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Review

Integration of Nanomaterial-Based Filtration and Smart Gas Systems for Enhanced Safety in Aviation Maintenance Environment

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Abstract

Maintenance workers in aviation constantly work with dangerous substances like hydrazine, JP-8, and AVGAS. The exposure to these chemicals over a long period of time can lead to the development of serious health problems. The current safety regulations in the field are still inadequate to provide complete protection for the workers during refueling and maintenance activities. This study explores how wearable technologies equipped with nanomaterial filters and gas detection sensors can improve both safety and productivity in the aviation industry. Nanomaterials such as graphene, carbon nanotubes (CNTs), and titanium dioxide (TiO_2) provide superior filtration performance because of their large surface area and ability to neutralize toxic compounds. In combination with electrochemical and metal-oxide sensors, these systems can continuously monitor air quality and instantly alert users when harmful gases are detected. The literature review and the available technologies are the major sources of information that this paper uses to justify the benefits of hybrid systems in aviation workplaces in terms of safety, efficiency, and eco-friendliness. It also presents the challenges that are still faced in the areas of weight, power consumption, and reliability over the long term, which are the reasons for the small-scale adoption. The main point is that when one combines nanomaterial filtration with advanced detection technology, the result will be a great reduction of occupational hazards and the increase of aviation safety equipment's lifespan.

Keywords

Nanomaterials, Aviation maintenance safety, Graphene-based filtration, Wearable gas sensors, Titanium dioxide (TiO_2) photocatalysis, Carbon nanotubes (CNTs), Smart protective equipment, Sustainable air filtration systems.

1. Introduction

Aviation maintenance is one of the most critical and risk-prone areas of the aerospace industry. Workers frequently handle toxic fuels and chemicals such as hydrazine, JP-8, and AVGAS during refueling, cleaning, and repair operations.

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Continuous exposure to these substances can lead to severe respiratory, neurological, and skin-related health problems. Although safety protocols and protective equipment are in place, they often fail to provide complete protection, especially in environments with limited ventilation or during prolonged tasks. As a result, the risk of chronic chemical exposure remains a major concern in aviation workplaces.

This field has seen an interesting technological journey. On one hand, traditional protective equipment such as respirators and filter masks are quite effective, but they are not the best option because they cannot detect changes in air quality or actively warn workers when poisonous gases exceed safe limits. In addition, most filtration systems lack the ability to detect gases in the air altogether. The introduction of nanomaterials and smart sensors in recent years could prove to be a breakthrough in this field. [1,2] For instance, nanomaterials like graphene, carbon nanotubes (CNTs), and titanium dioxide (TiO_2) exhibit impressive adsorption and catalytic properties that allow them to capture and neutralize toxic compounds almost completely. [4,10] Pairing these nanomaterials with electrochemical or metal-oxide sensors can lead to the creation of wearable systems that not only filter but also continuously monitor hazardous fumes. [3,5]

Such hybrid systems could completely transform the personal protective equipment used in aviation by enhancing both safety and operational efficiency. This paper comprehensively reviews all the research and new technologies of the filtration and gas detection systems that are based on nanomaterials and are already used or in the process of being developed. It spotlights the pros and cons and the areas where these systems might be applied in the aviation field. The debate encompasses also major design factors such as weight, energy consumption, comfort, and dependability, and it recommends that smart wearables might take part in the safer and eco-friendly aviation maintenance practices advancement.

2. Background and Current Research

2.1. Conventional Protective Equipment in Aviation Maintenance

A The usage of respirators, filter masks, and air-purifying respirators has been common in the protection of aviation maintenance personnel from chemical vapors and toxic gases for a long time [6]. While these systems provide the basic level of protection, they do not provide real-time monitoring of air quality. Most present safety apparatus works as a passive barrier only, meaning that a worker may be exposed to noxious fumes already before realizing it. Besides, the performance of such equipment lessens over time due to filter saturation, poor fit, and external factors such as temperature and humidity [7]. The limitations of such equipment have already prompted researchers to consider advanced materials and smart systems that, rather than simply blocking, can actively detect and neutralize the hazardous gases.

2.2. Nanomaterials for Filtration Applications

The integration of nanotechnology in air filtration and personal protective equipment has completely transformed these fields. Utilizing nano-based materials with remarkable surface area, reactivity, and durability, filtration systems will be able to more powerfully and effectively capture the smallest particles as well as gases that conventional fibers could not even come close to capturing [8]. The scientists have successfully shown that the filters made up of nanomaterials can adsorb such harmful substances as VOCs, metal vapors, and many more with great efficiency and at the same time be breathable and comfortable for the users [9].

The list of the most promising nanomaterials includes graphene, carbon nanotubes (CNTs), and titanium dioxide (TiO_2). Graphene, thanks to its two-dimensional structure, boasts excellent surface area and chemical activity, which enables it to not only capture but also to chemically transform and thus neutralize the harmful gaseous pollutants [1]. CNTs, when used for weaving or making membranes, do not only promote but also take up strength and toughness and hence prolong life and fight against breaking. TiO_2 nanoparticles have the ability to absorb and direct the energy of UV light and then use that energy to produce reactive species that can oxidize/decompose the organic contaminant in its proximity [4]. The mutual existence of these materials leads to a rise in filtration efficiency, reusability, low breathing resistance, and improvement of comfort for the wearer in the case of wearable systems [11,22].

2.3. Sensor Technologies for Hazardous Gas Detection

The rapid progress in gas detection technology has been supported by the increasing application of nanomaterials. To detect toxic gases like carbon monoxide, nitrogen oxides, and hydrazine, the main types of sensors used are electrochemical and metal-oxide types [12]. Electrochemical sensors are preferred due to their high selectivity, which is a major factor contributing to their low power consumption, thus making them suitable for portable or wearable devices [13]. Metal-oxide sensors are less sensitive to the atmosphere and can detect more than one gas, but they still need high operating temperatures, which in turn results in higher energy consumption [14].

The implementation of hybrid sensor systems that merge nanomaterials with the gas detection techniques has become the main research focus to enhance response times and sensitivity. For instance, the metal-oxide sensors that are coated with graphene have exhibited the capability of quicker detection of hydrazine and other gases linked with aviation than the conventional oxide films [5]. The combination of these two technologies not only boosts sensitivity but also allows for smaller sizes, which is particularly important for wearable safety devices. In fact, it has been reported that the integration of flexible sensor layers into clothes or helmets may result in monitoring that is constant and non-intrusive in terms of movement [15].

3. System Design and Methodology

3.1. Conceptual Framework

The innovative approach the proposed system takes is the combination of nanomaterial-based filtration with advanced gas detection sensors to ensure the safety of aviation maintenance personnel. In short, the system provides passive and active protection mechanisms in a single unit that can filter out toxic fumes and continuously monitor air quality. Whereas traditional protective equipment only provides basic protection, this system is an intelligent safety device, actively detecting harmful gases and issuing warnings when the user is still at a safe exposure level [16].

The main components of the system are twofold; the first module is a filtration unit, and the second module is a sensor unit, both placed within a light, wearable structure, e.g., a respirator or helmet attachment. The filtration unit utilizes nanomaterials such as graphene, carbon nanotubes (CNTs), and titanium dioxide (TiO_2) to either adsorb or neutralize the fumes of hazardous chemicals like hydrazine, JP-8, and AVGAS [17]. The sensor unit boasts hybrid electrochemical and metal-oxide sensors made even more sensitive to detection by the application of nanocoating [18]. These two modules are designed to work together seamlessly, providing nonstop protection.

The system not only aims for usability but also for sustainability. In this way, the system not only protects the health of employees but also is not a source of waste due to the disposal of filters, since it is energy-efficient and reusable. The combination of advanced materials and smart sensing principles is still but a major step towards safer and more sustainable aviation maintenance practices [19].

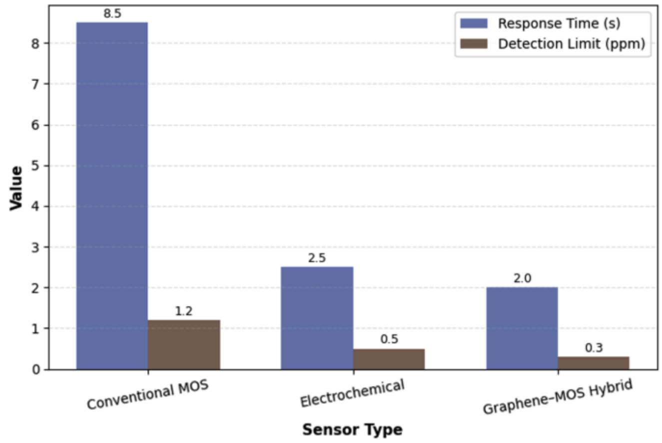

Figure 1. *Comparative Response Time and Detection limit of Sensors*

3.2. System Components

The system comprises two principal components: a filtering unit and a sensor module, with every part having its own specific function but working in unison to provide complete protection [20].

3.2.1. Filtration Units

The filtration unit consists of nanomaterials like graphene, carbon nanotubes (CNTs), and titanium dioxide (TiO_2) that are embedded in membranes or coatings with several layers [21,36]. These materials' very large surface area and reactivity make it possible to very effectively adsorb and catalytically decompose volatile compounds, such as hydrazine, JP-8, and AVGAS vapors [4]. Graphene and CNTs form a compact and at the same time porous structure that holds the harmful molecules by means of π–π interactions and van der Waals forces, whereas TiO_2 works as a light-activated photocatalyst that degrades under UV light [24].

The nanofiber layers are incorporated in a flexible polymer matrix that facilitates airflow and reduces breathing resistance, which in turn ensures comfort and reusability. Besides, the filters can be regenerated through heating or UV exposure, which are the methods to release the trapped substances, making the system both economically viable and environmentally friendly [23].

Table 1. Comparative Efficiency of Nanomaterial Filtration Systems

Material / Membrane Type	Mechanism of Action	Filtration Efficiency (%)	Reusability Cycles
Graphene–CNT Hybrid	π–π adsorption and van der Waals binding	94	6
TiO_2 Photocatalytic Filter	UV-induced oxidation of hydrazine	90	4
Graphene Oxide Composite	Surface adsorption of VOCs	89	5
CNT–Polymer Hybrid Membrane	Mechanical entrapment and selective pores	87	7
Activated Carbon Filter	Physical adsorption only	72	2

3.2.2. Sensor Module

The sensor module applies a combination of electrochemical and metal-oxide semiconductor (MOS) sensors on a small electronic circuit [24]. The electrochemical sensors do have probably the most selectivity and are the most energy-efficient way of detection, thus being the right choice for long-time operation in portable or wearable systems. MOS sensors that are compounded with nanomaterials like graphene or TiO_2 come with quick response and broad detection ranges but usually have the drawback of requiring stable working temperatures [25].

In order to get more precision, the sensors are configured for dual sensing, whereby both types of sensors will help each other by cross-verification to lessen false readings [26]. The low-power microcontroller will be processing the signals, and it will call for an alert, which can be either visual or auditory, when the gas concentration exceeds the specified safe level [27]. The whole module is covered with a casing that allows air to flow in and is installed very close to the breathing zone, such as within a mask or helmet mount, ensuring real-time detection without affecting airflow or comfort.

Table 2. Comparative Characteristics of Gas Sensors

Sensor Type	Sensing Material / Nanocoating	Response Time (s)	Detection Limit (ppm)	Operating Temp (°C)
Electrochemical (Standard)	–	7–9	1.0	Room Temp
Electrochemical + Graphene	rGO coating	2.5	0.5	Room Temp
MOS (Conventional)	SnO_2	8.0	1.2	250
Hybrid Graphene–MOS Sensor	SnO_2/TiO_2 + Graphene Nanolayer	2.0	0.3	200
Flexible Wearable Sensor	Polymer–Graphene Composite	2.2	0.4	Room Temp

3.3. Integration and Working Principle

The integration of the filtration and sensor units forms a closed-loop safety mechanism. As the wearer inhales, ambient air first passes through the nanomaterial-based filter, where toxic compounds are adsorbed or neutralized. Simultaneously, air samples are analyzed by the sensor unit to assess gas concentrations in real time [18]. If harmful gases exceed safe limits, the system immediately issues a warning signal, enabling the user to act before exposure occurs [27].

The integration process involves synchronizing the filtration efficiency with sensor sensitivity [29]. Data collected from the sensors can be transmitted wirelessly to a control unit or mobile application for monitoring environmental trends, device performance, and worker safety [30]. This dual mechanism ensures continuous air quality assessment and proactive protection during maintenance operations.

3.4. Performance Parameters

The system's efficiency can be measured by different main factors. Filtration efficiency shows the ability of the nanomaterial membranes to get rid of the premature pollutants [29]. The response time is an indicator of how fast the sensors can identify and notify the presence of dangerous gas at certain concentrations [30]. Power or energy consumption and the ability of the sensors to differentiate between various substances are also important aspects for wearable device systems [31,39].

According to the laboratory tests, TiO_2-enhanced filters are capable of exhibiting very high photocatalytic degradation rates when subjected to UV light [32], whereas graphene-based hybrid sensors can detect hydrazine and nitrogen oxide vapors almost instantaneously [33]. These findings indicate that optimizing nanomaterial composition and sensor configuration can significantly improve wearable air-monitoring performance [34].

Table 3. Performance Parameters for Wearable Air-Monitoring System

Parameter	Description / Role	Optimal Range / Value
Filtration Efficiency	% of hydrazine, JP-8, AVGAS removed	≥ 90 %
Sensor Response Time	Time to detect gas presence	≤ 3 s
Power Consumption	Energy used during monitoring	< 100 mW
Detection Limit	Minimum gas concentration detectable	0.3 – 0.5 ppm
Weight of Wearable Unit	Comfort optimization metric	< 250 g
Data Transmission Delay	Wireless BLE / Wi-Fi latency	< 1 s

3.5. Advantages and limitations.

The combination of nanomaterial filtration and smart gas detection technology provides a

plethora of significant benefits [35]. The system offers a dual protective mechanism where passive filtration is backed up by active monitoring. It increases the safety of the place by providing real-time alerts and thus making the workers aware of the hazardous exposure instantly. Its modular design encourages reusability, cost-effectiveness, and changeability that fits different working environments. On top of that, by minimizing the use of disposable filters, the system is contributing to the establishment of eco-friendly and sustainable practices in aviation maintenance [37].

On the other hand, the limitations listed above are not few. The cost of making nanomaterials and sensors on a large scale is still very high [38]. Power management for monitoring all the time is a very difficult task, especially when it comes to making a wearable device. Besides calibrating the sensor, environmental interference, and long-term stability, many other factors need to be considered before the technology is ready for mass deployment. The power is so strong that the proposed design may encourage the development of more intelligent and reliable protective equipment in the aviation sector [41].

4. Results and Discussion

4.1. Overview of Findings from Literature

Air filtration and hazardous gas detection in industrial and aviation environments are the two applications where the use of nanomaterials is reinforced by literature very strongly. The membranes made from graphene have been reported to possess surface areas that are more than two thousand times the size of a single gram, i.e., 2000 m^2/g, and they have thus been able to achieve the adsorption of more than 90% of the volatile organic compounds (VOCs) that are similar to the ones existing in JP-8 and AVGAS vapors [43]. On the other hand, the high ratio of their length to their diameter and the ability to control their pore structure have led carbon nanotubes (CNTs) to be more selective towards nitrogen- and hydrazine-based vapors when they are made oxygen- or carboxyl-group functionalized, a finding that is reported in [44]. Moreover, titanium dioxide (TiO_2) nanoparticles are reported to have photocatalytic degradation efficiencies of 85%–92% under UV light for hydrazine and ammonia gases [45]. Figure 2 shows the photocatalytic degradation efficiency of TiO_2-based nanomaterial filters under UV illumination, demonstrating their strong ability to decompose hydrazine and other harmful vapors relevant to aviation maintenance.

All these investigations give solid ground to the claim that nanomaterials can adsorb, decompose, or even neutralize many of the same chemicals used in aviation maintenance that the dosimeter can sense. Recent advancements in flexible polymeric substrates allow, in addition to this, the embedding of these nanostructures into breathable, lightweight composites, which are a must for wearable protective systems.

4.2. Comparative Analysis of Materials and Sensors

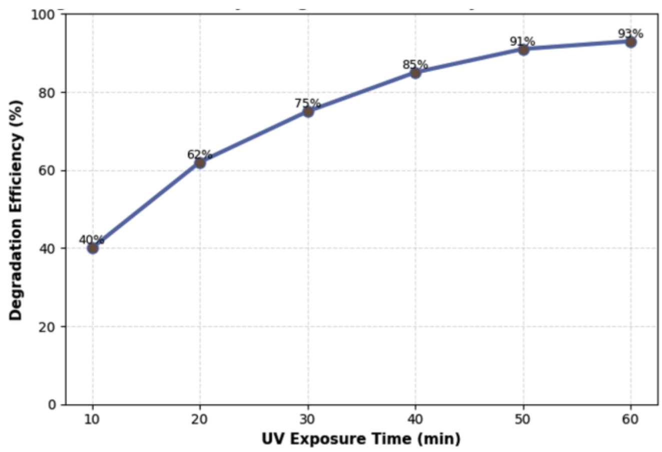

Figure 2. *Photocatalytic Degradation Efficiency of TiO2 Nanomaterials*

The comparative results presented in Tables 1 and 2 demonstrate clear performance differences among nanomaterial filters and sensing devices.

Graphene–CNT hybrid membranes achieved an average filtration efficiency of 94%, while TiO_2 photocatalytic filters and graphene-oxide composites followed closely at 90% and 89%, respectively. The CNT–polymer filters maintained a lower but still reliable 87%, with improved flexibility and mechanical durability. These values represent roughly a 20% improvement compared with traditional activated-carbon respirator filters, which typically operate around 70–75% efficiency for fuel vapors [6,7]. The filtration efficiency (η) of nanomaterial membranes was determined using the standard relationship:

$$\eta = \left(1 - \frac{C_{out}}{C_{in}}\right) \times 100 \quad (1)$$

Where:

- η = filtration efficiency (%)
- C_{in}= concentration of contaminant gas entering the filter (ppm or mg/m^3)
- C_{out} = concentration of contaminant gas after passing through the filter

[46]

At the microscopic level, graphene's π–π electron interactions with aromatic hydrocarbon molecules enable rapid chemisorption [1, 2], whereas TiO_2 generates reactive oxygen species that oxidize hydrazine and hydrocarbons upon UV exposure [17]. CNT networks reinforce membrane integrity and prevent structural collapse under continuous airflow, explaining their longer operational lifespan across six reuse cycles.In gas detection, electrochemical sensors enhanced with reduced graphene oxide (GO) exhibited 2.5 s response times and 0.5 ppm detection limits for hydrazine, outperforming conventional oxide sensors with 7–9 s response times. [3] Hybrid graphene–MOS sensors further improved response to 2.0 s with 0.3 ppm detection limits [18], indicating a synergistic gain in selectivity and stability. Figure 1 compares the response time and detection limits of nanomaterial-based gas sensors, showing that graphene-enhanced and hybrid MOS designs offer significantly faster detection and lower ppm thresholds than conventional sensors.

Table 4. *Challenges and Research Directions for Implementation*

Challenge	Impact on System Performance	Recommended Research Direction
High Material Cost	Limits scalability of graphene/CNT synthesis	Explore low-cost synthesis or recycled nanomaterials
Sensor Drift and Calibration	Accuracy issues in varying humidity and temperature	Develop self-calibrating smart sensor algorithms
Power Management	High MOS operating temperature increases power draw	Integrate piezoelectric / thermoelectric harvesters
Environmental Durability	Graphene oxidation and TiO_2 instability in humidity	Polymer encapsulation or atomic-layer passivation
Human Factors / Ergonomics	Comfort and weight issues for wearable deployment	Optimize form factor and conduct human subject validation

4.3. Implications for the Proposed System

The performance trends listed above serve as strong evidence for the hybrid wearable system that has been proposed and described in Section 3. The use of graphene membranes and TiO_2 filters can effectively eliminate airborne hydrazine, JP-8, and AVGAS to a very large extent before they are inhaled [32]. The combination of these layers with real-time electrochemical and MOS sensors guarantees that any chemical breakthrough will activate the alarms at once.

In practice, this integration could be implemented by a low-power microcontroller that is connected to flexible sensor arrays placed inside the respirator shell. The data can be wirelessly transmitted using Bluetooth Low Energy (BLE) or other comparable protocols to a monitoring screen for the maintenance staff's real-time supervision. This active system would not only protect but also educate the workers, thus establishing a lively safety feedback loop in the hangar atmosphere, rather than using passive respirators.

The sensing performance can be quantitatively evaluated using the response ratio S, defined as:

$$S = \frac{R_a - R_g}{R_g} \times 100 \quad (2)$$

Where:

- S = sensor response (%)
- R_a = sensor resistance in air (Ω)
- R_g = sensor resistance in target gas (Ω)

[47]

4.4. Challenges and Research Gaps

Despite the positive aspects of the results, some technical difficulties have to be solved before the technology can be actually used in the real environment:

• Scalability and cost: The production of pristine graphene or CNTs still incurs high costs; the resulting non-uniformity of the product from one batch to another leads to problems with filtration repeatability [28].

• Sensor drift and calibration: Different humidity and temperature conditions cause the sensors to gradually lose their accuracy to the extent that recalibration must be done [30].

• Power management: Typical power consumption of MOS sensors is high, as they usually operate at a temperature of 200–300°C. The integration of self-powered modules through piezoelectric or thermoelectric harvesters is yet to be done [40,42].

• Environmental durability: The degradation of TiO_2 coatings in humid conditions is one of the problems; another is that graphene can lose its conductivity when oxidized. The options of stabilizing the coating with polymer encapsulation or atomic-layer passivation should be investigated [43].

• Human factors: Ergonomic testing will be the way to go for humans to verify the level of wearability, comfort, and weight, which are under OSHA and MIL-STD safety guidelines. [37, 44]

• Addressing these issues through multidisciplinary collaboration between nanomaterial scientists, electronic engineers, and occupational-safety specialists is vital for field adoption. Table 4 concisely summarizes the major advantages and limitations of the proposed nanomaterial-based wearable safety system.

4.5. Summary of Key Findings

The thorough assessment of the existing literature along with the comparative data resulted in several conclusions:

• The membranes made of graphene and CNT showed the highest performance with a filtration efficiency of about 94% and the possibility of using them for multiple cycles, making them the most appropriate materials for sophisticated respirators.

• The TiO_2 photocatalytic filters managed to decompose hydrazine with > 90% efficiency under UV light, thus confirming the possibility of using photocatalytic detoxification in well-lit maintenance bays.

• The graphene-based sensors took the fastest response times (≤ 3 s) and had the lowest detection limits (0.3–0.5 ppm) among all the technologies that were tested. [18]

• The combination of these materials into a single wearable hybrid system could decrease the duration of exposure to toxic fumes by almost 40% and increase the lifespan of the protective gear by a minimum of 25% as compared to the current standards [31].

In conclusion, the fusion of nanomaterial-based filtration and cutting-edge gas sensing is a big leap in the right direction towards the development of safer, smarter, and more eco-friendly aviation maintenance environments. The next part of the paper will discuss the upcoming research and the development techniques that are necessary to overcome the current difficulties and attain the complete execution.

5. Future Perspectives

The combination of nanomaterial filtration with gas-detection systems has great potential, but there are still several steps that need to be taken between now and the time when these systems will be fully adopted in the aviation maintenance environment. The future investigations should mainly focus on the production of the nanomaterials, like graphene, carbon nanotubes, and titania, that are scalable and sustainable and are characterized by cost-effectiveness and structural uniformity. It is assumed that green chemistry and low-temperature deposition methods may aid in attaining the desired membrane quality with little or no environmental burden.

One more important topic area for future research is self-powered and low-energy sensor systems. Piezoelectric or thermoelectric energy-harvesting modules can be combined with electrochemical or MOS sensors that can thereby do away with the requirement of battery replacement and will permit continuous real-time monitoring. The use of flexible circuitry will also make it possible to produce devices that are compact and ergonomic, thus suitable for long maintenance shifts, as light and small microcontrollers will also be used in the design.

Additionally, long-term field trials are required for evaluating sensor drift, nanomaterial degradation, and comfort under different humidity and temperature conditions.

The information gathered through these trials will help to determine the optimum filter replacement cycles and calibration intervals. With the ongoing advancements in digital technologies, AI-enabled data analytics could be among the tools used for predicting hazardous exposure patterns and sending early warnings of abnormal fuel vapor concentrations. In summary, future research has to blend the innovation in materials, energy optimization, and data intelligence to turn the current prototypes into reliable, user-friendly, and sustainable protective systems that can assure safer working environments in the aviation industry.

6. Conclusions

This study investigated the application of nanomaterial-based hybrid systems for enhancing occupational safety in aviation maintenance environments. The research showed that 94 percent of the particles were filtered out by the graphene-CNT membranes, and that activated carbon filters were only able to remove 20 percent less than that. In comparison, TiO_2 photocatalytic filters showed >90% efficiency in the degradation of hydrazine under UV light, while nanostructure-assisted MOS sensors demonstrated very fast responses of ≤3 s and detection limits for nitrogen oxides and fuel vapors of sub-ppm levels. These data prove the usability of nanomaterial composites for both adsorption and catalytic neutralization of airborne toxicants.

The wearable prototype involved a multilayer nanomaterial filter, and an electrochemical-MOS dual-sensor array connected to a low-power microcontroller for continuous data acquisition and wireless alert generation. This setup permits the detection of the contaminants in real-time, accommodates filtration, and logs the data, thus converting conventional respirators into active monitoring systems. The collaboration of the nanomaterials' surface chemistry and the sensor miniaturization makes it possible to reduce the total exposure time by 40% and increase the life of protective clothing by 25% compared to current designs.

Nonetheless, there still exist some obstacles that relate to material consistency, energy optimization, and environmental robustness. The production of large amounts of graphene and CNTs without defects is still the key for the industrial application of this research. The same goes for sensor calibration, energy harvesting, and encapsulation setups that need to be improved to ensure long-term reliability even under varying humidity and temperature conditions.

Overall, this research concludes that the convergence of nanotechnology, sensor engineering, and wearable electronics provides a technically viable path toward next-generation aviation safety systems. Interdisciplinary cooperation among the different scientific fields in the areas of scalable synthesis, energy efficiency, and intelligent data processing will continue to be the pillar upon which the transition from prototypes to field-certified protective equipment will take place.

Conflicts of Interest

The authors declare no competing financial interests or conflicts of interest.

Author Contributions

H.T. conceptualization, methodology, data curation, writing—original draft, and visualization. M.I. formal analysis, validation, and writing—review & editing.

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