NANOSENSORS AS A PRINCIPAL TOOL FOR REMEDIATION OF HAZARDOUS AIR POLLUTANTS

Abstract

Air pollution has become a serious problem over the past few decades. High levels of air pollutant and their chemical residues in the atmosphere has a severe impact on human health and the ecosystems. Hazardous gases in the atmosphere include an oxide of carbon, nitrogen, and sulphur, and toxic volatile gases such as ammonia, amides, amines, etc. It is imperative to effectively and in real-time surveillance of the type, amount, composition, and quantity of hazardous air pollutants in the environment. The evaluation, management, and reduction of environmental contaminants are all become feasible through nanotechnology. In the expanding field of nanotechnology, nanosensors are essential for several purposes such as spotting alterations in the environment and assessing harmful and toxic substances found in the workplace and the surroundings. With advancements in nanotechnology, nanosensors can detect minute amounts of air pollutants in the environment. This may foster healthy living and working conditions and guard against negative health impacts. This chapter would help readers understand how nanotechnology may be used to develop extremely effective nanosensors for air pollution detection. The most current advancements associated with the detection and sensing of air contaminants are thoroughly explored.

Keywords: Nanotechnology, Nanosensors, nanomaterials, Air pollution, hazardous

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I. INTRODUCTION

Climate change, global warming, air and water pollution, deforestation, overpopulation, and waste disposal are some of the major environmental concerns that need to be addressed urgently. Air pollution has become a global threat to health and the environment. Air pollution is estimated to cause millions of deaths every year. 6.7 million deaths every year are attributed to outdoor and indoor air pollution. 99% of the world's population lives in the areas where air pollution limit exceeds the world health organization (WHO) guideline limit (https://www.who.int/data/gho/data/themes/air-pollution). WHO estimated 4.2 million premature deaths worldwide per year in 2019 due to ambient pollution in cities and rural areas (https://www.who.int/news-room/fact-sheets). The contamination of the indoor and outdoor environment by chemical, physical, or biological entities that changes the characteristics of the atmosphere is referred to as air pollution. Urbanization, Industrial facilities, transport, extensive use of fertilizers, forest fire, household combustion devices, and improper waste management are some of the common sources of air pollution [1].The environment and public health are greatly compromised due to the negative impact of air pollutants. Smoke from cigarettes, volatile organic compounds (VOCs), dusts from ventilation or the gases of combustion such as carbon monoxide (CO), oxides of nitrogen (NOx), and oxides of sulphur (SOx), and airborne microorganism pollution are all examples of indoor air pollutants. However, burning fossil fuels, industrial and vehicular emissions, and human activity all contribute to outdoor air pollution. Hazardous gases in the atmosphere include poisonous volatile gases such as ammonia, formaldehyde, ozone, amides, oxides of sulphur, and nitrogen. The composition and amount of hazardous air pollutants must thus be accurately and in real-time monitored [2].

Over the recent years, researchershave concentrated their efforts on accurate screening and monitoring of contamination sources including heavy metal ions, poisonous gas species, and volatile organic compounds (VOCs), due to their severe toxic and harmful impacts on the environment and human health [3,4] Traditional approaches to assessing contaminants, such chromatographic methods, require a lot of time, it demand for expensive equipment and reagents, and require sample preparation. Traditional methods that are furnished with sophisticated analytical tools have significant disadvantages. The equipmentsare large, bulky, challenging to use, energy-intensive, and expensive to operate and maintain. With the use of modern technology like nanotechnology, it may be possible to develop novel nanomaterials with unique characteristics that can be utilized to reduce pollution over the long term [5]. Improved catalytic activity, high electrical conductivity, better rigidity and strength, large surface-to-volume ratio, increased electrochemical signals, long-term preservation of nanomaterial activity, and expansion of research tools are some of the common nanomaterial features.

Nanosensors are nanoscale sensing devices that collect information at the nanoscale, monitor and transform physical quantities into signals that are detectable and analyzable.Nanosensors are very sensitive, portable, low-cost, and simple-to-use sensing devices for detecting chemical and biological contaminants. A nanosensor consists of three basic components namely a receptor probe, a transducer element, and an amplifier as shown in Figure 1. A receptor interacts with the air pollutants and generates a response that is converted to an electrical signal by a transducer, later it is amplified by an amplifier and converted to a quantifiable output by the signal processing unit. For the objective of identifying chemical and biological pollutants, nanosensors are very sensitive, portable, inexpensive, and easy-to-use sensing devices. Nanomaterials are used as the sensing element in nanosensors [6-10]. Nanomaterials have high surface area-to-volume ratios and their sensitivity can be enhanced by surface functionalization. They are more efficient and more robust due to their greater surface area. In comparison to traditional electrochemical approaches, immediate contact between the nanoscale electrode and the sample results in significant signal enhancement and better signal/noise metrics. Quantum dots, hybrid nanomaterials, carbonaceous nanomaterials, and metal and metal oxide nanoparticles are employed as receptors [11]. Excellent conductivity, stability, affordability, and simplicity of surface functionalization are all characteristics of carbon-based nanomaterials [12]. Graphene and nano/mesoporous carbon, carbon nanotubes (CNTs) are used in a variety of electroanalytical applications. Their nanostructures effectively expose surface groups for the binding of analyte-transduction materials, leading to high environmental pollutant detection capability. Metal nanoparticles offer distinctive physical and chemical properties that have made them popular in many different domains. Au, Cu, Ag, Pt, Pd, and Co nanoparticles have been used for sensing. By adopting specialized signal amplifications, metal nanoparticle-based sensors have great promise for enhancing sensitivity and selectivity. Metal nanoparticles, bio-functionalized nanoparticles, and nanocomposites have sparked interest in nanosensor research.

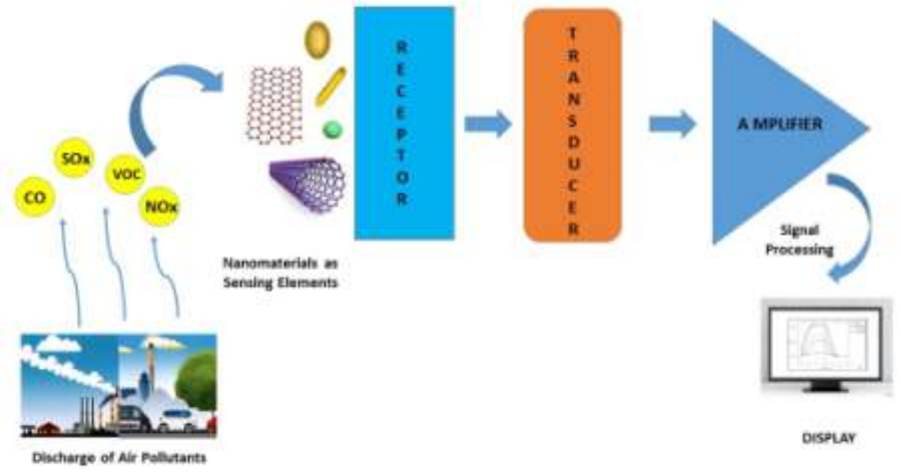

Figure 1: The schematic representation of components of the nanosensor.

II. TYPES OF NANOSENSOR

Physical, chemical, optical,and biological nanosensors are the four main categories of nanosensors (figure 2). Some of the most common types of nanosensors include optical, mechanical, vibrational, and electromagnetic. Physical nanosensors are used to track and transform physical characteristics like temperature, force, pressure, and other factors into detectable signals. Chemical nanosensors are used for a variety of purposes, including the examination of environmental sample residue and the monitoring of environmental contaminant levels [13]. Electrochemical sensing of pollutants involves several methods such as Conductometry, Potentiometry, Voltammetry, Colometry, and Impedance spectroscopy [14]. Biological nanosensors contain antibodies, enzymes, proteins, DNA, etc. as biological recognition systems for selective and real-time measurements [15]. Molecular nanosensors translate biological communication systems into coded signals. Electromagnetic nanosensors detect variations in electromagnetic waves while accounting for quantum events. To power mechanically acquired energy from nanosensor vibration and surrounding biochemical material, mechanical nanosensors may be used to feed the molecular nanosensors. Fluorescent nanosensors work by measuring the emission of a fluorophore as it transitions from an excited state to its ground state [16]. The change in sensor's conformation or interaction of pollutants with the nanoparticle results in a change in fluorescence signals. Optical nanosensors may immobilize nanomaterial known as surface Plasmon resonance (SPR) and employ electromagnetic irradiation to detect samples [17].

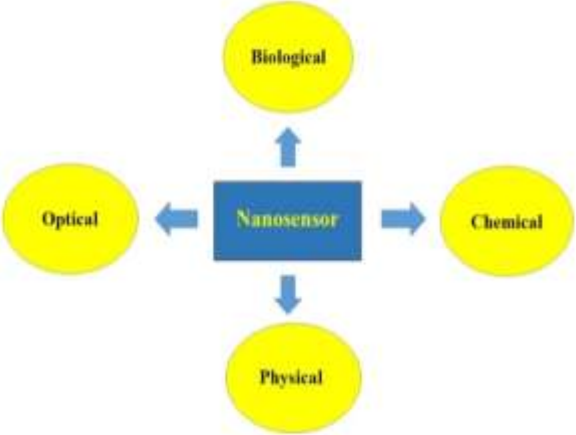

Figure 2: Types of nanosensors.

III. LATEST ADVANCEMENT IN NANOSENSORS FOR AIR POLLUTION REMEDIATION

Appropriate control systems with quick pollutant source detection and quantification capabilities are crucial to avoid or reduce the harm caused by air pollution. Sensing air pollutants such as carbon mono oxide, oxides of nitrogen and sulphur, ozone and other volatile compounds is crucial for reducing industrial and transportation emissions, and improving home security and environmental management. The nanostructured materials-based nanosensors recently developed for air pollution remediation are briefly discussed here.

Tin oxide nanowire sensors can be easily incorporated into a multi-component array which makes themquick, sensitive, stable, and reliable gas sensors.Palladium-doped tin oxide nanosensor containing 0.1%, 0.2%, and 0.3% palladium concentration by weight was prepared by chemical precipitation method. The nanosensorwith 0.2% Pd-doped SnO2 demonstratedthe highest susceptibility to the discharge CO gas pollutant [18]. The Au/SnO_2 sensor responses to 40-1000 ppm CO wereapproximately 2-15 times greater than those of the pure SnO_2 sensor. In another study, the CuO-doped SnO_2 NPs of the size of 20 nm were found to be sensitive to 4.3 to 1000 ppm NO in dry air at 200 ºC for roughly 3 min. response time[19].A group of researchers synthesized Au/Nd_2O_3–$Ca_3Nd_2O_6$ composite-based carbon monoxide sensor. These sensors revealed a linear association between carbon monoxide concentrations in the range of 0.6-125 mg/m3 and chemiluminescence intensity with a CO detection threshold value of 0.2 mg/m^3 [20]. Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate)/poly(*p*-anisidine) nanocomposite sensor was synthesized by the cost-effective “in situ chemical oxidation polymerization” technique and investigated for carbon monoxide (CO) detection property. The nanosensor responded linearly ($R^2 = 0.9885$) to CO gas concentrations ranging from 50 to 300 ppm. The CO gas sensor's reaction and recovery times were discovered to be around 58 and 61 s, respectively[21].

Quantum dots (QD) have a wide range of shapes, sizes, and chemical compositions, they can be activated by a single energy source. The QDs frequently used in sensors includeCdSe,ZnS,CdSe/ZnS, CdTe/CdS Graphene quantum, etc. In a nanosensor,QD with a sensing element is linked to a graphene sheet, and when a pollutant is present, a change in the sensor separates the graphene from the QD and turns the sensor on [22-24]. In a research, one-pot method was used to synthesize NO_2 gas sensors consisting of reduced graphene–oxide–carbon dots (rGO-CDs) hybrid materials. It was discovered that the addition of carbon dots (CDs)considerably improved rGO’s ability to detect gases. At room temperature, the composite structures could sensevery low NO_2 concentrations [25]. In a study,ZnO and carbon dots composites-based nanosensors demonstrated high NO gas sensitivity response compared to traditional methods [26]. Gold nanoclusters are great materials for air pollutant sensing due to their unique physicochemical properties such as light stability, good biocompatibility, light-induced fluorescence, etc. Nanocluster of Gallium Nitride (GaN) submicron wires with titanium dioxide (TiO_2) displayed high selectivity to NO_2 detection. Several metal oxide nanoclusters had reported good long-term performance stability at room temperature and humidity, and they are also stable and reliable in various climatic conditions [27, 28]. Nitrogen dioxide is a toxic gas that can have a severe impact on plant growth and the human respiratory system.According to research, decorating phosphorene surfaces with silver can improve the sensitivity, selectivity, and adsorption capacity of NO_2 molecules, and thus the silver-trimmed phosphorene composite systemis considered as ideal material for NO_2 gas sensors [29]. A group of researchers investigated gold and polyaniline nanocomposite-based sensors for their CO gas sensing ability and found that these nanosensorspossessed a large dynamic range of sensing, good stability, low noise, and high responsiveness [30].

Carbon nanotubes based nanocomposites are good gas sensing materials due to their excellent electrical conductivity, high surface area, and unique hollow structure. The ability to obtain high sensing sensitivity at ambient temperature is another benefit of using CNTs as sensors. Several gases, including nitrogen dioxide (NO_2), sulphur dioxide (SO_2), hydrogen (H_2), ammonia (NH_3), methane (CH_4), and carbon monoxide (CO), can be detected using CNT sensors. Another advantage of CNTs as sensors is the possibility to achieve high sensing sensitivity at ambient temperature. CNT sensors are adapted to detect several gases like ammonia (NH_3), nitrogen dioxide (NO_2), hydrogen (H_2), methane (CH_4), carbon monoxide (CO), hydrogen sulphide (H_2S), and sulphur dioxide (SO_2) [13]. A study reported that polyethylenimine functionalized single-walled carbon nanotubes (SWCNTs) had 50% higher gas sensitivity towards greenhouse gases compared to single-wall carbon nanotubes [31]. Fluorinated carbon nanotubes have a good sensing response to nitrogen dioxide and ammonia. Polyaniline-modified multi-walled carbon nanotubes show good sensing characteristics of transparent gas and are excellent sensors of CO and NH3 gas at room temperature [32].

Graphene-based Nanosensors possess unique physical, chemical, and mechanical properties for gas sensing and ultra-low detection limits for air pollutants. Graphene has excellent mechanical, and thermal characteristics. Additionally, they have been widely employed for the detection of gaseous and heavy metal contaminants [33]. Graphene-based

NH_3 gas sensors have reported excellent sensing response and gas sensing capability. Strong ammonia gas selectivity was observed in functionalized graphene oxide, demonstrating excellent sensing properties of ammonia gas. Graphene oxide nanosheets revealed a good sensitive factor and exhibit a good response to toxic gases, including NO_2, SO_2, CO, and NH_3 [34]. Two-dimensional mesoporous $ZnSnO_3$ nanomaterials displayed high gas sensitivity and sensing capabilities to formaldehyde gas [35].Zhou and co-workers fabricated NiO-ZnO nanodisks as sulfur dioxide (SO_2) gas sensors through the hydrothermal method. They observed that, when exposed to 20 ppm SO_2 gas at an optimized temperature of 240 °C, the sensors'response timeand recovery time were 52 s, and 41 s, respectively[36]. Recently,graphite-phase carbon nitride (g-C_3N_4) functionalized tin diselenide ($SnSe_2$) showed great responsiveness, high reversibility, and good selectivity for ppm-level SO_2 gas detection [37]. A sensitive SO_2 gas sensor based on nanocellulose-prepared tin dioxide has been reported to have high sensitivity and selectivity with a response toward SO_2 at 1 ppm was 4.68 s [38].

Volatile organic compounds (VOCs) are a diverse group of chemical compounds that are rapidly absorbed into the lungs, tracts, and surfaces like the epidermis, where they may have both short and long-term negative health effects due to their varying lipophilicity and volatility, as well as their smaller molecular size and lack of charge. Metallic nanoparticlesand metal oxide nanoparticles-based VOC nanosensors offer various advantages over classical sensors such as detection down to very low concentrations (ppm–ppb), higher reproducibility with faster reflexes, and mechanical stability [39]. The detection of alcoholic vapors was carried out using several doped nanoparticles such as Sn_3N_4 NPs, Ni-doped SnO_2 NPs, C-doped TiO_2 NPs, Pr-doped In_2O_3 NPs, and Au/Cl co-modified $LaFeO_3$ NPs[40]. Semiconducting nanoparticles (NPs) TiO_2 NPs, α-Fe_2O_3 NPs, and Pt-decorated Al-doped ZnO were consumed in selective device-based quantification of acetone with part per billion/parts per million (ppb/ppm) detection limits (LODs) [41]. Co_3O_4/ZnO hybrid NPs, Ho-doped SnO_2 NPs, and $CuCrO_2$ NPs-based sensors have successfully been deployed to detect volatile triethylamine (TEA) and n-butylamine with good response time[42]. In the latest research, quantification of volatile organic amines was carried out employing V_2O_5-decorated α-Fe_2O_3nanorods (NRds), Au NPs decorated WO_3 NRds, Ag NPs decorated α-MoO_3 NRds, Cr doped α-MoO_3 NRds, acidic α-MoO_3 NRds, and $NiCo_2O_4$ microspheres[43]. In another study, quantification of xylene and BTX (Benzene, Toluene, and Xylene) vapors was achieved usingAu-loaded ZnO NPs and cobalt porphyrin (CoPP)-functionalized TiO_2 NPs at 377 °C and 240 °C, respectively, whereas cobalt porphyrin (CoPP)-functionalized TiO_2 NPs showed high selectivity for these toxic gases with a limit of detection of 0.005 ppm [44]. DNA-based nanosensors have also been reported that use ssDNA, dsDNA, complementary mismatched DNA, aptamers, and G-quadruplex DNA as a recognition element for the detection of environmental pollutants [45].

IV. CONCLUSION

Air pollution is a rising issue in the world. Air pollution affects different aspects of health and the environment. Consequently, it has become critical to monitor and control the rising air pollutants that are entering the environment via numerous sources. Today we need mechanisms, technologies, mitigation strategies, and policies to achieve sustainable development goals regarding air pollution and global threats to health and the environment. Nanotechnology is an emerging technology that provides opportunities to monitor, measure, manage, and reduce air pollutants in the atmosphere. Nanosensors are bioanalytical tools that operate at the nanoscale and are used for the detection and monitoring of environmental pollutants. The development and application of physical, chemical, and biological instruments, systems, and processes build up the market for nanosensors. This chapter intends to provide information on the connection between air pollution control and nanotechnology, as well as establish a relationship between air pollution concerns and the recent development in the field of nanosensors.

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