Ultrasensitive Nano-Sensor for Organic Contaminants

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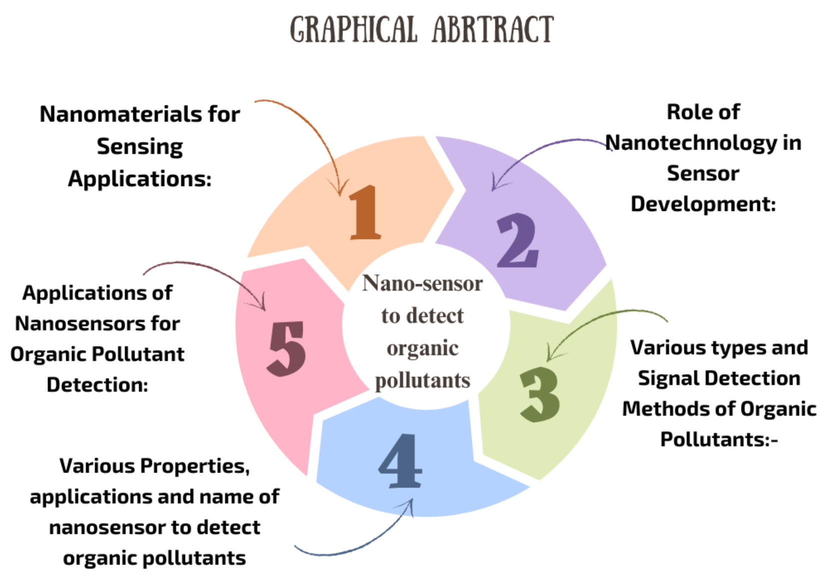
Abstract

Nanosensors have emerged as powerful tools for the detection and monitoring of organic pollutants in diverse environmental matrices. This review paper provides a comprehensive overview of recent advancements in nanosensor technology for the detection of organic pollutants, focusing on the utilization of various nanomaterials and sensing mechanisms. We discuss the unique properties of nanomaterials, including carbon-based nanomaterials, metal oxides, quantum dots, and nanocomposites, and their applications in sensing organic pollutants. Furthermore, we explore the integration of nanotechnology with advanced signal transduction techniques, such as electrochemical, optical, and piezoelectric methods, to enhance sensing performance. The review also highlights the challenges and opportunities associated with nanosensor development, including sensor stability, selectivity, miniaturization, and scalability. Finally, we discuss future research directions and the potential impact of nanosensors on environmental monitoring and human health. Overall, this review provides insights into the current state-of-the-art in nanosensor technology for organic pollutant detection and outlines future prospects for advancing environmental monitoring practices.



Keywords: - Nanosensor , organic pollutant, sensing application ,Nanotechanology

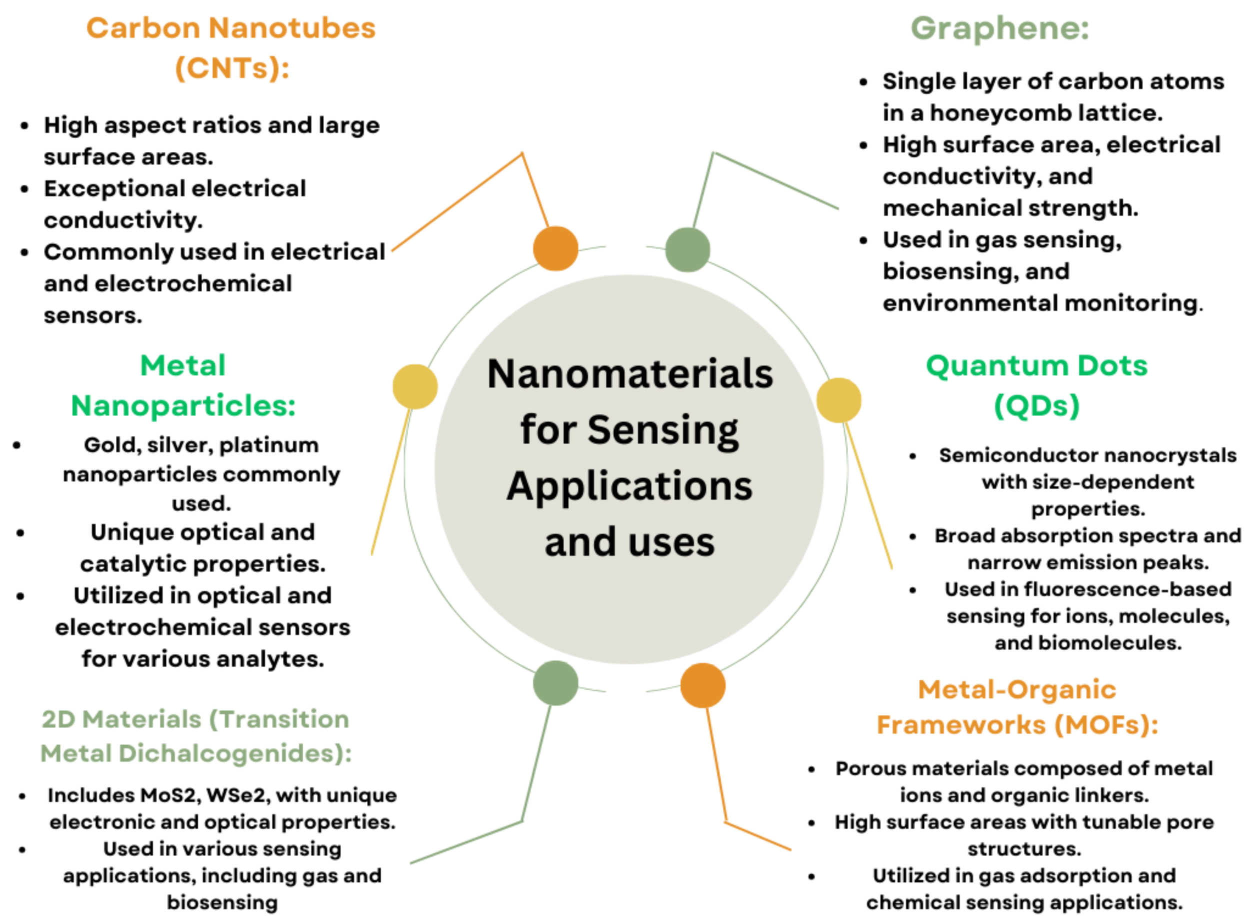
Introduction:-

In recent years, the global concern over environmental pollution, particularly by organic pollutants, has escalated, necessitating the development of advanced detection and monitoring technologies. The problem is in the fact that the organic pollutants of industrial origin, organic pollutants of the agricultural runoff, and pollutants that urbanization results in are very dangerous for the ecosystem and human health [1]. New sensing approaches need to be developed as a result, which are more sensitive, selective, and portable than the traditional detection methods. Thus, from the viewpoint of this consideration, nanotechnology appears to be the only technique for providing unparalleled opportunities for designing and developing sensors that are highly efficient in identifying organic pollutants with extreme sensitivity and specificity [2]. In this introduction, overviews of organic pollutants, importance of detection and monitoring of organic pollutants, and role of nanotechnology in sensor development are provided. Organic pollutants constitute a diverse group of chemical compounds derived from natural and anthropogenic sources, characterized by their carbon-based molecular structures. These pollutants encompass a wide range of substances, including polycyclic aromatic hydrocarbons (PAHs), pesticides, industrial chemicals, pharmaceuticals, and personal care products. Organic pollutants are released into the environment through emission to the air, discharge to wastewater, as well as leaching into landfills, and they are stable and can persist in the soil, water, and air for a long period. Such pollutants are poisonous to the ecosystem and human beings [3]. Most of these PBTs are characteristic of bioaccumulation in organisms, disruption of endocrine systems, carcinogenicity, and mutagenicity, forming a major environmental and public health concern.

The detection and monitoring of organic pollutants are essential for assessing environmental quality, safeguarding human health, and ensuring regulatory compliance. Timely and accurate identification of pollutant sources, determination of their concentrations, and evaluation of their fate and transport dynamics are crucial for implementing effective pollution control measures and remediation strategies [4]. Among the conventional analytical techniques, gas chromatography-mass spectrometry (GC-MS) and high-performance liquid chromatography (HPLC) are considered reliable but are often challenged by their high cost and complexity, laborious procedures for sample preparation. Moreover, application may be limited in real-time, on-site monitoring since the analyzed samples need to be transported for some distance before they reach the monitoring centers [5].

2. Nanomaterials for Sensing Applications:

Various nanomaterials exhibit unique properties that make them suitable for sensing applications across different detection mechanisms [6]:-



3. Role of Nanotechnology in Sensor Development:

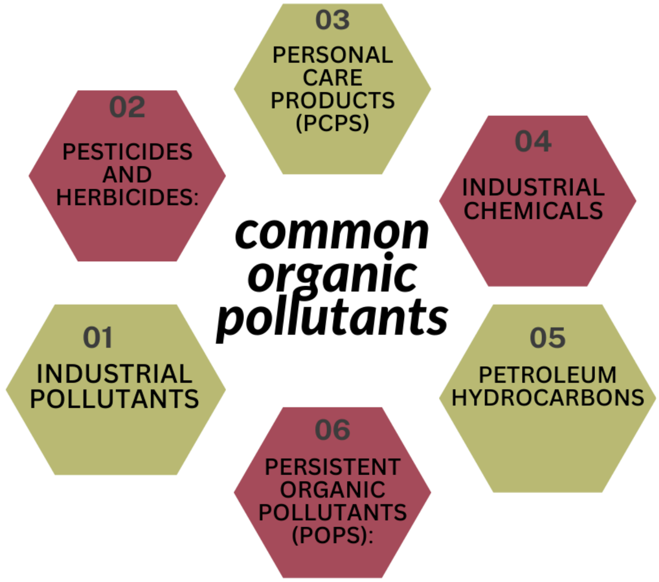
Nanotechnology, which involves the manipulation and utilization of materials at the nanoscale, has revolutionized sensor development by offering unprecedented control over material properties and device performance [7]. Nanomaterials, characterized by their high surface-to-volume ratios, unique electronic, optical, and catalytic properties, and enhanced reactivity, serve as ideal building blocks for sensing platforms.

Table: 1

Role of Nanotechnology in Sensor Development	**Nanosensor Name**	**Organic Pollutant Detected**	**reference**
Enhanced Material Properties	Carbon Nanotube Sensors	Polycyclic Aromatic Hydrocarbons (PAHs)	[8][9]
Improved Device Performance	Graphene-Based Sensors	Pesticides	[10][11]
High Surface-to-Volume Ratios	Metal Nanoparticle Sensors	Industrial Chemicals	[12][13]
Unique Electronic Properties	Quantum Dot Sensors	Pharmaceuticals	[14][15]
Enhanced Reactivity	Nanowire Sensors	Personal Care Products	[16][17]
Miniaturization and Integration	Nanoparticle-Decorated Microsensors	Volatile Organic Compounds (VOCs)	[18][19]
Compatibility with Emerging Technologies	Nanocomposite Sensors	Endocrine Disruptors	[20][21]

4. Various types of Organic Pollutants:-

Organic pollutants emanate from diverse sources that may include those from industrial activity, normal and usual consumer products used in everyday life, and those from the practice of agriculture among other sources [22]. Organic pollutants contribute substantially to the health of the environment.



Organic pollutants emanate from diverse sources that may include those from industrial activity, normal and usual consumer products used in everyday life, and those from the practice of agriculture among other sources. Organic pollutants contribute substantially to the health of the environment The most common include polycyclic aromatic hydrocarbons (PAHs) that develop from incomplete combustion of organic materials, widely found in industrial emissions and polluted soils [23]. The others are volatile organic compounds (VOCs) and incorporate chemicals including benzene and toluene that are pervasive in industrial solvents and vehicle emissions**.** Pesticides and herbicides, such as organochlorine and organophosphate compounds, are extensively used in agriculture for pest control but can persist in the environment and pose risks to ecosystems and human health [24]. Personal care products, including pharmaceuticals and cosmetics, contribute to pollution through their presence in wastewater effluents and surface waters. Industrial chemicals like polychlorinated biphenyls (PCBs) and polybrominated flame retardants (PBDEs) are persistent in the environment, originating from electrical equipment, insulation materials, and consumer products [25]. Petroleum hydrocarbons, such as BTEX compounds found in gasoline and diesel, are associated with fuel spills and underground storage tanks finally, the organic pollutants that are persistent (POPs) like dioxins and furans, resulting from industrial processing and waste incineration, represent major health risks both through their toxicity and bio-accumulation in the food web. Hence, the effective monitoring of the scenario and efforts of remediation are highly critical in reducing the possible adverse impacts of these organic pollutants on the environment and health [26].

5. Signal Detection Methods: for organic pollutes:-

Signal detection methods for organic pollutants aim to detect and quantify the presence of these contaminants in various environmental matrices [27]. Here are common signal detection methods used for organic pollutants:

A. **Optical Detection:** Optical detection methods for organic pollutants utilize the interaction between light and matter to identify and quantify target compounds. More specifically, these methods leverage the changes in optical properties, such as absorption, fluorescence, or scattering, induced by the presence of organic pollutants [28].

1. **Fluorescence Spectroscopy**: This technique involves the absorption of light energy by fluorescent molecules within the organic pollutants, followed by their re-emission of light at longer wavelengths. By measuring the intensity and wavelength of emitted fluorescence, analysts can determine the concentration of the target compounds. Fluorescence spectroscopy is highly sensitive and selective, making it suitable for detecting trace levels of organic pollutants in environmental samples [29].

2. **Absorbance Spectroscopy**: Absorbance spectroscopy measures the extent to which organic pollutants absorb light at specific wavelengths. Different compounds exhibit unique absorption spectra, allowing for their identification and quantification based on characteristic absorbance patterns [30]. This method is widely used for rapid and quantitative analysis of organic pollutants in various environmental matrices

3. **UV-Visible Spectroscopy:** This is one of the derivative forms of the absorbance spectroscopy that focuses on the detection of ultraviolet (UV) and visible light. Very many organic pollutants absorb light in the ultraviolet and visible spectral ranges and so UV-Visible spectroscopy will always be an effective tool in their detection and quantification [31]. This method is relatively simple, cost-effective, and widely applicable to a broad range of organic pollutants.

4. **Raman Spectroscopy**: Raman spectroscopy measures the scattering of monochromatic light by organic pollutants, providing information about their chemical composition and molecular structure. Raman spectra contain characteristic peaks corresponding to specific vibrational modes within the molecules, enabling identification and analysis of the target compounds. Raman spectroscopy offers high sensitivity and molecular specificity, making it valuable for detecting and characterizing organic pollutants in complex samples [32].

Optical detection methods offer powerful tools for analyzing organic pollutants in environmental samples, providing rapid, sensitive, and selective detection capabilities crucial for pollution monitoring and control efforts.

B. Electrochemical Detection

Electrochemical detection methods offer sensitive and selective means to identify and quantify organic pollutants based on their electrochemical properties. Two common techniques used in electrochemical detection are amperometry and cyclic voltammetry

1. **Amperometry:** The instrument measures the current that results from the electrochemical reactions between the organic pollutant and the electrodes. An interaction of the pollutant with the surface of the electrode will cause a redox reaction, which will lead to a change of current. This current could then be monitored over a given period of time to make it possible for the determination of the concentration of

the analyte [33]. In conclusion, amperometry is a highly sensitive method with a fast response time, and it is suitable for detecting trace levels of organic pollutants in environmental samples.

2. **Cyclic Voltammetry**: Cyclic voltammetry involves applying a potential sweep to the working electrode while measuring the resulting current. During the sweep, the potential is varied linearly, causing the organic pollutants to undergo oxidation or reduction reactions at specific potentials. By analyzing the resulting cyclic voltammogram, which plots the current as a function of applied potential, analysts can characterize the redox behavior of the analyte [34]. Cyclic voltammetry provides insights into the electrochemical properties, kinetics, and concentration of organic pollutants, making it a valuable technique for understanding their behavior in solution.

Both amperometry and cyclic voltammetry offer advantages in terms of sensitivity, selectivity, and versatility, making them widely used in electrochemical sensors for detecting organic pollutants [35]. These techniques play a critical role in environmental monitoring, enabling the assessment of pollution levels and contributing to efforts aimed at preserving environmental quality and human health.

C. Mass Spectrometry:

Mass spectrometry (MS) is a powerful analytical technique used for the identification and quantification of organic pollutants based on their mass-to-charge ratios. Two common methods of coupling mass spectrometry with separation techniques for the analysis of organic pollutants are gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS) [36].

1. **Gas Chromatography-Mass Spectrometry (GC-MS)**:

- GC-MS is the conjugation of gas chromatography (GC) with mass spectrometry for the separation and analysis of volatile organic compounds.
- In gas chromatography, the sample is vaporized and then introduced into a column, in which separation is initiated due to differences in volatility and affinity to stationary phase.
- The separated compounds are fragmented into ions that are analyzed with respect to the mass-to-charge ratio after ionization [37].
- Gas chromatography-mass spectrometry is the method of choice in separating and identifying individual compounds in complex mixtures with a high potential for environmental analysis of volatile organic pollutants such as benzene, toluene, and chlorinated solvents.

2. **Liquid Chromatography-Mass Spectrometry (LC-MS)**:

    1. LC-MS combines liquid chromatography (LC) with mass spectrometry to separate and analyze non-volatile or semi-volatile organic compounds.

2. In LC, the sample is dissolved in a liquid solvent and injected into a column where it undergoes separation based on differences in polarity, size, and chemical properties [38].
3. The separated compounds are then ionized in the mass spectrometer and analyzed based on their mass-to-charge ratios.
4. LC-MS offers high sensitivity and selectivity for the analysis of complex mixtures of organic pollutants, making it suitable for environmental analysis of pharmaceuticals, pesticides, and other non-volatile contaminants in water, soil, and biological samples [39].

Both GC-MS and LC-MS are widely used in environmental monitoring, forensic analysis, and pharmaceutical research for the detection and quantification of organic pollutants. These techniques provide valuable information about the composition, concentration, and distribution of pollutants in various environmental matrices, contributing to efforts aimed at protecting public health and the environment.

An eluent of a halogenated organic pollutant and other compounds' separated mixture is passed through a column where they would be eluted depending on their affinity with the stationary phase and volatility [40]. As they elute, they would be passed through a detector that contains a radioactive source, which is normally nickel-63 or tritium.

D. Electron Capture Detection (ECD)

Electron Capture Detection (ECD) is a specialized form of gas chromatography (GC) that is particularly effective for detecting halogenated organic pollutants, including pesticides and polychlorinated biphenyls (PCBs) [41]. This technique relies on the unique electron-capturing properties of these compounds.

The source will emit beta particles, and these beta particles are no more than highly energetic electrons. These beta particles, when they actually enter the detector chamber and start to interact with carrier gas molecules, will give rise to a set of low-energy electrons owing to the process of ionization [42].

- ECD is highly sensitive and selective for halogenated organic pollutants, making it a valuable tool for environmental monitoring, forensic analysis, and industrial hygiene. It is particularly useful for detecting trace levels of pesticides, PCBs, and other halogenated compounds in environmental samples such as air, water, soil, and biota.

E. Surface Plasmon Resonance (SPR):

Surface Plasmon Resonance (SPR) is a powerful optical technique used for detecting binding events between molecules in real-time. It relies on the phenomenon of surface plasmon resonance, which occurs when polarized light interacts with a thin metal film, typically gold or silver, causing collective oscillations of free electrons at the metal surface.

- In SPR-based sensing, a sensor chip with a thin metal film is typically coated with a layer of recognition elements, such as antibodies, aptamers, or molecularly imprinted polymers (MIPs), that are specific to the target analyte, in this case, organic pollutants [43]. When a sample containing the analyte is flowed over the sensor surface, any binding events between the analyte and the recognition elements lead to a change in the refractive index near the metal surface.

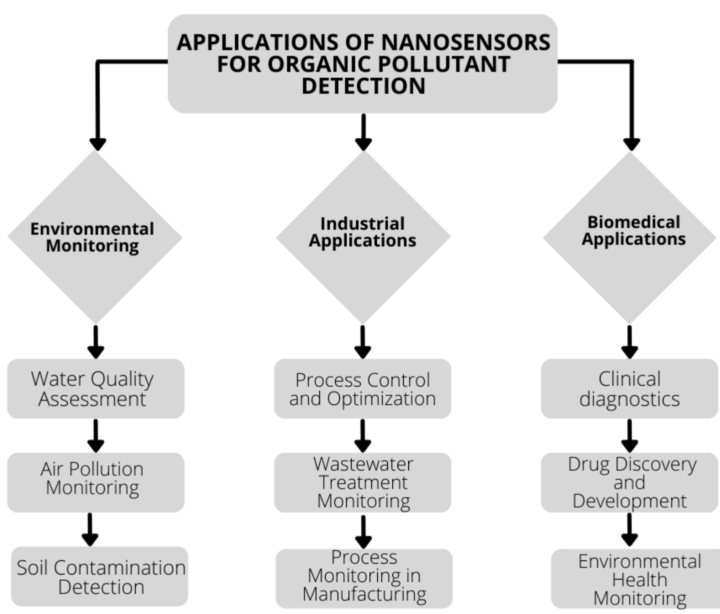
6. Various Properties, applications and name of nanosensor to detect organic pollutants:-

Table: 2

Aspect	Advantage	Disadvantage	Application	Nanosensor Example	Reference
Sensitivity	- High sensitivity due to nanoscale interactions	- Potential for false positives/negatives	Detection of trace levels of PAHs in soil and water	Carbon nanotube-based sensor for PAH detection	[44]
Selectivity	- Enhanced selectivity with tailored nanomaterials	- Cross-reactivity with similar compounds	Specific detection of pesticide residues in agricultural products	Molecularly imprinted polymer sensor for pesticide detection	[45]
Miniaturization	- Miniaturization enables portability and integration	- Fabrication complexity and cost	Portable detection of VOCs in indoor air quality monitoring	Microfluidic-based nanoparticle sensor for VOC detection	[46]
Real-time	- Real-time detection and monitoring	- Limited lifetime and stability of nanomaterials	Continuous monitoring of pharmaceutical contaminants in water	Quantum dot-based sensor for pharmaceutical detection	[47]
Multiplexing	- Ability to integrate multiple functionalities	- Complexity in data interpretation	Simultaneous detection of multiple pollutants in environmental samples	Plasmonic nanoparticle array sensor for simultaneous detection of multiple pollutants	[48]
Rapid response	- Rapid response time for quick detection and analysis	- Potential for signal interference from sample matrix	Rapid screening of food products for chemical contaminants	Graphene-based sensor for rapid analysis of food contaminants	[49]

Lower sample volume	- Requires smaller sample volumes for analysis	- Increased susceptibility to sample handling errors	Environmental monitoring in limited resource settings	Nanowire-based sensor for water quality assessment	[50]
Remote sensing	- Enables remote and distributed sensing capabilities	- Challenges in signal transmission and data transfer	Remote monitoring of pollutant levels in remote or hazardous areas	Nanoparticle-enhanced remote sensing system for environmental monitoring	[51]
Reduced cost	- Offers cost-effective detection solutions compared to traditional analytical methods	- Initial investment in equipment and infrastructure	Affordable monitoring of pollutants in developing regions	Paper-based nanoparticle sensor for on-site water quality testing	[52]
Versatility	- Versatile platforms can be customized for different applications and target analytes	- Optimization required for each specific application	Adaptable detection of pollutants in various environmental matrices	Functionalized nanomaterial-based sensor for multi-analyte detection	[53]

7. Applications of Nanosensors for Organic Pollutant Detection:-



A. Environmental Monitoring:

Environmental monitoring encompasses a wide range of activities aimed at assessing the quality of natural resources and identifying potential threats to ecosystems and human health. Nanosensors play a crucial role in environmental monitoring, particularly in the detection of organic pollutants [54]. Here are some specific applications within the realm of environmental monitoring:

I. **Water Quality Assessment**: Nanosensors are integral to water quality assessment, as they provide sensitive and real-time detection of organic pollutants in aquatic environments. These pollutants, which include pesticides, industrial chemicals, and pharmaceuticals, can contaminate water sources and pose significant risks to both ecosystems and human health [55]. Nanosensors offer the merits such as detection of trace levels of pollutants even in complex matrices with high sensitivity and selectivity. In sum, the nanosensors assist environmental authorities to source out pollution sources, measure success in clean-up activities, and verify if regulations are being followed by monitoring water bodies without In addition, the portability and deployment convenience of nanosensors lend themselves to on-site monitoring in remote or difficult environments—cases in which laboratory-based techniques would not be practical [56].

II. **Air Pollution Monitoring**: Nanosensors play a crucial role in monitoring air pollution by detecting volatile organic compounds (VOCs), particulate matter, and other pollutants in the atmosphere. These pollutants originate from various sources such as industrial emissions, vehicle exhaust, and agricultural activities, and can have detrimental effects on air quality and public health [57]. Nanosensors offer rapid response times and high sensitivity, allowing for continuous monitoring of air quality in urban, industrial, and residential areas.

III. **Soil Contamination Detection**: Nanosensors are instrumental in detecting organic pollutants in soil, aiding in the assessment and remediation of contaminated sites. Soil contamination, which can result from industrial activities, agricultural practices, or improper waste disposal, poses risks to ecosystems, groundwater quality, and human health [58]. Nanosensors offer advantages such as high sensitivity, low detection limits, and the ability to analyze small sample volumes, making them suitable for rapid and accurate detection of pollutants in soil samples.

- The sensors can identify, with a higher degree of the area contaminated, to what extent the contaminated areas have gone as well as the concentration of pollutants, supporting decisions in planning lands affected, help find solutions for environmental remediation, and reduce the risks involved with contaminated soil [59]. More importantly, the adaptability of nanosensors permits their integration into field-deployable devices, hence enabling on-site analysis and real-time monitoring of soil quality.

IV. **Ecological Monitoring:-** Nanosensors are very efficient and key tools when it comes to the detection of organic pollutants which may cause any damage to the health of wild animals and other ecosystems. Pollutants such as heavy metals, pesticides, and pharmaceuticals may cause ecosystem damage by accumulating in the ecosystem, which in turn disturbs the biotic and abiotic systems at these levels, and thus results in a loss of biodiversity and habitat degradation [60]. This is in line with the fact that nanosensors enable the sensitive and selective detection of pollutants from environmental samples and therefore will enable the researchers to estimate the degree of pollution and its effects on ecosystems. This includes not only measures to control pollution on sensitive species and ecosystems through the help of nanosensors, but also the pollution load in the key habitats, which include forests, wetlands, and marine environments, further aids in conservation and mechanisms for good ecosystem management [61].

B. Industrial Applications:

Industrial applications of nanosensors involve their utilization in various processes and operations within industrial settings to monitor and control organic pollutant levels [62]. Here's a detailed explanation of how nanosensors are applied in industrial contexts:

Table: 3

Application	Description	Example	reference
Process Control and Optimization	Nanosensors are used to monitor and control organic pollutant levels in industrial processes to optimize efficiency and ensure regulatory compliance.	Integration of graphene-based nanosensors in chemical production processes to monitor solvent concentrations and optimize reaction conditions.	[63]
Wastewater Treatment Monitoring	Nanosensors are employed in wastewater treatment plants to monitor organic pollutant concentrations and optimize treatment processes for effective pollutant removal.	Use of carbon nanotube-based nanosensors in wastewater treatment facilities to detect and quantify pharmaceutical contaminants and optimize treatment efficiency.	[64]
Contaminant Detection in Industrial Effluents	Nanosensors are utilized to detect organic pollutants in industrial effluents, enabling industries to identify and mitigate sources of pollution to	Integration of metal oxide nanoparticle-based nanosensors in industrial wastewater treatment systems to monitor oil and grease concentrations and	[65]

	minimize environmental impact.	prevent discharge of harmful pollutants.	
Process Monitoring in Manufacturing	Nanosensors are deployed in manufacturing processes to monitor organic pollutant levels, ensuring product quality, minimizing waste generation, and optimizing resource utilization.	Implementation of quantum dot-based nanosensors in semiconductor fabrication processes to monitor solvent vapors and ensure product quality and yield.	[66]
Emission Control and Monitoring	Nanosensors play a role in monitoring and controlling emissions of organic pollutants from industrial sources to comply with regulations, minimize air pollution, and reduce environmental impact.	Deployment of plasmonic nanoparticle-based nanosensors in industrial exhaust systems to detect and quantify volatile organic compound (VOC) emissions and ensure regulatory compliance.	[67]

C. Biomedical Applications

Biomedical applications of nanosensors involve their utilization in healthcare and life sciences to detect and monitor organic pollutants, toxins, and biomolecules in biological samples [68]. Here's a detailed explanation of how nanosensors are applied in biomedical contexts:

a) **Clinical diagnostics:** Nanosensors are applied to the detection and quantification of organic pollutants, toxins, and biomarkers in biological samples, including blood, urine, and saliva, in clinical environments. These sensors provide sensitivity, specificity, and rapid response time, which help in early disease and health condition detection [69]. Through detecting heavy metals, pesticides, and environmental toxins, nanosensors assist in the diagnosis, prognosis, and monitoring of diseases and health conditions related to the environment. Devices such justjson as the point-of-care diagnostic incorporating the nanosensors also facilitate the prompt testing of environmental contaminants on patients' samples, consequently facilitating timely intervention and treatment [70].
b) **Drug Discovery and Development**: Nanosensors contribute to drug discovery and development efforts by enabling high-throughput screening of organic pollutants for pharmacological activities. These sensors facilitate the identification of potential drug candidates, toxicity testing, and drug efficacy studies. By detecting interactions

between organic pollutants and biological targets such as enzymes, receptors, and nucleic acids, nanosensors help identify compounds with therapeutic potential and assess their safety and efficacy profiles [71].

c) **Environmental Health Monitoring**: Nanosensors are utilized in environmental health monitoring initiatives to assess human exposure to organic pollutants and environmental toxins. These sensors enable the detection and quantification of pollutants in air, water, soil, and food samples, providing valuable data for risk assessment and regulatory decision-making. By monitoring environmental contaminants such as heavy metals, pesticides, and industrial chemicals, nanosensors help identify sources of exposure, assess health risks, and inform public health policies and interventions[72]. For example, wearable nanosensors integrated into personal monitoring devices enable individuals to track their exposure to environmental pollutants and make informed lifestyle choices to minimize health risks.

8. Future Outlook and Recommendations for nanosensor to detect organic pollutants

The future outlook for nanosensors in detecting organic pollutants is promising, with continued advancements expected to enhance their performance, applicability, and impact. As technology continues to evolve, nanosensors are likely to become even more sensitive, selective, and versatile, enabling the detection of a broader range of organic pollutants at lower concentrations and in diverse environmental matrices. Furthermore, the integration of nanosensors with emerging technologies such as artificial intelligence, Internet of Things (IoT), and cloud computing is expected to revolutionize environmental monitoring by enabling real-time, remote, and autonomous sensing capabilities.

- The complete potential of the nanosensors in sensing organic pollutants can be realized only when all the actors come together with scientists, engineers, policymakers, and stakeholders. This collaboration can help to develop standardized protocols, methods of validation, and frameworks of regulation which can guarantee the reliability, accuracy, and reproductivity of measurements that are being performed with the help of the nanosensor technique.
- Moreover, there should be investments in R&D that are education- and infrastructure-related, to further the translation of nanosensor technologies from the lab to real uses for monitoring of the environment, maintaining public health, and further enabling policy development. This can only be achieved through supporting interdisciplinary partnerships that would leverage the capabilities of nanosensors in addressing complex organic pollutant challenges to foster sustainable and healthier conditions for the current and future generation.

Conclusion: -

The development of nanosensors for the detection of organic pollutants is known to unlock new and unexplored prospects, given the strides in nanotechnology. Interdisciplinary research, sustainable through handling the contemporary challenges and improving the performance of the nanosensors, will enable the nanosensor technology's full potential for environmental monitoring and health of humans and ecosystems. whereas this has spurred significant work in the area of developing nanosensors for the detection of organic pollutants, this is seen to be an area which still needs much research and innovation in order to live up to the hype of being a revolutionary technology. Together with the scientific community's collaborative efforts, the future potential of nanosensors to revolutionize environmental monitoring practices is high, bringing forward the initiative for a cleaner and safer environment for the posterity.

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