, which explains the rapid elimination of solid and gas sources of pollution. There are metal nanomaterials like titanium dioxide (TiO_2), silver nanoparticles, and zinc oxide (ZnO) which have a reputation for utilising light to perform chemical reactions and also disposing of germs. It has been widely established that titanium dioxide (TiO_2) is capable of removing organic contaminants when subjected to UV light irradiation. On the other hand, the antibacterial effect of silver nanoparticles makes it very useful in the air filtration of unit operations (Kim et al, 2022). Zinc oxide has photocatalytic properties enabling degradation of codes containing VOCs and PM (Chen et al 2021) Enhanced polymer-based nanomaterials for example PEI coated nanofibers and electro spun nanofibers have added advantages of high surface area, mechanical flexibility and ease of modification. Zhao et al. (2020) reports that $PM_{2.5}$ and VOCs capturing efficiency of pure PEI-coated nanofibers improved by great extent. While the electro spun nanofibers on the other hand are effective in the fabrication of filters with high surface area and porosity. The research investigates the capabilities of these advanced

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nanomaterials in tackling the issues of air pollution, specifically examining their efficiency, modes of operation, and practical uses in improving air filtration and purification technology.

METHODOLOGY

The research was conducted through a series of laboratory experiments to evaluate the performance of different nanomaterials in air filtration and purification. The nanomaterials investigated include:

1. Activated carbon, carbon nanotubes (CNTs), and graphene oxide.
2. Titanium dioxide (TiO_2), silver nanoparticles, and zinc oxide (ZnO).
3. Polyethyleneimine (PEI)-coated nanofibers and electro spun nanofibers.

Experimental Setup:

• **Air Filtration Testing:** A specially designed filtration chamber was utilized to replicate contaminated air conditions. Air samples comprising particulate matter with a diameter of 2.5 micrometers or less (PM2.5), particulate matter with a diameter of 10 micrometers or less (PM10), and volatile organic compounds (VOCs) were filtered using media that included nanomaterials. The efficacy of pollutant elimination was assessed utilizing high-precision sensors and analytical tools.

The nanomaterials were characterized using scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR) to analyze their structure, morphology, and chemical content.

• **Data Analysis:** The nanomaterials' filtering effectiveness, pressure drop, and reusability were examined and compared in various experiments.

RESULT

1. Filtration Efficiency

The observation from Table 1 with the least pressure drop of 10Pa can reduce PM2.5 particles by 80%, using activated carbon, to where the level was able to be reduced from 250 $\mu g/m^3$ to 50 $\mu g/m^3$. This ensures filtering is done efficiently without a constraint in the flow of air. Removing the CNTs decreased the concentration of PM10 from 300 $\mu g/m^3$ to a mere 30 $\mu g/m^3$. However, the pressure drop enhancement by 15 Pa could impose some restricted airflow rates. For the VOCs, Graphene oxide could remove almost all the VOCs from 200$\mu g/m^3$ to 20$\mu g/m^3$ with only registering a pressure drop of 12Pa. This was further

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substantiated by the research studies that showed TiO2 achieved a 90% removal efficiency of PM2.5, thus reducing the formaldehyde concentration to as low as 25 µg/m³, with a low pressure drop comparable to that of active carbon. Therefore, under a pressure drop of 14 Pa, the silver particles achieved the highest removal efficiency in respect of PM10 of 93 %, which reduced the concentration from 300 to up to 20 µg/m³. At approximately 13 Pa, the zinc oxide was found effective to reduce VOCs by a reduction percentage of 92% through their decreases in the level of concentration from 200 to 15 µg/m³. The pressure drop was 11 Pa while it was machined with PEI-coated nanofibers. It had stronger anti-fouling ability and filtration moderate; thus, PM2.5 reduced the concentration to 35 µg/m³. It was confirmed that the samples were able to filter PM10 with efficiency of 87% using electro-spun nanofibers under conditions of pressure drop of 13 Pa; thus, it reduces the concentration to 40 µg/m³. This was good because it gave the right amount of airflow without it taking too much of the time or effort.

Table 1: Filtration Efficiency of Various Nanomaterial's

Nanomaterial	**Pollutant Type**	**Initial Concentration (µg/m³)**	**Final Concentration (µg/m³)**	**Removal Efficiency (%)**	**Pressure Drop (Pa)**
Activated Carbon	PM2.5	250	50	80	10
Carbon Nanotubes	PM10	300	30	90	15
Graphene Oxide	VOCs	200	20	90	12
Titanium Dioxide	PM2.5	250	25	90	10
Silver Nanoparticles	PM10	300	20	93	14
Zinc Oxide	VOCs	200	15	92	13
PEI-coated Nanofibers	PM2.5	250	35	86	11
Electro spun Nanofibers	PM10	300	40	87	13

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2. Reusability and Durability

Table 2 illustrates that activated carbon experienced an efficiency decline of 5% after 10 cycles; nevertheless, its efficiency is a stable indicator of a high level of reusability and moderate structural integrity, signifying continued reliability, even though it loses performance at a nominal pace. Carbon nanotubes (CNTs) demonstrated their durability when they had a loss of 2% efficiency after 15 cycles, attributing their high efficiency due to their high reusability and structural efficiency. The efficiency of graphene oxide, after 12 cycles, decreased by 3% but maintained acceptable structural integrity and high reusability, suggesting that it would be a reusable material.

Table 2: Reusability and Durability of Nanomaterial's in Filtration

Nanomaterial	Pollutant Type	Number of Cycles Tested	Efficiency Loss (%)	Reusability Score*	Structural Integrity**
Activated Carbon	PM2.5	10	5	High	Moderate
Carbon Nanotubes	PM10	15	2	Very High	High
Graphene Oxide	VOCs	12	3	High	High
Titanium Dioxide	PM2.5	20	1	Very High	Very High
Silver Nanoparticles	PM10	15	2	Very High	High
Zinc Oxide	VOCs	10	4	High	Moderate
PEI-coated Nanofibers	PM2.5	8	6	Moderate	Low
Electrospun Nanofibers	PM10	10	5	Moderate	Moderate

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Titanium dioxide (TiO2) had the most efficiency even though it had lost 1% after 20 cycles, showing it had excellent durability and reusability. After 15 cycles, silver nanoparticles had exceptional durability with only a 2% drop in efficiency and maintained structural integrity and high reusability. However, zinc oxide experienced a 4% decrease in efficiency after 10 drops but did maintain high reusability. Nevertheless, this was less durable than some other materials due to having a moderate structural integrity. After 8 cycles, the effectiveness of PEI-coated nanofibers declined by 6%, moderate reusability, and decreased structural integrity, indicating they would need greater maintenance. Electrospun nanofibers showed a 5% reduction in efficiency after 10 cycles, indicating a reasonable degree of reusability, structural integrity, and good performance with only a slight increase in wear over time.

DISCUSSTION

These tested nanomaterials have actually shown quite different performances under different pollutants and operating conditions. So activated carbon is, therefore, still a good option for PM2.5 for removing at a high removal efficiency with very low pressure drop, although the efficiency decreases by 5% after 10 cycles. At the same time, CNTs are best for PM10 removal; however, their higher pressure drop may affect the airflow. The properties were excellent for graphene oxide in the removal of VOC at an efficiency of 90%, while for TiO2, with outstanding durability and efficiency for PM2.5, its efficiency hardly repressed after more than 20 cycles. The effectiveness of silver nanoparticles in PM10 was high with a low pressure drop, while that of zinc oxide in VOC removal was effective with a manageable pressure drop. On the other hand, PEI-coated and electrospun nanofibers have presented a balance between filtration performance and pressure drop. However, they have been shown to exhibit higher loss in efficiency after multiple cycles.

The results indicate that no one material fits all applications, but some materials are better at other factors. For example, TiO2 and silver nanoparticles remain the best due to their stability, whereas graphene oxide and zinc oxide are the best in terms of efficiency with regards to VOC removal. However, other materials, such as CNTs and silver, create larger pressure drops, and need to be accounted for in applications where airflow is considered.

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CONCLUSION

The study's conclusions included a comprehensive evaluation of many nanomaterials for air filters and identified advantages and disadvantages within each category. These include several nanoparticles that are thought to be extremely durable and effective, such as TiO2, silver, and activated carbon, which makes them suitable for long-term usage in air filters. Certain pollutants, such as volatile organic compounds (VOCs), can be effectively removed by materials like zinc oxide and graphene oxide. However, CNTs and silver nanoparticles work well for certain pollutants; however, their impact on airflow should also be taken into account when pressure drops are significant. The kind of pollutant, allowable pressure drop, and other durability criteria of the filtering application should all be taken into consideration while choosing the right nanomaterials.

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