CHAPTER SIX

Development of nano-sensor and biosensor as an air pollution detection technique for the foreseeable future

Elham Farouk Mohamed[a,*] and Gamal Awad[b]

[a]Air Pollution Department, Environmental Research Division, National Research Centre, Dokki, Giza, Egypt
[b]Chemistry of Natural and Microbial Products Department, Pharmaceutical and Drug Industries Research Division, National Research Centre, Dokki, Giza, Egypt
*Corresponding author: e-mail address: elham_farouk0000@yahoo.com

Contents

Comprehensive Analytical Chemistry, Volume 99
ISSN 0166-526X
https://doi.org/10.1016/bs.coac.2021.11.003

1. Introduction

Before evaluating the implication of nanomaterials and its action in air pollution control, an overview of air pollution must be discussed as a priority. A general brief of air pollution is highlighted in this section including this main question: what is the meaning of air pollution and air pollutants?

1.1 Environmental air pollution problem

The term air pollution is a significant issue today. The quality of air is actually a global concern, which can be attributed to large scale growth of population and urbanization, and their products increase in industrialization, traffic and energy uses.

Air pollution can be defined as a decrease in the air quality due to the presence and release of inorganic and organic pollutants into the environment. These toxic pollutants lead to not only the biodiversity demolition, but also the human health harmful. Air pollutants have adverse effects with a significant damage to the earth. It was noticed that long-term exposure to pollutants, such as the particulate matters and heavy metals is an important factor in provoking diverse problems in the heart and lung [1–3].

Today, due to the modernization and advancement of industries, the environment is filled with different types of pollutants generated from human activities or industry.

Air pollution includes two main categories: outdoor and indoor air pollution. Each year, almost two million people die from the exposure to the indoor air pollutants estimated by the World Health Organization. **Indoor air pollutants** include particulate matter, as in the case of dusts from ventilation or solid combustibles which represent a main source of indoor air pollution; gases of combustion like carbon monoxide (CO), nitrogen oxide (NO), and sulphur dioxide (SO_2); cigarette smoke; volatile organic compounds (VOCs); and airborne microorganism pollutants. However, **outdoor air pollutants** include human activities, fossil fuel burning, and exhaust of vehicle and industries. Examples of some pollutants emitted by industries or human activities are heavy metals (arsenic, chromium, etc.), chlorofluorocarbons (CFCs), hydrocarbons, VOCs, dioxins, pathogenic microorganisms, and suspended particulates [1]. Moreover, heavy metals are not biodegradable. There are many difficulties to develop a recent technology able to detect the pollutant levels that rise day by day due to the increase in human and industrial activities before their concentration reaches dangerous levels.

1.2 Emergence of nanotechnology in air pollution remediation

As explained previously, the environmental control is one of the preferences at global scale due to the relationship between the human health development and the environmental pollution. New strategy is strongly required, including innovative procedures of synthesis and manufacture that have the possibility to reduce the footprint of human on the environment [2–4]. Conventional strategies based on a network of a few fixed stations, filled with accuracy analytical devices have many drawbacks. The equipment is heavy, massive, difficult to use, high consumption of energy and high operational and maintenance costs. In urgent situations, for example, the current problem of Covid-19, the decision is based on the measure of real-time or, in the case of absence of such measurements, models of the pollutant distribution in the atmosphere are predicted, their importance depends on the validation of such models. Therefore, although stations detect accurately air pollutants, their spatial-temporal resolution are not enough to record the spatial–temporal change of air pollution. Indeed, nanotechnology is an advanced technology that can introduce a promising solution to create new nanomaterials with unique properties used for sustainable pollution control. Among these nanomaterial properties are greater catalytic performance, high electrical conductivity, improved hardness and strength, high activated surface area, electrochemical signals increment, retention of nanomaterial activity for a long time, and investigating tools extension [1].

In these ways, nanotechnology presents an excellent opportunity to measure, monitor, manage, and reduce pollutants in the environment. Titanium dioxide-based nanomaterials have also been used for potential issue in the photocatalytic degradation of several organic products in water pollution [5,6]. Nanomaterials have also been investigated for their ability to remove air contaminants, such as TiO_2/Ag tissue nanocomposites can efficiently be used for toluene and airborne pathogen removal from vapours [7]. Additionally, other authors have demonstrated Cu-Cd/TiO_2-Pt nanostructured hollow sphere can degrade isopropanol from gas phase under solar irradiation [8]. More recently advanced bionanotechnology can integrate in the remediation fields [9]. Mohamed and Awad [10] cited a novel technology for preparing nanomaterial involving Cu hollow sphere with monooxygenase enzyme and applied this system in the gas contaminant removal under visible irradiation. However, to prevent or minimize the damage caused by the atmospheric pollution, suitable control systems are critically required that can rapidly detect and quantify the pollutant sources.

Eventually, sensing of gases (such as CO_2, SO_2, O_2, O_3, H_2, and various organic vapours) is important for controlling industrial and vehicle emissions, and enhancing the household security and environmental control.

Recently, the advanced nanotechnology offers a promising issue to develop a cost efficient and rapid system over the past 20 years, for the selection and sensitively determination of environmental pollutants. Using facile and low cost technology, the ability to quantitatively understand nature in a systematic route will become soon as a real. Nanomaterials helped well to improve the detection and tracking of pollutants [1]. Nanotechnology can offer innovative materials and products that will directly advance our possibility to detect and control environmental pollutants. Among these nanomaterials, sensors have advantages of their potential for the facile, in field contaminant detection without the need for expensive lab equipment. As it was mentioned before, the aim of this chapter is to deeply highlight the application of nanoparticles as sensing materials based on nanoscience and technology. Recently, the use of various nanomaterials in detecting and sensing several air pollutants will be discussed here.

Among the innovative sensors, we will discuss briefly the following three main sections:

First section: nanosensor performance; second section: nanobiosensor; third section: eco-friendly synthesis of nanostructure; important examples of air pollutant sensors based on various biomass nanomaterials are elaborately represented, and challenges for the future development are outlined in this chapter.

2. Nano-sensors

Nowadays air pollution caused by chemical gaseous pollutants becomes the main concern for the adverse effects on human health, plant and animal life. The pollution detection was considered as an important point to control the pollutants. Rapid and accurate sensors able to determine the pollutant levels may augment the possibility to protect the sustainability of the environment and human health. Augmentation in ecosystem process control and environmental-based decision-making can carry out if the technology of pollutant detection is more sensitive and inexpensive. One of the most effective technologies is a continuous monitoring tool that is capable of providing information, especially about the pollutants in very short time of analysis. Traditional methods of analysis used for the environmental control of pollutants include different chromatographic techniques

(GC/MS and HPLC/MS), however, they require expensive reagents, time-consuming sample pre-treatment, and high cost equipments [11,12]. Therefore, cost-effective, more sensitive, easy to operate, rapid, and portable sensing tools are urgently required to control such pollutants caused adverse effects on ecosystems and human health, which overcome the large increases in environmental problems. In this manner, focusing on waste management and pollution control, one of the near-term research products of nanotechnology for environmental applications is the development of fast, new, smart and enhanced sensors to detect chemical and biological pollutants. Nanotechnology may be able to create innovation of advanced sensing systems for pollutants [12,13].

Given the benefits and concerns related to the use of nanomaterials for sensing pollutants, a number of questions arise. In particular:

- How can a sensor detect the presence of a pollutant?
- How can nanomaterials be used in the development of sensors to detect both chemical and pathogenic pollutants?
- How can nanosensors detect really the pollutants?
- How these nanosensor systems be developed and designed to detect different types of pollutants?
- What are the major challenges in the nanosensors production?

With that goal, a comprehensive overview of these questions, highlighting operational challenges, and a way forward, is therefore presented. Before moving to a deep explanation of nanosensors, let us answer the first question and describe the concept of sensor devices.

2.1 First question: *How can a sensor detect the presence of pollutant?*

Simply gas sensor can be defined as: an investigative device includes three main parts: a receptor probe or detection element, a transducer element, and an enhancer that changes over the reaction of a transducer to a quantified sign, when a pollutant existed as represented in Fig. 1. The contaminants in the air interact with the receptor to generate a response. The latter from the receptor is recorded by the transducer part via diverse transducers, followed by amplification and conversion of the signal to a quantifiable term in the microelectronic signal processor part [14]. The basic parts of the sensors are elements that respond to changes in chemical or physical characteristics, which are converted to electrical signals by the transducers [15]. Sensors detect the gases by the reaction between the sensing material and target gases.

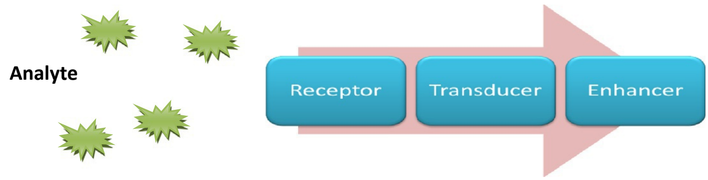

Fig. 1 Simple diagram represents the main parts of air pollution sensor device.

Indeed, there is a critical need to enhance the efficiency of numerous contaminant detections. However, many challenges are facing the sensor development including:

(a) Techno-operating challenges regarding the sensors improvement for air pollutant detection more sensitive, selective and stable under ambient conditions.

(b) Further challenges include improvement of the real-time control sensors.

(c) Reducing maintenance includes: calibration and reduce the extravagant consumption of many chemicals and reagents with an added advantage of on-site detection of pollutant composition prior to discharge into the environment, battery change and data analysis costs, which in several cases exceed the cost of the sensor device itself.

The question here is: **How can scientists overcome all these challenges?**

Nano-materials offer a solution to overcome these challenges and can give advantages in the next-generation development owing to their unique properties that already mentioned in the previous sections. Recently, the application of nanotechnology has been a promising in developing sensors and biosensors that reduce some limitations with gas sensors like less sensitivity, high power consumption, and low stability [16,17]. The need of smart sensing devices of portable, selective, high sensitive, inexpensive, quick response, and great reliability explains the recent sensors development with new transduction materials created by nanotechnology. Exploring the present forms of nanomaterials employed as a receptor in chemical sensors to detect the air pollutants is temporarily considered [17]. Nanosensor improves the exposure estimation by helping to collect different pollutants at a lower cost and improve the specificity. The advantage of using nanomaterials in gas sensors is due to the high surface area to volume ratios and easy functionalized surface renders them highly sensitive to changes in the surface. Therefore, nanosensors enable to realize considerably low detection limits and can detect specific harmful pollutants in the environment at very low concentrations [16]. Nanomaterials receptors are such as metal and metal oxide semiconductors, insulators, solid electrolytes, catalytic materials, polymers, etc. For detecting various chemical and biological issues, the nanotube surface is modified with a certain functional group. Many types of nanomaterials used as receptors in nanosensors include inorganic (carbon and metal products) [18], organic (polymers, bio-molecules, etc.), and hybrid nanomaterials [19] (Fig. 2).

There are briefly three different nanoparticle backbones [17] used in gas sensor development: (a) carbonaceous nanomaterials, (b) quantum dots (QDs), and (c) metal nanoparticles and hybrid nanomaterials.

(a) Carbonaceous nanomaterials

Carbon nanotubes (CNTs) and graphene are often used in nanosensors because of their large surface area, excellent electrical and thermal conductivity, and mechanical strength [18]. Different nanotubes exhibit a faster response and high detection performance for detection of gases like NO_2 and NH_3 [20]. In this case, gases are directly linked to the surface of CNTs and affecting the electrical sensor resistance. Another advantage of CNTs as sensors is the possibility to achieve high sensing sensitivity at ambient temperature. Particularly, CNT sensors are adapted to detect several gases like ammonia (NH_3), nitrogen dioxide (NO_2), hydrogen (H_2), methane (CH_4), carbon monoxide (CO), hydrogen sulphide (H_2S), and sulphur dioxide (SO_2) [18–22].

Graphene also has high mechanical and thermal properties. Therefore, it has efficient applications in the electrochemical sensors and biosensors field. They have been also broadly used for detecting the gaseous and heavy metal pollutants [23].

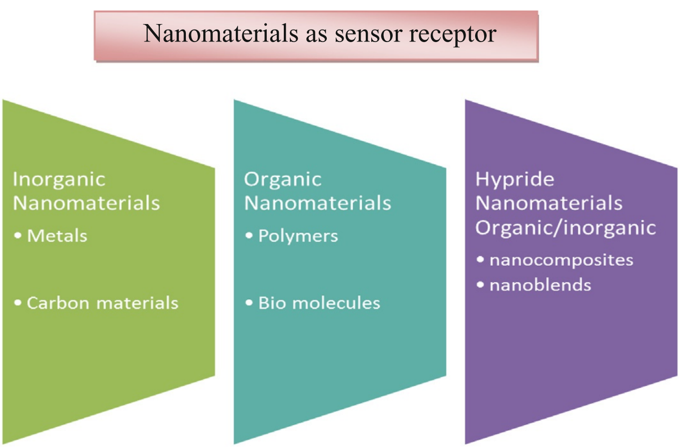

Fig. 2 Common types of nanomaterials used as sensor receptors.

(b) Quantum dots

Quantum dots (*inorganic nanoparticles)* have specific narrow fluorescence emission bands, thus rendering them excellent optical transducers. Furthermore, quantum dots (QD) wavelengths can be easily adjusted by changing the size, shape or quantum dots composition. Thus, quantum dots are ideal for multi-detection of several different analytes. The QD varied in shape, size, and composition can be excited by a single energy source since they have broad absorption spectra. The common QDs applied in sensors include: CdSe, CdSe/ZnS, CdTe, CdTe/CdS, ZnS, and graphene quantum [24–28]. In such system, a QD with a recognition element is combined to a graphene sheet and in the presence of a pollutant the sensor passes a change that separates the graphene from QD and "switch-on" the sensor [27,28].

(c) Metal oxide nanoparticles and nanohybrids

The metal oxides are broadly used for this purpose. Several studies cited that the one-dimensional (1D) nanostructures give a model system for electrochemical sensing of environmental contaminants. The 1D nanostructures have exhibited a high performance as a result of their large surface area/volume ratio, which are suitable to the surface charge region [29–31]. A wide range of nanostructures based on metal oxides (NMOs) has been used for gas sensors like oxides of iron, titanium, zinc, tin, and cerium. The gas sensors based on NMOs play an important role for detection of environmental contaminants like toxic gases and VOCs. The working principles of gas sensors depend on the electrical conductivity variation provoked by the test gas change on the surface of electrodes. Several researches have been conducted on the production and design of the NMOs due to their smaller size and specific charge carriers to improve the detection extent and sensitivity [19,32]. The TiO_2 has also been involved in nano-sensor system, but it is more specific to its photocatalytic characteristics [7,8]. Many proteins were immobilized into sheet electrodes of nanoporous TiO_2. This method was successfully employed to create optical and electrochemical nanobiosensors [19]. Tin oxide is still the most significant nanostructure applied for the gas detection of air pollution, due to its high sensitivity at low temperatures and low cost as compared to other oxides. The 1D SnO_2 nanosensor has a high sensitivity via ethanol gas with better selectivity for interfering gases like NH_3, H_2, CO_2, and CO [19,33]. The most familiar NH_3 sensors are based on ZnO, CuO, TiO_2, WO_3, and SnO_2. The nanorods of ZnO were capable of detecting NH_3 in the range 0.1–2 ppm at a temperature of

25–300 °C [34]. However, the inorganic semiconductors as well as polymers as receptors for chemical pollutants are highly linked to several problems such as poor selectivity, poor response, incomplete recovery, low performances, etc. [35]. However, polymeric nanostructures provide different strategies for the detection of the chemical and biological toxic pollutants in air and water applications [36]. Some of those problems could be easily treated by using the inorganic nanohybrids with organic nanomaterials. The manufacture of nano-composites with different combinations like; metal oxide nanoparticles, carbon nanotube (CNT), and graphene further improve the electrochemical sensing characteristics of nanopolymers. A nanosensor has potentially been created to detect some metal ions without pre-concentration needed. Particularly, this sensor is efficient for the on-site heavy metal ion detection, including radioactive elements. Nanosensors can be made in very small size and automatic mode to be easily used on-site or taken to the land.

As defined at the outset of this review, a wide variety of diverse pollutants can be determined by nanosensors. In this portion of the review, the overall aim is to clarify the principles of **how *can these nanosensors be created and designed to detect diverse types of pollutants***?

A sensor is a device that gives an observable signal by interacting with a certain analyte through physical, chemical, and bio-routes. Therefore, three kinds of sensors are classified based on the signal transduction, including: optical, electrochemical, and magnetic techniques [17].

(a) Optical-based techniques

The recent technology has been pointed towards the nanomaterials since it is well settled that the capacity to show specific colours based on the size with a wide diversity of shapes, metal nanoparticles (NP) have been broadly employed in different sensor applications. This technique of colour change with size can be used in visual colorimetric sensors, where the presence of an analyte provokes smaller NPs to accumulate and a solution colour change. Optical methods used a transducer to determine changes of the optical characteristics are the optical sensor's design principle [37]. Schematic diagram of the optical sensor working technique is represented in Fig. 3. The basis of optical transduction is the interaction between the sensing analyte with the electromagnetic radiation. Analytical methods can control the emission or absorption of an analyte under ultraviolet, visible, or infrared light irradiations [38]. Optical nanosensors can use electromagnetic irradiation for detecting samples and could immobilize nanomaterial which is

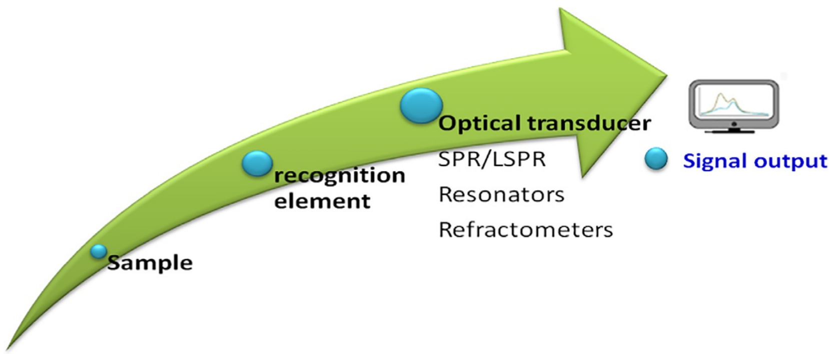

Fig. 3 Schematic diagram of optical sensor working technique.

recognized as surface plasmon resonance (SPR) [37–39]. The latter uses the change in the refractive index of surface noble nanometals for determination. Moreover, the excitation of nanoparticle can lead to the regular vibration of conduction electrons. The latter results in localized SPR [40] based spectroscopy like SPR and Surface Enhanced Raman Spectroscopy (SERS). Gold NPs are biocompatible, stable, and have been broadly utilized for sensing applications [41]. On the other hand, fluorescent nanosensors are based upon emission measurement of a fluorophore when it descends to its ground state via the excitation process. Designs are developed by the change in the fluorescence signal via interaction between the pollutant and the nanoparticle or a change in the sensor conformation occurred [42,43].

(b) Electrochemical-based techniques

Electrochemical techniques detect the changes in current that arise from the interaction between an electrode and an analyte. Electrochemical sensing techniques are highly specific and can be simple and they have diverse advantages like real-time control, miniaturization, and highly selective and sensitive [44]. Several methods involve Electrochemical sensing for contaminants, such as potentiometry, voltammetry, conductometry, colometry, and impedance spectroscopy [45]. Nanosensors can include a solid electrode modification (e.g. Pt, Au, Ag) with nano-carbons (e.g. carbon nanotubes, graphene) or functional issue (e.g. antibodies) [46]. Direct contact between the electrode nanoscale design and the analyte produces large signal amplification and improved ratios of signal/noise compared to the conventional electrochemical methods [47]. Plus to the electrode characteristics, the morphology and size of analyte have an important role to affect the sensor performance. Excellent detection limits have been found for smaller particles with high diffusion and low steric effect [48]. Generally, the mechanism for a metal oxide sensor is a change in the sensor conduction or resistance when it is exposed to pollutant gas. The sensor resistance is the best sensor output signal and is optimally used at constant temperature. Fig. 4 shows how metal oxide sensor used to detect the pollutant gases. The depletion zone at the metal oxide sensor surface is due to the oxygen absorption. When the metal oxide sensor absorbs a reducing gas the depletion area at the surface will be reduced, thus the conductivity increases. On the other hand, if a metal oxide sensor absorbs an oxidizing gas, the depletion zone at the surface will be increased and the conductivity decreases [49,50]. Consequently, a change of conductivity/resistance is related to the gas concentration as in the case of a ZnO sensor, the conductivity decreases and then the resistance increases when the sensor absorbs NO_x, which depends on its concentration [49].

Actually, the most promising tool for controlling air pollutants is the use of a sensor array based on electronic noses (e-noses). The development of electronic noses for environmental applications is decreasing the sensors cost. These sensors are needed, because of their huge advantages such as low cost, autonomous, accurate and easy to use. Their weight, size, and energy consumption must also be diminished. Metal oxide semiconductors are convenient issues used as electrochemical sensor receptors due to their low-cost, high performance, simple and high sensitive to use. Tin oxide nanosensors were used to develop electronic noses for pollutants and odour control [51]. Other kinds of e-noses are those based on surface sonic wave sensors [52]. Development of mobile devices were reported for the urban pollutant measurement [53,54].

(c) Magnetic-based techniques

Magnetic transduction has been involved in the biological sample detection because of the low magnetic signal [55] and the fact that the collection of magnetic nanoparticles (MNP) can be carried out

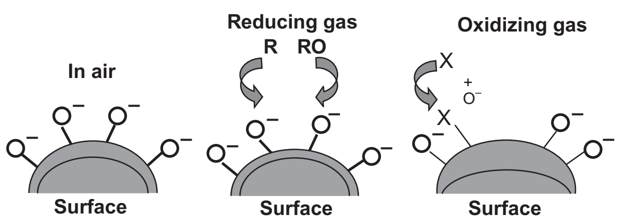

Fig. 4 Detection of pollutant gases by metal oxide sensors [49].

under a magnetic field regardless of the solution optical characteristics [42]. Usually, in the detection, the use of magnetic nanoparticles to concentrate, separate and purify the sample is recognized as the magnetic transduction. These involved high paramagnetic iron oxide nanoparticles in a pure form. The principle detection mechanism is the clustering of individual nano-magnetic probes into larger assemblies followed by the interaction with a target. The analyte binding leads to the NP cluster formation and increased de-phasing of the spins of the surrounding protons of water. The successive change in the spin–spin can be determined by magnetic resonance relaxometry [56]. The latter can be used to detect DNA and mRNA, proteins [57] and viruses [58]. Compared to the previous optical and electrochemical techniques, magnetic transduction methods show a lower signal, thus rendering them more efficient at lower concentrations.

3. Nano-biosensors

Biosensors have been broadly used as fast, inexpensive, highly specific, sensitive, and real-time tool for pollutant detection. The term biosensor can be defined as an analytical tool able to sense target molecules such as pesticides, and small organic molecules via interaction of these substances with sensing molecules like enzymes, antibodies, or DNA sequences [59]. The biosensor composed of a signal processing system and a transducer as in the sensor except the using of a biological analyte [60,61]. Determination of the pollutant is made by a bioreceptor (biomolecule), and the sample is converted into a measurable signal by the transducer [62]. Several kinds of biosensors have been manufactured for this goal. Biosensors can be categorized either by the kind of biological signalling or by the signal transduction as represented in Fig. 5. The diverse categories of biosensors based on their transduction main methods, which bind the sensing and target materials reactions are: fluorescence, electrochemical, mass changes, optical and thermal biosensors [63].

3.1 The electrochemical biosensors

The electrochemical biosensors detect the electrical characteristics of biological samples. Electrodes employed in biosensors allow converting the biological signals into a measurable signal. The signal selectivity and sensitivity can be carried out via modification with certain biological molecules like enzymes, DNA, or cells. Three electrodes are utilized in the

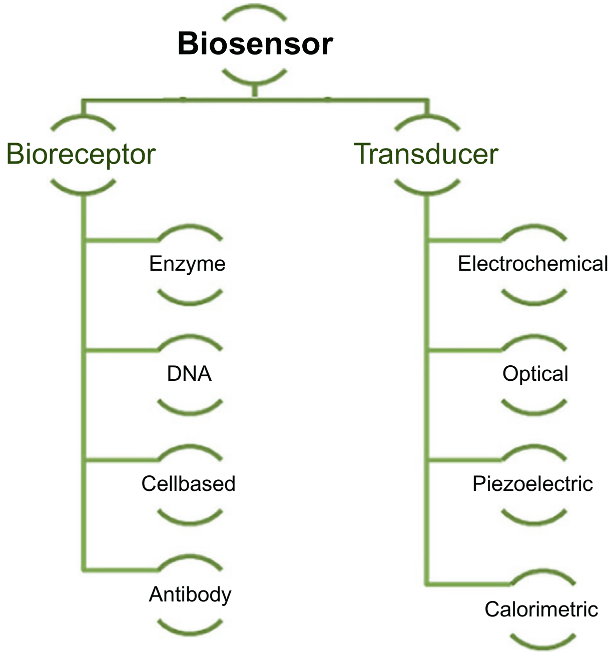

Fig. 5 Classification of biosensors based on the types of receptors or transducers.

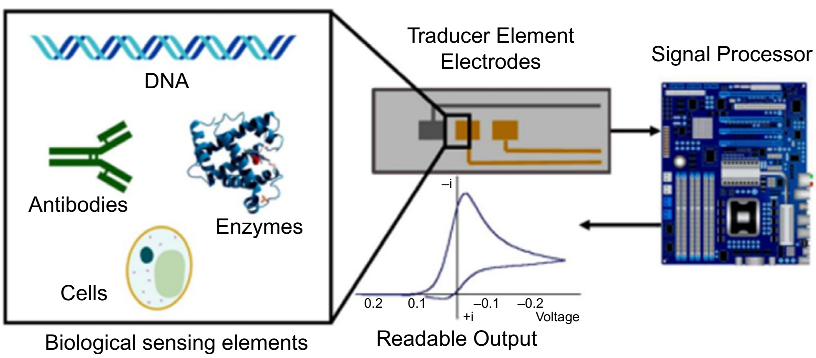

Fig. 6 Schematic diagram of an electrochemical biosensor [63].

electrochemical biosensors: reference electrode (often Ag/AgCl) for keeping stable current, counter electrode for getting a link to the electrolyte solution, and working electrode. Meantime, electrochemical affinity sensors have a linking recognition analyte that gives rise to a signal when it is combined to the target (e.g. antibodies) as observed in Fig. 6.

Actually, the most important mechanism of electrochemical biosensors—development strategies include Screen-Printed Electrode sensors (SPEs). To design SPEs require; screen, materials, ink, and substrate selections, plus curing and drying steps. In this case, the major idea is to possess an electrochemical reaction from a determined analyte and a sensor substance that is converted as current, voltage, and impedance which lastly is measured by an electronic system [64]. The major theme of this section is about transducers as a detecting mechanism for ecological applications (Fig. 7).

3.2 The optical biosensors

Optical biosensors that use fluorescence, light absorption, reflectance, luminescence, refractive index and Raman scattering are efficient analytical methods (Fig. 8). These biosensors have many advantages such as more sensitive, real-time, fast, and sample pre-treatment steps are not needed [65].

3.3 The electeral and thermal biosensors

The electric biosensors are more sensitive to density, viscosity, or mass changes of analyte in contact with its active surface. The principle of electric biosensors is the relationship between the vibrating electric crystal and the deposited mass on the surface [66]. On the other hand, the theoretical principle of thermal biosensors is the determination of thermal energy release or absorbance through a biochemical reaction [67]. Since thermal action is one

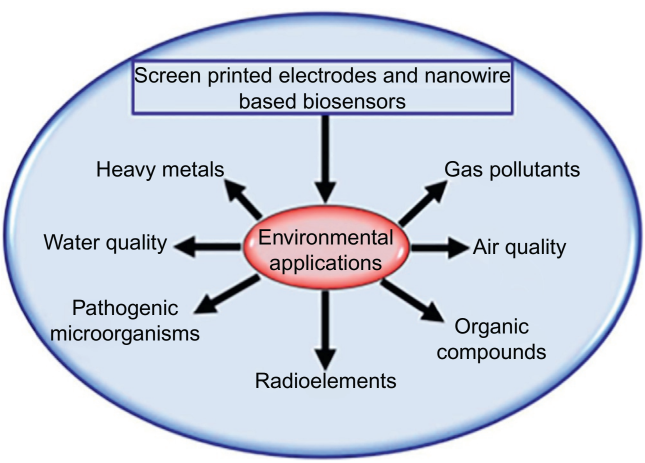

Fig. 7 Ecological applications of SPEs and nanobiosensors [63].

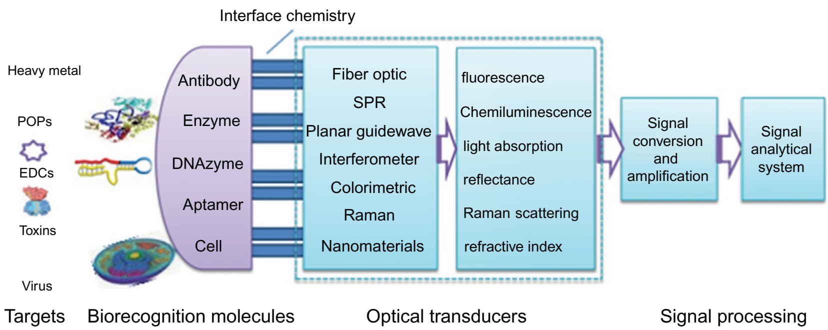

Fig. 8 Main operations of optical biosensors in environmental applications [65].

of the fundamental biochemical reaction parts, thermal bio-sensors are a widely applicable technique.

As mentioned previously, the essential property of biosensors is the biological identify element of the interaction with the target analyte like: enzyme, antibody, DNA, living cells for detection. Therefore, based on the kind of bio-identification method, the classification of biosensors can be divided into four categorizes; (1) Enzyme based biosensors; (2) DNA based biosensors; (3) Immunosensors; (4) Whole cell-based biosensors as represented in Fig. 5 [68].

3.4 Enzyme based biosensors

In enzyme based biosensors, specificity, availability and variety of functions make the enzymes appropriate to be used as identification analytes through direct and indirect systems. Control of pollutant concentration during enzymatic reactions is named direct mode and the control of enzyme inhibition by the analyte is called indirect mode. The latter biosensors are used for controlling several environmental contaminants [69]. In ecological control, the plurality of biosensors is known as enzymatic biosensors, in which enzymes or DNA is used as probes for the target element detection due to their highly advantages. In biosensors, the bio-part can be immobilized with other substances by the modification of surface via the recombination or introducing chemical linkages. However, previously cited biosensors have some essential restrictions owing to instability and low signals coming from the biomolecules detector [70,71].

3.5 DNA based biosensors

DNA based biosensors depend on high specific hybridization of DNA complementary strands. They are classified into two groups: (1) Affinity-based is classified into two types, genosensors and aptasensors. In genosensors, the probe and signal transducer hybridization are the main biosensor design. In aptasensors, selected DNA plays the role of extremely specific receptor biochemical targets [72]; (2) Catalytic possibility of DNA gives new class of biosensors named DNAzymes. The combination of DNAzymes, which are able to produce a chemical modification on the nucleic acids and aptamers generates aptazymes [73].

3.6 Immunobiosensors

In immunosensors, specific interactions between antibody and antigen are the principle role in this type [65]. In electrochemical biosensors, changes in the electrical characteristics in the gap between two electrodes come from antigen-antibody interactions.

3.7 Cell-based biosensors

Whole cells have been employed as a bio-identification part in biosensors through cell immobilization on a transducer electrode. These cells provide an excellent source of enzymatic action, especially for high-cost or non-available enzymes. A microbial source is a biosensor in which microbes are immobilized on a transducer to control biochemical reactions [46]. Another kind of whole cell-based biosensors is the yeast biosensors, which are specific for certain analytes [74].

Several different kinds of sensing systems based on nanomaterials for air contaminants have been created through the efforts of scientists. In this section, it will be tried to focus on the applications of sensors for detection of diverse types of gaseous air pollutants using nanomaterials including: oxides of carbon and nitrogen, VOCs, and airborne pathogen microorganisms.

4. Applications of sensors

4.1 Oxides of carbon

The major kinds of carbon oxides are CO and CO_2. The exposure to CO to a certain limit of 25 ppm is harmful because it becomes more toxic for human and animals. Generally, the sensing of CO is more than that of CO_2. Kolmakov et al. [75] cited that tin dioxide nanowire manufactured by porous alumina template was successfully used to sense CO and O_2. As shown in Fig. 9, the sensing pathway was explained by oxygen electron depletion, whereas electron withdrawal was discussed by a reducing gas such as CO [75].

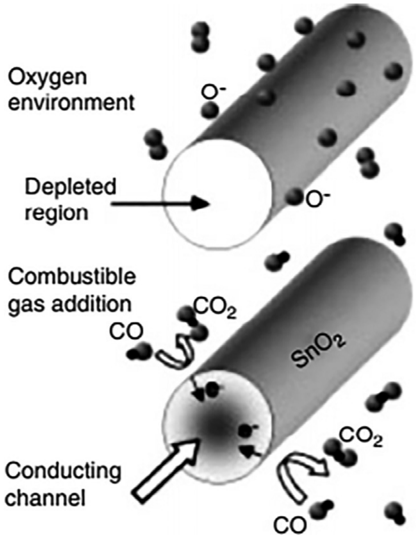

Fig. 9 Sensing pathway of tin dioxide nanowire for O_2 and CO [75].

4.2 Oxides of nitrogen

Ultimately, NO_2 is a polluting gas with a nippy odour; it is produced from the plant combustion and automotive emissions, and it plays a main role in the photochemical fumes, acid rain formation, and ozone, which are effectively dangerous to human health and the environment. The limit value is at 3 ppm/10 h a day for NO_2 exposure. Furthermore, oxides of nitrogen, particularly NO_2 are a toxic gas that can cause negative effects on the human respiratory system and the growth of plants. Lately, several gas sensors based on metal oxides like SnO_2, ZnO, CuO, WO_3, Fe_2O_3, In_2O_3, TeO_2, CdO, and MoO_3 are broadly used [76]. Different studies cited that ZnO is considered as an excellent nanomaterial for creating highly selective and sensitive gas sensors due to their high mobility of electrons, non-toxic, high specific surface area, and high stability [76–80].

4.3 Volatile organic compounds

The exposure to hydrogen and hydrocarbon (e.g. methane) above the maximum limit value of 4% in the atmosphere leads to an explosion risk. Furthermore, hydrocarbon gas such as CH_4 is greatly stronger greenhouse gas than that of CO_2. The hydrocarbon gases resulted from different sources

Table 1 Application of nanotechnology for VOCs sensing.

VOCs for air pollutants sensing	Nanomaterials as sensing layers	References
Acetone gas sensor with high gas sensing performance	Rh-doped tin dioxide nanofibers	[81]
High sensitivity to acetone even at 0.2 ppm and lower response to other gases like ethanol, methanol, toluene, ammonia, nitric oxide, and carbon monoxide	Carbon-doped tungsten trioxide hollow spheres	[82]
Acetone sensor having high response, good selectivity, long-time stability, low operating temperature of 180 °C, detection limit of 10 ppm	Perovskite praseodymium ferrite hollow nanofibers	[83]
Selective methanol vapour sensing	Poly(*m*-aminophenol)–copper nanocomposite	[84]
Acetone sensing at 300 °C showing high response, good selectivity, and long-term stability	Platinum-decorated copper ferrite nanotubes	[85]
A stronger response to ethanol than to n-butanol	Graphene-like layers	[86]
Selectivity towards 2-propanol against interfering neighbours like ethanol, methanol, acetone, and benzene	Reduced graphene oxide and three-dimensional zinc oxide nanoflower composite	[87]

such as landfills, fossil fuels, petrochemical industries, and agricultural fields. Table 1 summarized some examples of important nanomaterials used for the sensing of certain types of VOCs.

4.4 Airborne pathogen detection

In indoor, airborne pathogenic microorganisms such as bacteria, fungi, yeasts, moulds and viruses can arise from aerosols that are emitted by ventilation, heating, and air conditioning or humidifier devices. They exist in the environment and its particles regularly spread in the air. The airborne pathogens differently affect humans, animals and plants. Infectious diseases caused by pathogenic microorganisms threaten the human health, reduce the productivity and augment efficiently the economic losses to each sector. Airborne pathogens enter the body via different infection ways and over

15 million/year worldwide die [88]. They vary in virulence, contagiousness, transmission mode, and infectious dose. For example, the world is currently facing a great pandemic associated with the COVID-19 virus, in which the data of virulence and infectious dose are still ignored. Techniques for sensitive and rapid detection of pathogens in complex matrices, like body fluids and aerosols, and on surfaces are very effective for the treatment of infectious diseases and control the disease diffusion. Consequently, development of an accurate detection and identification of airborne pathogen is technically challenging for researchers all over the world. Moreover, detection of indoor airborne pathogenic microorganisms by biosensors and sensors based on nanoparticles is considered as promising solutions for speed and effective airborne pathogenic microorganisms sensing due to their simplicity, miniaturization and real-time analysis [89]. A highlight of electrochemical biosensors for pathogenic detection is depicted in Fig. 10. Various biomarkers such as proteins, DNA, and RNA are applied for airborne pathogen detection. The analytical mechanism of formats attributed to biosensors for pathogen detection is based on: (a) recognize a target biomarker, specific for each pathogen, through an immobilized sensing material named "bioreceptor" (monoclonal antibody, RNA, DNA, glycan, lectin, enzyme, tissue, or whole cell). The bioreceptor has biochemical properties, confirming the highly sensitive and selective of the biomarker detection and allow overcoming the

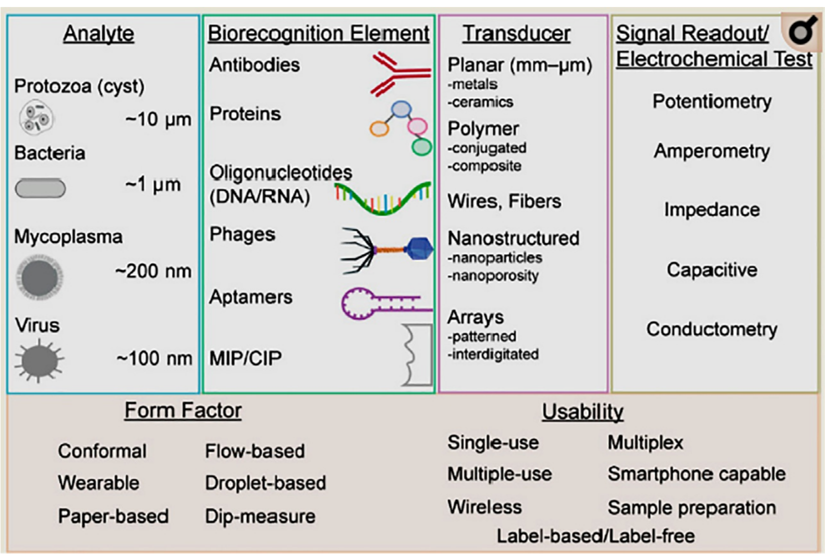

Fig. 10 Schematic diagram of biosensors principle for pathogen detection [90].

interferences from other microorganisms present in the tested sample, (b) the specific biochemical interaction between the biomarker and bioreceptor is translated to a measurable signal by the transducer detector [90].

5. Eco-friendly synthesis of nanosensors

The challenges of scientists and tool manufacturers are the improvement of nanomaterials that are able to reduce the increasing problems attributed to the environmental pollutions and also to decrease the production costs. This goal can be carried out through the term of "**Green chemistry**" or "**eco-friendly technology**."

Recently, the research is focused on environmentally benign techniques, which leads to the bio-nanotechnology development. Green chemistry is eco-friendly, economic, feasible, high biocompatible, low cytotoxic, and high antioxidant and antimicrobial activities of the produced nanomaterials. These advantages help in various areas of environmental control and cleaning. In this section, we introduce the greenest nanoparticles of metals, metal oxides with emphasis on recent developments ways. Several products from biotic natural sources, like extracts of plants, tea, coffee, banana, as well as diverse microorganisms [91], these nature raw materials enter into the nanoparticle formation with different shapes and sizes, hence serving as an excellent source for the nanoparticles biosynthesis with an ecological benign method. Utilizing the natural materials not only reduces the synthesis cost, but also diminishes the energy consumption as compared to physical or chemical techniques. Recently, the use of bio-raw nanomaterials for environmental control provides various efficient features like the excellent control capacity of diverse pollutants, besides these materials are low-cost, non-toxic and biocompatible [91]. It is suggested that these may be used in the future at large scale environmental remediation and control. Table 2 presents an overview on the biosynthesis of various semiconductor nanomaterials.

Table 2 Biosynthesis of different nanoparticles.

Biomass raw materials	Nanomaterials	References
Aloe vera plant	Fe_3O_4	[92]
Leaf extract of *Ocimum sanctum*	Nickel nanoparticles	[93]
Lemon extract	MnO nanoparticles	[94]
Azadirachta indica extract	Platinum nanoparticles	[95]
Malva sylvestris (plant) source leaves	CuO nanoparticles	[96]

6. Conclusions

All over the world, there is an augmenting demand for a safe environment with enhanced awareness about the health. In this chapter, we primarily gave a quick look of environmental air pollution problems, including the definition and different kinds of air contaminants. Moreover, we discussed in brief current progress in the advanced nanotechnology and nanobiotechnology applications in ecological pollution control, offering a potential to reduce the high cost and technical capacity. Furthermore, this chapter leads to gain better knowledge of the nanotechnology possibility to provide highly efficient nanosensors methods for air pollutant detection. Then, we discussed in details the recent progress via the use of nano-biosensors innovation in the field of environmental pollutant detection, particularly for air pollutants sensing and airborne pathogenic detection. To bring this technology as well as commercially viable, the safety rules, including the biosource development related to nanostructures should be promoted by nanotechnology industries in the future for the development of advanced technologies, namely eco-friendly materials and green systems, that are compatible with environmental requirements. Eco-friendly substances with related applications like separation, catalysis, adsorption, biosensing, and sensing will surely be confirmed in the future research for the sustainable use of renewable resources. Recently, green nanofabrication has been actively followed to meet the required large amounts of highly purified, structurally well-identified, and accurately functionalized nanomaterials. In the present chapter, an overview of natural nanomaterials arising from plant derived materials, and a discussion of their efficient applications in different fields is presented. Despite the advancement achieved to date, large challenges exist to obtain maximum benefits from the use of these plant-based green nano-systems. Finally, this chapter will supply valuable knowledge to be referenced by scientists for designing various gas sensors and biosensors based nanomaterials for improving the indoor air quality in the future by using eco-friendly nanomaterials.

References

[1] E.F. Mohamed, Nanotechnology: future of environmental air pollution control, Environ. Manag. Sustain. Dev. 6 (2017) 429–454.

[2] E.F. Mohamed, M.A. El-Hashemy, N.M. Abdel-Latif, W.H. Shetaya, Production of sugarcane bagasse-based activated carbon for formaldehyde gas removal from potted plants exposure chamber, J. Air Waste Manag. Assoc. 65 (2015) 413–1420.

[3] E.F. Mohamed, S.A. Sayed Ahmed, N.M. Abdel-Latif, A. Mekawy, Air purifier devices based on adsorbents produced from valorization of different environmental hazardous materials for ammonia gas control, RSC Adv. 6 (2016) 57284–57292.
[4] E.F. Mohamed, G. Awad, C. Andriantsiferana, A. El-Diwany, Biofiltration technology for the removal of toluene from polluted air using *Streptomyces griseus*, Environ. Technol. 37 (2016) 1197–1207.
[5] C. Andriantsiferana, E.F. Mohamed, H. Delmas, Photocatalytic degradation of an azo-dye on TiO2/activated carbon composite material, Environ. Technol. 35 (2014) 355–363.
[6] C. Andriantsiferana, E.F. Mohamed, H. Delmas, Sequential adsorption—photocatalytic oxidation process for wastewater treatment using a composite material TiO_2/activated carbon, Environ. Eng. Res. 20 (2015) 181–189.
[7] E.F. Mohamed, G. Awad, Photodegradation of gaseous toluene and disinfection of airborne microorganisms from polluted air using immobilized TiO_2 nanoparticle photocatalyst–based filter, Environ. Sci. Pollut. Res. 27 (2020) 24507–24517.
[8] E.F. Mohamed, T.-O. Do, Synthesis of new hollow nanocomposite photocatalysts: sunlight applications for removal of gaseous organic pollutants, J. Taiwan Ins. Chem. E. 2020 (2020) 6/10.
[9] E.F. Mohamed, G. Awad, Nanotechnology and nanobiotechnology for environmental remediation, in: K. Abd-Elsalam, M. Mohamed, R. Prasad (Eds.), Magnetic Nanostructures, Nanotechnology in the Life Sciences, Springer, Cham, 2019, pp. 77–93.
[10] G. Awad, E.F. Mohamed, Immobilization of P450 BM3 monooxygenase on hollow nanosphere composite: application for degradation of organic gases pollutants under solar radiation lamp, Appl. Catal. Environ. 253 (2019) 88–95.
[11] S. Hassani, S. Momtaz, F. Vakhshiteh, A.S. Maghsoudi, M.R. Ganjali, P. Norouzi, M. Abdollahi, Biosensors and their applications in detection of organophosphorus pesticides in the environment, Arch. Toxicol. 91 (2017) 109–130.
[12] C.I.L. Justino, A.C. Duarte, T.A.P. Rocha-Santos, Review recent progress in biosensors for environmental monitoring: a review, Sensors 17 (2017) 1–25.
[13] G. Maduraiveeran, W. Jin, Nanomaterilas based electrochemical sensor and biosensor platforms for environmental applications, Trends Environ. Anal. Chem. 13 (2017) 10–23.
[14] G.W. Hunter, Z. Sheikh Akbar, S. Bhansali, M. Daniele, P.D. Erb, K. Johnson, C.-C. Liu, D. Miller, O. Oralkan, P.J. Hesketh, P. Manickam, R.L.V. Wal, Editors' choice—critical review—a critical review of solid state gas sensors, J. Electrochem. Soc. 167 (037570) (2020) 1–31.
[15] R.M. White, P.I. Frederick, F. Doering, W. Cascio, P. Solomon, L.A. Gundel, Sensors and 'Apps' for community-based atmospheric monitoring, Air Waste Manag. Assoc. 5 (2012) 36–40.
[16] H. Nazemi, A. Joseph, J. Park, A. Emadi, Advanced micro- and nano-gas sensor technology: a review, Sensors (Basel) 19 (2019) 1–23.
[17] M.R. Willner, P.J. Vikesland, Nanomaterial enabled sensors for environmental contaminants, J. Nanobiotechnol. 16 (2018) 1–16.
[18] V. Schroeder, S. Savagatrup, M. He, S. Lin, T.M. Swager, Carbon nanotube chemical sensors, Chem. Rev. 119 (2019) 599–663.
[19] R. Abdel-Karim, Y. Reda, A. Abdel-Fattah, Review—nanostructured materials-based nanosensors, J. Electrochem. Soc. 167 (2020), 037554.
[20] M. Meyyappan, Carbon nanotube-based chemical sensors, Small 12 (16) (2016) 2118–2129.
[21] M. Mittal, A. Kumar, Carbon nanotube (CNT) gas sensors for emissions from fossil fuel burning, Sens. Actuators B 203 (2014) 349–362.

[22] F. Rigoni, S. Tognolini, P. Borghetti, G. Drera, S. Pagliara, A. Goldoni, L. Sangaletti, Enhancing the sensitivity of chemiresistor gas sensors based on pristine carbon nanotubes to detect low-ppb ammonia concentrations in the environment, Analyst 138 (2013) 7392–7399.
[23] W. Li, et al., Reduced graphene oxide electrically contacted graphene sensor for highly sensitive nitric oxide detection, ACS Nano 5 (2011) 6955.
[24] M. Chern, J.C. Kays, S. Bhuckory, A.M. Dennis, Sensing with photoluminescent semiconductor quantum dots, Methods Appl. Fluoresc. 24 (7) (2019), 012005.
[25] Y. Liua, L. Wanga, H. Wanga, M. Xionga, T. Yanga, G.S. Zakharova, Highly sensitive and selective ammonia gas sensors based on PbS quantum dots/TiO2 nanotube arrays at room temperature, Sens. Actuator B Chem. 236 (2016) 529–536.
[26] A. Lesiak, K. Drzozga, J. Cabaj, M. Bański, K. Malecha, A. Podhorodeck, Optical sensors based on II-VI quantum dots, Nanomaterials (Basel) 9 (2019) 192.
[27] D. Raeyani, S. Shojaei, S. Ahmadi Kandjani, W. Wlodarski, Synthesizing graphene quantum dots for gas sensing applications, Procedia Eng. 168 (2016) 1312–1316.
[28] D. Raeyani, S. Shojaei, S. Ahmadi-Kandjani, Optical graphene quantum dots gas sensors: experimental study, Mater. Res. Express 7 (015608) (2020) 1–9.
[29] X. Chen, Z. Guo, W.-H. Xu, H.-B. Yao, M.-Q. Li, J.-H. Liu, X.-J. Huang, S.-H. Yu, Templating synthesis of SnO_2 nanotubes loaded with Ag_2O nanoparticles and their enhanced gas sensing properties, Adv. Funct. Mater. 21 (2011) 2049–2056.
[30] M.R. Alenezi, S.J. Henley, N.G. Emerson, S.R. Silva, From 1D and 2D ZnO nanostructures to 3D hierarchical structures with enhanced gas sensing properties, Nanoscale 6 (2014) 235–247.
[31] N. Nasiriand, C. Clarke, Nanostructured gas sensors for medical and health applications: low to high dimensional materials, Biosensors (Basel) 9 (2019) 43.
[32] Q. Wang, J. Lin, G. Lu, Gas-sensing properties of in-Sn oxides composites synthesized by hydrothermal method, Sensors Actuators B 234 (2016) 130.
[33] Z. Pan, F. Sun, 8th International Conference on Manufacturing Science and Engineering (ICMSE 2018), Advances in Engineering Research, vol. 164, Atlantis Press, Paris, 2018.
[34] S. Jung, K.H. Baik, F. Ren, S.J. Pearton, S. Jang, AlGaN/GaN heterostructure based Schottky diode sensors with ZnO nanorods for environmental ammonia monitoring applications, ECS J. Solid State Sci. Technol. 7 (2018) Q3020.
[35] P. Kar, A. Choudhury, S.K. Verma, Sensing and responsive materials, conjugated polymer nanocomposites based chemical sensors, in: P. Saini (Ed.), Fundamentals of Conjugated Polymer Blends, Copolymers and Composites, John Wiley & Sons, Inc., 2015, pp. 621–686.
[36] S. Rothemund, I. Teasdale, Preparation of polyphosphazenes: a tutorial review, Chem. Soc. Rev. 45 (2016) 5200–5215.
[37] C.S. Law, L.F. Marsal, A. Santos, Handbook of nanomaterials in analytical chemistry modern trends in analysis, in: Electrochemically Engineered Nanoporous Photonic Crystal Structures for Optical Sensing and Biosensing, Elsevier, 2020, pp. 201–226 (Chapter 9).
[38] F.-G. Bănică, What are chemical sensors? in: Chemical Sensors and Biosensors, Wiley, Chichester, 2012, pp. 1–20.
[39] P. Damborsk'y, J. Svitel, J. Katrl'ık, Optical biosensors, Essays Biochem. 60 (2016) 91–100.
[40] M.A. Garcia, Surface plasmons in metallic nanoparticles: fundamentals and applications, J. Phys. D Appl. Phys. 44 (2011), 283001. IOP Publishing.
[41] K. Saha, S.S. Agasti, C. Kim, X. Li, V.M. Rotello, Gold nanoparticles in chemical and biological sensing, Chem. Rev. 112 (2012) 2739–2779.

[42] P.J. Vikesland, K.R. Wigginton, Nanomaterial enabled biosensors for pathogen monitoring—a review, Environ. Sci. Technol. 44 (2010) 3656–3669.
[43] S.W. Bae, W. Tan, J.-I. Hong, Fluorescent dye-doped silica nanoparticles: new tools for bioapplications, Chem. Commun. 48 (2012) 2270–2282.
[44] S.K. Chaulya, G.M. Prasad, Sensing and monitoring technologies for mines and hazardous areas, in: Gas Sensors for Underground Mines and Hazardous Areas, Monitoring and Prediction Technologies, Elsevier, 2016, pp. 161–212 (Chapter 3).
[45] G. Hernandez-Vargas, J.E. Sosa-Hernández, S. Saldarriaga-Hernandez, A.M. Villalba-Rodríguez, R. Parra-Saldivar, H.M.N. Iqbal, Electrochemical biosensors: a solution to pollution detection with reference to environmental contaminants, Biosensors 8 (2018) 1–21.
[46] N.J. Ronkainen, H.B. Halsall, W.R. Heineman, Electrochemical biosensors, Chem. Soc. Rev. 39 (2010) 1747.
[47] N. Sanvicens, C. Pastells, N. Pascual, M.P. Marco, Nanoparticle-based biosensors for detection of pathogenic bacteria, TrAC trends, Anal. Chem. 28 (2009) 1243–1252.
[48] C. García-Aljaro, L.N. Cella, D.J. Shirale, M. Park, F.J. Muñoz, M.V. Yates, A. Mulchandani, Carbon nanotubes-based chemiresistive biosensors for detection of microorganisms, Biosens. Bioelectron. 26 (2010) 1437–1441.
[49] P. Saravanan, B. Suguanya, M. Shanmugham, Air quality monitoring using nano sensors and real-time analysis, Indian J. Sci. Res. 17 (2018) 61–64.
[50] C. Wang, L. Yin, L. Zhang, D. Xiang, R. Gao, Metal oxide gas sensors: sensitivity and influencing factors, Sensors 10 (2010) 2088–2106.
[51] I. Sayago, M. Aleixandre, J.P. Santos, Development of tin oxide-based nanosensors for electronic nose environmental applications, Biosensors 9 (2019) 1–12.
[52] G. Panneerselvam, V. Thirumal, H.M. Pandya, Review of surface acoustic wave sensors for the detection and identification of toxic environmental gases/vapours, Arch. Acoust. 43 (2018) 357–367.
[53] A. Hannon, Y. Lu, J. Li, M.A. Meyyappan, Sensor array for the detection and discrimination of methane and other environmental pollutant gases, Sensors 16 (2016) 1163.
[54] J.L. Herrero, J. Lozano, J.P. Santos, J.A. Fernandez, J.I.S.A. Marcelo, Web-based approach for classifying environmental pollutants using portable E-nose devices, IEEE Intell. Syst. 31 (2016) 108–112.
[55] M. Koets, T. van der Wijk, J.T.W.M. van Eemeren, A. van Amerongen, M.W.J. Prins, Rapid DNA multi-analyte immunoassay on a magneto-resistance biosensor, Biosens. Bioelectron. 24 (2009) 1893–1898.
[56] L.H. Reddy, J.L. Arias, J. Nicolas, P. Couvreur, Magnetic nanoparticles: design and characterization, toxicity and biocompatibility, pharmaceutical and biomedical applications, Chem. Rev. 112 (2012) 5818–5878.
[57] Y. Zhang, Y. Yang, W. Ma, J. Guo, Y. Lin, C. Wang, Uniform magnetic core/ shell microspheres functionalized with Ni^{2+}—iminodiacetic acid for one step purification and immobilization of his-tagged enzymes, ACS Appl. Mater. Interfaces 5 (2013) 2626–2633.
[58] J.M. Perez, F.J. Simeone, Y. Saeki, L. Josephson, R. Weissleder, Viral-induced self-assembly of magnetic nanoparticles allows the detection of viral particles in biological media, J. Am. Chem. Soc. 125 (2003) 10192–10193.
[59] J. Yoon, M. Shin, T. Lee, J.-W. Choi, Highly sensitive biosensors based on biomolecules and functional nanomaterials depending on the types of nanomaterials: a perspective review, Materials 13 (2020) 1–21.
[60] V.K. Nigam, P. Shukla, Enzyme based biosensors for detection of environmental pollutants—a review, J. Microbiol. Biotechnol. 25 (2015) 1773–1781.
[61] H.H. Nguyen, S.H. Lee, U.J. Lee, C.D. Fermin, M. Kim, Immobilized enzymes in biosensor applications, Materials (Basel) 12 (2019). 121.1–34.

[62] J. Svorc, S. Miertus, J. Katrlík, M. Stred, Composite transducers for amperometric biosensors. The glucose sensor, Anal. Chem. 69 (1997) 2086–2090.
[63] G. Hernandez-Vargas, J.E. Sosa-Hernández, S. Saldarriaga-Hernandez, A.M. Villalba-Rodríguez, R. Parra-Saldivar, H.M.N. Iqbal, Electrochemical biosensors: a solution to pollution detection with reference to environmental contaminants, Biosensors (Basel) 8 (2018) 29.
[64] D. Grieshaber, R. MacKenzie, J. Vörös, E. Reimhult, Electrochemical biosensors—sensor principles and architectures, Sensors (Basel) 8 (2008) 1400–1458.
[65] F. Long, A. Zhu, H. Shi, Recent advances in optical biosensors for environmental monitoring and early warning, Sensors 13 (2013) 13928–13948.
[66] G. Marrazza, Piezoelectric biosensors for organophosphate and carbamate pesticides: a review, Biosensors 4 (2014) 301–317.
[67] R. Monošík, M. Streďanský, E. Šturdík, Biosensors—classification, characterization and new trends, Acta Chim. Slov. 5 (2012) 109–120.
[68] P. Koedrith, T. Thasiphu, J.-I. Weon, R. Boonprasert, K. Tuitemwong, P. Tuitemwong, Recent trends in rapid environmental monitoring of pathogens and toxicants: potential of nanoparticle-based biosensor and applications, Scientific World J. 510982 (2015) 12.
[69] G.L. Turdean, Design and development of biosensors for the detection of heavy metal toxicity, Int. J. Electrochem. 343125 (2011) 15.
[70] J. Zhuang, A.P. Young, C.-K. Tsung, Integration of biomolecules with metal-organic frameworks, Small 13 (2017) 1700880.
[71] J. Yoon, M. Shin, T. Lee, J.-W. Choi, Highly sensitive biosensors based on biomolecules and functional nanomaterials depending on the types of nanomaterials: a perspective review, Materials (Basel) 13 (2020). 299.1–21.
[72] T. Hianik, J. Wang, Electrochemical aptasensors—recent achievements and perspectives, Electroanalysis 21 (2009) 1223–1235.
[73] I. Palchetti, M. Mascini, Nucleic acid biosensors for environmental pollution monitoring, Analyst 133 (2008) 846–854.
[74] S. Jarque, M. Bittner, L. Blaha, K. Hilscherova, Yeast biosensors for detection of environmental pollutants: current state and limitations, Trends Biotechnol. 34 (2016) 408–419.
[75] A. Kolmakov, Y.X. Zhang, G.S. Cheng, M. Moskovits, Detection of CO and O2 using tin oxide nanowire sensors, Adv. Mater. 15 (2003) 997–1000.
[76] R. Kumar, O. Al-Dossary, G. Kumar, A. Umar, Zinc oxide nanostructures for NO_2 gas–sensor applications: a review, Nano-Micro Lett. 7 (2015) 97–120.
[77] S. Bai, C. Sun, T. Guo, R. Luo, Y. Lin, A. Chen, L. Sun, J. Zhang, Low temperature electrochemical deposition of nanoporous ZnO thin films as novel NO_2 sensors, Electrochim. Acta 90 (2013) 530–534.
[78] Q. Li, Y. Cen, J. Huang, X. Li, H. Zhang, Y. Geng, B.I. Yakobson, D. Yu, X. Tian, Zinc oxide–black phosphorus composites for ultrasensitive nitrogen dioxide sensing, Nanoscale Horiz. 3 (2018) 525–531.
[79] H.M. Fahad, H. Shiraki, M. Amani, C.C. Zhang, V.S. Hebbar, W. Gao, H. Ota, M. Hettick, D. Klriya, Y.-Z. Chen, Y.-L. Chueh, A. Javey, Room temperature multiplexed gas sensing using chemical-sensitive 3.5-nm-thin silicon transistors, Sci. Adv. 3 (2017) 1602557.
[80] X.H. Liu, T.T. Ma, N. Pinna, J. Zhang, Two-dimensional nanostructured materials for gas sensing, Adv. Funct. Mater. 27 (2017) 1702168.
[81] X. Kou, N. Xie, F. Chen, T. Wang, L. Guo, C. Wang, Q. Wang, J. Ma, Y. Sun, H. Zhang, G. Lu, Superior acetone gas sensor based on electrospun SnO_2 nanofibers by Rh doping, Sens. Actuators B 256 (2018) 861–869.

[82] J.Y. Shen, L. Zhang, J. Ren, J.C. Wang, H.C. Yao, Z.J. Li, Highly enhanced acetone sensing performance of porous C-doped WO3 hollow spheres by carbon spheres as templates, Sens. Actuators B 239 (2017) 597–607.
[83] L. Ma, S.Y. Ma, X.F. Shen, T.T. Wang, X.H. Jiang, Q. Chen, Z. Qiang, H.M. Yang, H. Chen, $PrFeO_3$ hollow nanofibers as a highly efficient gas sensor for acetone detection, Sens. Actuators B 255 (2018) 2546–2554.
[84] M. Bhuyan, S. Samanta, P. Kar, Selective sensing of methanol by poly(m-aminophenol)/copper nanocomposite, Electron, Mater. Lett. 14 (2018) 161–172.
[85] C. Zhao, W. Lan, H. Gong, J. Bai, R. Ramachandran, S. Liu, F. Wang, Highly sensitive acetone sensing properties of Pt-decorated $CuFe_2O_4$ nanotubes prepared by electrospinning, Ceram. Int. 44 (2018) 2856–2863.
[86] V. Gargiulo, B. Alfano, R.D. Capua, M. Alfé, M. Vorokhta, T. Polichetti, E. Massera, M.L. Miglietta, C. Schiattarella, G.D. Francia, Graphene-like layers as promising chemiresistive sensing material for detection of alcohols at low concentration, J. Appl. Phys. 123 (2018) 024503–024510.
[87] D. Acharyya, A. Saini, P. Bhattacharyya, Influence of rGO cladding in improving the sensitivity and selectivity of ZnO nanoflowers-based alcohol sensor, IEEE Sens. J. 18 (2018) 1820–1827.
[88] Dye C., After 2015: Infectious diseases in a new era of health and development, Philos. Trans. R. Soc. Lond. B Biol. Sci. 369(2014) 20130426–20130426.
[89] C. Ibacache-Quiroga, N. Romo, R. Díaz-Viciedo, M. Alejandro Dinamarca, Detection and Control of Indoor Airborne Pathogenic Bacteria by Biosensors Based on Quorum Sensing Chemical Language: Bio-Tools, Connectivity Apps and Intelligent Buildings, 2018 (Chapter 6).
[90] E. Cesewski, B.N. Johnson, Electrochemical biosensors for pathogen detection, Biosens. Bioelectron. 159 (2020), 112214.
[91] S. Iravani, R.S. Varma, Greener synthesis of lignin nanoparticles and their applications, Green Chem. 22 (2020) 612–636.
[92] S. Phumying, S. Labuayai, C. Thomas, V. Amornkitbamrung, E. Swatsitang, S. Maensiri, Aloe vera plant-extracted solution hydrothermal synthesis and magnetic properties of magnetite (Fe_3O_4) nanoparticles, Appl. Phys. A 111 (2013) 1187–1193.
[93] C.J. Pandian, R. Palanivel, S. Dhananasekaran, Green synthesis of nickel nanoparticles using *Ocimum sanctum* and their application in dye and pollutant adsorption, Chinese J. Chem. Eng. 23 (2015) 1307–1315.
[94] M. Jayandran, M. MuhamedHaneefa, V. Balasubramanian, Green synthesis and characterization of manganese nanoparticles using natural plant extracts and its evaluation of antimicrobial activity, J. App. Pharm. Sci. 5 (2015) 105–110.
[95] A. Thirumurugan, P. Aswitha, C. Kiruthika, S. Nagarajan, C.A. Nancy, Green synthesis of platinum nanoparticles using Azadirachtaindica—an eco-friendly approach, Mater. Lett. 170 (2016) 175–178.
[96] A.M. Awwad, B.A. Albiss, N.M. Salem, Antibacterial activity of synthesized copper oxide nanoparticles using Malva sylvestris leaf extract, SMU Med. J. 2 (2015) 91–101.