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*Editorial*

# Recent Advances in Low-Cost Chemical Sensor Technologies for Environmental Monitoring Applications

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**Abstract**

This Special Issue based on eight Articles/Reviews focuses on low-cost chemical sensor technologies, bio-chemical sensors, advanced active materials, sensing nanomaterials, sensor nodes, wireless sensor networks for chemical sensing, functional characterization, miniaturized transducers, advanced proofs of concept, and chemical detection applications. Promising advanced materials such as metal oxide nanostructures, carbon nanomaterials, composite heterostructures, multilayered coatings, and more have been explored for chemical sensing applications and environmental sustainability. Sensing solutions have been applied in the context of bio-chemical detection and gas monitoring, representing the current state of the art.

**Keywords:** gas sensors; chemical sensors; sensor active materials; advanced functional nanomaterials; portable chemical sensor systems; IoT sensing devices; sensor engineering; chemical sensor applications; new concepts in chemical sensing

## 1. Introduction

Global warming and climate change are serious environmental threats at the global level. Air pollution due to rapid urbanization is one of the major causes of environmental deterioration. The emission of air pollutants and toxic gases such as nitrogen oxides ($NO_x$), ozone ($O_3$), carbon monoxide (CO), sulfur dioxide ($SO_2$), and volatile organic compounds (VOCs) is extremely dangerous for ecosystems and human beings. Particulate matter ($PM_{10}$, $PM_{2.5}$, $PM_{1.0}$ and Ultrafine Particles) is highly nocive for the public and the environment. Greenhouse gases (GHGs), including carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$), are the main drivers of global warming. Thus, their continuous monitoring at high spatial-temporal resolution is crucial to prevent environmental disasters. In Europe, the threshold limits are currently regulated by Ambient Air Quality and Clean Air for Europe (*EU Directive 2008/50/EC*) [1] and its successors (*PE-CONS 88/24*) [2].

Advanced functional materials [3–13] are key enabling technologies for high-performance sensing devices [14–23] to address detection at the sub-ppm level for environmental monitoring.

Air quality monitoring based on low-cost sensor technologies is very popular in several emerging applications such as citizen science, community sensing, public health protection, environmental information, smart city planning, environmental monitoring and sustainability. Ensuring these air quality sensors' compliance to regulatory data quality objectives is still a challenge [1,2,8,14].

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Current sensor technologies include several types of transducers and system configurations, which are evolving quickly with different open questions and considerable challenges in terms of sensitivity, selectivity, stability, limit of detection, accuracy, calibration, repeatability, and so on. The evolution of sensor performance for air quality monitoring through networked low-cost sensor systems equipped with artificial intelligence (AI) is crucial for future applications in real scenarios [14–18,22,23].

This Special Issue of the *Chemosensors* (MDPI journal), entitled *Recent Advances in Low-Cost Chemical Sensor Technologies for Environmental Monitoring Applications*, brings together eight articles presenting recent developments in these areas. The publications range from advanced sensing materials, sensor devices, chemical detection, biosensing, new sensing solutions, proof of concepts, practical applications for environmental monitoring and sustainability, including bio-sensing measurements. The featured research highlights significant advancements in bio-chemical sensing applied as smart technology for a sustainable future based on environmental, social and governance methodology.

## 2. Overview of Published Papers

Peiqingfeng Wang et al. (Contribution 1—Review) present a comprehensive overview of recent advances in resistive gas sensors, focusing on their fundamental working mechanisms, sensing material design, device architecture optimization, and intelligent system integration. In terms of materials, metal oxide semiconductors, conductive polymers, carbon-based nanomaterials, and their composites demonstrated enhanced sensitivity and selectivity through strategies such as doping, surface functionalization, and heterojunction engineering, while also enabling reduced operating temperatures. Device-level innovations—such as microheater integration, self-heated nanowires, and multi-sensor arrays—have further improved response speed and energy efficiency. Moreover, the incorporation of artificial intelligence (AI) and Internet of Things (IoT) technologies has significantly advanced signal processing, pattern recognition, and long-term operational stability. Machine learning (ML) algorithms have enabled intelligent design of novel sensing materials, optimized multi-gas identification, and enhanced data reliability in complex environments. Composite material systems, particularly metal oxide/graphene heterojunctions, have further optimized detection accuracy and response kinetics. Despite these advances, critical challenges remain in long-term stability and interference resistance. This study suggests that future research may leverage emerging biomimetic approaches such as molecularly imprinted polymers alongside novel two-dimensional materials such as MXenes to achieve next-generation performance enhancements.

Marwen Mezyen et al. (Contribution 2—Article) present a study devoted to RF-sputtered $SnO_2$ thin films subjected to a modification process through doping with a rare earth element, dysprosium (Dy), and subsequently deposited onto two different types of substrates: alumina and glass substrates. All thin films underwent a comprehensive series of characterizations aimed at ensuring their suitability as $NO_2$ sensors. The dysprosium doping levels ranged from 1 to 7 wt.% in increments of 2% (wt.%). X-ray patterns showed that all deposited films exhibited the tetragonal rutile structure of $SnO_2$. Gas sensing tests were conducted at different operating temperatures, where the highest response to nitrogen dioxide, over 42%, was recorded for the higher dopant level at 250 °C. Moreover, the sensor's selectivity toward nitrogen dioxide traces was evaluated by introducing interfering gases at higher concentrations. However, the sensors showed also significant responses when operated at room temperature. In addition, the authors have demonstrated that higher stability is related to the temperature of the sensors and Dy ratio. Hence, a detailed discussion of the gas-sensing mechanisms was undertaken to gain a deeper insight into the $NO_2$ sensitivity of the Dy-doped $SnO_2$ layer. As a future direction, tests will be

conducted at varying humidity levels to better simulate real-world conditions and ensure the reliability of gas sensors in humid environments.

Ibn e Abbas et al. (Contribution 3—Review) present a review devoted to the importance of adopting ethical and sustainable practices in chicken farming, in response to the increasing global demand for poultry products driven by the expanding world population. Some ambient gases, such as hydrogen sulfide ($H_2S$), nitrous oxide ($N_2O$), ammonia ($NH_3$), carbon dioxide ($CO_2$), and methane ($CH_4$), affect the welfare of farm workers. The use of various gas sensor technologies is crucial for effective management and monitoring of these gases. This research emphasizes the vital importance of precise gas concentration measurements in mitigating environmental impact. It is noteworthy that there is a closely intertwined relationship between $CO_2$ levels and chicken health, requiring vigilant monitoring and care. There are potential risks associated with $NH_3$ exposure, and waste management and ventilation practices are necessary. Furthermore, the contribution of $CH_4$ sensors to environmental sustainability and safety is addressed. The review also examines $H_2S$ emissions, providing mitigation strategies to safeguard avian health. This study identifies an important gap between the limited use of commercially available metal oxide semiconductor (MOS) sensors in commercial Internet of Things (IoT) systems for poultry farms and their potential to detect a wider range of chemical gases. Realizing the full potential of gas monitoring systems in livestock management will require ongoing improvements in sensor technologies, as well as initiatives to overcome the difficulties associated with industrialization and mass production. Farms can improve productivity, increase transparency, and support more-sustainable farming methods by implementing these technologies.

Rayssa Silva Correia et al. (Contribution 4—Article) propose a study devoted to rGO/ZnO composites for use as toxic gas sensors due to the synergistic effect between the materials and the reduction in sensor operating temperature promoted by rGO. This paper reports on a study of ZnO/rGO/ZnO-based sensors with different ZnO NP morphologies for ozone sensing. ZnO nanoparticles with needle- and donut-like morphologies were synthesized via the precipitation method, and bare ZnO and ZnO/rGO/ZnO composite sensors were fabricated by layer-deposition of ZnO and/or rGO via drop-casting, forming a "sandwiched" structure that protects the rGO sheets. Bare ZnO and ZnO/rGO/ZnO composites were analyzed by varying the temperature from 200 to 300 °C. The ZnO/rGO/ZnO sensor provided a high response of 13.3 ($R_{gas}/R_{air}$) and recovery times of 442 s and 253 s, respectively, for 50 ppb of $O_3$, as well as high selectivity to ozone gas compared to CO, $NH_3$, and $NO_2$ gases. Under ozone exposure, the efficient charge transfer at the composite interface modulates the band structure, resulting in a significant variation in sensor resistance. Furthermore, rGO has oxygenated functional groups and additional structural defects, which provide more active sites for gas adsorption. On the other hand, the uniform distribution of ZnO NPs within the rGO sheets enhances the formation of more active adsorption sites for $O_3$. The presence of the n-p junction can also accelerate charge transfer, thereby improving the detection response. No oxidation or degradation of the sensor was observed during ozone detection measurements, indicating that the adopted manufacturing methodology was successful.

Nesrine Hafiene et al. (Contribution 5—Communication) present a report on the development of indium-doped $Cu_xS$ heterojunction-based conductometry sensors. To fabricate the sensors, thick films of In-$Cu_xS$ heterojunctions were sprayed directly on an alumina sensing platform provided with interdigitated Pt electrodes. The effect of doping with different nominal amounts of $InCl_3$ additive (0%, 3%, and 5%) on the structural, morphological, and optical properties of $Cu_xS$ films was first studied by XRD, AFM, UV-Vis and Raman spectroscopy. Moreover, the electrical and sensing characteristics towards low

concentrations of hydrogen sulfide ($H_2S$) in the air were investigated. The tests carried out clearly demonstrated the positive effect of In doping on the $H_2S$ sensing performance of $Cu_xS$. The 5% doped $Cu_xS$ sensor showed the highest sensitivity to the target gas compared to the other sensors, as well as good stability and selectivity properties. Gas-sensing tests at 200 °C showed that the nominal 5% In-doped CuS sensor exhibits higher sensitivity than the nominal 3% In-doped CuS sensor, with a detection limit of 0.125 ppm, a rapid response time of 37 s, a recovery time of 135 s, and excellent long-term stability over ten months. The enhanced sensing performance is attributed to increased charge carrier density, improved conductivity, and the formation of more uniform and active surface sites due to indium incorporation. Overall, the CuS–In5% sensor demonstrates competitive performance compared to previously reported CuS-based sensors, highlighting its potential as a sensitive and reliable $H_2S$ detection material.

Teresè Kondrotaitè-Intè et al. (Contribution 6—Article) propose a study on the combined effect of electrodeposited gold nanoparticles (AuNPs) and AuNP–polypyrrole (PPy)-modified Saccharomyces cerevisiae on electrochemical glucose sensing. AuNPs were deposited onto electrode surfaces via cyclic voltammetry, and the resulting interfaces were characterized using atomic force microscopy, cyclic voltammetry, and electrochemical impedance spectroscopy. AFM analysis confirmed increased surface roughness and height variability after deposition, indicating substantial restructuring of the electrode interface. Electrochemical measurements showed that AuNP deposition altered interfacial charge storage and transfer and increased the measured charge-transfer resistance. Glucose sensing was evaluated in a ferricyanide-mediated system using yeast layers with or without AuNP and PPy modification over a 0–60 mM concentration range. All configurations exhibited saturating, non-linear glucose responses described by Hill fitting. Among the evaluated yeast-modified electrodes, the AuNP-PPy-modified yeast produced the strongest glucose-induced current increase and the best low-concentration performance, achieving a limit of detection of 0.540 mM, compared with 1.016 mM and 1.330 mM for single-modified layers and 3.360 mM for unmodified yeast. These results show that combining AuNP electrodeposition with AuNP-PPy yeast modification improves interfacial properties and enhances mediator-assisted electrochemical glucose sensing. Within the proof-of-concept scope of this study, Sc:PPy:Au/ecAu/GR therefore emerges as the most promising configuration, providing the most favorable balance between glucose-induced signal gain and low-range detectability among the tested sensing layers.

Michele Penza et al. (Contribution 7—Article) propose a study on a sensor network based on 10 stationary nodes distributed in Bari (Southern Italy) and deployed for urban air quality (AQ) monitoring. The low-cost sensor systems have been installed in specific sites (e.g., buildings, offices, schools, streets, ports, and airports) to enhance environmental awareness of the citizens and to supplement the expensive official air-monitoring stations with cost-effective sensor nodes at high spatial and temporal resolution. Continuous measurements were taken using low-cost electrochemical gas sensors (CO, $NO_2$, $O_3$), an optical particle counter ($PM_{10}$), and an NDIR infrared sensor ($CO_2$), as well as micro-sensors for temperature and relative humidity. The sensors were used to assess the performance during a campaign (July 2015–December 2017) of several months for citizen science in sustainable smart cities. Typical values of $CO_2$, measured by distributed nodes, varied from 312 to 494 ppm (2016) and from 371 to 527 ppm (2017), depending on seasonal micro-climate change and site-specific conditions. The results of the long-term AQ monitoring campaign for selected sensor nodes are presented with a relative error of 26.2% ($PM_{10}$), 21.7% ($O_3$), 25.5% ($NO_2$), and 79.4% (CO). These interesting results suggest partial compliance, excluding CO, with Data Quality Objectives (DQOs) from the European Air Quality Directive (2008/50/EC) for Indicative (Informative) Measurements. This study is one of a few to

deploy a wireless sensor network, referenced by public official data, that was operated over a 30-month long-term campaign of continuous monitoring, including a full pool of air pollutants using low-cost and low-power consumption sensors in an urban scenario. Finally, wireless sensor networks for air-quality monitoring are key to enabling technologies to develop the concept of the sustainable city in the era of the Internet of Things (IoT), supporting decision-making and engaging citizens according to the goals of sustainable development.

Yanting Tang et al. (Contribution 8—Review) propose a study on the advancement of high-performance, low-cost, and highly integrated gas sensors for intelligent environmental monitoring. Silicon-compatible semiconductor gas sensors provide a promising platform to achieve this goal by leveraging their compatibility with complementary metal oxide semiconductor (CMOS) processes. The established mass-manufacturing capabilities of micro-electromechanical systems (MEMSs) and the high sensitivity and signal amplification characteristics of field effect transistors (FETs) in recent years have made the development of next-generation sensing devices feasible. In this review, we systematically summarize the latest advances in silicon-compatible gas sensors, with a focus on MEMSs and FET technologies. The authors discuss the sensing mechanisms and performance optimization strategies and further highlight the evolution of gas sensor technology toward on-chip intelligent olfactory systems that integrate sensing, computing, and storage capabilities. These low-power, highly reliable intelligent sensing systems will provide core technical support for cutting-edge fields such as personalized health monitoring, real-time environmental sensing, early warnings promoting industrial safety, and the Internet of Things, empowering precise decision-making and dependable services in complex and dynamic environments.

Finally, the presented research is pivotal in shaping the future of chemical sensing by means of advanced sensor systems and devices integrating innovative functional materials for advancements in environmental monitoring applications.

## 3. Statistics and Trend Analysis

The results of the trend analysis are reported in Table 1. This Special Issue offers an outstanding overview of recent advancements in bio-chemical sensors for environmental monitoring applications. The statistics were taken from eight published papers, including three Reviews, four Articles and one Communication, co-authored by 42 international scientists from 6 countries located in Europe, Africa, Asia and South America. The total number of the rejected or withdrawn manuscripts is 5.

The challenges highlighted in this Special Issue are linked to advanced sensing materials (graphene-based materials, carbon nanomaterials and composites, metal oxide nanoparticles, heterostructures, hybrid functional materials) and related material processing to produce sensors with optimal bio-chemical sensing properties. Furthermore, the findings extend the knowledge in the field of advanced transduction of bio-chemical sensing (electrochemical, chemo-resistive, optical). Sensor calibration has also been explored.

Challenging applications have been addressed, such as sub-ppb detection of toxic gases and volatile organic compounds for environmental monitoring, particulate matter detection, biosensing, and wireless sensor networks for urban air quality monitoring.

**Table 1.** The main features of the papers published in this Special Issue.

| Paper | Type | Nr. of Authors | Corresponding Author Country | Other Author Countries | Keywords |
|---|---|---|---|---|---|
| Contribution 1 | Review | 6 | China | China | resistive gas sensor; metal oxide; smart sensing; machine learning; material design; device optimization; environmental monitoring |
| Contribution 2 | Article | 5 | Spain | Tunisia; Spain | $SnO_2$; Dy; sputtering; optical and morphological properties; $NO_2$; gas sensing |
| Contribution 3 | Review | 2 | Italy | Italy | metal oxide semiconductor (MOS); parts per million (ppm); parts per billion (ppb); volatile organic compounds (VOC); room temperature (RT); response/recovery (res/rec); Internet of Things (IoT); Global Livestock Environmental Assessment Model (GLEAM); Food and Agriculture Organization of the United Nations (FAO) |
| Contribution 4 | Article | 5 | Brazil | Brazil | gas sensors; ozone detection; ZnO-rGO-ZnO sensors |
| Contribution 5 | Communication | 6 | Italy | Spain; Tunisia; Italy | copper sulfide; indium-doped copper sulfide; spray pyrolysis; gas sensor; hydrogen sulfide ($H_2S$) |
| Contribution 6 | Article | 6 | Lithuania | Lithuania | biosensors; gold nanoparticles; polypyrrole; electrodeposition |
| Contribution 7 | Article | 6 | Italy | Italy | air quality sensors; gas sensors; particulate matter devices; low-cost sensor-systems; wireless sensor network; urban air quality monitoring; air quality EC directive |
| Contribution 8 | Review | 6 | China | China | gas sensors; silicon compatible; micro-electromechanical systems; field effect transistor; intelligent olfactory systems |
| Total Authors involved | | 42 | | | |
| Total Author Countries | | 6 | | | |
| Total Rejected/Withdrawn Papers | | 5 | | | |
| Total Published Papers | | 8 | | | |

## 4. Summary and Conclusions

The work presented in this Special Issue reflects the drive to increase the knowledge on chemical sensors by applied research in advanced materials, sensing devices, new transducers, and practical applications. In this Special Issue, front-line scientists have been kindly invited to submit original research and review articles on exploring *Recent Advances in Low-Cost Chemical Sensor Technologies for Environmental Monitoring Applications*.

Potential topics included but were not limited to gas sensors, chemical detection, advanced materials for chemical sensing, novel gas sensor materials, sensor calibration, sensor systems, wireless sensor networks, chemical threat monitoring, environmental measurements, sensors for smart city applications, sensors for environmental sustainability, sensors for IoT applications, case studies of chemical detection campaigns, new concepts, and trends in chemical sensing.

The impactful findings presented in this Special Issue are a valuable contribution to the theory and practice of chemical sensing. Additional development of these trends can be expected in the future to consolidate the development of a new generation of chemical sensors applied for environmental monitoring applications.

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