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Recent advancements in nano sensors for air and water pollution control

Abstract

Increased environmental pollution is becoming one of the greatest problem the world is facing nowadays causing irreparable damage to the earth. Because of their novel and tunable physicochemical properties, nano materials have attracted great attention among researchers as promising materials to combat environmental challenges. Developing nanotechnology have triggered a great deal of interest in these structures for pollution monitoring and treatment, enabling new technologies for identifying and addressing environmental problems. Even though achieving environmental pollution control is a challenging task using conventional materials, revolutionary progress has been observed with the advancements in nanotechnology, showing that precisely modified nano materials can be used for purposes such as treatment of polluted atmosphere, industrial and domestic wastewater, natural water, and soil. In this paper we review and discuss the environmental applications of nano materials as nano sensors employed for combating atmospheric and aquatic pollution.

Keywords: environmental pollution, sensors, nano materials, water contamination, air pollution

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Iva Dimitrievska, Perica Paunovic, Anita Grozdanov

Faculty of Technology and Metallurgy, University Ss Cyril and Methodius, Macedonia

Correspondence: Anita Grozdanov, Faculty of Technology and Metallurgy, University Ss Cyril and Methodius in Skopje, Rugjer Boskovic 16, 1000 Skopje, Macedonia, Email anita.grozdano@yahoo.com

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Introduction

The rapid technological modernization brought by industrial revolution, urbanization, and the capitalist society that we live in are the main reason for fathomless exploitation of natural resources.[1] With the nonrenewable and pollutant laden fossil fuels dominating the global energy supply, air pollution is worsening in many parts of the world especially where the economy is heavily dominated by low-tech manufacturing.[2] In the past decade, air pollution is becoming a global phenomenon that has reached concerning levels. Vohra et al.,[3] are raising awareness, implicating that the death toll caused by fossil fuels in outdoor air pollution is much higher than other studies suggest. The authors estimate that 8.7 million deaths globally in 2018 are caused by air pollution originating from burning fossil fuels. Speaking particularly about CO_2, global fossil emissions in 2020 decreased by 5.3% compared to 2019, mainly due to the COVID-19 pandemic. However, in 2021, global emissions returned almost to the level of 2019, reaching 37.9 Gt, just 0.36% lower than in 2019, getting back to pre-pandemic CO_2 emission levels.[4] Not only atmospheric but also aquatic pollution represents a burgeoning environmental problem, causing world scale concerns for public health. Inadequate and poor management of wastewater leads to contaminated or chemical polluted drinking water which leads to serious health problems and even deaths. According to the World Health Organization (WHO), unsafe drinking water is the culprit for 1.5 million deaths every year, most of them of infants and small children.[5] Water scarcity and decline in aquatic biodiversity are caused due to population growth and pollutants contaminating all remaining water sources.[6] Climate change, severe droughts, and usage increase are just a few reasons that have further stressed the scarce freshwater resources.[7] Limited water resources prompted the modern world to adopt sustainable measures for saving water by increasing its control, reuse, and recycling.[8] Nanotechnology offers a potential for providing sustainable solutions to the global challenges, and thus cleaner air and water1. Having a chance to manipulate materials at atomic and molecular level, the application of nanotechnology could greatly improve treatment efficiency.[9] Rapid and precise sensors able to detect pollutants at the molecular level may enhance the ability to protect the sustainability of human health and the environment.[10] Nano materials are of great importance for the further development of electrochemical sensors. From the viewpoint of application as potential electrode material, they possess novel properties due to their nano scale dimensions, such as high ratio of surface area to volume, unique optical, electrical, mechanical, and thermal properties which are the crucial factor for their use (Figure 1).

Due to their large specific surface area and high reactivity, nano materials are showing incredible performance and can be employed as excellent sensors, adsorbents, and photo/electro-catalysts.[11] Nano sensors can be defined as sensors that have at least one of the dimensions less than 100 nm and have the ability to collect information at nano scale and convert it to analyzable data. These nano sensors are using the unique characteristics of nano materials due to the ability for interaction with the surrounding environment at a nano scale level (Figure 2).[12]

Recently, nanostructured electrodes have been actively used as sensors for clean technology environmental applications, where precisely modified working electrodes can be implemented as an excellent system for detection of environmental pollutants such as chemical, physical, and biological agents. Modified nanostructures with specific functionalities can recognize a particular pollutant within a mixture.[13,14] Sensors based on nano materials have also been successfully used for industrial discharge monitoring of toxic compounds such as flue gases.[15] Compared to conventional sensors, this nanomaterial-based sensors offer superior properties and are identified as more accurate, sensitive in nature and selective. Moreover, nano materials can significantly increase the sensors sensing capability16. In this paper we highlighted and discussed the roles of nano materials and the application of nanotechnology to combat environmental pollution, using nano sensors as devices for control and monitoring (Figures 3&4).

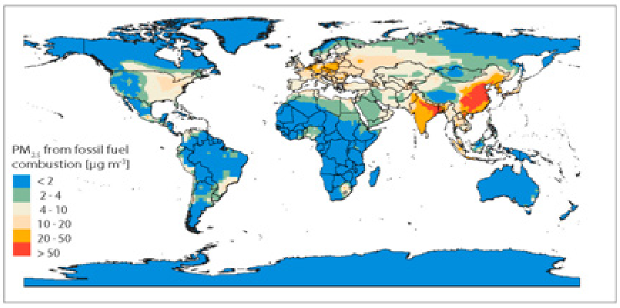

Figure 1 Surface $PM_{2.5}$ originating from fossil fuel combustion, calculated by chemical transport model GEOS-Chem. Statistical data and image cited from Vohra et al.[3]

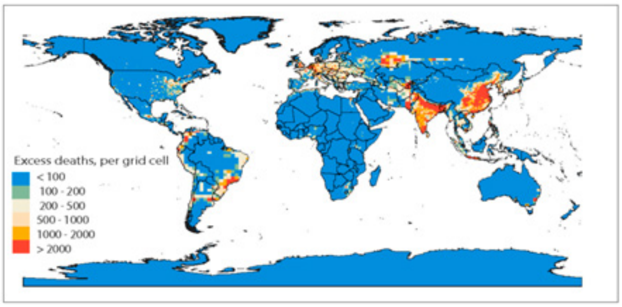

Figure 2 Estimated excess annual deaths due to exposure to surface $PM_{2.5}$. Statistical data and image cited from Vohra et al.[3]

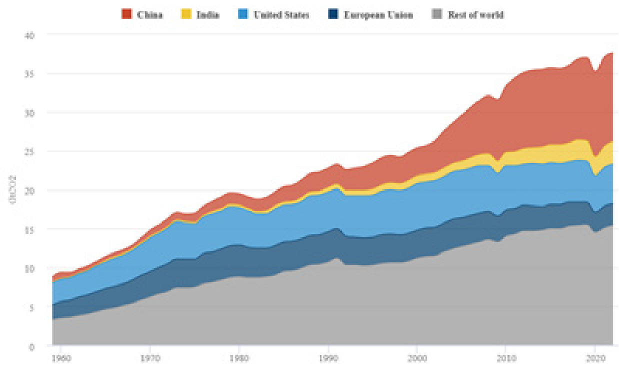

Figure 3 Global CO_2 emissions from fossil fuels by region, 1959-2022. statistical data and image cited from global carbon budget 2022.[13,14]

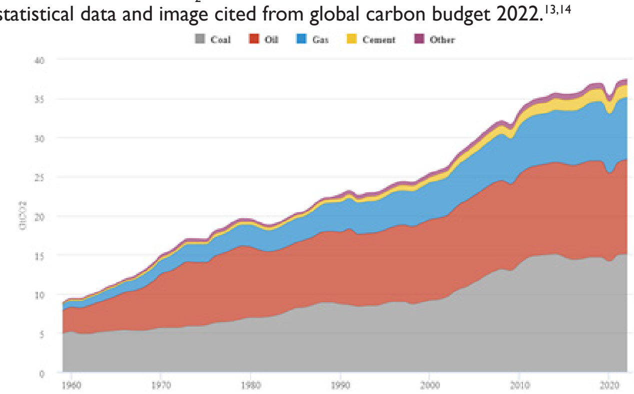

Figure 4 Annual CO_2 emissions by fuel, 1959-2022. Statistical data and image cited from global carbon budget 2022.[13,14]

Control and monitoring of air pollution

Monitoring is the first prerequisite procedure for environment pollution treatment, but it still represents a major challenge – conventional monitoring methods are not sensitive to detect micro-pollutants in traces.[9] Therefore, it is imperative to develop novel sensors with advantages over conventional sensors such as miniaturization, higher selectivity and sensitivity, fast response, real time sensing and so on. Nano sensors' design is based on incorporation of nano materials with unique properties (noble metals – Ag and Au, transition metal oxides, carbon-based materials – carbon nanotubes, graphene, carbon quantum dots and g-C_3N_4) into sensing devices for effectively enriching pollutants with extremely low concentration (parts-per-trillion) and therefore, more accurate detection. Moreover, some nano materials can enhance the spectroscopic response, improving the sensitivity of the device. The type of used nanomaterial and its structure has an important role in determination of the sensors' physicochemical properties.[12] Here we are summarizing nano sensors based on the used nanomaterial, divided by some major classes.

Carbon-based nano sensors

Also known as "wonder materials", carbon allotropes such as carbon nanotubes (CNTs), fullerenes and graphene present encouraging resources for various application fields, due to their special capabilities.[16,17] Each allotrope is characterized with notably different electrical properties,[18] making them particularly interesting in electrochemical applications. Thanks to the excellent electro catalytic behavior and chemical inertness, carbon-based nano materials have found huge application as electrochemical sensors, and have been used for detection of numerous environmental contaminants. Highly selective gas sensors for detection of organic (chloroform, benzene, toluene, dichloromethane, carbon tetrachloride etc.) and inorganic gases (NOx, COx, H_2, NH_3 etc.) have been developed using carbon-based nanomaterials.[12] Kong et al.,[19] developed gas sensors using semiconducting single-walled carbon nanotubes (SWCNTs) which electrical resistance changed by three orders of magnitude right after exposure to NO2 and NH3 concentration in traces, at room temperature. The incredible properties of the developed sensor (fast response, high sensitivity, and low detection limit) are originating from SWNTs large specific surface area.[20] Modified CNTs exhibit interesting electrochemical behavior, due to the presence of reactive functional groups on the nanostructure's surface. Change in the resistance of SWCNTs was also reported by Collins and al.,[12] under exposure of O_2. Grozdanov et al.,[21] developed polymer-modified multi-walled carbon nanotubes (MWCNTs) and graphene nano sensor used for sensing of NH3 vapors with different concentration. The sensor design was based on screen-printed electrodes, offering great sensitivity towards ammonia and non-cost efficiency. NO_2 and hazardous organic molecules detection gas sensor was designed by Nguyet at al.,[12] using SnO_2 nanowires and CNTs. Kar and Choudhury[12] reported nanocomposite sensor developed using PANI doped with functionalized MWCNTs for detection of chloroform. This modification showed better sensing response compared to pure PANI, due to the better synergy of modified PANI with the pollutant. Metal oxide (ZnO and SnO_2)-incorporated carbon fibers are reported by Jang et al.,[22] for detection of dimethyl methyl phosphonate (DMMP) at room temperature. Sensors showed high sensitivity and minimum detectable limit of 0.1 parts-per-billion (ppb), contributing to the presence of metal oxide nano nodules on the carbon nano fiber's structure. Bekyarova et al.,[23] investigated m-amino benzene sulfonic acid (PABS) functionalized SWCNTs, tested for detection of ammonia. Sensors showed two times enhanced response compared to pristine SWCNTs, resulting from the reactions between NH_3 and PABS-functionalized SWCNTs and changing the electronic structure of PABS. For ammonia detection are also used flexible SWCNTs films functionalized with carboxylic acid, showing 30% better response for detection of 300 ppm NH_3 compared to 15% for un functionalized SWCNTs. The authors elaborate that the functionalized carbon nanotubes have enhanced response because of the formation of hydrogen bonds between ammonia and oxygen/OH groups present on the CNTs surface, thus forming possible charge traps.[23] Rigoni et al.,[23] reported a more that 100-fold resistivity increase for SWCNTs functionalized with CTAB (cetyltrimethylammonium bromide) surfactant compared to carboxylic acid for detection of ammonia in the range of 10-30 ppm. However, the active layer of the CTAB functionalized SWCNTs sensor was not that stable in the range of 10-30 ppm, compared to COOH-SWCNTs (Table 1).

Table 1 Carbon-based nanosensors

Nanostructure	Targeted contaminants	Reference
$Ca_{12}O_{12}$ nanocage	CO_2, SO_2, NO_2	Hitler et al.[24]
Laser-induced graphene (LIG)	NOx	Yang et al.[25]
$B_{24}N_{24}$ fullerene	COS, H_2S, SO_2, CS_2	Ding et al.[26]
MoSe2/MWCNT	N,N-Dimethylformamide	Singh et al.[27]
CNT-rGO-Co_3O_4	C_2H_6O	Hu et al.[28]
Pd/SWCNT	Acetonitrile, styrene, perchloroethylene	Yoosefian et al.[29]
ZnO/CuO@graphene	NH_3	Jagannathan et al.[30]
GNWs/NiO-WO_3/GNWs	NO_2	Kwon et al.[31]
Pt-COFs@SnO_2@carbon nanospheres	Triethylamine	Shao et al.[32]
(Ag)-decorated laser-induced graphene (LIG) foam (Ag/LIG)	NO_2	Yang et al.[33]

Mousavi et al.,[34] reported using MIL-101(Cr), a highly porous metal-organic framework (MOF), for fabrication of resistive gas sensor for detection of low concentration volatile organic compounds (VOCs). The authors synthesized MIL-101(Cr)/CNT nanocomposite for sensing of methanol, ethanol, formaldehyde, isopropanol, acetone, tetrahydrofuran, acetonitrile, dichloromethane, and n-hexane at room temperature. Implementing MOFs leads to better sensing activity and higher gas molecules adsorption because of their large active surface area. Kheirabadi et al.,[35] joined two similar Folded Armchair Graphene Nano ribbons (FAGNRs from their open sides, and constructed a new structure called Attached FAGNR tube (AFAGNT). The authors tested the gas sensing performances of CNT and AFAGNT in presence of CO, O_2 and CO_2 gases molecules, which resulted in significant sensitivities to CO gas molecule at various bias voltages, especially at 0.8V. Polyimidazole multi-walled carbon nanotubes (Plm/MWCNTs) nanocomposite films have been synthesized by Yahaya et al.,[36] and tested against contrasting mixtures of gas. The proposed sensor provided fast response and recovery, high repeatability, and increased sensitivity for methanol, as it can be seen on Figure 5.

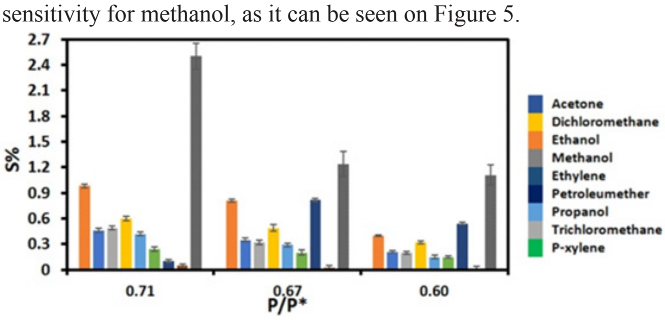

Figure 5 Plm/MWCNTs composite sensing of VOCs.

Shooshtari et al.,[37] used a CNT-TiO_2 hybrid sensor, to increase the sensitivity level of intrinsic CNT gas sensors. A threefold increase in sensitivity and a 30-second decrease in response time have been observed for CNT-TiO_2 sensor compared to the pristine CNT sensor. The authors reported achieving 97.5% accuracy in sensing four different VOC gases. Carbon nanotubes-anatase titanium dioxide (CNT/a-TiO2) film-based sensor have been also reported by Chang et al.,[38] for detection of NO at room temperature. As authors reported, the CNT/a-TiO_2 sensor exhibited high sensitivity of 41% to 50 ppm NO, rapid and reversible response at room temperature, and high selectivity toward NO among several toxic gases including NH_3, NO_2, CH_4 and H_2S.

Pure, mixed, and doped metal oxides (MOX) have attracted such attention for development of electrochemical sensors since their low-cost, operation simplicity and capability of real-time identification.[39] Because of their ability to display high sensitivity towards chemical environmental changes, MOX have been explored for construction of highly efficient nanosensors for environmental application.[12] ZnO, In_2O_3, TiO_2, NiO, WO_3 and SnO_2 are some of the frequently used semiconductive MOX for design of environmental gas sensors used for detection of toxic gases (H2, CO, NO_2) and volatile organic compounds (VOCs) (acetone, ethanol etc.). Zhang et al.,[12] reported nanosensor based on ZnO nanostructures with 3D flower-like morphology tested for detection of n-butanol. The gas sensor demonstrated excellent sensing ability due to the large specific surface area and more numerous surface-active sites. Excellent electrochemical activity has been reported for nanosensors based on flower-like NiO nanoparticles, displaying high sensitivity for detection of formaldehyde.[12] Fazio et al.,[39] reported developing of nanosensor based on V-doped ZnO:Ca nanopowders, which shows increase in the resistive sensor response for detection of ammonia. Ca-doped ZnO nanosensor has been reported by Dhahri et al.,[39] who investigated the performance over CO_2. Doping Ca_{2+} ions with larger ionic radius with respect to Zn_{2+} ions help increase the adsorption of acidic CO_2 as a result of creating larger lattice distortion and finally resulting in enhance sensor properties. Zhang et al.,[40] report PdO particle decorated ZnO nanostructures with promising gas sensing properties towards various gases. The decorated ZnO was reported to show a good sensing response to ethanol in range of 35.4 to 100 ppm. Other doped nanocomposites such as ZnO/Co_3O_4 and Al-doped ZnO/CuO were reported for detection of NO_2 and NH_3, respectively. Gao et al.,[40] report synthesis of CuO nanoparticles decorated MoO_3 nanorods, tested against H2S, with greater sensor response compared to pure MoO3, mainly attributed to the formation of n-p heterojunctions. Au-doped ZnO (Au-ZnO) ultra-selective nanosensor was designed by Suematsu et al.,[41] for toluene sensing. Metal oxide modification with Au nanoparticles enhances the selectivity towards toluene and the recovery of electrical resistance compared to undoped ZnO sensors. Gao et al.,[41] reported a nickel oxide sensor incorporated with Stannic oxide (SnO_2), designed for detection of toluene. The doped sensor response to toluene is 50 times superior to the pristine ZnO. This type of sensor stands as an ultrasensitive toluene sensor because of the nature of the incorporated material which can act as a catalyst. Authors report CNTs nanocomposites modified with hexagonal tungsten oxide (WO_3) are shown to detect low concentration (100 ppm) of NO_2 at room temperature.[42] WO_3 is defined as most promising material for detection of NO_2, being able to detect ppm concentrations. Wang et al.,[42] recently reported N and SnO_2 doped rGO nano composites for detection of such low NO_2 concentrations in the range of 5 ppm. The reported sensors are characterized with fast response and excellent recovery. In summary, metal-oxide doped carbon nanomaterials provide excellent sensors for detection of NOx at room temperature.

Zhai et al.,[53] loaded metal-organic framework (MOF) (UiO-66-NH2) onto a polyacrylonitrile nanofibermembrane and prepared UiO-66-NH_2/PAN-based capacitive gas sensor with excellent sensing performance for SO_2 gas in the range 1–125 ppm. The authors further improved the detection ability of the sensor toward trace SO_2 by modifying the structure with 2,3,4-trihydroxybenzaldehyde (THBA), revealing that the abundant hydroxyl groups present on THBA improved the SO_2 adsorption performance of the material, enabling a low detection limit (0.1 ppm). Panigrahi et al.,[54] investigated the selected transition metal dichalcogenides (MoX_2: X = Se, Te) monolayers toward the toxic sulfur-containing gases, such as H_2S and SO_2. Authors found that doped MoX_2 with As, Ge, and Sb at lower doping concentrations of around 2%, strongly adsorbed H_2S/SO_2 yielding significant changes in their electronic properties, which are fundamental for efficient sensing mechanism. In conclusion, As–$MoSe_2$, Ge-$MoSe_2$ and Sb–$MoTe_2$ have shown a superior and selective sensing performance. Araújo et al.,[55] synthesized a network of SnO_2 nanobelts decorated with palladium nanoparticles, for sensing of CO and CO_2. Results showed a sensitivity of up to 125% for CO in 60 s, and when doping with nanoparticles from 130 ppm to 1360 ppm the response increased for 30 seconds to CO (Table 2).

Table 2 Metal oxide-based nanosensors

Nanostructure	Targeted contaminants	Reference
rGO/Pd coated SnO_2 film	NO_2	Akshya S[43]
ZnO:Eu nanowire	H_2	Lupan et al.[44]
Single SnO_2 nanowire	C_3H_6O, NH_3, CO, C_2H_6O, H_2, NO_2, C_7H_8	Tonezzer M[45]
Zn, Fe modified SnO_2	CO	Dascalu et al.[46]
Comb-like ZnO	H_2S	A. Dawood Faisal[47]
WOx	NO_2	Isaac et al.[48]
Ni, Zn doped SnO_2	CO	Zhou et al.[49]
ZnO/CuO	C_2H_6O	Shinde et al.[50]
Porous rod-like In_2O_3	NO	Li et al.[51]
WO3-graphene@Cu	CO, NO_2, C_3H_6O	Haiduk et al.[52]

Qomaruddin et al.,[56] presented nitrogen dioxide (NO_2) gas sensors based on zinc oxide nanorods (ZnO NRs) decorated with gold nanoparticles (Au NPs) working under visible-light illumination with different wavelengths at room temperature. The authors demonstrated the contribution of localized surface plasmon resonant (LSPR) by Au NPs attached to the ZnO NRs, showing that the presence of LSPR not only extends the functionality of ZnO NRs towards longer wavelengths (green light) but also increases the response at shorter wavelengths (blue light) by providing new inter-band gap energetic states (Figure 6).

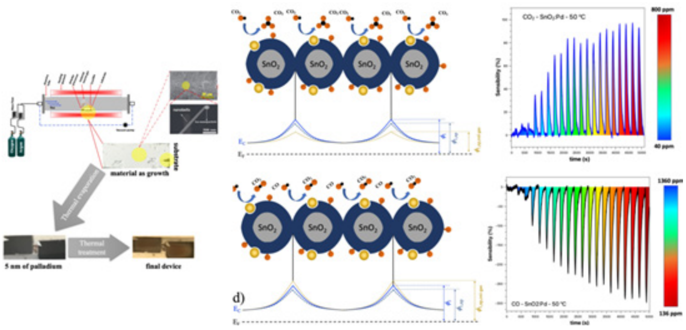

Figure 6 Palladium decorated SnO_2 nanobelts networks for detection of CO and CO_2.[55]

Electrospun nano fibers

Nanofibers are promising materials due to their flexibility, tunability, and high surface area, properties making them suitable for integration into sensor devices. Their sensor related properties such as fast response, sensitivity and better activity can be easily tailored to enhance absorption and diffusion rates. Electrospun nanofibers are found to be potential candidates for nanosensors to improve the sensing phenomenon, producing ready to implement nanofibers with smaller diameter, more surface functionality, better permeability, and better mechanical properties12. An ammonia gas sensor was recently developed by Chen et al.,[57] based on electrospun cobalt trioxide nanofibers and molybdenum telluride (Co_3O_4-$MoTe_2$) with low detection limit (26 ppb). The introduced sensor showed better sensing performance compared to the pristine Co3O4 and $MoTe_2$ film sensors respectively, mainly attributed to the p-n heterojunction formed between $MoTe_2$ and Co_3O_4. Ramakrishnan et al.,[58] developed p-Co_3O_4 supported heterojunction carbon nanofibers (CNF) based sensor for detection of trace level concentration of NH3. Nanofibers are often utilized to create heterojunctions for boosting conductivity and rapid response, hence enhanced sensor activity. Wu et al.,[59] prepared Cu doped Fe_2O_3 electrospun nanofibers, studying the electrical resistance change against NO¬2 gas in the range of 5-50 ppm. ¬ ZnO-polystyrene sulfonate nanofibers based nanosensor was designed by Andre et al.,[59] with ability to sense ammonia gas in a mixture of NO_2, CO and NH_3. Wei et al.,[59] introduced an Ag doped $LaFeO_3$ nanofiber sensor with excellent selectivity for detection of formaldehyde. Salehi et al.,[59] reported reduced graphene oxide-ZnO nanofiber sensor, tested against acetone detection. Graphene addition enhanced sensitivity and reduced the functioning temperature of the developed nanosenor. Metal-organic framework (MOF)-derived Zn2+ doped SnO_2 (ZZS) hollow nanofibers (HNFs) based nanosenor was designed by Zhu et al.,[60] for detection of formaldehyde. The sensor exhibited excellent gas-sensing properties such as rapid response and fast recovery. A novel Al-doped $CdIn_2O_4$ nanofibers (ACO NFs) based sensor was recently reported by Tian et al.,[61] for sensing n-butanol. The developed

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sensor shows excellent long-term stability and sub-ppm detection limit, hence making the ACO NFs promising sensing material. Zhang et al.,[62] are describing a facile fabrication of a flexible gas sensor for rapid detection of hydrogen sulfide (H_2S) through integrating NO_2-UiO-66 on electrospun nanofibers membrane (NO_2-UiO-66 NM). Good H_2S gas sensing properties has shown a study reported by Park et al.,[63] describing the fabrication of ZnO-$ZnFe_2O_4$ electro spun hollow nano fibers, enabling enlarged surface area and increasing gas sensing sites. The interface of ZnO and $ZnFe_2O_4$ forms a p-n junction for improved sensor response and lowers the operation temperature. Calcinated WO_3 nanofibers were reported by Morais et al.,[64] as high signal sensor for detection of low and high NO_2 concentrations. The sensor showed high selectivity against potential interferents (H_2 and CO), due to the interactions between NO_2 molecules and the surface of the WO_3 nanofibers.

Cai et al.,[75] prepared $ZnWO_4$/ZnO hetero-structured nanofibers which exhibited an enhanced selectivity to triethylamine with excellent stability and repeatability. The excellent sensing performance authors mainly ascribed to the porous structure and synergetic sensing effect of $ZnWO_4$ and ZnO. The results showed a high relative response of 108.5 achieved for 50 ppm triethylamine (TEA) and a low detection limit of about 150 ppb. Kgomo et al.,[76] developed belt-like In_2O_3 based sensor for methane detection. The In_2O_3 sensor displayed good sensing capabilities with a response of 1.1 to 90 ppm of methane at a lower operating temperature of 100□. The sensor has response and recovery times of only 36 and 44 s, respectively, displaying good stability and selectivity as well as a lower detection limit of 0.18 ppm. The authors revealed that the enhanced sensing behavior originate from the mesoporous nature of the synthesized nanostructure offering many active sites for methane gas molecules because of the high surface area and high concentration of oxygen vacancies, which enabled greater channels for methane gas adsorption and desorption capacity (Table 3).

Table 3 Electrospun nanofibers-based nanosensors

Nanostructure	Targeted contaminants	Reference
PAN@ UiO-66-NH_2 PAN@UiO-66-NH_2@CNT	SO_2	Zhai et al.[65]
ZIF-67/PAN	CH_3OH, C_2H_6O, C_3H_6O	Zhai et al.[66]
ZnO-PANI	NO_2	Bonyani et al.[67]
PAN	Chloroform	Yardimci et al.[68]
WO_3	NO_2	Qiu et al.[69]
PAN/NiO	C_3H_6O, C_2H_2	Kaidar et al.[70]
Au-WO_3	NO_2	Lin et al.[71]
(1D) CuO	NO_2	Liu et al.[72]
ZnO/NiO	NO_2	Xu et al.[73]
In_2O_3/ZrO_2	C3H6O	Feng et al.[74]

Quantum dots (QDs)

QDs are semiconductor nanocrystals with typical MX composition, where M is commonly Zn or Cd and X is Se, S or Te. QDs are characterized as outstanding optical transducers due to broad absorption bands and narrow fluorescence emission bands. Often, they are synthesized with a shell or a coated second MX alloy for generation of highly tuneable core/shell QDs.[12] ElShamy[77] presents a Schottky device based on carbon dots (CDots) decorated magnesium oxide (MgO) nanoparticles (CDots@MgO) engineered for H_2S sensing with high response. Chen et al.,[78] are presenting a novel artificial neuron-like gas sensor constructed from CuS Quantum Dots/Bi_2S_3 nanosheets for ultra-sensitive capture of NO_2 molecules. Sawalha et al.,[79] reported the first example of using C-dots (CDs) as conductometric gas sensor for monitoring low concentrations of NO_2 in ambient air. The designed sensor was found to exhibit excellent sensing properties in terms of rapid and selective response to sub-ppm concentrations, reproducibility, and stability. Lv et al.,[80] successfully designed a novel nitrogen-doped graphene quantum dots (N-GQDs) modified SnO_2 (NG/Snx) gas sensor for detection of NO_2. The NG/Snx sensing material exhibits rapid response and fast recovery speed, good selectivity, repeatability, long-term stability, and outstanding detection ability for low concentration NO_2 (100 ppb). He et al.,[81] proposed a carbon monoxide (CO) sensor based on a Michelson interferometer combined with α-Fe_2O_3/reduced graphene oxide quantum dots (rGOQDs) composite film, with good sensing performance and advantages such as simple structure, high sensitivity, and selectivity. Šutka et al.,[82] demonstrated a photodoping-inspired gas sensing approach based on a thin solid film made of ultrasmall (<5 nm) anatase TiO_2 quantum dots for detection of volatile organic compounds. In summary, quantum dots can be employed for efficient sensing of multiple pollutants.

Menezes et al.,[93] investigated the adsorption of carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ammonia (NH_3) on Graphene Quantum Dots (GQD). The results showed that doping with B, N, or Al can greatly improve GQD's adsorbing capabilities and they serve as a promising application towards NO_2 gas sensing. Kumar et al.,[94] designed a novel 2D-material/0D-quantum dot (MoS_2/SnS) heterostructure with highly sensitive sub-ppb-level NO_2 gas-sensing capability. The structure showed 3 times enhanced NO_2 gas-sensing capability and recovery increase by more than 90%. The highest sensor response of 0.33 with good repeatability was observed at 250 ppb of NO_2, while ultra-fast response time of 74 s, was found at 50 ppb of NO_2. The limit of detection have been found to be as low as 0.54 ppb (Table 4).

Table 4 Quantum dot-based nanosensors

Nanostructure	Targeted contaminants	Reference
ZnO	H_2S	Zhang et al.[83]
SnS	NO_2	Li et al.[84]
C(S, N)-WO_3	NO_2	Patel et al.[85]
MoS_2/SnO_2	NO_2	Luo et al.[86]
ZnO-multilayer graphene	NO_2	Lee et al.[87]
TiO2/PbSnS	CO, NO_2	Kumar et al.[88]
PbCdSe	NO_2	Geng et al.[89]
N-Graphene QDs/SnO_2	CH_2O	Chen et al.[90]
ZnO-SnO_2	CH_2O	Sun et al.[91]
Carbon/In_2O_3	NO_2	Cheng et al.[92]

Polymer-based nano materials

Polymeric nanomaterials combined with various novel scientific and analytical techniques can be used as electrochemical sensors for sensing of gaseous and liquid environmental pollutants. The electrochemical sensing and conducting properties of polymer-based nanomaterials can be improved by integration of graphene, CNTs, metal and metal oxide NPs, etc. In the last decade, Navale et al. reported polypyrrole (PPy)/a-Fe2O3 nanocomposite for detection of reducing (NH_3, H2S, C_2H_5OH, CH_3OH) and oxidizing (Cl_2 and NO_2) gases. Bentonite nanohybrid modified polyaniline (PANI) nanofibers were used by Pramanik12 for construction of gas sensor for toxic gases like toluene, ethanol, benzene, and acetone. Thangamani et al.,[95] reported titanium dioxide (TiO_2) nanoparticles reinforced polyvinyl formal (PVF) nanocomposite-based gas sensor (PVF/TiO_2) for sulfur dioxide (SO_2) monitoring. The fabricated sensor exhibited good sensitivity, selectivity, fast response time and long-term stability of 60 days. Muthusamy et al.,[96] recently reported a new ternary conducting polymer composite of polypyrrole (PPy), prussian blue (PB), titanium dioxide (TiO_2), PPy-PB-TiO_2 for fiber optic gas sensing applications. The gas sensing properties of this sensor were investigated upon ethanol, ammonia, and acetone with varying concentrations (0-500 ppm). Experimental results showed best sensor performance i.e., high sensitivity and selectivity properties for ammonia detection. Yoon et al.,[97] developed a polymer-based chemiresisitve CO_2 sensor, incorporating 4-vinylpyridine (4VP) and azide groups on SWCNTs' surface, exhibiting response of 25% at room temperature for 2% CO_2 concentration. However, the sensor resulted with a very long response time of thousands of seconds. This behavior suggests that further studies are required for improvement of the sensing performance of organic-inorganic hybrid sensors towards practical gas sensing applications.[98] A flexible hydrogen sulfide (H_2S) sensor based on polyaniline–polyethylene oxide (PANI–PEO) nanofibers doped by camphorsulfonic acid (HCSA) was presented by Mousavi et al.,[99] The proposed sensor has good characteristics and shows superior performance compared to other PANI-based H_2S sensors. Wang et al.,[100] reported a room-temperature NH_3 core-shell nanocomposite gas sensor with high response and great long-term stability, including CeO_2 NPs conformally coated by cross-linked PANI hydrogel. The nanohybrid's enhanced response could once more be attributed to p-n heterojunctions formed by the contact between used materials. Ammonia (NH_3) gas sensor based on reduced graphene oxide (RGO)–polyaniline (PANI) hybrids was presented by Huang et al.,[101] The characterization showed synergetic behavior between both materials allowing excellent sensitivity and selectivity to ammonia. Xiang et al.,[102] synthesized polypyrrole (PPy) and graphene nanoplatelets (GNs) based composite decorated with titanium dioxide (TiO_2) nanoparticles (TiO2@PPy–GN). The proposed nanocomposite exhibited good electrical-resistance response to ammonia at room temperature and enhancing sensing properties such as higher sensitivity and rapid response compared to the undoped PPy-GN film. Jian et al.,[103] fabricated a polyaniline (PANI)/tin oxide (SnO_2) composite-based sensor for detection of CO. The sensor excellent response was attributed to two properties: a) high surface area of SnO2 significantly enhancing the response during concentration change at low operating temperature (<75 °C) and b) good PANI properties in the redox reaction during sensing, producing resistance between air and CO gas. DBSA doped PPy–WO_3 hybrid nano composite sensor operating at room temperature was presented by Mane et al.,[104] The gas sensing sensor performance was studied for various pollutants such as NO_2, C_2H_5OH, CH_3OH, H_2S and NH_3 with highest selectivity towards NO_2 with 72% response at 100 ppm. Copper nanoparticles intercalated-polyaniline nanocomposites (NC) has been proposed by Patil et al.,[105] for detection of ammonia. Cu nanoparticles incorporation improved the sensor response and response kinetics.

Pasupuleti et al.,[116] combined graphene oxide-Poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (GO-PEDOT:PSS) nanocomposite and piezoelectric LGS substrate to develop a NO_2 sensor. Compared to the pristine GO/LGS sensor, the developed GO-PEDOT:PSS/LGS exhibited superior NO_2 gas sensing performances. The sensor showed good cycling stability, excellent sensitivity, and a low detection limit at 175 ppb at room temperature. Liu et al.,[117] developed polyethyleneimine/polyethylene-glycol (PEI/PEG) functionalized black phosphorus (BP) gas sensor for detection of carbon dioxide (CO_2). Black phosphorus is an attractive gas sensing material due to the layer-dependent direct bandgap, and high carrier mobility. The authors reported low limit of detection of PEI/PEG-BP gas sensor at 200 ppm CO_2 under air conditions and high limit of detection of 250,000 ppm CO_2 under N_2 conditions. Moreover, the sensor showed high selectivity, and excellent repeatability – superior properties that can be attributed to the meso-macropores sensor structure, recognition function of amino groups, and formation of P-N heterojunction between BP and PEI. Ta_2O_5–SnO_2–PANI hybrid composite for efficient sensing of CO at room temperature at very low concentration, have been reported by Aranthady et al.,[118] The hybrid material exhibited superior CO sensing performance with high sensitivity, low operating temperature, fast response and fast recovery compared to the individual components. The enhanced sensing ability of the hybrid material has been attributed to the synergistic properties such as conductivity of PANI, improved oxygen vacancies and the heterostructure formed between the PANI and the (Ta_2O_5–SnO_2) composite (Table 5).

Table 5 Polymer-based nanosensors

Nanostructure	Targeted contaminants	Reference
Poly(3-aminophenylboronic acid) (PAPBA)	CO, NO, NO_2, SO_2, SO_3	Taremi et al.[106]
rGO/Chitosan	NO_2	Park et al.[107]
TiO2/PANI	NH_3	Conti et al.[108]
rGO/ZnO QDs/Nylon	NO_2	Lin et al.[109]
Poly(5-carboxyindole)–β cyclodextrin (P5C-BCD)	CH_2O	Hodul et al.[110]
PEDOT:PSS/PPA	CO	Farea et al.[111]
Poly(3-hexylthiophene)/ molybdenum disulfide (P_3HT/MoS_2)	NH_3	Verma et al.[112]
PPy/TiO_2	CO	Farea et al.[113]
PANI	NH_3	Zhu et al.[114]
Poly(N-methyl pyrrole)/reduced graphene oxide (P(NMP)/rGO)	CO	Mohammed et al.[115]

Control and monitoring of aquatic pollution

Control and monitoring of water quality present challenging tasks because of the trace contaminants, complexity, and versatility of wastewater matrices.[119] The purpose of surface water monitoring is to develop a system for characterization and detection of physical, chemical and biological changes over time, which allows rapid identification of specific events or new and emerging problems.[120] Surface water is susceptible to pollution majorly stemming from urbanization, industrialization, and agriculture. Natural aquatic resources have become the most common discharge sites for wastewater containing microorganisms, pathogens, heavy metals, and other harmful and toxic compounds.[121] Nanomaterials provide an opportunity to addressing these issues using nanosensors, offering reliable solutions with huge impact on humanity. Amongst the already mentioned incredible properties like miniature size and high specific surface to volume ratio, nanomaterials have significant monitoring character with potential use in water quality management.[121,122] Nano sensors offer superior properties for monitoring water quality, such as proficient recognition of extremely low concentrations of pollutants and fast analysis.[123] Studies show that nanosenors are three to four orders of magnitude more sensitive than thin film sensors, because of their high signal-to-noise ratio.[124] So far, developed nano sensors based on nano materials with distinctive electrochemical, optical, or magnetic properties including magnetic nanoparticles, carbon nanostructures (graphene and carbon nanotubes), noble metals (Ag or Au) and quantum dots show ability to detect pathogens, organic and inorganic pollutants.[122,125] Here we are summarizing some advancements in nanosensors based on the pollutant sensing, divided by some major classes.

Inorganic pollutants - heavy metals

Heavy metals toxicity poses treats to health and organs system functioning in human beings. Beside humanity, it also affects other forms of living beings such as flora, fauna and even the microbiota.[126] The notorious one, mercury, causes side effects that are fatal and therefore receives much attention for proper sensing. Gao et al.,[127] reported a simple and green method for preparation of amino-functionalized fluorescent carbon dots (FCDs) for detection of Hg^{2+} in aqueous solution. Synthesized FCDs presented a high quantum yield (36%) at 440 nm of emission wavelength with a detection limit of 20 nmol L-1, indicating potential application for detection of trace Hg^{2+} in water samples. N and S doped carbon dots (N, S-CDs) synthesized from a wild plant, Typha angustata Bory (Patera), for ultra-low level, rapid detection of Hg^{2+} are reported by Samota et al.,[128] The authors reported extreme sensitivity for the developed sensor exhibiting an unprecedented quantum yield of 83 % that has never been reported previously. Owing to extraordinary quantum yield, the sensor exhibited ultra-low limits of detection of 3.1 nM for Hg^{2+} and satisfactory recoverability in the range 95–102 % for real water samples. Hydrophilic graphene quantum dots (GQDs) are reported by Anusuya et al.,[129] for detection of heavy metal ions in aqueous media, including Hg^{2+}, Cd^{2+} and Pb^{2+}. Using CQDs photoluminescence property an optical nanosensor has been constructed with detection limit of 1.171 μM, 2.455 μM and 2.011 μM for Hg2+, Cd2+ and Pb2+ ions, respectively. Tian et al.,[130] proposed greenly synthesized L-cysteine functionalized graphene oxide nanosheet (CGO) nanosensor with good colorimetric sensing of 5 μg L−1 of mercury ions. The reported metal-free sensor is economical and sensitive, presenting considerable anti-interference ability over other metal ions. Boron and nitrogen co-doped carbon dots-based nanosensor (B, N-CDs) was designed by Fu et al.,[131] for fluorescent and colorimetric dual-mode detection of Hg^{2+}. The application potential of B, N-CDs nanosensor for complex water matrices has been demonstrated as excellent, with limit of detection of 5.3 nM. Tümay et al.,[132] synthesized pyrene base novel fluorescent iron oxide nanoparticles (Py@Fe_2O_3) for highly selective determination of Hg^{2+} ions in environmental samples. The limit of detection and quantification were reported to be 3.650 nmol L−1 and 10.960 nmol L−1 in the linear working range of 0.010–1.000 μmol L−1 Hg^{2+}. Silver nanoparticles (AgNPs) embedded sulfur-doped graphitic carbon nitride (gCN) quantum dots-based fluorescent nanosensor (Ag-S-gCN QDs) was proposed by Pattnayak et al.,[133] employed for sensitive and selective detection of Hg^{2+} ions under optimal conditions. The limit of detection and quantification have been measured to be 0.13 μM and 0.43 μM, respectively, with a linear range of 0.1–0.6 μM. The sensor emitted strong blue fluorescence with relative quantum yield of 36.5%. Along mercury, environmental pollution with cadmium stands as a major concern with prolonged exposure causing serious health damage.[134] Al-Qasmi et al.,[135] managed to greenly synthesized cuprospinel nanoparticles and successfully used them for detection of low-concentration Cd^{2+} ions in aqueous solutions. The prepared curospinel nanoparticles nanosensor demonstrated ability to detect trace Cd2+ ions with concentration reaching about 3.6 ng/L. Graphene oxide/urease nanobiosensor was reported by Ballen et al.,[136] for cadmium detection in river water. The developed nanobiosensor showed high sensitivity (0.0147 nm/ppt), low detection limit (18 ppt) and satisfactory response. An electrochemical CNT-Cu-MOF sensor based on multi-walled carbon nanotubes (CNTs) and copper metal-organic framework (Cu-MOF) was synthesized and reported by Singh et al.,[137] for detection ultrasensitive potentiometric detection of Cd^{2+} ions. The developed sensor demonstrated excellent selectivity, stability, repeatability and 100.4% recovery in a real-time sample of tap-water. Mohammadzadeh et al.,[138] performed green synthesis of phenolic capping silver nanoparticles (PC-Ag NPs) and applied them as a colorimetric sensor for detection of Cd^{2+} and Ni^{2+} ions. The introduced nanosensor exhibited good selectivity, sensitivity, and linearity, under optimal conditions. Moreover, the sensor achieved satisfactory recovery within 90.57 to 113.61%. Wu et al.,[139] reported synthesis of monodisperse sphere-like Fe_2O_3 nanoparticles (Fe_2O_3 NPs) for simultaneous Pb2+ and Cu^{2+} detection. The authors demonstrated that the optimal presence of Fe^{2+} and oxygen vacancies are beneficial for better adsorption of heavy metal ions and enhanced electrochemical sensing performance. Functional N- and S-co-doped carbon dots for detection of trace amounts of Fe^{3+} with detection limit as low as 1.72 nM were reported by Cui et al.,[140] Nitrogen-doped graphene quantum dots (N-GQD) for portable detection of Fe^{3+} were introduced by Yao et al.,[141] The N-GQD showed high production yield of 64% and high blue fluorescence providing a new strategy for controlling Fe3+ levels in environmental water. Functionalized $CoFe_2O_4$/Ca-alginate nanocomposite was designed by Al-Gethami et al.,[142] as nanosensor for detection of Pb^{2+} ions in aqueous solutions at different temperatures. High sensitivity, stability, and rapid detection are among the reported properties of the proposed sensor, while the lowest detection limit for Pb^{2+} ions could reach 125 ng. A novel copper doped boehmite (CBH) based nanomaterial, capable of simultaneous detection and removal of Cr^{6+} has been reported by Roy et al.,[143] The nanosensor exhibited exceptional sensitivity with limit of detection of about 6.24 μM and selectivity towards hexavalent chromium ions. The sensor also showed multi-functionality when it comes to the adsorption-based removal of Cr^{6+} from wastewater, with remarkably high adsorption rate of around 85% in just 5 minutes.

Sayyad et al.,[154] reported fabrication of poly(3,4-ethylenedioxythio phene):poly(styrenesulfonate) (PEDOT:PSS) reduced graphene oxide (rGO) nanocomposite used as a selective Hg^{2+} sensor. The inadequate structural and chemical properties of (PEDOT:PSS) can be overcome with inclusion of carbon nanomaterials, such as rGO. The authors tested the sensor toward variety of metal ions (Hg^{2+}, Cd^{2+}, Pb^{2+}, Cu^{2+}, Zn^{2+}, Na^{+}, and Fe^{3+}), manifesting highest sensitivity and selectivity to Hg^{2+} with a low detection limit of 2.4 nM. Highly sensitive mercury detection have been also reported by Narouei et al.,[155] using a novel conductive nanofibrillar structure with high number of nitrogen binding sites. The nanofibers are made of a conductive copolymer, poly(aniline-co-o-aminophenol) – PANOA – homogenously decorated with gold nanoparticles (Au NPs). The sensor showed high affinity and selectivity for Hg^{2+} among As, Pb, Cu, Zn and Cd ions, due to the synergistic effect caused by the large number of nitrogen functional groups (imine, amino, amido) in the PANOA and the Au NPs. The tested sensor exhibited low detection limit of 0.23 nM, and linear dynamic range between 0.8 and 12.0 nM, using a 180 s pre-concentration step (Table 6).

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Table 6 Nanosensors for detection of heavy metals in water

Nanostructure	Targeted contaminants	Reference
Greenly synthesized carbon dots from microalgae biomass biochar	Cr^{6+}	Pena et al. [14]
Carbon dots synthesized from Poria cocos polysaccharide	Cr^{6+}	Huang et al. [145]
diphenylcarbazide (DPC) combined with Semiconducting polymer dots-based fluorescence nanosensor	Cr^{6+}	Dou et al.[146]
Fe_3O_4@Pectin-polymethacrylimide@graphene quantum dot	Cr^{3+}	Barzegarzadeh et al.[147]
Schiff base immobilized mesoporous SBA-15 silica	Cu^{2+}	Zhang et al.[148]
Bis-Schiff base functionalized Fe_3O_4 nanoparticles	Cu^{2+}	Zhu et al.[149]
Quaternized salicylaldehyde Schiff base side-chain polymer grafted magnetic Fe_3O_4 nanoparticles (Fe_3O_4@SiO_2-PAP)	Cu^{2+}	Zhang et al.[150]
Avocado seeds derived carbon dots	Cu^{2+} ; Cr^{6+}	Ávila et al.[151]
L-cysteine (L-Cys) capped Fe_3O_4@ZnO core-shell nanoparticles	Fe^{3+}	Chaudhury et al.[152]
Rice husk carbon quantum dots	Fe^{3+}	Kundu et al.[153]

Organic pollutants

Phenolic compounds, dyes, surfactants, pesticides, and pharmaceuticals are important organic pollutants in wastewater.[156] The occurrence of organic pollutants in wastewater have become a serious concern because of their toxicity, semi volatile nature, low water solubility, high bioaccumulation, and non-biodegradability under normal environmental conditions.[157]

Pharmaceuticals

Ling et al.,[158] developed a magnetic fluorescent molecularly imprinted polymers (MFMIPs) sensor based on Fe_3O_4 and carbon dots for rapid detection of methcathinone, a stimulant drug like methamphetamine. The proposed sensor presented high sensitivity with a linear range of 0.5–100 nM and a detection limit of 0.2 nM, under optimal conditions. Moreover, the authors reported that the sensor is recyclable and reusable at least five times using an external magnetic field. Blue luminous nitrogen-doped carbon quantum dots (N-CQDs) have been developed by Raut et al.,[159] and used for detection of doxycycline, a drug that has been globally employed for treatment of COVID 19. The reported detection approach is fluorescence quenching mechanism, even when there are other tetracycline derivatives interfering. The sensor showed great sensitivity (with limit of detection 0.25 µM) and selectivity, making N-CQDs ideal candidates for sensing doxycycline in environmental matrices. Research for doxycycline detection and its degradation was also reported by Kaur et al.,[160] The authors proposed a novel single step strategy for synthesizing Fe-doped carbon dots (Fe-N@CDs) for detection and iron oxide-carbon dot hybrid nanoparticles (Fe3O4-CDs) for degradation of doxycycline. The results demonstrated selective sensing of doxycycline with a limit of detection value of 66 ng mL^{-1} and degradation by 70.26% in 5 minutes by applying shear force. Tito et al.,[161] developed electrochemical sensor systems by depositing functionalized nickel selenide quantum dots (NiSe2QD) onto an L-cysteine or Nafion-modified gold electrode, capped with banana peel extract (BPE) and 3-mercaptopropionic acid (3-MPA) for stability improvement and agglomeration prevention. Of all synthesized sensors, 3-MPA-NiSe2QD/L-cyst/Au produced the best signal with high sensitivity of 6.15 µA/pM and recovery of 85%-108% in real wastewater samples indicating suitability for real-time sample analysis. Dhanapal et al.,[162] reported synthesis of vanadium and phosphorous doped graphitic carbon nitride nanosheets for detection of nimesulide. The analytical parameters of the proposed sensor are adequate, with high recovery values, and low detection (0.2 – 80 µM) and quantification limit (3 nM). Binder-free zinc oxide nanograins on carbon cloth (ZnO NGs@CC) have been synthesized by Kokulnathan et al.164 and employed for a flexible electrochemical sensor fabrication used for quantification of hydroxychloroquine. The fabricated ZnO NGs@CC-based electrochemical sensor displayed good performance in terms of wide sensing range (0.5–116 µM), low detection limit (0.09 µM), high sensitivity (0.279 $\mu A\ \mu M^{-1}\ cm^{-2}$), and strong selectivity (Table 7).

Table 7 Nanosensors for detection of pharmaceuticals in water

Nanostructure	Targeted contaminants	Reference
Carbon dots embedded hydrogel spheres	rifampicin	Li et al.[170]
Polyvinyl alcohol functionalized tungsten oxide/reduced graphene oxide (PVA/WO_3/rGO) nanocomposite	4-aminophenol	Buledi et al.[171]
Graphitic carbon nitride (g-C3N4) -coupled with CuS nanoparticles (g-C3N4@CuS)	carbamazepine	Goudarzy et al.[172]
CaO nanoparticles conjugated with l- Methionine polymer film onto carbon paste electrode	levofloxacin	Assaf et al.[173]
Chitosan-molybdenum vanadate nanocomposite $V_{3.6}Mo_{2.4}O_{16}$-chitosan (MV-CHT)	hydroxychloroquine sulfate	Monsef et al.[174]
$ZrMo_2O_8$-MWCNTs nanocomposite	adefovir	Li et al.[175]
N-CQD/Fe_3O_4 nanoparticle/N-buty-3-methylimidazolium tetrafluoroborate (N–B-3-MITFB) onto carbon paste electrode (N-CQD/Fe_3O_4/N–B-3-MITFB/CPE)	raloxifene; tamoxifen	Shalali et al.[176]
Sanghuangporus Lonicericola derived nitrogen doped carbon dots	tetracyclines	Wang et al.[177]
Sulfur and nitrogen-doped graphene quantum dots (S, N-GQDs)	furazolidone	Manshadi et al.[178]
La_2O_3-ZrO_2-MWCNTs nanocomposite	tenofovir	Zeng et al.[179]
1-ethyl-3-methylimidazolium methyl sulfate (EMMS) and NiO doped Pt decorated SWCNTs (NiO@Pt/SWCNTs) in carbon paste matrix (NiO@Pt/SWCNTs/EMMS/CPE)	atropine	Tavana et al.[180]
Red-emitting carbon dots	tetracyclines	Wang et al.[181]
CHO-GO/CP (cholesterol-graphene oxide nanohybrid-modified carbon paste)	cetirizine	Killader et al.[182]

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Sherlin V. et al.,[164] developed well-structured functional material based on $ANbO_3$ (A = Na,K) perovskites, for electrochemical sensing of hydroxychloroquine. The synthesized NaNbO3 and $KNbO_3$ have been pinned to functionalized carbon nanofibers (f-CNF) creating synergistic effect of rapid electron transfer and improved surface area, resulting to enhanced electrochemical activity for $NaNbO_3$@f-CNF. The fabricated sensor displays high sensitivity, wide dynamic range, outstanding selectivity, and reproducibility, proving capability for real-time analysis with good recovery rates (±97.67–99.81%). Halligudra et al.,[165] reported Fe_3O_4 nanoparticles (NPs) supported MoS_2 nanoflowers (Fe_3O_4–MoS_2) modified carbon paste electrode used for detection of paracetamol, ascorbic acid, hydrogen peroxide, and tetracycline, showing well-separated peaks. The results indicated the potential use of Fe_3O_4–MoS_2 as electrochemical sensor material for industrial applications. Facile synthesis of NiO/ZnO nanocomposite have been reported by Qambrani et al.,[166] successfully employed to modify a glassy carbon electrode for construction of a sensitive and reliable electrochemical sensor for detection of carbamazepine, an anticonvulsant drug. The NiO/ZnO nanocomposite exhibited excellent electron transfer kinetics and less resistance than the pristine NiO and ZnO nanoparticles. The developed sensor showed exceptional response and selectivity for carbamazepine under linear dynamic range from 5 to 100 µM and calculated limit od detection of 0.08 µM. The sensor also showed acceptable recovery ranging from 96.7 to 98.6% (Figure 7).

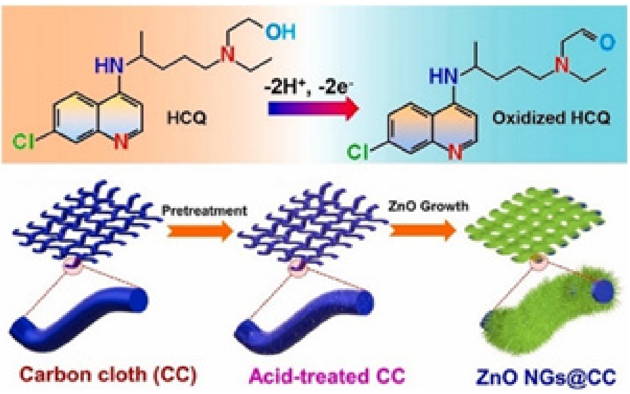

Figure 7 Zinc oxide nanograins on carbon cloth as flexible electrochemical platform for hydroxychloroquine detection.[163]

A colorimetric and surface-enhanced Raman scattering dual-mode electrochemical sensing platform for amoxicillin detection have been developed by Tuan Anh et al.,[167] by employing copper nanoparticles (CuNPs) and copper-graphene oxide (Cu-GO) nanocomposites. Cu-GO-based colorimetric nanosensor revealed superior properties against CuNPs nanosensor, with 1.3 times lower limit of detection (1.71 µM). The developed sensor exhibited practical applicability for real tap-water samples with high calculated recovery of about 95%. Beitollahi et al.,[168] reported on achieving a sensing platform based on a screen-printed electrode modified with Ni-Co layered double hydroxide (Ni–Co LDH) hollow nanostructures for detection of sumatriptan. The obtained limits of detection and sensitivity have been reported as 0.002 ± 0.0001 µM and 0.1017 ± 0.0001 µA/µM, respectively. In addition, authors studied the performance of the developed nanosensor for simultaneous analysis of sumatriptan in the presence of naproxene, showing well-separated peaks leading to a quick and selective analysis of sumatriptan. Kurç et al.,[169] developed a molecularly imprinted polymers-based surface plasmon resonance (SPR) sensor chip performing rapid, selective analysis for detection of sulfamethoxazole. As a receptor, the authors reported use of sulfamethoxazole imprinted methacrylic acid-2-hydroxyethyl methacrylate-ethylene glycol dimethacrylate polymer [poly (MAA-HEMA-EGDMA)]. The obtained results for limit of detection and limit of quantification were found to be 0.0011 µg/L and 0.003 4 µg/L, respectively (Figure 8).

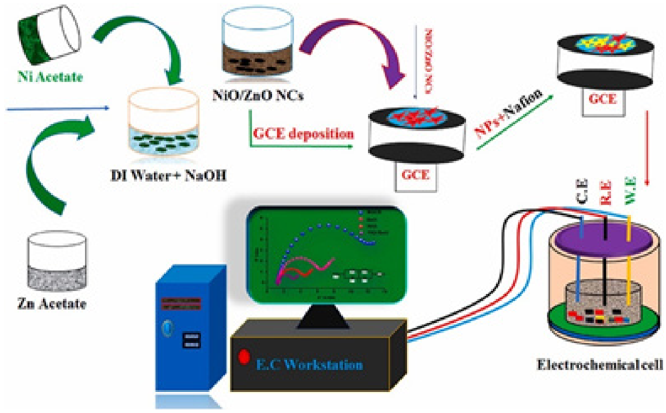

Figure 8 Synthesis of NiO/ZnO nanocomposite as an effective platform for electrochemical determination of carbamazepine.[166]

Phenolic compounds and dyes

Nitroaromatic compounds (NACs) find their way into the environment via anthropogenic activities. Because of their explosive and toxic behavior, soil and groundwater pollution control is essential[183]Garg et al.,[183] reported synthesis of hydrophobic carbon nanoparticles (HCNPs) applied towards selective sensing of NACs, specifically 2,4,6-trinitrophenol (TNP) and 2,4-dinitrophenol (DNP). Synthesized HCNPs exhibit fluorescence property with brightly blue emission at □464 nm with □24% quantum yield, used for selective sensing activities. The obtained detection limit for TNP and DNP has been reported to be □242 nM and □276 nM, respectively. Rapid detection of 2,4,6-trinitrophenol (TNP) has been also reported by Ilyas et al.,[184] using fluorescein based fluorescent and colorimetric sensors, accomplishing highly sensitive fluorescence detection of TNP (LOD, 0.73–1.7 nM). Catechol, also known as pyrocatechol or 1,2 -dihydroxybenzene, is a toxic benzenediol. Wang et al.,[185] reported gold nanostars-based (Au NSs) plasmonic colorimetric nanosensor for ultrasensitive catechol detection with ultra-wide detection range (3.33 nM to 107 µM) and limit of detection at 1 nM. Le et al.,[186] synthesized fluorescence-incorporated mesoporous nanosilica (F-NS), for detection and removal of 4-nitrophenol, dangerous compound found in insecticides and pesticides. The authors reported that modulation of the fluorescein isothiocyanate amount allowed detection of 4-nitrophenol in traces through fluorescence quenching. Catechol and hydroquinone detection was also reported by Ranjith et al.,[187] via hybrid electrochemical sensor with electrospun one-dimensional (1D) $MnMoO_4$ nanofibers coupled with a few-layered exfoliated two-dimensional (2D) MXene. The proposed 1D–2D hybridized $MnMoO_4$–MXene–GCE sensor showed a low detection limit of 0.26 nM and 0.30 nM for hydroquinone and catechol with high stability, respectively. Dhiman et al.,[188] developed tyrosinase-gold nanoparticles (Ty-AuNPs) for ultrasensitive sensing of phenolic compounds, obtaining an ultralow limit of detection at 0.01 ppb. Highly sensitive nanoscale detection of nitrobenzene in both solution and vapor phase has been reported by Majeed et al.,[189] via piezofluorochromic and AIEE active receptor free sensors, marked as 2 and 3. The highly selective fluorescence detection of nitrobenzene has been attributed to its adjustable small sized molecules that can penetrate the cavities of both sensors. Developed 2 and 3 sensors showed limits of detection as 1.21 nM and 1.55 nM, respectively. Moreover, both sensors being used

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as fluorescence ink showed highly sensitive colorimetric detection of nitrobenzene. Kumar et al.,[190] developed a fluorescent sensor based on p-xylylenediamine capped $CH_3NH_3PbBr_3$ perovskite nanocrystals for picric acid (2,4,6-trinitrophenol) sensing. The developed sensor exhibited high sensitivity and selectivity, with a good linear range of 1.8 µM–14.3 µM achieving detection of limit of 0.3 µM. Detection of picric acid in industrial effluents was also reported by Keerthana P, et al.,[191] using multifunctional green, fluorescent B/N-carbon quantum dots-based sensor. The synthesized B/N-CQDs exhibited high quantum yield (24%) and bright green fluorescence under UV light and were found to be an effective fluorescence probe for selective and sensitive sensing of picric acid in industrial effluents, with a good linear range of 37 nM-30 µM and a detection limit of 1.8 nM. Yahya et al.,[192] developed a simple and sensitive electrochemical method to determine ethyl violet (EV) dye in aqueous systems employing a glassy carbon electrode modified with acidic-functionalized carbon nanotubes (COOH-fCNTs). Under optimal conditions, the limit of detection with a value of 0.36 nM demonstrated high sensitivity of COOH-fCNTs/GCE. Sadrolhosseini et al.,[193] developed surface plasmon resonance sensor used for detection of environmental contaminant dyes such as methylene blue (MB) and methylene orange (MO). The sensor consisted of gold layer modified with NiCo-layered double hydroxide, which thickness was proven to control the sensitivity of the sensor. Exhibiting performance for limit and response time of about 0.005 ppm and 268 s, respectively, it can be concluded that the developed system is fast and efficient for detection of MB and MO dyes in a short time. An electrochemical sensor using a modified glassy carbon electrode with amine functionalized multi-walled carbon nanotubes (NH_2-fMWCNTs) for detection of nanomolar concentration of Metanil Yellow (MY), an azo dye used illegally in food industry was reported by Hakeem et al.,[194] Under optimal conditions, the limit of detection of was calculated to be 0.17 nM. Among detection, the dye was found to follow pseudo first order kinetics with a degradation extent of 98.7%, holding great promise in the context of water purification. Mehmandoust et al.,[195] developed of a sensitive and novel electrochemical sensor for the detection of Allura Red in the presence of tartrazine using a screen-printed electrode modified by functionalized nanodiamond covered using silicon dioxide and titanium dioxide nanoparticles (F-nanodiamond@SiO_2@TiO_2/SPE). The as-fabricated electrode demonstrated two wide dynamic ranges of 0.01–0.12 and 0.12–8.65 µM with a limit of detection as low as 1.22 nM.

Pathogens

Water-borne pathogen contamination in surface water resources is a major worldwide concern for water quality, posing as a direct thread to human health and life.[196] Hence, ensuring control over pathogens (bacteria and viruses) is crucial. Nair et al.,[197] developed a novel silicon nanowire (SiNWs) coated with reduced graphene oxide (RGO)-based sensing platform aimed for direct detection of *Escherichia coli* (*E. coli*) bacteria. During the analysis, *E. coli* showed preferential adhesion to the SiNWs network, resulting in a resistance decrease thereby leading to a current increase. The obtained device poses as a promising nanosensor for the direct, rapid, and precise detection of *E. coli* bacteria in aqueous solutions. Panchal et al.,[198] designed a sensitive nanoplatform based on interchangeable sandwich ELISA composed of a novel, multifunctional magneto-plasmonic nanosensor (MPnS) with target antibodies (MPnS-Ab). The nanoplatform based on enzyme-linked immunosorbent assay (ELISA) is featuring synergistic properties of gold and iron oxide nanozymes, replacing the conventional enzyme horseradish peroxidase (HRP), therefore the experiments demonstrated a 100-fold increase in catalytic activity in comparison to HRP. Silicon nanowires-based biosensors for electrical detection of Escherichia Coli have been reported by Salaun et al.,[199] The sensors exhibited high specificity ensured by chemical functionalization of the nanowires for binding of specific antibodies to target *E. coli*. Nqunqa et al.,[200] demonstrated green synthesis of banana peel (Musa paradisiaca) and grape (Vitis vinifera) fruit extracts-functionalized silver nanoparticles (Ag-NPs) used as optical and electrochemical sensors developed for detection of *E. coli*. The obtained limit of detection values for constructed sensor systems are within the range for *E. Coli* in seawater and have been reported as 1 × 102 CFU/mL and 3.5 × 101 CFU/mL for the optical and electrochemical sensor, respectively. Gunasekaran et al.,[201] developed an electrochemical method for detection of *E. coli* using bi-functional magnetic nanoparticle (MNP) conjugates, prepared by terminal-specific conjugation of anti-*E. coli* IgG antibody and the electroactive marker ferrocene. The results indicate that the bi-functional conjugates pose as an ideal candidate for electrochemical sensing of waterborne bacteria, exhibiting high sensitivity (10 cells/mL) and providing specific signals within 1 hour. Chen et al.,[202] constructed a chemiluminescence system based on the peroxidase-like property of 4-mercaptophenylboronic acid (MPBA)-functionalized CuSe nanoprobes (CuSeNPs@MPBA), designed for improved accurate and sensitive detection of Staphylococcus aureus and Escherichia coli. The reported limit of detection is as low as 1.25 and 1.01 cfu mL^{-1} for Staphylococcus aureus and Escherichia coli detection, respectively and bacteria can be efficiently eliminated due to excellent photothermal property of CuSeNPs@MPBA. Juang et al.,[203] reported on in-situ magnetic capturing and surface-enhanced Raman scattering (SERS) detection of bacteria *E. Coli*, based on a substrate platform consisted of immobilized gold nanoparticles (AuNPs) and iron-oxide (Fe_3O_4) nanoparticles on exfoliated nanoscale silicate platelets (NSPs). The prepared magnetic SERS nanosheets (Fe_3O_4@AuNPs@NSP nanosheets) were able to magnetically capture and separate *E. Coli*, and then monitor the samples by Raman spectroscopy for rapid SERS detection. The SERS sensitivity increased by approximately 2 times after magnetic capturing, while the limit of detection was below 103 CFU/mL. Arreguin-Campos et al.,[203] presented an imprinted polymer-based thermal biomimetic sensor for detection of Escherichia coli. Graphene oxide (GO)-functionalized polydimethylsiloxane (PDMS) films have been investigated as a novel and simple imprinting protocol. The limit of detection for PDMS-GO has been reported to be 80 ± 10 CFU/mL, a full order lower than pristine PDMS (670 ± 140 CFU/mL), emphasizing the beneficial effect of the dopant (Figure 9).

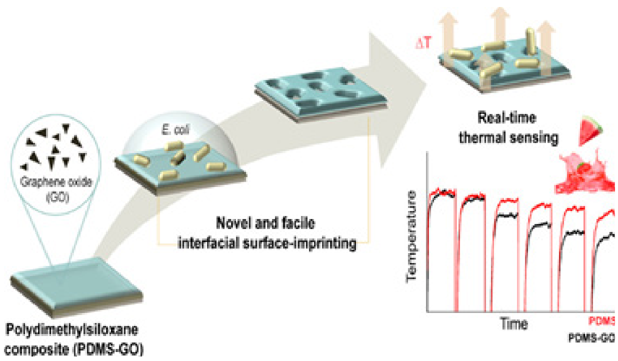

Figure 9 Imprinted polydimethylsiloxane-graphene oxide composite receptor for the biomimetic thermal sensing of Escherichia Coli.[203]

Conclusion

To conclude, in this paper we have discussed some recent advances in the nanosensors field for detection and monitoring of hazardous gas

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and water pollutants. Due to the novel physicochemical properties, nanomaterials have huge potential to combat environmental pollution. Different types of attractive nanomaterial classes were reviewed for highly sensitive and selective performance against a wide variety of organic and inorganic targeted gases. Moreover, nanosensors advancements based on the specific water pollutant were reviewed. Nanosensor technology advancement presents the promising response to the urgent demand for environmental contamination, offering simple and effective solutions.

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Conflicts of interest

There are no conflicts of interest.

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