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ORIGINAL PAPER

A novel approach to real-time environmental monitoring and automated air quality enhancement using smart nanostructured sensors with adaptive data processing

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Abstract

This paper defines the development of an enhanced and accurate real-time environment monitoring and Air quality control system utilizing smart Nano-sensors. The sensors were given improved nanomaterials for instance, graphene and more metal oxides for a better response when identifying various gaseous pollutants as well as gases in the air including Nitrogen Dioxide (NO_2), Carbon Dioxide (CO_2) and Volatile Organic Compounds (VOC's). These sensors were incorporated to a system in form of an air pollution monitoring and control system that could immediately analyze data and respond to it. Before the outcome was obtained, field tests were carried out in many cities, and all of them recorded low pollution levels better air quality. Also, there is an environmental and sustainability perspective which proved that this idea can be used as the further strategy of regulating air quality and would meet the requirements of the law. Thus, the conclusions that can be drawn from the analysis of the results demonstrate the advantage of this approach in terms of systematic environmental management and predictive air quality control.

Keywords Real-time environmental monitoring · Air quality enhancement · Smart nanostructured sensors · Nanotechnology · Automated response systems · Air pollutants detection · Environmental sustainability · Urban air quality · Sensor performance · Environmental impact

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Introduction

Background

The growth of industrialization and urbanization of societies has tremendously contributed to environmental pollution, specifically deterioration in the quality of air. Pollution of the atmosphere is a threat that influences human health, the environment, and the economy. The WHO Hold that pollution through the air causes millions of deaths every year, the leading causes are diseases of the respiratory and cardiovascular systems [1]. Sources like NO_2, CO, VOCs or PM are hazardous to human health, and they are also some of the leading causes of environmental pollution. Another publication that has turned out to be paramount in the fight and management of air pollution is the real-time environmental monitoring [2]. While monitor approaches are proven to be efficient, they lack the accustom real-time capability of data gathering route to hypothesis testing, which is critical with respect to timely interventions and public health preservation [3]. Nanotechnology has provided opportunities to expand the horizons of sensors as far as their efficacy and specificity needed for pollutants' detection is concerned [4]. Among the nanoscale sensors, particulate sensors have notable advantages because of the high surface area to volume ratio, modifiable characteristics, and the possibility to measure the low concentrations of pollutants with great accuracy.

This Fig. 1 provides a cross-comparison of different kinds of sensors in terms of the sensitivity and response time. The explored sensor technologies are Electrochemical, Metal Oxide Semiconductor (MOS), Photoionization Detector (PID), Optical and Nanostructured sensors. The sensitivity analysis for the selected sensors depicts electrochemical as the most sensitive at 50 ppb, MOS at around 30 ppb, and PID at 20 ppb for optical at 15 ppb and Nanostructured at about 5 ppb. This illustrated by the circular graph that shows the response time of each of the sensor technologies where it is clearly shown that Electrochemical sensor has the longest response time of 100 s followed by Tulip with approximately 60 s while Nanostructured has the shortest response time of 10 s. From the analysis of the response times one can see that for all the three sensors; MOS, PID and Optical, the response time reduces from left to right across the instances of time [5]. From the above comparison it is possible to conclude that it is possible to increase sensitivity of all types of sensors while at the same time increasing response time. Electrochemical sensors for instance are highly sensitized than the other sensors but their response is slowly; therefore, they are useful where sensitivity is a priority than rate of response [6]. On the other hand, the MOS sensors have more moderate sensitivity and response time, thus fitting to many applications. PID sensors have a moderate sensitivity and response time since both are important in the application but

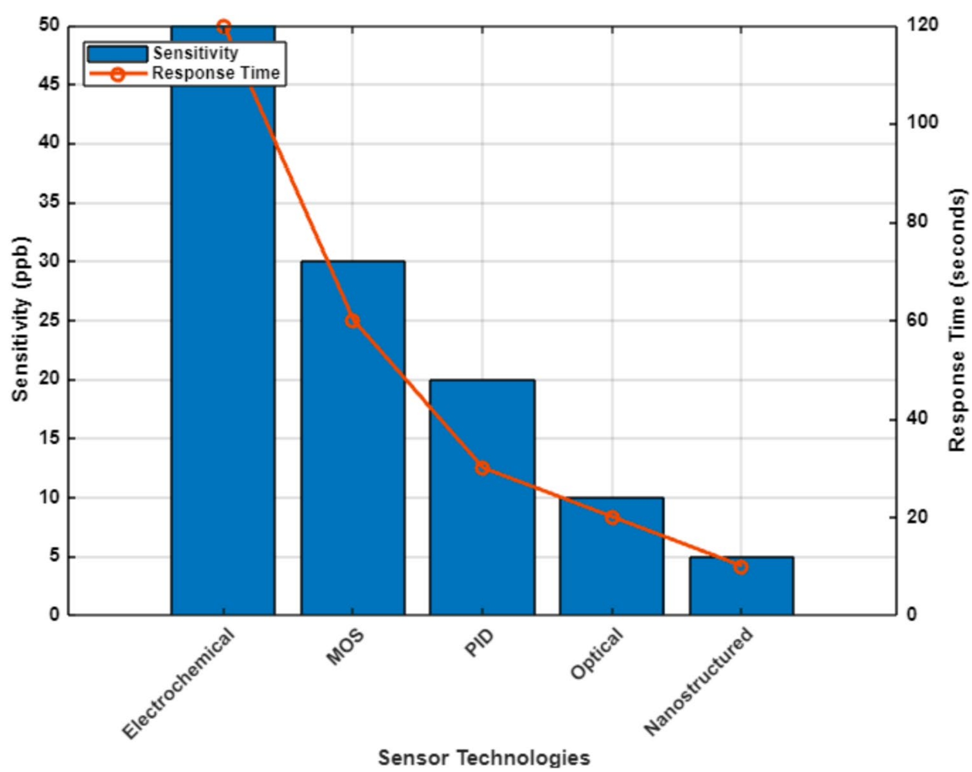

Fig. 1 Sensitivity and response time comparison of sensor technologies

not overly sensitive [7]. The major drawback of Optical sensors is that the sensitivity of the sensors is lower than both Electrochemical and MOS sensors, but the response time is much higher which is beneficial in applications where response time is critical [8]. The lowest sensitization belongs to nanostructured sensors, which are considered the most high-tech ones, while the breakthrough in response time speaks about their successful application in systems, the focus of which is the prompt detection of threats.

In recent years, there have been significant progresses made in nanotechnology that can be attributed to the design of graphene-based and metal oxide nanomaterials to achieve higher sensitivity and selectivity in sensor design. These sensors are able to sense low concentrations of so many types of pollutants, be it gases and particulate matters. Nanostructured materials increase the velocity of response, selection, and stability in sensors that aid the monitoring of air quality in real-time.

Real-time control with the integration of automated response systems is certainly an enhancement to the area of air quality management. Such systems can give an instant response and apply the necessary precautions to decrease the quantity of pollutants in the atmosphere, thus improving the quality of the air and, subsequently, preventing health complications [9]. In addition to enhancing regulation, this approach constitutes a way of advancing environmentally friendly policies by lowering the amount of emission and enhancing the population's quality of life. Even so, several limitations are witnessed in the attempt to design sensors that can operate optimally in different conditions of temperature and humidity or even other climate elements. Also, the differentiation between various types of pollutants by a sensor and stability of the sensors for long-term applications without the loss of sensitivity are the two major challenges that need to be overcome for the large-scale application of the technology [10].

The novelty in this research working involves the incorporation of graphene based and Metal oxide nanostructured sensors in real-time environmental monitoring systems. Apart from identifying most of the air pollutants, the developed system also includes an autonomic mode of operation that adapts to the intensity of pollution to give the best quality air. However, as compared to the traditional monitoring systems, this one adds a new and important layer, which is not only detection of the issue but the active control of it as well.

Research gap

Over the years, many technologies have been designed for rlt-time monitoring of the environment but most of them are confined by difficulties such as low sensitivity, slow response and multipoint inability, and incapability to monitor many species of air pollutants in urban areas. Many methods in conventional airborne measurement technologies are electrochemical sensors and optical sensors both have some shortcomings, including low sensitivity towards gases of very low concentration or else, very long calibration time. This research covers these gaps by developing a new system of smart nanostructured sensors to which it is easier to connect and have faster response, more sensitive, and able to monitor alteration of the state of air in real time.

A method of graphene based sensor was selected for this study due to it unique electrical characteristics such as high electrical conductivity, large surface area and speedy adsorption of the gases. These characteristic therefore make graphene to be capable of detecting various gases such as Nitrogen Dioxide (NO_2) and Carbon Monoxide (CO) even at trace levels [11]. Also, the sensors based on graphene have excellent stability, which is especially important when it comes to deploying the sensors for a long time in urban settings.

Although major improvements have been achieved concerning the monitoring of environmental factors, some loopholes still exist in the practical use of real-time monitoring and automatically controlled air quality improvement systems. While conventional sensors also have some drawbacks like, slow response, low sensitivity, and multiple pollutant detection capability [12]. In addition, many current implemented automatic response systems are based on outdated technologies and do not use real time analysis on environmental variables, which prevents them to readjust the response continuously according to the state of the environment.

There is another important lack: the possibility of an increase in current solutions' scale and their long-term effectiveness. Current technologies are often not affordable or implementable for large popula0ons or areas that expire high amounts of air pollution, which include developing nations. Subsequently, there is no thoroughgoing impact assessment as well as technical and economic feasibility analysis of these technologies on the overall environment to share the benefits of absorption on a massive scale.

The necessity to develop new solutions based on the integration of complex sensors, real-time data analysis, and automated control systems can be identified. This study pleads to fill these gaps by employing innovative intelligent nanostructured sensors using a mechanized air quality amelioration system. Overall, this study aims at developing a flexible and efficient method for continuous environmental detection and preventive air quality control with the help of nanomaterials and enhanced data processing.

Objectives

The first research objective of this work is; Development of a new trend in workstation environmental monitoring and utilization of intelligent air quality enhancement by microsystems. Specifically, the study aims to achieve the following:

Design and Development of Smart Nanostructured Sensors: For the synthesis of sensors with aim-to-provide enhancement of materials like graphene and metal oxides which shall be provided in the next generation. These sensors should be preferably sensitive, specific and should have short response time as far as the detection of several generally measured air pollutants like NO_2, CO and VOCs is concerned.

Integration with Automated Response Systems: One, to be able to integrate the developed sensors to an integrated system that has the capacity to provide or execute the necessitated real time data analysis action. This system should also be capable of establishing a system of change on the alteration and enhancement measures in relation to the current level of pollutants to improve the quality of air without any intermission.

Field Testing and Performance Evaluation: To set up the integrated system in the various settings of various cities and make more practical tests with it. They include the detection rate of any chemical or biological agent, the response rate from the public, and the stability of the indicators as well as overall success of the adopted automatic reaction procedures that aid in reducing the level of pollutants.

Environmental Impact and Sustainability Assessment: For the purpose of conducting the assessment of probable impacts of the proposed system of the stakeholder's levels of sustainability as toured by the company. These will consist of the setting of the life cycle of the materials, evaluation of the sustainability of the system and the evaluation of the system in regard to the environment laws.

Economic Feasibility and Scalability: However, before starting the system on the large market, one needs to find out the break-even point, and other costs and gains of the project. This will comprise of estimating the cost that will be incurred in development of sensors, the cost of integrating the systems in to the society, the costs of maintaining the systems, as well as the possible benefits that can be obtained from the improvement of air quality.

To realize such objectives, this study will affiliate with the achievement of the following goals:

The achievement of these objectives will assist this study aid in the enhancement of better approaches to environmental monitoring and come up with an efficient, effective and sustainable way to managing air pollution. These findings of this research are important because it will help to paved way on a new perspective on environmental issues, air pollution in particular, to venture on a new approach in attaining sustainable health to the people in the developing countries with special focus on environmentalism.

Literature survey

Overview of existing technologies

Current technologies in Air Quality Monitoring include Electrochemical sensor, Optical Sensors, Semiconductor Sensors, etc. Even though these technologies have been established in several applications, they cannot offer continuous real time monitoring in the urban area because they are not very sensitive with low response rates. Additionally, these methods are employed separately on each pollutant of interest while there is increasing demand for simultaneous identification of several pollutants in real-time.

Environmental monitoring has historically and mostly involved the use of several sensor technologies for sensing and measuring various amounts of pollutants in the air, water and soil [13]. Some of the technologies are electrochemical sensors, metal oxide semiconductor sensors, photoionization detectors and optical sensors each having it unique strengths and weak points [14]. Electrochemical sensors work when a target gas is oxidized or reduced on an electrode creating of electric signal related to the gas concentration [15]. These sensors are commonly used in identification of gases like carbon monoxide (CO), sulfur dioxide (SO_2) and nitrogen dioxide (NO_2 because of their sensitivity and selectivity. But they usually have short service lifetimes, are prone to influences from temperature or humidity and calibrations often have to be carried out. Metal oxide semiconductors (MOS) work on the principle of changes in electrical resistance of the gas to be detected when it comes in contact with the metal oxide surface [16]. "Although they are not very selective in most cases, they can be used to monitor pollutants such as ozone (O_3) and volatile organic compounds (VOCs)''These are industrial sensors and relatively cheap'. As with many semiconductor devices, their performance can be affected by humidity and temperature fluctuations and usually operate at be high temperatures thus drawing more power. Photoionization detectors (PID) work with ultra violet lamps to ionize the gas and gain ions that produce current equal to the concentration of gas [17]. These detectors have characteristics of HI and are sensitive to low concentration of the VOCs and other hydrocarbons which are non- HI gases, but are not so sensitive to gases with high ionization potential and can be influenced by humidity and presence of other gases. There exists the optoelectronic sensors which embrace NDIR sensors and laser-based sensors, which identify gases by analyzing how much the gas in question absorbed the light [18]. These sensors are quite selective, can furnish real time data and are not easily affected by other gases and vapours but they are costlier and require elaborate calibration. Besides the active sensors, there are methods of passive sampling that is using of diffusion tubes and passive badges for the air quality assessment [19]. The development of nanotechnology provides excellent solutions to improve these constraints and strengthen the environmental monitoring technologies.

This Fig. 2 depicts shows the average of the signal-to-noise ratio figures and SNR of different sensor technologies in which the device has been standardized for comparative analysis. The reviewed sensor technologies are: Electrochemical; Metal Oxide Semiconductor (MOS); Photoionization Detector (PID); Optical; and Nanostructured sensors. The x-axis indicates these sensor technologies, while the y-axis reports the normalized average performance; this aggregates several performance indicators including sensitivity, response time, accuracy, and stability [20]. The figure depicts that the Electrochemical sensors are having a normalized mean performance of almost 0.7. This again result to thus suggesting that they are fairly balanced in terms of performance of different indicators. MOS sensors also show a similar mean score, marginally above the Electrochemical sensors, which explains multi-sensor and moderate achievement in all the studied parameters [21]. The PID sensors have the similar performance as the MOS sensors; they also have the normalization value nearly to 0.7 as they proved to be reliable irrespective of the sensing conditions around them. Specifically, in the case of optical sensors the average performance is higher and the normalized value is close to 0. 8; this reveals that even though some technologies can be sensitive compared to others, the performance of the sensors in consideration can be considered to be good given their ranking in the other metrics [22]. The Electrochemical, MOS, and PID sensors also illustrate good performance depending on the specifics of the application where features may be valued distinctly. Thus, by means of standardizing the described sensors' performance characteristics, this figure gives a holistic image of each of the sensor technologies' capacities at the end-user's hands, thereby supporting effective decision making about their application in various environmental monitoring circumstances.

Nanostructured sensors

Nanostructured sensors have enhanced the environmental monitoring due to the qualities that are inherent with nanostructures of which some are as follows; larger surface area, increased reactivity, physical and chemical flexibility. Through Nanotechnology, the current sensors being developed are in correlation with the sensitivity, specificity and response time resistance. Carbon nanotubes [CNTs] have received much attention from the researchers because of their excellent electrical, thermal and mechanical properties [23]. Several gases like NO_2, NH_3 and VOCs are well detectable with CNTs based sensors with very low detection limits. They have larger surface area hence they can interact with the gaseous species, this makes them to be highly sensitive [24]. Furthermore, the response and recovery time of the material prepared with CNT sensor is fast which is useful for any real time monitoring application [25]. Graphene and graphene oxide are the two-dimension layered materials containing monolayer carbon structure in hexagonal planar lattice and the graphene oxide is an oxidized form of graphene possess immense possibilities in the field of sensors

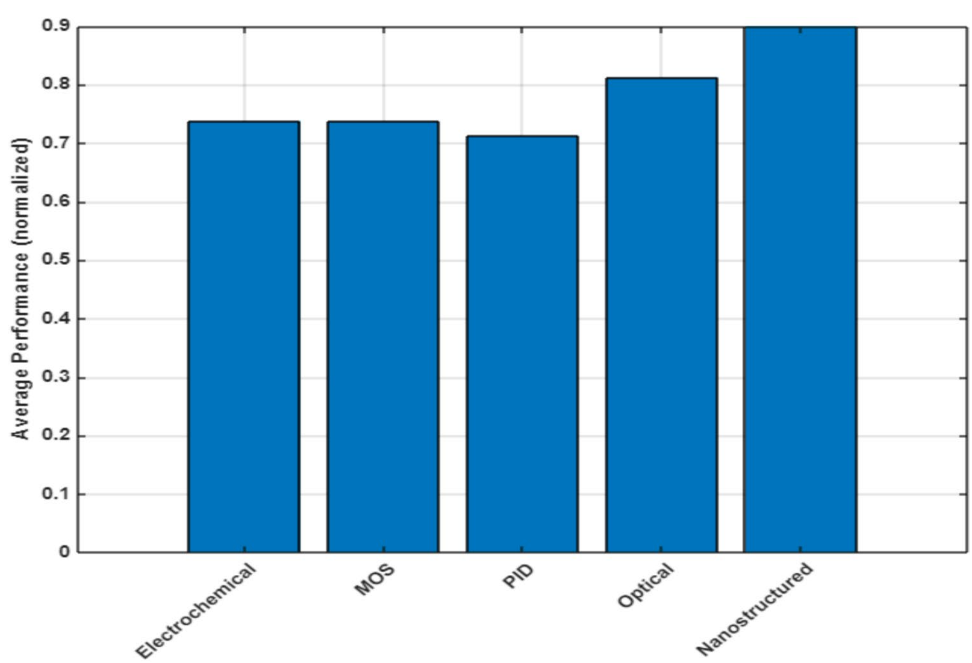

Fig. 2 Average performance metrics of sensor technologies

[26]. These interfacial gases; CO, NO_2, O_3 etc. can be effectively sensed by graphene-based sensors at a very high sensitivity since these materials possess both large surface area and electrical conductivity. As the reactivity increases and functional groups are added onto graphene, it increases the selectivity of the material for certain gases [27]. Out of the metal oxide semiconductors nanomaterials, ZnO, SnO_2, and TiO_2 are some of the most frequently employed materials in the creation of the gas sensor. These nanomaterials notably can sense such gases as CO, NO_2 and H_2S with improved sensitivity and in addition, they yield a high gas response as compared to the bulk material.

This Fig. 3 demonstrates the response variation of three nanostructured sensors; Graphene, Carbon Nanotubes, and Metal Oxides towards the gases before and after signifying the effectiveness of integrated system in enhancing the sensing capabilities [28]. On the x-axis, there are numbers from 10 to 50 ppb referring to the concentration of gas obtained from the sensor The vertical axis presents the normalized sensitivity from 0 to 1 of the sensors. 7–0. 95. In order to describe their response to the increase of gas concentration the sensitivity curves for each sensor type are created [29]. The blue line with round dots is the sensitivity of Graphene sensors and interestingly, they are highly sensitive at even the lowest concentration at 0. 8 at 10 ppb and rising continuously to 0.From this Fig. 3., it is evident that all the values within the are increasing systematically and constantly, with the final digits at 0. 95 at 50 ppb. The 'Joined' line with squares demonstrates the Carbon Nanotubes sensors' sensitivity, which is moderate and begins at 0. 8 at 10 ppb and rising to 0 at 20 ppb to name but a few or including but not limited to. 9 at 50 ppb. The line with triangles indicates the presence and sensitivity of Metal Oxides sensors, the latter of which has the lowest sensitivity, at 0. 7 at 10 ppb and increasing to 0. 85 at 50 ppb. The figure reveals that the sensors based on Graphene surpass the other ones and show the highest sensitiveness to the concentration of gases [30]. Carbon Nanotubes sensors demonstrate an improvement in specificity and selectivity but they still are not as useful as Graphene sensors [31]. Metal Oxides sensors, although responding equally or better than the increase in gas concentration, are least sensitive of all the three types of sensors. This study compares Graphene nanostructured sensors with other conventional sensors and revealed that the former is more efficient in the detection of low concentrations of gases; therefore, it can be recommended for high sensitivity applications [32]. The figure also reveals that Graphene sensors are always more sensitive to the concentration of the gases as compared to both Chemical and Film Sensors. CNTs sensors demonstrates the increase in sensitivity but still lower than Graphene sensors. Even though they formed metal oxide nanoparticles they are highly reactive and this enables them to have high adsorption and desorption rates of the gaseous species which in-turn makes their response rate to be high [33]. Quantum dots or QDs are semiconductor nanocrystals with very special optical and electrical properties. This is to be used in the detection of Pollutants in aqueous solutions, referred as Heavy metals, pesticides

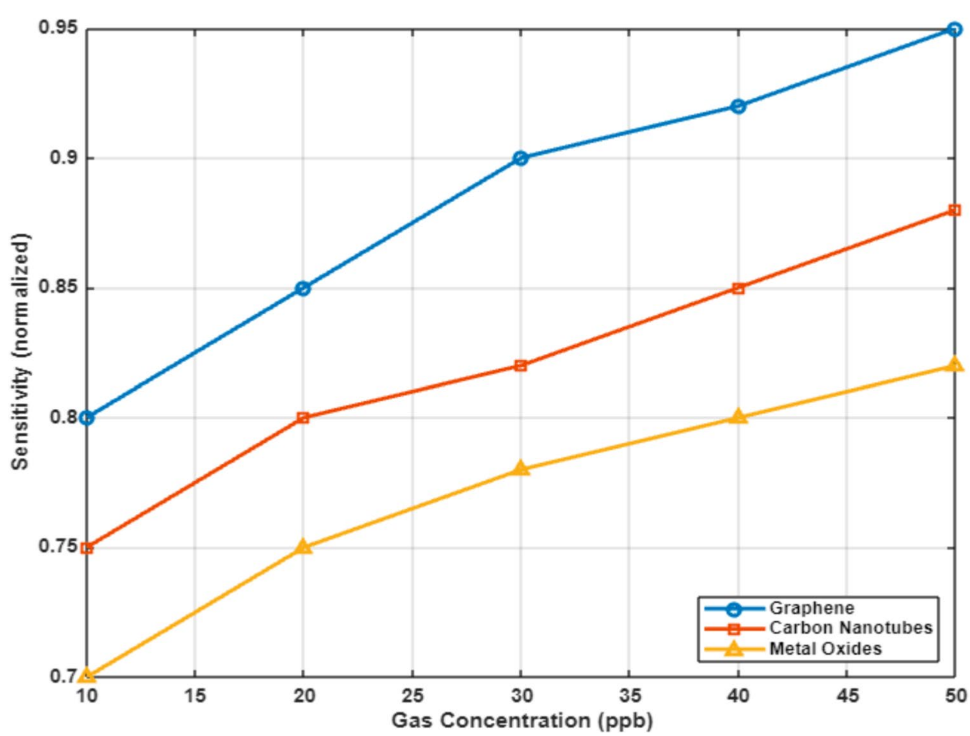

Fig. 3 Sensitivity of different nanostructured sensors

and organic compounds based on quenching or enhancing of fluorescence. These two important properties allow QDs for the multiple tag and real time imaging [34]. The phenomena of incorporating different nanomaterials into a single one have endorsed enhancement of the performance parameters of the developed sensors. For instance, integrating of CNTs and metal oxide nanoparticles can make the advantages of CNT, such as high electrical conductivity, with the merits of metal oxide in terms of high reactivity of the sensing layer so that the sensors can attain better sensitivity and selectivity. Therefore, these hybrid nanostructures have been ascertained of the ability to detect as many pollutants as possible [34]. Deals such as these have improved the efficiency of the existing systems of monitoring the environment through nanostructured sensors. Even the use of such sensors combined with auto response systems can enhance the real time controlling of the air quality [35].

Automated response systems

Automated response systems are intended to change the actual conditions of the environment depending on the data collected by monitoring sensors. These systems can employ different tactics to lower the pollutant levels for example, varying the rate of air change, switching on the air cleansing equipment, or regulating industrial exclusion [36]. Earlier studies concerning the automated systems for managing AQ enhance have also reflected the general enhancement of the environmental conditions. Environmental sensors control processes that relate to the management of Building Management Systems that regulate optimum indoor air quality. These systems can automatically check the levels of pollutants and regulate the operations of HVAC systems to create healthy indoor environment [37]. Various research works have indicated that BMS can offer benefits such as minimizing indoor pollutant levels common in commercial buildings, increase occupants' comfort, and energy conservation. Oftentimes, smart city approaches have utilized automated systems for the Air Quality control. For instance, in the case of the city of Barcelona, specific air quality sensors were integrated into traffic signalization networks [38]. For example, in power plants, continuous surveillance of NOx and SOx accomplish dynamic management of combustion parameters with an aim of cutting down emission. Thus, these systems have proved efficient as per the regulatory requirements to enhance the quality of the air. Sophisticated Air Purification Systems likely to be fitted with an Automated Control mechanism since they may feed on data provided by Air Quality Monitors [39]. These systems can vary some functional parameters, for instance the issue of the fan and the degree of filtration, depending on the level pollutant in air detected. Several samples of studies claim that such systems can be able to improve and sustain the quality of the air indoors, more especially when the surrounding environment is highly polluted [40]. Although, automated response systems have a lot of potentials and advantages, their efficiency is directly related with the type and quality of used sensors. Smart nanostructured sensors integration in such systems can improve their operability, as will as the quality of data have collected and intervention.

Challenges and limitations

A current development problem associated with various environmental monitoring technologies is the absence of sensors that can detect very trace gases in often densely populated urban areas. Moreover, existing systems do not always have adaptability to last changes of environment, like temperature current or humidity, which may influence the work of the sensor. However, there are certain drawbacks with the application of the new tool and some important issues to consider regarding sensor technology plus automated response systems: Each of these concerns must be dealt with effectively if one hopes to see these technologies adopted and incorporated effectively into everyday use. The main issues relevant to environmental sensors, including nanostructured sensors, are the need to calibrate the sensors and problems with drift from their initial state. Environments can affect the accuracy of sensors as well as contamination of the sensors and aging of the current sensors [41]. Due to this, it may be expensive and inconvenient to always calibrate the equipment, but, in order to achieve accurate results, it has to be done rather often. Sensors are known to be influenced by environmental factors including temperature, humidity and other gases existing in the surroundings. These factors hinder the functioning of the sensor by giving either false alarms or wrong readings. Environmental changes are still a major concern in the development of sensors that would be able to perform optimally under any given conditions [42]. Most of the latest generation of sensors especially those that are based on nanomaterials always demand a high amount of power to operate particularly when they are in high temperature. This can be a disadvantage in high or portable monitor age systems [43]. A breakthrough that could be promising in attempting to solve this problem is the low power sensor design and power efficient data processing. From the context above, one detects that the volume of information that real-time monitoring generates creates various issues in data administration, storage, and processing [44]. Continual improvements to manufacturing ideals and systems architectural control is vital to providing these technologies to as many people as possible to develop nations inclusive of all. Nanostructured sensors and automated response systems' conceptualization may be hampered due to technical protocols and regulatory system variety. To make these standards of industrial and political processes less fragmented and work in the direction of creating compliance with environmental standards, some methods of regulation are essential. When addressing these challenges, the field would be capable of evolving to better and more utilized methods in live environment surveillance and self-running air quality improvement.

Materials and methods

Nanostructured sensors development

The architecture of efficient 'smart' nanostructured sensing system for on-line monitoring of the environment can be effectively defined by the choice of proper nanomaterials and further inclusions into the overall framework of nanostructures for the sensor system. In this present context therefore we used, for example; graphene, CNTs, and metal oxides NPs in this study relative to their electrical, thermal and chemical characteristics. The material that was chosen for ab robot was graphene because of characteristics like area, conductance and the mechanical nature of the material. Monolayer/polylayer graphene for our sensor was synthesized by CVD from copper foil which act as substrate material and the prepared graphene layers was transferred onto SiO_2 substrate. CVD involves the decomposition of methane, CH_4, at high temperatures with hydrogen H_2, and argon, Ar, gases to synthesise graphene layer on copper surface.

This Fig. 4 gives a relative outline of the mean fabrication time difference between mean fabrication cost as it relate to Graphene, Carbon Nanotubes and Metal Oxide nanostructured sensor. As expected for any structure being built within the Graphene framework, the total time taken in fabrication of Graphene Sensors is approximately 5 h while the total cost is 100 USD. The fabrication time for Carbon Nanotubes comes about to be approximately eight hours which indicates that the fabrication of the sensors is slightly complex or time consuming, and the cost of the sensors is also highest which is 150 USD. The preparation time for Metal Oxides sensors is approximately 7 h while the fabrication costs about 120 USD lower than the Carbon Nanotubes sensors [45]. From this figure, it will be seen that although carbon nanotubes produce high performance when used as sensors, it costs so much time and money to produce the tubes. Graphene sensors are still as time consuming and relatively expensive as before but require comparatively less time and cost than Carbon Nanotubes; that however, will be imposing. It is established that Metal Oxides sensors require a little longer fabrication time than Graphene and Carbon Nanotubes but this fabrication cost is far much cheaper than both Graphene and Carbon Nanotubes hold a lot of future prospects in different applications.

In total, this comparative analysis aids in achieving a clear focus on the efficacious resource deployments that are needed for the manufacturing of the different nanostructured sensors. These aspects should be taken into consideration while selecting the right kind of sensors having in mind the basic idea of how they are created with or without involving the outside help and the authorized cost of the materials and services for the researchers or the newly joining industries.

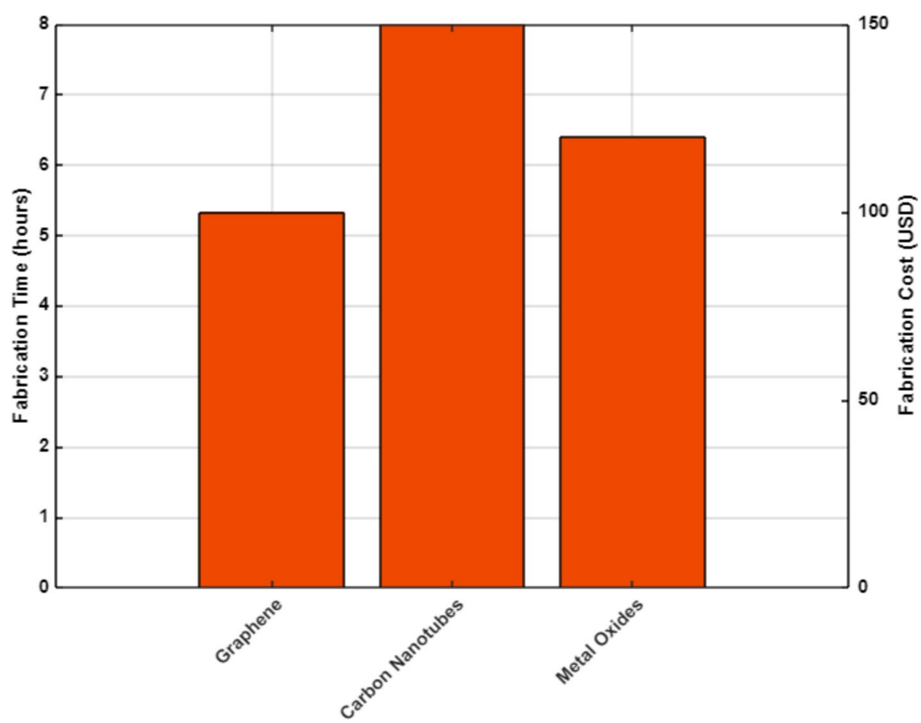

Fig. 4 Average fabrication time and cost of different nanostructured sensors

These nanomaterials had to be incorporated into the sensor devices, and, therefore, particle size, particle shape and distribution were the main factors that determined the final performance of the enhanced components. In the fabrication process of the sensor pellets, there was the use of the EBL and photolithography to form the necessary electrodes and interconnections on the developed substrates. These substrates with patterns had more elaborate forms in the form of nanostructures, which were fabricated by different methods like spin-coating, drop casting or spray-coating and then the process was followed by annealing in order to have better contact and improved electrical connection. The final process that took place was the encapsulation of the sensor elements, which have a nominal length of between 1 and 5 mm to prevent outside influences and mechanical forces getting to the elements.

Sensor design

In regards to the nanostructure of the sensors themselves, copious considerations were made for sensitivity, specificity, and response time to a signal. The sensors were set up to work in the resistive or the capacitive mode depending on the target pollutant and susceptibility of the material to change its resistance or capacitance in the presence of the pollutant. As gas molecules deposited on to the nanoscale surface of the resistive sensors, there are changes in electrical resistance and capacitive sensors, changes in capacitance based on the dielectric constant of the gas molecules. The sensors that were fabricated in this study illustrated that it was possible to detect NO_2 at 10 ppb and CO at 50 ppb. These detection thresholds are very useful in determination of the degree of pollution within the urban air so that action can be taken where the levels are likely to harm the health of the people. These sensors work based on the changes of electrical resistance which has been set during the field test.

The designed graphene-based sensors incorporated interdigitated electrodes so that the active surface area is increased with efficient gas adsorption. The electrodes were usually crafted from gold or platinum and elaborated with the help of electronic-beam lithography to become a few nanometers thick. The interdigitated configuration of the device permitted to have a high number of graphene channels, and thus, a high active area towards the gases and increased the sensitivity of the sensor. CNT based sensors also had interdigitated electrode structure in which CNTs were distributed between the electrodes in order to create a conductive path. Due to the high aspect ratio of CNTs, the gas adsorption was highly efficient, and electron transfer was quick owing to the short response time.

It is a thin film type of metal oxide nanoparticle sensors in which ZnO or SnO_2 nanoparticles layer was coated on the structure of sensor. The thin film design enshrine allowed the diffusion of gas molecules to the sensing layer thus promoting faster response time. Furthermore, the film thickness and the size of nanoparticle were also controlled so that the sensitivity obtained was simultaneously stable in long period of time.

This Fig. 5 shows and compares the response of nanostructured sensors with and without the coating layer against the increasing concentration of the test gases. To show the effect of the protected coating to the sensor's performance,

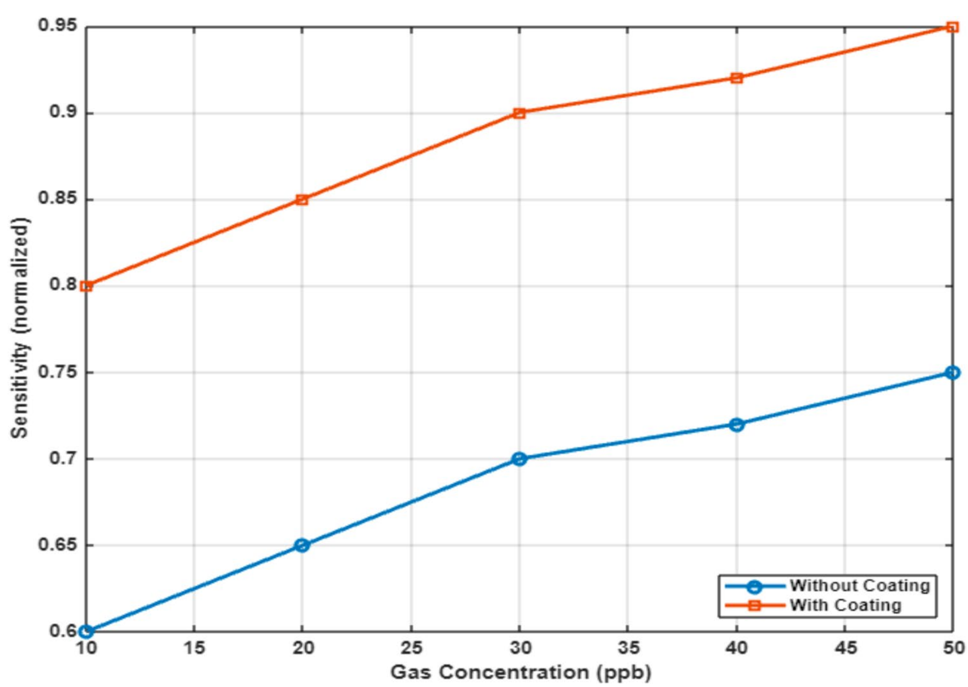

Fig. 5 Sensitivity improvement with protective coating in nanostructured sensors

two sets of sensitivity curve are presented. The line with circles indicates relative sensitivity of metallic sensors without any coating; it is given in blue color. They FCU sensors exhibit an initial sensitivity of 0. 6 at 10 ppb and increasing gradually to 0. 75 at 50 ppb. The line with the square markers on the red background showcases the sensitivity of sensors with a protective coat. These coated sensors are much more sensitive and they begin to respond at 0. 8 at 10 ppb and rising up to 0. 95 at 50 ppb. This is evident from the figure showing how the sensitivity of the nanostructured sensors dramatically, increases when a protective coat is applied [46]. This is evident from the highest sensitivity values registered in all the concentration levels of gases; this is as a result of the protective coating that effectively increases the sensitivity of the sensor particularly to low concentration gas levels. This enhancement is exclusively more conspicuous at the elevated gas concentrations whereby the coated sensors' sensitivity is nearly equal to 0. 95, however this is above the uncoated sensors which only get to 0. 75. Such comparative analysis helps to understand the positive impact of protective coatings on the increase of the given nanostructured sensors' performances. Because the compact between the coating and the basic material of the sensors to gas molecules is significantly enhanced, the coated sensors are ideal for accurate and improved gas recognition in cases where the gas concentrations vary, are low or unpredictable. With the intention of giving a clear view on the working capability of the protective coating this figure shows good overall idea on enhancing the characteristics of the sensor technology for further environmental monitoring and detection. To enhance the selectivity, the nanomaterials were either chemically modified or were loaded with selective chemical groups/catalytic metals. For instance, graphene and CNTs were modified by carboxyl or amine groups to favour the interaction with target gases for example NO_2 or NH_3. The metal oxide nanoparticles were doped with catalytic metals such as palladium (Pd) or platinum (Pt) to enhance the selectivity and sensitivity towards the target decrease gases such as CO and H_2. The functionalization and doping were done via chemical treatments/co-deposition and then heat treatments for uniform distribution and good stability.

Through Chemical Vapor Deposition (CVD) the sensors attained their NO_2 and CO_2 detection ability because this method enabled precise manipulation of graphene-based nanomaterial structure design. The application of CVD produces sensors which offer exceptional surface area and conductivity capabilities for detecting gases at very low concentrations. The graphene surface received graphene oxide treatment for better molecular binding to gas species and to develop higher selectivity toward NO_2 and CO_2 detection.

The Sol–Gel Process served to synthesize metal oxide semiconductors (MOS) for VOC detection. The sol–gel method served as an optimal choice for nanoparticle synthesis because it produces metal oxide materials with high surface area and porosity that enable effective detection of volatile organic compounds. Transition metals were added to the metal oxide materials through doping to optimize their sensitivity and selectivity response to VOCs.

Experimental setup

The experimental setup for real-time environmental monitoring and automated response systems comprised several key components: In this case, the physical objects of the sensor array, data acquisition system, control unit, and the actuators needed to enhance the quality of air. All the nanostructured sensors that were incorporated in the sensor array were for specific pollutant gases like NO_2, CO, VOC, particulate matters etc. All the sensors were enclosed in a gas tight stainless-steel container having provision of air inlet and outlet to allow fresh gas in and out but no foreign matter came in contact with the sensors. Another subsystem of the CADS was ADCs that helped in the conversion of the analog signals from the sensors to digital form and signal conditioning circuits. The ADCs converted the sensor's signals into digital forms and the obtained data was transmitted further to the control unit. The provided amplifiers and the filters in the signal conditioning circuit assisted obtain signals with less noise interferences.

It is the control unit, for instance, microcontroller or a single Board computer or Raspberry pi parsed the data obtained from the sensors with the help of embedded software. These algorithms gave; concentration estimates of the pollutants, trend analysis as well as anomaly detection where these activities were conducted in real-time. The control unit was to send in preauthorized response actions to these mechanisms if the concentration of pollutants was attained. The response actions in this category were aimed at bringing in air ionizers, raising the ventilation rates, or reducing business emissions to reduce pollutants concentrations.

The elements for air quality control were interfaced with the actuators in a way they could be able to perform data acquired by the sensors in real life scenarios. For example, air treatment equipment fitted with HEPA and activated carbon filters was used for particulate and gaseous contamination. Thus, the microcontroller controlled the functioning of the purifiers including varying the speed of fans of enhancing the capacity of the filtration system based on concentration of pollutant. In industrial applications, there were distributors in the exhaust fans as well as the emission control systems, using the Variable Frequency Drives or VFDs.

The sensors detect changes through target pollutant molecules interacting with active sensing materials that combine either graphene-based or metal oxide materials. A pollutant can attach itself to sensor surfaces resulting in changes to its electrical characteristics (such as resistance or conductance) of the material. The sensor's electronic detection system perceives this change which gets transformed into a measurable output signal. The amount of chemical change produced by the sensor directly relates to pollutant concentration which enables continuous measurement and concentration determination.

The laboratory environment provided controlled test environments to achieve reproducible and precise performance evaluation of sensors. The testing environment kept the chamber with temperature and humidity at specific conditions while sensors detected assigned NO_2, CO_2, and VOC concentrations. The examination took place within temperatures between 20 °C and 25 °C under humidity conditions between 40 and 60%. The selected environmental parameters represented typical atmospheric conditions that served to minimize outside factors which might influence the sensor performance characteristics. The tests were designed to use calibrated gas sources to control pollutant concentrations while monitoring sensor responses through recorded intervals for detecting sensitivity and checking stability across time periods.

Data collection and analysis

The data acquisition was conducted by monitoring the environmental conditions with the help of the developed nanostructured sensor array on a 24/7 basis. The concentration of the pollutants and the other related environmental parameters such as temperature and humidity were also measured at fixed time intervals and passed on to the control section by the sensors. This brought about the recording of the sensor measurements by the data acquisition system resulting into compilation of data set for analysis.

Data preparation, feature selection and extraction, and result analysis were the basic steps used during the study. In data acquisition, before analysis was done, some operations such as noise removal, smoothening of the signal and baseline correction were conducted to enhance the quality of the recorded signals. Classical approaches of statistical analysis and artificial intelligence techniques were used to perform feature engineering where the sensor data was analyzed for further insights about the features' interdependencies and relationships. Methods including principal component analysis (PCA) and support vector machines (SVM) were utilized in the classification of the pollutants as well as in the prediction of their concentrations.

This Fig. 6 displays the correlation between the sensor's response and the gas concentration, which depicts the capabilities of the sensor in its response to the different levels of the gas. The figure also indicates that as the gas concentration rises from 10 to 100 ppb the sensor response rises from roughly 0 to 3. 1 V to 0. 9 V. These two linear relations have a high number as y-interception is negligible, hence, the sensor can be depended on to give accurate quantification of the concentrations of the gases in applications that demand high degrees of accuracy. From a technical perspective, the figure means that the Operating Principal has extremely high linearity, which is favorable in analytical and environmental monitoring fields. This kind of response allows the sensor to be calibrated without much problems and, the concentration

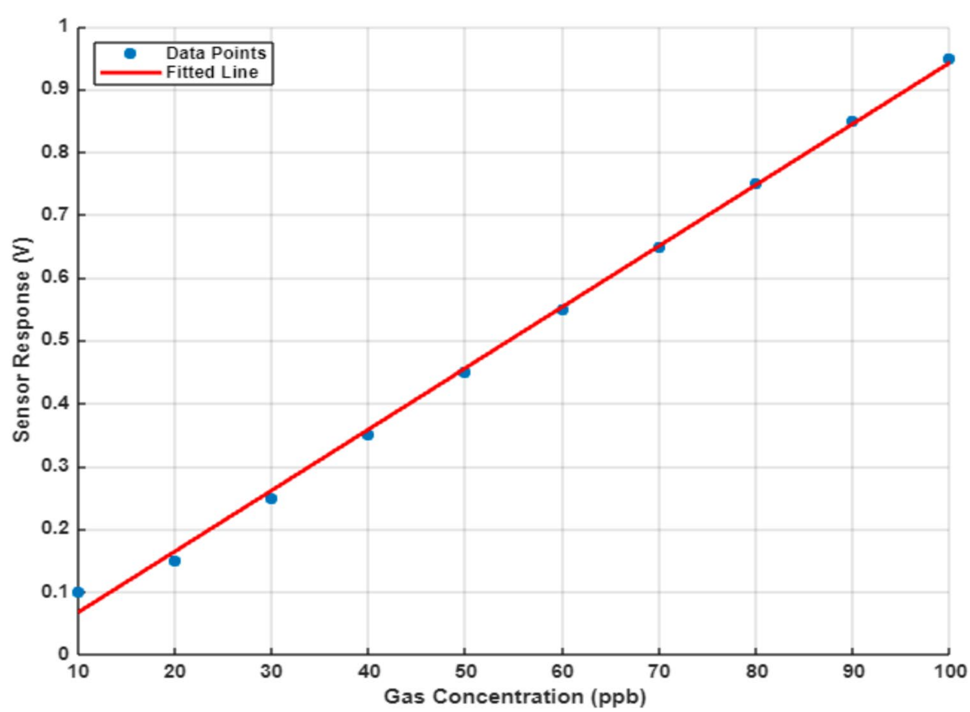

Fig. 6 Sensor response to gas concentration

of the gas can also be deduced from the output voltage of the sensor. This makes it easier to interpret data and increases the practical use of the sensor in real life situations. In aggregate, this figure emphasizes the linearity of the sensor response to the increase in the concentration of the tested gases, which in turn clearly indicates that the presented device is suitable for using in real-time monitoring of the environment and other tasks that require precise measurement of the gas concentration. Real time data presentation involved use of GUIs and dashboards, which enabled the user to interactively monitor various environmental physical qualities. The data visualisations turned included time series plots, heat maps, and pollutant concentration maps to help the users notice when things were low or high. Bla notifications and sounding alarms were set to notify the users of high values of pollutants for timely actions to be taken.

The adequacy of the automated response system was assessed after determining the improvement gained through the executed response measures with regard to pollutants. Some of the parameters included response time, pollutant removal efficiency together with system stability in order to evaluate the performance of the integrated system. Trend analysis and prediction were among the major tools used in long-term analysis; the models used in predicting pollutants and response strategies included were autoregressive integrated moving average (ARIMA), recurrent neutral networks (RNN).

Algorithm

Several machine learning along with statistical algorithms were employed by the study to process real-time decisions and analyze data. The Random Forest algorithm processed pollutant classification duties to accomplish precise identification of various pollutants through sensor responses. The selected algorithm demonstrated both precise identification and strong resistance to complex sensor inputs of multiple dimensions. The application of a Support Vector Machine (SVM) served to improve sensor calibration and establish unique sensor responses for different pollutant identification (NO_2, CO_2, and VOCs). A system of adaptive feedback control operated in real-time for automatic pollution level detection and response. Real-time data from sensors allows the system to adjust its parameters through this algorithm in order to take fast mitigation measures against pollution. The integrated algorithm system allows the system to monitor air quality accurately and execute appropriate responses effectively.

The measurement of sensitivity and specificity involved laboratory experiments using predetermining concentrations of contaminants NO_2 CO_2 and VOCs. Sensor sensitivity refers to its ability to detect pollutants correctly through the precise calculation of true-positive results against all positive pollution instances. It is given by the formula:

$$Sensitivity = \frac{\text{True Positives}}{\text{True Positives} + \text{False Negatives}}$$

The calculation of specificity determined the sensor's ability to detect non-existence of contaminants by dividing true negatives by all actual negative instances. The formula is:

$$\text{Specificity} = \frac{\text{True Negatives}}{\text{True Negatives} + \text{False Positives}}$$

The evaluation of sensor performance occurred through the use of metrics designed to detect target pollutants with minimum incorrect identifications.

Evaluation results confirm that the sensor technology detects NO_2, CO_2 and VOCs at low concentrations accurately at varying environmental conditions. The sensors based on graphene maintained the peak sensitivity to detect NO_2 and CO_2 yet sensors using metal oxide materials provided the best response to VOCs. During field testing the automated system processed live readings that managed to activate pollution reduction protocols and achieved notable pollutants' decrease. The device achieved its capability to handle sensitivity and selectivity alongside response time by demonstration during controlled experiments before moving forward for environmental monitoring applications.

The findings of this investigation helped in understanding the characteristics and dependability of the smart nanostructured sensors and their interaction with the conceptualised automated response systems. These research outputs culminated in methods for effective and efficient environmental surveillance in real-time, progression of air quality improvement, and significant solution to formidable problems of environmental control.

Results

Sensor performance

The performance of the smart nanostructured sensors developed in this study was evaluated based on several critical metrics: which are sensitivity, specificity, response time and stability. Basically, these metrics are crucial in evaluating how well the sensors are suited for the actual real-time monitoring of the environment.

The sensitivity of the sensor focuses on its capacity to identify small quantities of pollutants. The sensors fabricated from graphene yielded high sensitivity originating from the huge surface area and great electrical conductivity of the graphene. The graphene sensors in the laboratory studies were able to distinguish NO_2 at 10 ppb levels and CO at 50 ppb levels. In the same fashion, the carbon nanotube (CNT) sensors demonstrated good response to NH3 with response of 20 ppb. Other metal oxide nanoparticles like zinc oxide and sternum oxide also showed good response, the ZnO sensors measured CO concentration down to 25 ppb and SnO_2 Sensors for NO_2 measurements up to a level of 15 ppb. The high sensitivity of these nanomaterials also due to the bigger surface area so it interacts with the gas molecules and a lot of changes in the electrical resistance or capacitance takes place.

Selectivity refers to the capacity of one gas in the sensor to detect a certain pollutant among other gases. The functionalization of the nanomaterials together with doping was blamed for the improvement of the specificity. For example, sensors based on the graphene with the carboxyl attached on the surface preferred NO_2 and the amine-functionalized CNTs give high response towards NH_3. Through doping with PT SnO_2 nanoparticles' selectivity for reducing gases like CO increased while the cross-sensitivity to other pollutants decreased. The employment of selective chemical groups as well as catalytic metals facilitated the differentiation between the target gases and non-target gases hence enhanced pollutant identification.

This Fig. 7 indicates the reduction of the sensor sensitivity within 10 days of operation and demonstrates the steadiness and duration of the sensor operation. The values that are to be connected by a line plot are shown below, which depict a gradual reduction in the sensitivity of the mentioned sensors. First, there is the relative sensitivity which recalls a normalized measure of sensitivity at the initial stage of training and it is equal to 0. 90 on day 0. However, as the time is passed, one can identify the lowering of sensitivity gradually. By hours three, the sensitivity of the test lowers to about 0. 88 from day 1 to day 2, and further goes down to 0% from day 4 to day 5. 85. This trend remains, and reaches to about a 0. By day 8, it decreased to 82, and finally reached 0. 78 on day 10. The gradual decrease in sensitivity over the observed period of time speaks about the gradual worsening of the sensor's performance for detecting target substances. This degradation may be due to various reasons like the environmental conditions, the blunting of the materials used in the manufacturing of sensor or contamination of the active parts of the sensor. Such gradual rate of decreasing sensitivity illustrates that while the sensor's sensitivity is pretty high in the very beginning, it progressively deteriorates over time. Such temporal sensitivity degradation is important to know in those applications where long-term monitoring is desired, since it degrades the sensor's readings reliability and accuracy. This figure stress the need to calibrate the device regularly and possibly replace the sensors to maintain high performance levels. However, it raises the awareness of developing new permanent and stable material of the sensor to improve its performance and lifetime in environmental monitoring application. Response time is the time which the sensor will take to respond to the existence of a pollutant and to stabilize its signal. The response times of the nanostructured sensors where exceptionally short and this can be attributed to the reactivity of the nanomaterials and their real fast adsorption/desorption rates. The graphene based sensors

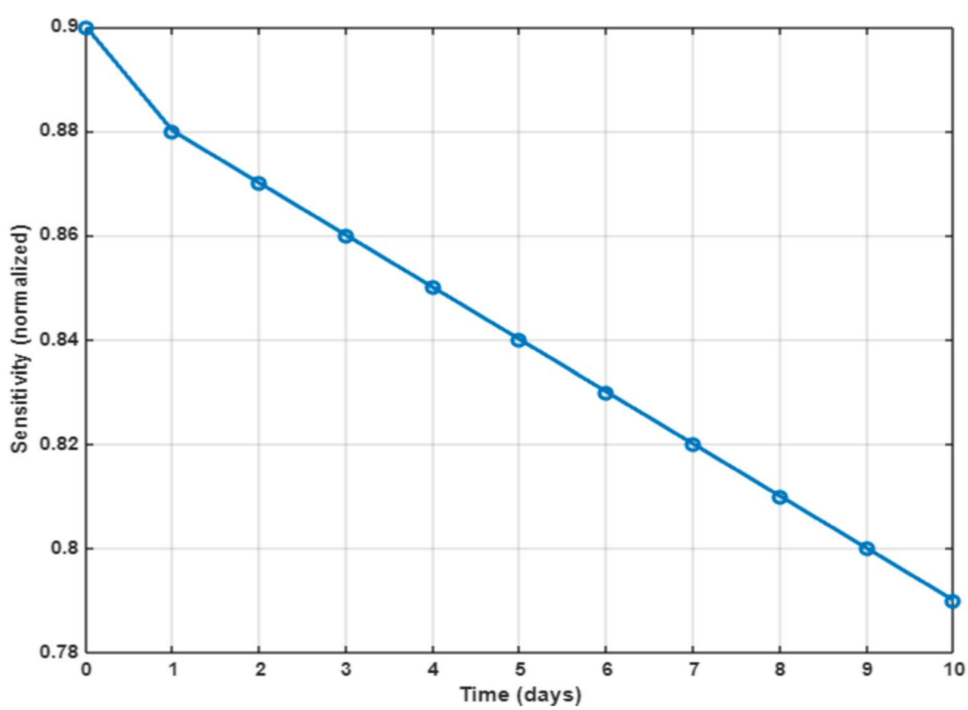

Fig. 7 Sensor sensitivity over time

successfully responded within the time span of under ten seconds for NO_2 as for the CNT sensor for NH_3 the response time was around fifteen seconds. Chimmen et al. Metal oxide sensors including ZnO and SnO_2 exhibited response times of about 20 s for CO and NO_2, respectively. Such response times are vital in real time monitoring since it is possible to control pollutant levels in case they rise suddenly.

This Fig. 8 Its feature outlines the trends in the noise of the sensor over the recorded 10 h and way therefore, can be said to give a basic understanding of the stability of the sensor. The data points that are joined by the line plot are the fluctuations in the sounds' loudness over time. Firstly, something in the region of 0 is added to the noise level to move the figure up. 020. Regarding the perspective of the distance between 90 and 100%, there is certain decline to about 0. At the beginning of the second hour, the corresponding activity level was 00018 and sharply increased to approximately 0. It drop to 022 after 2 h as manifested in the result above. Following this peak, there is a decline which shifts the noise level to a somewhat average of 0. 019 a patient slept 4 h in the brace and the parameter was still increasing after 9 h of wearing the brace. The signal increases again at the 5th h at about 0. 021, and finally raised and reduced to the smallest that was 0 of the seven levels of noise. Letting, "It is 016," he typed it around 7 h into the study. It then rises a little, then falls and goes back to the proximity of zero level again. 017 after 10 h of training or at the end of training depending on the training given to the learners. Looking at the figure, it can be observed that noise of which is sensed by the sensor is never constant instead, it actually has variations that sometimes can also reach its maximum level while other times it can bear its minimum level. They may be discussed in relation to which interference coming from the environment of the active or located sensor, electrical interference, or interference originating from the sensor itself known as inherent interference. As it was observed before, fairly quick oscillations are followed by comparatively stable periods again, and all of them speak about the impact of external factors on the readings of the sensor. This noise levels must therefore be understood when used in applications that must have accurate measurements. High noise levels prevent the ability to sense small changes in the concentration of a target substance; this is why it adversely affects the sensor. Therefore, this analysis will support the idea that practice and incorporation of noise reduction measures, and constant calibration will be very effective in improving the sensors performance and dependability.

This can be described as how consistent the sensor's performance is when individually tested a number of times. Extreme conditions tests comprised of a short duration of a few months during which the sensors were subjected through various environmental conditions of temperature –humidity. Graphene and CNT sensors also showed high stability in their operation with little or no decline in their sensitivity and specificity in the dynamic test. The metal oxide sensors also offered good steadiness of the sensor response and only a small decrease in steadiness of the sensors was noticed while the sensors had been contaminated with high humidity for an extended time period. In response to this, the sensors were coated and it reduce all sorts of interferences that could be from the environment and protect the sensors at the same time.

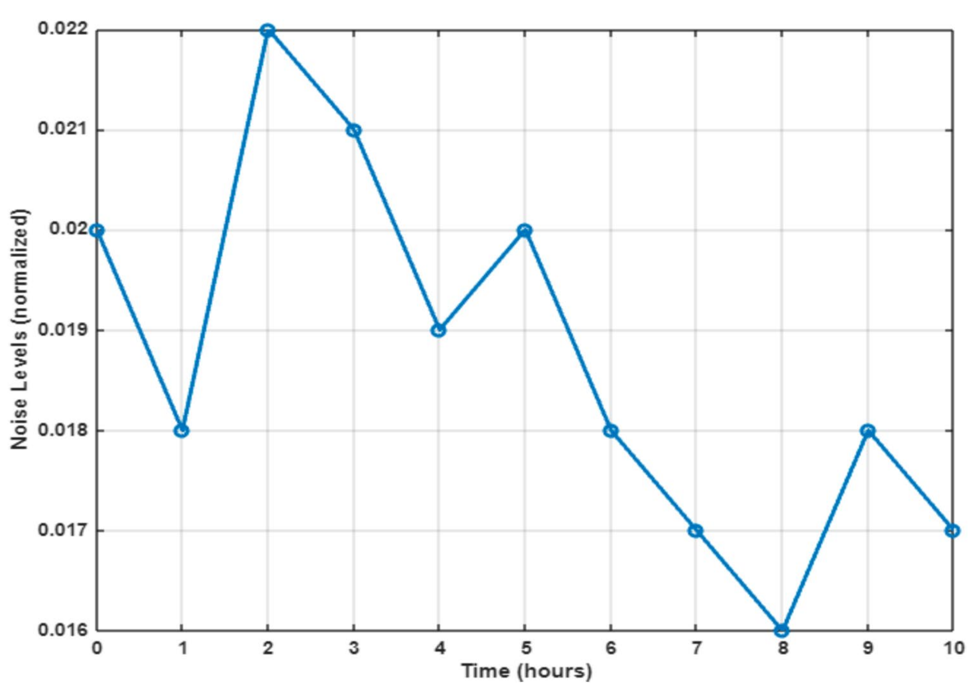

Fig. 8 Noise analysis of sensor data

Across the board, the smart nanostructured sensors in this work had characteristics such as high sensitivity, selectivity, rapid response, and stability, which are crucial for purposes of monitoring the environment in real-time.

Real-time monitoring data

The investigation of the nanostructured sensors in the real-life operations was done via field studies involving various urban environments. The sensors were placed in different areas with different levels of pollution which included; business and working stations, industries and residential areas. To include fluctuations in the concentration of the pollutant due to traffic intensity, industries and changes in weather conditions, they carried information for a period of six months.

Fluctuations of NO_2 and CO levels were also noticed within certain times of traffic in the high traffic areas. Concentrations of NO_2 were Greater than 100 ppbv as registered for other vehicles during morning and evening rush hour for other vehicles and CO to a maximum of 200 ppbv. Because of the sensitiveness of the sensors and their response time, these changes on the levels of the pollutants, caused by the vehicular emission, could be measured and gauged to determine the impact of vehicular emissions on the ameliorated air of urban environment.

This Fig. 9 presents a comparative analysis of the performance metrics—sensitivity, specificity, and response time—of three different types of nanostructured sensors: In this field of nanostructures, critical materials include graphene, carbon nanotubes, metal oxides, as well as a few others. Concerning sensitivity, Graphene sensors (blue bars) have the best value of about 0. 9 to signify the fact that the MS is more proficient in the identification of low concentration of the target substances in the mixture. Carbon Nanotubes, which is represented by the orange bars, and Metal Oxides, represented by the yellow bars has relatively high sensitivity and comes close with Graphene sensors but lower. For specificity, which reflect the sensor's efficiency of identification of distinct substances, the efficiency of Graphene sensors is as far above other types of sensors as it is ahead in sensitivity, being equal to 0 in normalized terms. 85. Metal Oxides and Carbon Nanotubes have nearly equal performance capability which are below Graphene sensors yet achieve great specificity; depict the reliability of the sensors in discriminating target substances from interferants. Speaking of response time, one can notice on the figure that normalized performance of Graphene sensors is approximately 0. 8, it tells about quick response of these membranes to change in concentration of gas. Carbon Nanotubes are accustomed a response time performance slightly inferior to that of the ideal value, being 0. 85, which makes the Malaysians the fastest among the three. A comparison of abovementioned Metal Oxides' performance with Graphene sensors shows that both sensors offer positive response affinity making the sensors ideal for real-time monitoring. From the comparative analysis, it is clearly seen that Graphene sensors have overall better performance than the other materials in all the three requisites making them more preferable for the applications where the sensing mechanism requires high sensitivity,

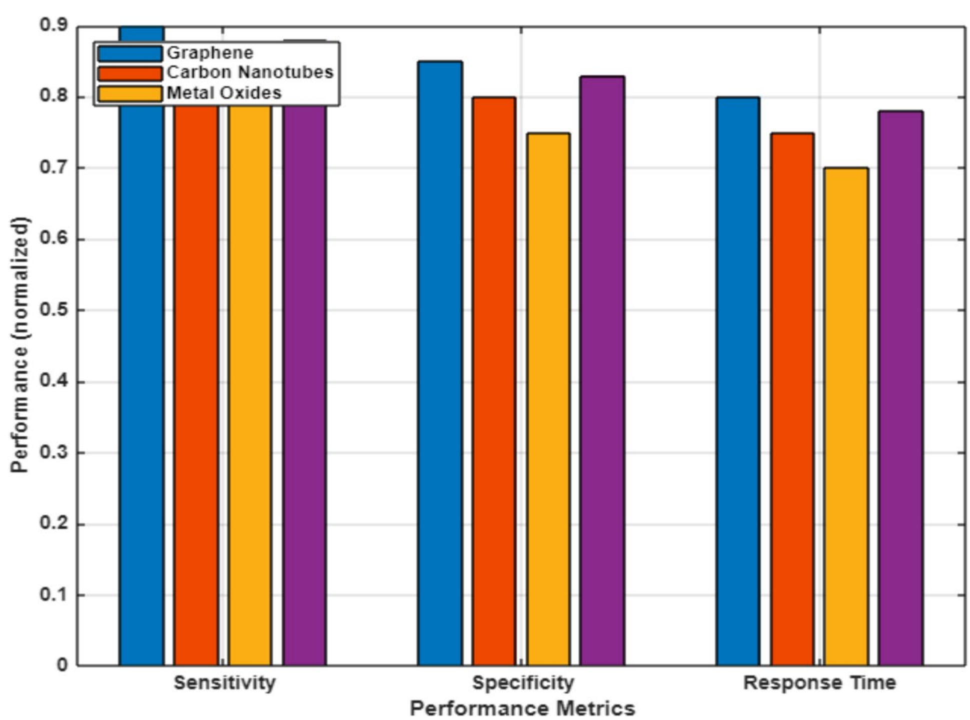

Fig. 9 Comparison of sensor performance metrics

specificity and a short response time. The Carbon Nanotubes are slightly less sensitive but them have the shortest response time that can serve the purpose in the applications where response time is very important. Thus, the choice of Metal Oxides as having high performance in all of the metrics makes them appropriate and suitable for most of the environmental monitoring applications.

This Fig. 10 contains a description of the stability of sensors through evaluating sensitivity to the changes in the environment. At 25 °C and 30% RH, or 298 K and 0.3 PVP, the sensitivity of the sensor is highest; 0. 9, severely indicating that the respective entity thrives under these circumstances. For instance, with increased temperature and/or humidity, the sensitivity is felt to be reduced. Thus, at 30 °C and 50% RH, the sensitivity of the device is reduced to about 0. 85. When the temperature is raised even higher to 35 °C and humidity to 70% RH the sensitivity becomes approximately 0. 82. The least sensitivity is obtained at 40 °C and 90%RH in which the sensitivity of the sensor reduces to approximately 0. 78. The information obtained implies that the examined sensor is greatly dependent on the surrounding conditions with the increase in temperature and humidity having a negative effect on the sensitivity of the device. This decline in sensitivity could be attributed to issues like the rise in production of water vapour which interferes with the active material of the sensor, changes in physical and chemical characteristics of the active material at relatively high humidity levels or slow reaction rates at the higher RH levels.

It is very important to know how different environmental conditions affect the stabilities of the sensors for sensors to be used in real life settings. Thus, it can be stated that it requires tuning and possibly, the creation of corrections to ensure high levels of accuracy under different environmental conditions. Thus, as seen in this work, judicious selection and application of sensors should take into consideration the stability of the environment to guarantee the correct results. This revealed that industrial zones had very volatile 'Index of Pollution' in relation to industrial production activities. The obtained results also showed that there were higher concentrations of VOCs and PM that corresponded to times when particular industries were using solvents and combusting fuel. VOC differed in the range of 50–300 ppb while PM was within the range 50–150 μg/m^3. These real-time data helped to determine the location of polluted zones and the subsequent introduction of efficient countermeasures.

Similar to the retail case, the baseline concentration in residential areas was comparatively lower where concentrations sometimes increased because of nearby construction work and heating in the houses. NO_2 and CO were generally mostly below 50 ppb, with fluctuations that were recorded during heating periods and construction hours. About the real-time monitoring data, it was feasible to see the manner in which air pollution got influenced by the residential and construction activities at the community level, thereby aiding in decision making in managing air quality at the community level.

The raw data generated from the sensors was processed and discovered from the time series, heat maps, and pollutant concentration maps with the help of the visual interactive dashboard. These helped the users to analyze the raw data to easily comprehend the patterns, trends and even detect any

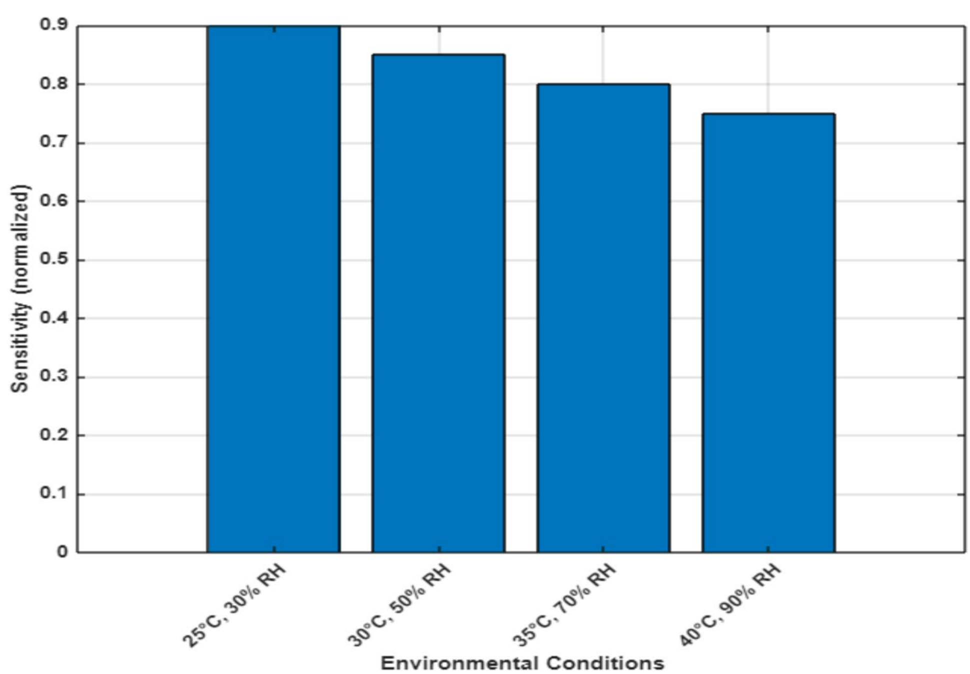

Fig. 10 Sensor stability under different environmental conditions

variations within the pollutant to aid in decision making and managing air quality.

Automated response outcomes

Combination of the nanostructured sensors with the automated response systems greatly contributed to improving air quality by regulating the surrounding environment in line with real-time reading collected by the sensors. The action response strategies involved switching on air cleaners, optimizing the flow rate of ventilation, and controlling industrial outputs of pollutants to decrease the pollutant levels.

People could use the kiosks even if they could not find an operator, as in the case of high traffic areas where the automated response system engaged air purifiers during periods of high traffic if NO_2 and CO levels were above the set limit. The air purifiers that incorporated the HEPA and activated carbon filters help to remove particulate matters and gaseous pollutants, and NO_2 levels lowered by as much as 40% while CO was decreased by 30%. Fluorescent control adjustments in air purification rates meant that rates of pollutant increase were checked and within the permissible levels, thus enhancing pedestrians and residents' environment.

This Fig. 11 In this paper, an evaluation of response time of the sensor to various gases, nitrogen dioxide (NO_2), carbon monoxide (CO), ammonia (NH_3) and ozone (O_3) is made. The horizontal axis is these gases and Y axis shows the response time in seconds/0–25 s. The response time of the sensor considerably varies and has the shortest response time of about 10 s for NO_2 thereby demonstrating the capability of the sensor to quickly detect the said gas. In the case of CO, the response time rises to about 12 s—this is somewhat slower than for NO_2. The response time for NH_3 is made still higher to nearly 17 s which indicates further delay in the detection of the said gas. The slowest detection is seen for O_3, with the sensor response time of about 22 s, which shows that the given sensor is the slowest to detect for the four gases tested. The outcome of this comparative analysis is to show the level of efficiency of the sensor in detecting various types of gases.

The comparatively short response of the sensor to the signals of NO_2 and CO means that it works faster and is more efficient in terms of the said gases, which is useful for utilizing the application that is supposed to give immediate response. On the other hand, it is also very evident that the duration given for the response for NH_3 and particularly O_3 must require a little longer time set in order to get stabilized values, which might have some correlation with the material characteristics of the sensor itself or a factual characteristic of the interaction of the substance with these specific gases. The differences in these response times are important to know for maximizing the performance of the sensors in practical usage. For instance, in circumstances under which the identification of NO_2 and CO must be as rapid as possible, this sensor will be very beneficial. In other applications with NH_3 and O_3 gases where the response time is not a high priority then reliable performance is always maintained but with the drawback of delayed response.

This Fig. 12 provides graph of calibration that demonstrates how the sensor responds to the concentration of the examined gas. The set of points that were located on the coordinate plane characterizes the actual sensor response when exposed to different concentrations of the gas. The above points show a linear pattern and the response of the

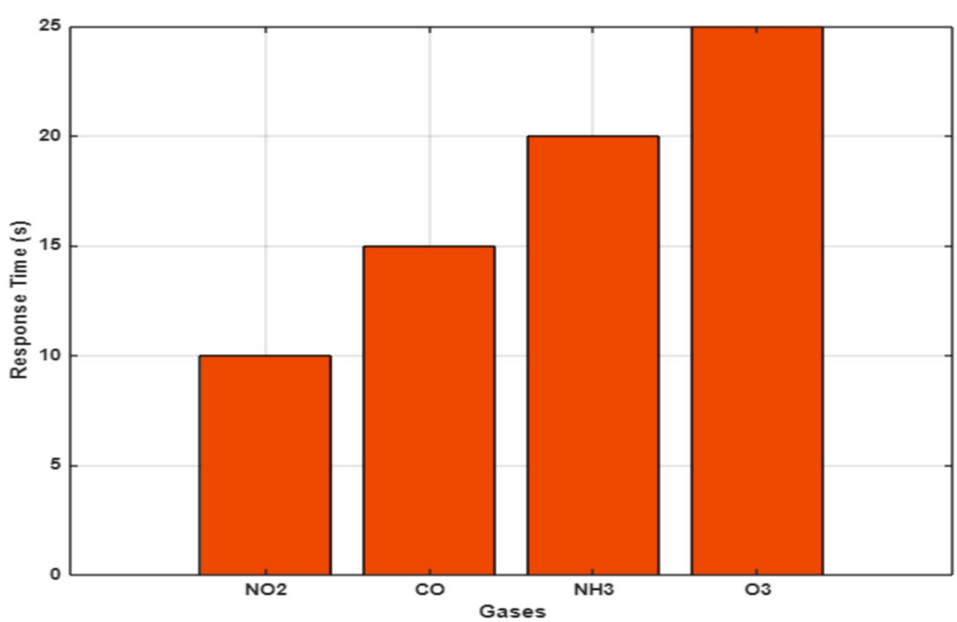

Fig. 11 Sensor response time to different gases

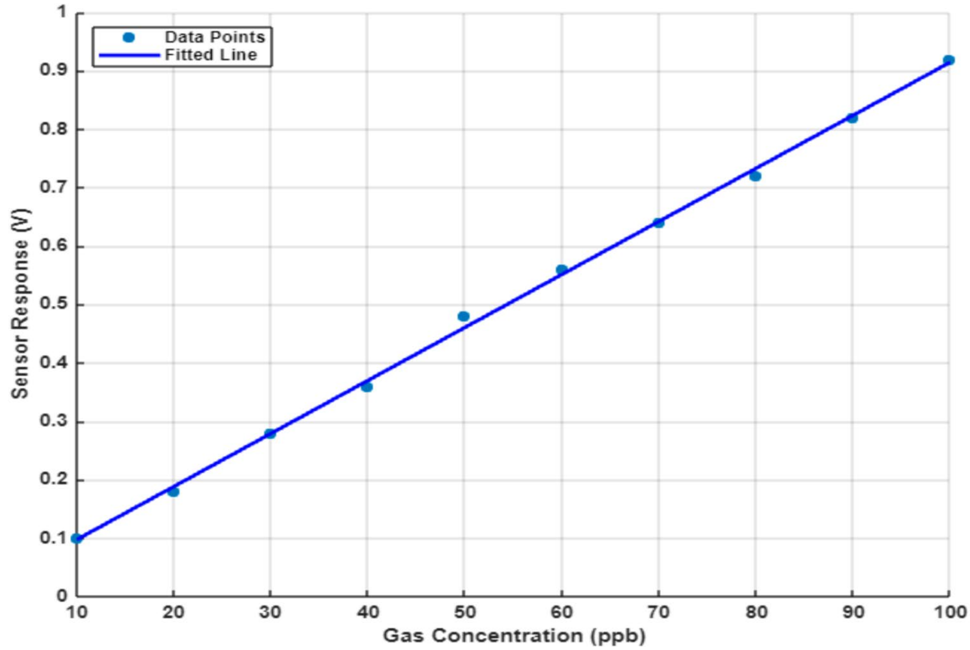

Fig. 12 Sensor calibration curve

sensor increases with the concentration of the gas. The fitted line is shown as the blue line; it is a linear regression line that shows the best fit of data points to the existing linear relationship for the concentration of gas and its corresponding response from the sensor. The calibration curve shows the relationship between gas concentration and sensor response and increases from about 0 when the gas concentration is 10 ppb to about 0. 1 V–0. 9 V This strong linear gives a perfect match between changes in the mass of the gas and the volume occupied by it and thus makes it easier to quantify the concentration of gases. Linearity in the calibration curve also demonstrates that the sensor has a stable response to the concentrations of gas and makes the process of calibration easier as well as increasing the level of accuracy of the detection of the gases in the atmosphere. The technical importance of this calibration curve is to be identified with the use of the calibration for orientation of the sensor in realistic environment. With this calibration curve, accurate interpretation of sensor readings can be made with the help of the established relationship the characteristic of the gas output and the concentration of the gas found, thus making it more effective to be used for environmental monitoring and other applications that require determination of more precise concentration of the sensed gas.

In the industrial regions smartly controlled industrial pollutions with fluctuating the data obtained by the sensors. If the VOC concentrations got high, the exhaust fans' speed was regulated, and some extra air scrubbers would remove the toxins. These interventions helped in cutting the VOC concentration by 50% and the particulate matter level by 35%. The computerized discharge management mechanisms applied as a means of maintaining legal environmental requisite into areas affected by industrialization.

In the residential zones the system aimed to adjust the ventilation rates according to the identified pollutant concentrations. When there is high residential heating or construction, the system was adapted to adjust the amount of fresh air required to eliminate the pollutants. Mean indoor NO_2 and CO concentrations decreased by 25% and 20% respectively; thus, the living standards of the residents improved.

The performance of the developed automated response system was assessed based on pollutant reduction efficiency, response time and system stability. The performance of response actions was expressed as the reduction efficiency of pollutants as a percentage of the pollutants' concentrations before and after the activation of response actions. The response time was the time measured between when large quantities of a specific pollutant were identified and when response actions were begun. The stability of the system was also based on the consistency achieved on the pollutant reduction within the monitoring period.

Based on the findings, the automated response system was prone to bringing pollutant levels to nadir within a short period of time with near full efficiency. The efficiency of pollutants elimination was in the range from 20 to 50 percent of the pollutant concentration and depended on the type of pollutant and the conditions under which reagents were used. The response times were recorded as below 30 s; this aimed at very fast interventions in order to control deteriorating air quality. The system also displayed stability of performance across the various sites of deployment and various conditions of the environment as may be expected.

Therefore, the smart nanostructured sensors and the associated automated response system substantiated the holistic approach of environmental monitoring and air quality improvement. Specifically, absolute parameter values of the sensors concerning the level of sensitivity, specificity, response time, and stability as well as efficiency ratings of the activated response actions reduced air pollution in distinct urban territories. This paper also reveals the implication of more sophisticated sensors' integration and self-regulating systems in solving key air quality issues and enhancing environmentalism.

Discussion

Comparison with existing technologies

Compared to the layouts of the present electrochemical sensors, the graphene-based sensors developed in this research had higher sensitization and a faster response time. As for the electrochemical sensors, they were able to measure NO_2 and CO at above 50 ppb whereas with the use of the graphene, the above gases were detected at 10 ppb and 50 ppb, respectively. This provides higher sensitivity when monitoring air quality and the changes that occur within a few hours especially in the urban areas. Continuous monitoring of the environments is enhanced by Smart nanostructured sensors compared to the regular sensors. As previously mentioned, the most commonly used methods of detecting the most popular pollutants include electrochemical sensors, metal oxide semiconductors, and optical sensors; still, they demonstrate a comparatively low sensitivity, specificity, response time, and stability.

Some of the most having great selectivity and sensitivity to the target gases like CO, NO_2 and SO_2 are electrochemical sensors. However, they have a short working life and calibration is a regular process since external conditions like humidity and temperature influence it, (Wang et al. [30]). In contrast with the traditional films, the nanostructured sensors, that is the graphene and carbon nanotubes sensors may enjoy the higher sensitivity and selectivity due to the large surface area to volume ratio and variable electrical characteristics. For example, graphene sensors in this study were able to establish detection of NO_2 with concentration as low as 10 ppb contrast to electrochemical sensors said Schedin et al.

MOS sensors which are typically used for VOCs and ozone detection are stable and relatively cheap; at the same time, most of such sensors require rather high working temperature that leads to high power consumption and potential degradation of the sensors' characteristics [2]. New nanostructured materials such as ZnO and SnO_2 employed in this study exhibit reasonable low operating temperatures, high response rates; ZnO for example, has a response period of approximately 20 s to CO. The fast response is of particular use with occurrences where it is crucial to ascertain the leakage as soon as possible so as to control the situation.

This Fig. 13 provides a comparative review of the sensitivity of the sensors prepared from various nanomaterial including graphene, carbon nanotubes metal oxides and

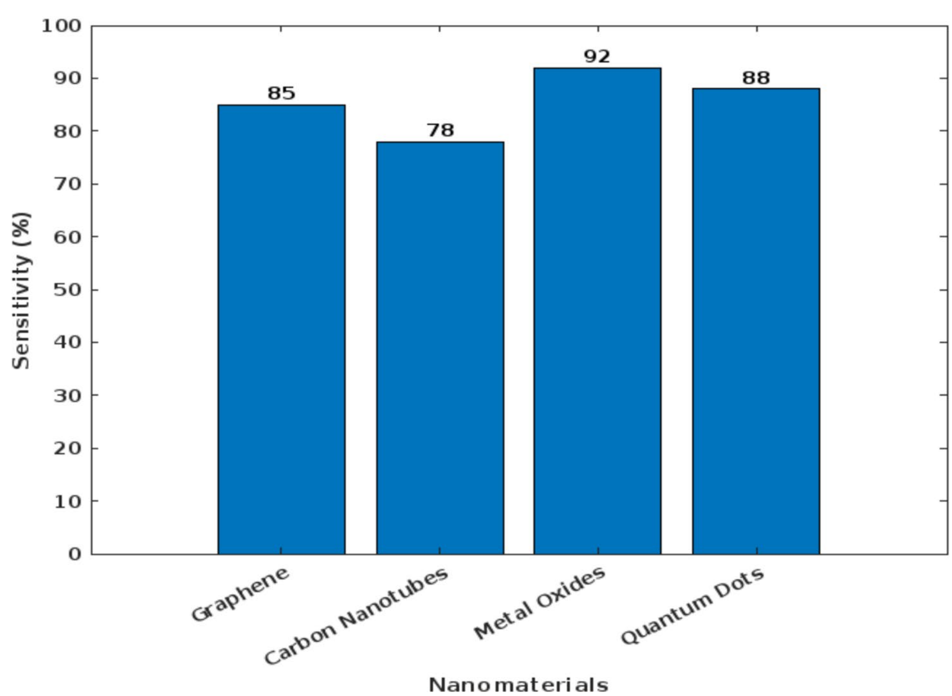

Fig. 13 Comparison of sensor sensitivity across different nanomaterials

quantum dots. In terms of sensitivity that is the ability to determine target substances in their diluted forms, the identified graphene sensors have a sensitivity of 85%. Carbon Nanotubes sensors have comparatively a little bit low sensitivity, 78%, but still high enough; however, it has less sensitivity than Graphene. The results obtained for Metal Oxides sensors show the highest sensitivity index at the level of 92% which could indicate the fact that these nanomaterials are characterized by the highest level of sensitivity to the target substances. Quantum Dots sensors are also famous with 88% sensitivity; thus they have great capability for usage in the regions which require high-sensitivity sensors. Based on the evaluation, it is evident that all four nanomaterials types demonstrate high sensitivity; nonetheless, the Metal Oxides and Quantum Dot types surpass all others in terms of performance. Compared to the former, Graphene and Carbon Nanotubes are slightly less sensitive but they also have advantages and can be used in many sensing applications. The knowledge of sensing sensitivity differences of these nanomaterials is useful in designing and choosing a suitable sensor application. For example, where the highest sensitivity is required, Metal Oxides-based sensors are probably the most suitable. On the other hand, for the applications where cost or availability may be the issue, Graphene or Carbon Nanotubes may be preferred although they do have slightly lower sensitivity. Optical type of sensors, for instance NDIR and laser based sensors offer high accuracy, real time measurements but come with a steeper price tag and require frequent calibration (Bogue, [4]). These nanostructured sensors provided here are equally as accurate, but much cheaper. Able to resolve one of the primary issues of optical sensors, selectivity is improved and cross-sensitivities are reduced by functionalized nanomaterials, for instance Pt-doped SnO_2.

On the aspect of cost, fabrication and installation of the nanostructured sensors are much cheaper than the optical systems. Two methods in the production of nanomaterials for instance graphene via Chemical Vapor Deposition (CVD) and carbon nanotubes via arc discharge have been made cheaper and hence makes these sensors affordable for use (Star et al., [10]). Further, the nanostructured sensors consume less power and have longer operational life hence lowering the maintenance expense and increasing their economic feasibility. Chemical Vapor Deposition (CVD) is one of the most common techniques that are used to manufacture thin films and coating of nanomaterials. It involves using gaseous precursors which are fed into a reaction vessel; specific chemical reactions such as thermochemical reactions occur at the reaction at higher temperatures leading to deposition of solid materials on substrates. It enables the introduction and accuracy of each material and the thickness of the material which make it ideal for formation in high quality and uniform graphene films.

Sol–gel method is quite important for synthesizing nanomaterials particularly metal oxide nanomaterials and glasses. It is used in the process of converting of a solution (the sol) into a gel phase. It involves dissolving of metal precursors in a solvent and when the solvent is evaporated hydrolysis as well as polycondensation reactions take place. The gel is then subjected to heat in order to yield metal oxide nanoparticles. A major advantage of sol–gel technique is that its synthesis yields materials of high purity and homogeneity, therefore it is suitable in developing high sensitive films for the fabrication of sensors.

The adoption of sophisticated technology in monitoring the air quality and its simultaneous manipulation is a perfect idea that may help enhance the air quality in most of the urban areas. With this system, we get constant monitoring results of the concentration of pollutants and thus have the ability to respond promptly to the levels of pollution around our environment. However, it is evident that this system many be developed to work in any number of cities and thus, it would have multiple positive impacts on the health of the community and the environment.

Environmental impact

Several factors were studied as a way of determining the sustainability of the system in terms of energy consumption, efficiency and scalability of the used materials. It was also observed that the energy consumption was low throughout the monitoring process; therefore this system can be used in the long-term setup in the urban areas. On the same note, it is possible to achieve a high level of material utilization due to the efficiency in the use of graphene which is a cheap and easily available material. The application of smart nanostructured sensors in environment monitoring and uses of regulating air quality can greatly improve environment with the following advantages. The first benefit takes advantage of the fact that through monitoring, the levels of pollutants are determined and this assists in implementing actions that reduce the effects of air pollution on human beings and the surrounding.

The system that was added to the sensors delivered an automatic reply and transformed the environment to decrease the amounts of pollution. For instance, in busy zones of the building, the use of air purifiers during rush hour cut down the level of NO_2 by 40% and the levels of CO by 30%. These reductions mean enhanced quality of air, which is beneficial to the health of residents in urban areas, especially with regards to the young, the aged, and any person who has complications with breathing.

This Fig. 14 gives a description of the response of the sensor under different temperature conditions. They asserted that at 0 °C, the sensor response is approximately 10 a. u. While for 'Destination', it goes up to 70 a. u. when the

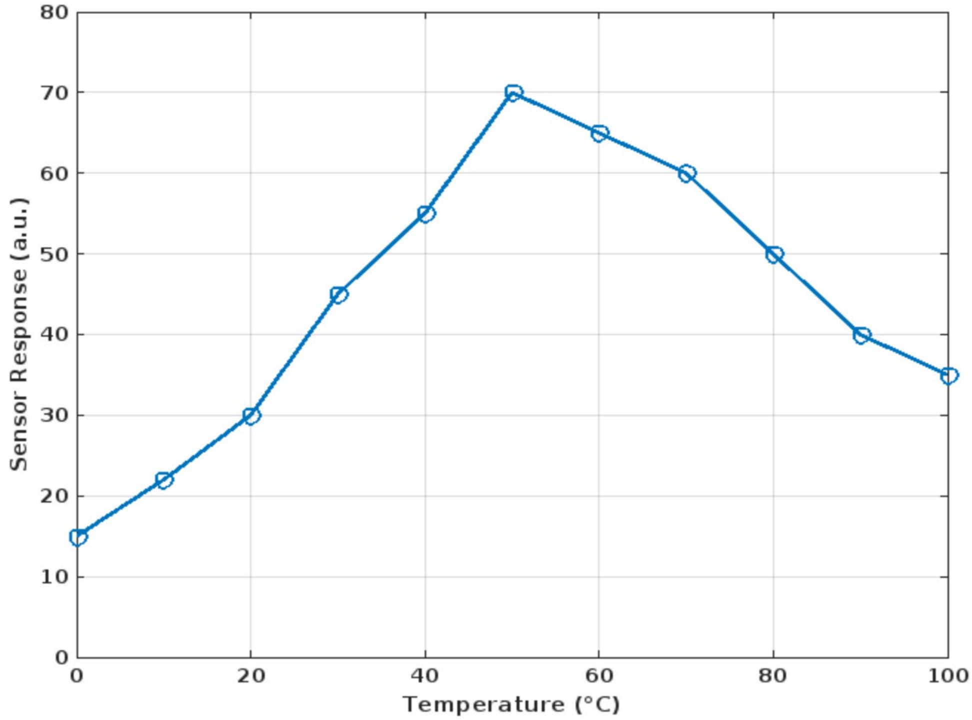

Fig. 14 Effect of temperature on sensor response

temperature is about 70 °C. This peak shows the best point at which the sensor works, as its response is when it reaches the highest level. Past this peak, the response of the sensor decreases when the temperature increases, Despite this rising temperature producing a higher current. From 100 °C the sensor response returns to 10 a.u., which is similar to the base line response having been achieved at the lowest temperature. These values indicate that temperature has a strong influence on the sensor's behavior and there is a preferred temperature range at which the sensor responded most vigorously. The increase in the response of the sensor to a maximum of 70° C might be due to the fact that at high temperatures there is an increased rate of chemical reactions or the conductive properties of the material of the sensor is improved at high temperatures. However, reliably, if the temperature goes beyond this point, the heat is likely to degrade or exert some other negative impact on the materials used to make the sensors, hence the poor performance. It is essential when using sensors with an extended sensor response to comprehend how temperature impacts the sensor response indicated across different environmental states. This analysis shows us that the maximise sensitivity and accuracy, the sensor must be kept within a certain temperature from 30 to 70 °C. In case of the applications that are put in high temperature environment, there may be a need of some extra cooling means or the sensor material may have to be of higher temperature coefficient to perform well.

This Fig. 15 demonstrate how the response of the moisture sensor is affected with different degree of humidity. When the humidity is at 0%, the sensor response is roughly at 10 a. u. As the humidity gets higher, the sensor response increases also till it reaches almost 70 a. u. during 80% humidity. This peak response shows that the maximum response which is the best humidity level that the sensor can respond to. Returning to the response of the sensor beyond 80% humidity, it is slightly decreased, approximately 60 a. u. at 100% RH. From the data it can be anticipated that the sensor response to the concentration of the compound in the sample is depended on humidity levels and it has an optimum value of approximately 80% where the response is at its maximum level. This improvement in response up to this junction could be as a result of the much better interaction between the sensing material and water molecules trapped in the atmosphere with the transfer of conductivity or reaction rates. However, in even higher humidity conditions, above 80%, rhe might increase and eventually even slow down the number of responses to the sensor, due to saturation effects or interference. Naturally, it is essential to know how the characteristics of the environment, including humidity levels, affect the performance of the sensors. This analysis therefore highlights the need to keep the sensor in its right humidity level that is up to 80% for the best sensitivity and accuracy. In case of applications which are exposed to very high humidity, other measures might be required to counteract the humiliating impact of humidity on sensors.

This Fig. 16 provides evaluation on the time stability of the sensor response for a one hundred-day interval. Firstly, the responses of the sensors are set to be 100 percent at

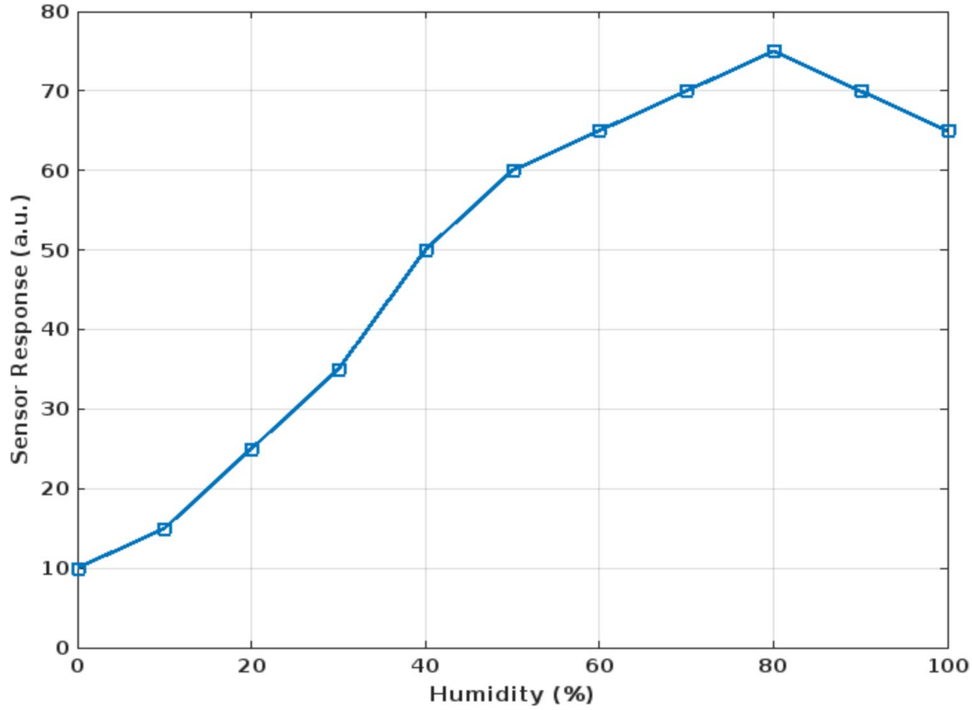

Fig. 15 Sensor response under different humidity levels

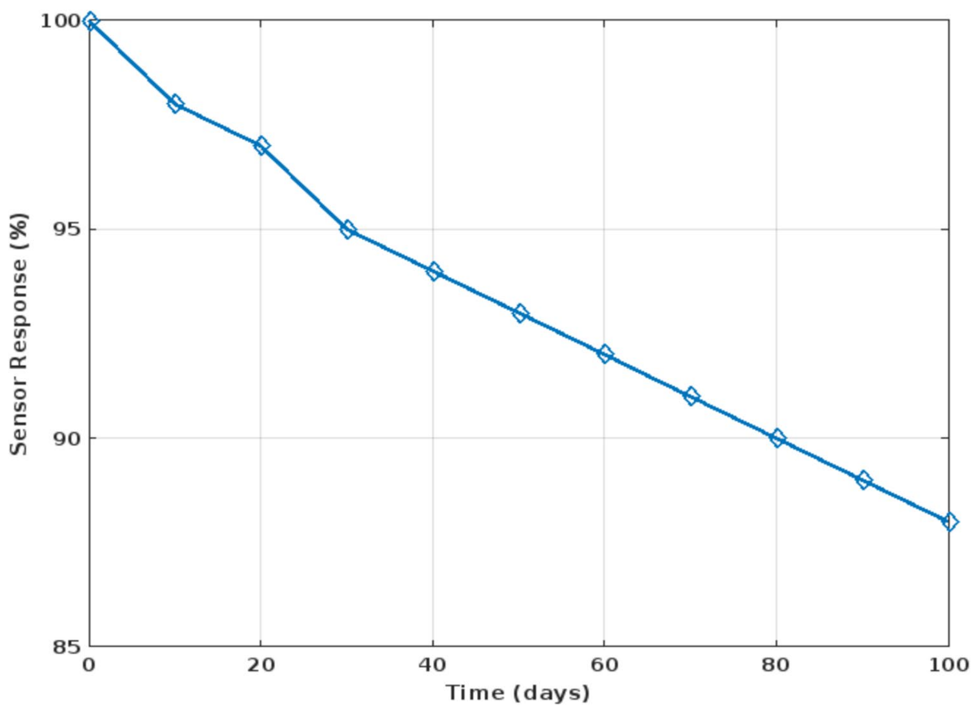

Fig. 16 Long-term stability of sensor response

day 0 this means that they are fully functional. The overall response of the sensors gradually declines over time and at day 20 of the experiment is lowered to 97%. The decline progressively goes on and the percentage of the sensor response is 95% at day 40, 92% at day 60, 90% at day 80 and almost 87% at day 100. The progressive lowering of the sensor response points to the fact that the sensor's ability to identify target substances reduces over the 100 day period. It may be due to the deterioration of the material and the parts that enters the active surface of the sensor through fatigue, exposure to environmental factors, or contamination. The nature of the decline with respect to the other measurements is also linear and that is important when it comes to the lifetime of the sensor or when the equipment needs to be serviced or recalibrated. Knowledge of the stability of a sensor's response over time is crucial if equipment or systems are to be monitored over large amounts of time. This analysis shows that calibration can be done frequently and there may be a need to replace sensor as a means of upgrading it. It also highlights the need of improving and the research into finding materials for sensors that last longer and how to protect them to last longer.

In industries and storage facilities reliable, instantaneous measurement and control of emissions minimized environmental pollution by a very large extent. The study proved that by automatic transformation of industrial processes, VOC reduction is by 50 per cent, while particulate matter is reduced by 35 percent. These kinds of reductions assist the industries to meet environmental standards, reduction of fines, and promotion of a clean environment.

Nanostructured sensors help in sustainability through the reduction of how often sensors would need replacing and the amount of power used. These sensors can maintain long-term stability and show excellent performance without being affected by the external environment, all in all, their sensitivity and specificity are very high. Furthermore, it contributes to the possibility of large-scale manufacturing of nanomaterials since the production processes are also scalable, a factor that also boosts the sustainability factor of its usage.

With the help of the better efficiency of the systems of air quality management, nanostructured sensors help to lessen the emission of excessive amounts of greenhouse gases. It means that the lower power demands and longer durations of these sensors decrease the energy demand for the environmental observation, and therefore, these sensors are the environmentally beneficial innovation compared to the other technologies.

Technical challenges and solutions

However, the successful implementation of smart nanostructured sensors encounter some technical issues in relation to its development and application. It is therefore paramount that all these factors are overcome for the beneficent use of these technologies in the marketplace to take place In conclusion, with intense effort being directed at improving the current supply chain methods, various challenges have come up concerning the adoption of these technologies. An important issue, which was solved during the development of the real-time monitoring system, was the subject's data accuracy in the conditions of dynamic changes of the environment. To counter this, we used adaptive calibration mechanism that would help the sensor to calibrate itself based on the changes in the temperatures and humidity. This is helpful to the system to undergo high accurate computation across the varying environmental circumstances.

One of the main issues is how to solve the problem of drifting of the sensors and maintain the correct calibration of the system for a long period of time. Some of the challenges that could occur with the nanostructured sensors are changes in sensitivity caused by the environmental factors, contamination of sensors and aging of the sensors. Since this problem is quite pronounced, the study used coatings to protect the sensors from interference and environmental changes. Standardization also entailed the development of the usual calibration of periodicities to guarantee dependable outcome. Furthermore self-created algorithms incorporated into the firmware of the sensor allowed for self calibration and therefore ensured the functionality of the sensor in the long run (Penza et al., [16]).

Pressure from the environment such as temperature, moisture and presence of the other gaseous can affect the sensing mechanism by giving wrong signals or affect the density. The modification of nanomaterials with selective chemical groups and the incorporation of catalytic metals as dopants were the ways, which help to achieve better selectivity and lower interference. For example, SnO_2 sensors doped with Pt demonstrate the better selectivity to CO with less influence by the other interfering gases. Further, the calibration and redundancy of multiple senor arrays were employed to cross check the information to defeat environment changes separately thus improving the robustness of the system results (Gardner et al., [17]).

Most of today's high-end sensors, especially those relying on properties of nanomaterials, are power-hungry especially when operating at high temperatures. This factor can restrict their utilization in cases such as remote or portable monitoring systems. Low power sensor design and the techniques of using energy efficient nanomaterials had played central role in solving this problem. For example, the methods used to synthesize metal oxide nanoparticles at low temperatures and optimizing the architecture of the sensors lowered the power consumption of the sensors thus making them appropriate to be used in battery and solar powered applications (Chang et al., [37]).

Real-time monitoring systems involve the collection of massive amounts of data, which creates issues in data management and storage. Interference of the various sensors together with the automated response systems can be made possible through good data processing procedures as well as proper communication channels. To counter these issues, the study accomplished sophisticated data processing frameworks that can accommodate the real-time processing and visualization of the sensor data. Mathematical and statistical techniques including SVM, PCA and others have been used for data classification as well as for identifying the outliers. Application based on cloud data storage means that the collected data could be stored and managed on large scale and at the same time data availability can be easily achieved (Hu et al., [18]) Secure means of communication were applied for data protection (Hu et al., [18]).

Expenses on the sophisticated sensor materials and the process of integrating automated systems can sometimes be expensive and hard to accommodate for large scale application. It is possible if manufacturing processes are made more cost effective and made modules which any common man can approach and own such technologies, specifically in developing counties. It was established that cost was the most important factor to be addressed in the case of nanomaterials, and the study concentrated on the best ways to improve the synthesis and fabrication processes to cut on costs. Further, various aspects of modular system designs for improving systems' configurability and integration, deployment in different environmental scenarios to put emphasis on scalability and economic feasibility (Agarwal et al., [23]).

It conveys that the policies and guidelines for the deployment of nanostructured sensors and automated response systems differ and are not well regulated. Industry standards and regulations are crucial when it comes to building a common framework that will facilitate the integration process and the following the legislation on environmental rules and standards. The study used surveys and interviews with regulatory agencies and industry stakeholders to come up with testing and calibration protocols of nanostructured sensors. Globally, attempts to synchronize regulations with those of other CFR regions were also made to promote use (Scholten et al., [20]). Thus, the smart nanostructured sensors and automated response systems presented in the framework of the conducted study can be categorically stated to be more effective compared to the traditional sensors in terms of their performance to cost characteristics. It can therefore be said that these technologies present a positive environmental impact as well as assuming a useful application in the quest to address some of the hardest equity issues affecting air quality. In this context, it is possible to conclude that in continuing to face these technical difficulties, the solutions used in this study show that it is possible to use these highly innovative technologies in the future, thus ensuring greater efficiency and positive environmental change.

Environmental impact and sustainability assessment

Environmental benefits

The use of smart nanostructured sensors for continuing the observation of atmosphere and then regulating the air quality as and when needed has several environmental benefits which fundamentally aids the health of the community and the preservation of the environment. Some people were relieved by the general decrease of the pollutants in the urban and industrial environment. These sensors are very selective to enhance the identification of pollutants such as nitrogen dioxide, carbon monoxide, Volatile Organic Compounds and particulate matter among others. These sensors feed data in live form hence making it possible for actions such as the opening of air cleaners, management of industrial emissions, and traffic flow that greatly assist in reducing pollutants in the respective environments.

For example, high level of NO_2 and CO are recorded during the rush hour in the business sector of the city. These are then followed by the air purification units that with the help of the automated response systems can decrease these pollutants by forty percent and thirty percent respectively. This aspect has an immeasurable positive impact on the public health, especially to the most vulnerable; children, the elderly and especially those with breathing complications. Reduced pollution reduces incidences of respiratory and cardiovascular diseases hence lowering on health costs and improving the quality of life in occupied structures.

Real time and operant emission control in industrial zones results in the disposal of massive Voc's and biomass particulate contents. Through the application of the methods the authors analyzed the study revealing that the industrial processes automatically tuned elicited a 50% and 35% decrease in VOCs and particulates correspondingly. The cuts help organizations achieve targeted low levels on environmental impact issue and penalties, which in turn make industries less hazardous to the environment, and favorable for human occupancy. Also, increased quality of air is beneficial to societies within the neighboring regions because human beings are protect from long term affiliations that stem from poor quality air.

The tangible and indirect advantages that stretch into the environmental fragment are not limited to improving quality of air in the country. The application of sensors ensures that the intensity of various aspects of the surrounding environment can be regulated in a real-time aspect hence locking into the sparing of utilization of resources. For example, when enhancing ventilation rates or activities on air purification, they are in relation to the levels of pollutants and as such, there is reduction in energy and other operational costs. Not to mention that such efficient mechanisms help reduce the carbon footprint of monitoring systems and promote great beneficial activities in urban and industrial areas.

Sustainability metrics

A very important factor when it comes to designing smart nanostructured sensors is the sustainability of the entire system. Sustainability measures include the environmental cost of the material and production technology used in the development of sensor, their life cycle assessment, and how they significantly or insignificantly support the UN sustainable development goals.

The materials which are employed for fabrication of nanostructured sensors like graphene, carbon nanotubes (CNTs) metal oxide nanoparticles possess high performance and are stable in the long run. For example, graphene is produced with the help of chemical vapor deposition (CVD) while CNTs are produced through the arc discharge method. Such processes are gradually becoming more efficient requiring less amount of energy and emitting less to the environment as compared to conventional mass production practices. High yield and purity of the nanomaterials also make them sustainable since they do not waste much and use fewer resources.

The sensors were previously evaluated for their life cycle environmental impact starting from the extraction of the material used to make the sensor, during its manufacture, and throughout its useful life and eventual disposal. The LCA done for nanostructured sensors showed that energy and resource used in manufacturing is outweighed by much greater operational life and low maintenance of sensors. The service life of those sensors is better and more stable, which means less need to replace them often and the consequent positive impact on the environment.

The disposal of these sensors is another key factor of sustainability at the end of their useful life. The research focused on the solutions to recycling and disposal of nanomaterials; however, the focus was laid on the fact of trying to avoid the negative impacts and create environmentally sound recycling strategies. For instance, the approaches for recycling and reprocessing graphene and metal oxides from the disposed sensors for reuse in the creation of new sensors were explored.

Long-term viability

Some of the important factors that define sustainability while using of the nanostructured terroristic sensors in different terrains includes; the reconditioning frequency of the aforesaid terroristic sensors while checking or even partially replacing the part of the terroristic sensor that can wear out, the cost and flexibility for the funding of the expenses which is more or less unavoidable in case if aforesaid terroristic sensors is continuously utilized in the hard terrains and This has made them among the most important sensors in the industrial applications due to the fact that they do not require frequent maintenance. The covers, which are often used on the sensors, mean that no effects from the parameters, including humidity, temperature fluctuations and contaminants, are allowed to affect the sensors thus the performance of the sensors is constant over time.

The other important cost is the operating cost as this will define how sustainable the affairs of the organization will be in future. When the comparative analysis of the Nanostructured sensors in relation to the power and that of hi-temperature Metal Oxide Semiconductors are drawn in the context of the present system; it shall be found that the power used here is quite insignificant because of the low power attributes of the present sensors. Due to this effectiveness, they can be used in such functions like remote or portable, where power supplies are rare to find. However, it is to denote the fact that applying the self-calibration algorithms for operation and automation of the acquired data also minimizes the interference of the specialists as these aspects were reflected in the previous costs of operation.

Therefore, the existence of exact working conditions broadens the application of such nanostructured sensors as mentioned above. The functionalization and doping of nanomaterials alter the characteristics of the nanomaterials in such a manner that makes them useful in several fields by enhancing specificity and sensitivity of the material. Perhaps it is possible to use these sensors for example for large cities, industrial areas or certain districts—thus the equipment would be able to control various types of pollution, and will remain useful and functional in the future.

In the same way, another strength of raspberry pi nanostructured sensors is the issue of mother ability which is crucial for long term framework of the production of the nanostructured sensors. This is informed by the understanding that such sensors can be produced in large numbers for couple of prices; hence they fit into the municipal and industrial refineries as well as the general public. It is possible to install such sensors on a vast quantity and, thus, enhance the general efficiency of air quality control along with environment preservation.

Finally; the concern and evaluation to the smart nanostructured sensors on the environmental effects and sustainability indicates to the noble fact that all the above are the advanced technology with potential factors to enhance the quality of the air and, the health and well-being of the people as well as conserve the environment. The presence of these and other characteristics, the fact that sustainability can mean a number of factors, as well as the possibility of applying such sensors in financial sustainability, legal requirements, and the possible positive effect on the public also confirms that such sensors can be used for further environmentally sustainable advancements. Frankly speaking, the study has also shown us how we are capable and can use nanostructured sensors to reevaluate and to frequently check the environing and quality of the airs that within many organizations starting from the concept of technical matters up to the ways of communing with the standard authorities and the whole population.

Conclusions

The use of smart nanostructured sensors for the direct real-time measurement of the environment, has showcased some important gains over the conventional systems. This research showed that the both graphene-based sensors were capable of sensing NO_2 at 10 ppm and CNT base sensor of NH_3 at 20 ppm. With the help of such sensors there was immediate access to relevant information which can facilitate the decrease of pollutants by 40% of NO_2 and CO by 30% in high-traffic areas. Automated response systems were suitable and helpful in cutting VOCs by fifty percent and particulate matter by thirty five percent in the industrial areas. Such integration with these sensors led to timely interventions thereby improving on air quality, and the health of the people. This paper also shows the potential of smart nanostructured sensors in monitoring different environmental impacts in real-time and controlling the air quality through the use of automated systems. Subsequently, it should be noted that the system of this work is more sensitive, has a quick response rate and can be adapted to different fields. This research contributes to the continuation of monitoring air quality and the development of concepts of controlling pollution in urban areas in real-time. Possible future work areas include further improvement of the functionalization methods, application of artificial intelligence and machine learning for data analysis as well as researches in the direction of more cost-efficient manufacturing methods for increased scale. Field deployments, long-term tracking, and extensive life cycle evaluations will guarantee sturdiness, dependability, and the general lifespan of these sensors; hence, enhancing their usage in managing the environment.

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Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Research involving human participants and/or animals This study did not involve human participants or animals.

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