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Chemical Sensors for Environmental and Medical Diagnostics

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Abstract:
Chemical sensors are now essential in environmental monitoring and medical diagnostics, as they offer immediate, sensitive, and specific detection of many chemical substances. These sensors play a vital role in detecting pollutants, overseeing the quality of air and water, and guaranteeing compliance with environmental regulations. The incorporation of cutting-edge materials, nanotechnology, and microfabrication processes has greatly enhanced the capabilities of sensors, allowing for the accurate and dependable detection of minute impurities. Chemical sensors are used in environmental applications to monitor volatile organic compounds (VOCs), heavy metals, and particulate matter. These sensors are crucial for evaluating air quality and determining the effects of industrial activity on ecosystems. The utilisation of wireless sensor networks and Internet of Things (IoT) technologies has augmented the capacity of these sensors to offer extensive and uninterrupted environmental data.

Chemical sensors are revolutionising medical diagnostics by significantly impacting illness detection and patient monitoring. These sensors are specifically engineered to identify distinct biomarkers linked to a range of health disorders, such as diabetes, cancer, cardiovascular illnesses, and infectious diseases. Advancements in wearable and implanted chemical sensors have facilitated the continuous monitoring of health, providing instantaneous information on physiological factors such as glucose levels, pH, and electrolyte balance. Continuous monitoring is especially advantageous for the management of chronic illnesses and the optimisation of individualised treatment strategies. The integration of nanomaterials and biorecognition elements in biosensor technology has significantly improved the precision and sensitivity of chemical sensors, enabling the early and precise detection of diseases.

This study presents a thorough examination of the many categories of chemical sensors, their operational principles, and their specific uses in environmental and medical diagnostics. The text explores different sensor technologies, such as electrochemical, optical, and mass-sensitive sensors, emphasising their individual strengths and weaknesses. The paper also addresses the difficulties linked to the advancement of chemical sensors, such as the requirement for enhanced selectivity, stability, and miniaturisation. The text explores the future possibilities in the sector, highlighting the potential of combining material science, biotechnology, and data analytics to develop advanced sensors using interdisciplinary techniques.

The combination of new materials, biotechnology, and data analytics is recognised as a crucial factor in driving innovation in chemical sensor technologies. The report emphasises the significance of ongoing research and development to overcome current obstacles and fully exploit the capabilities of chemical sensors in improving environmental protection and healthcare outcomes. The incorporation of these sensors into intelligent systems and wearable technologies is expected to have a pivotal impact on the progress of public health and environmental sustainability.

Keywords: Chemical Sensors, Environmental Monitoring, Medical Diagnostics, Nanotechnology, Biosensors, Internet of Things (IoT), Wearable Devices, Pollutant Detection

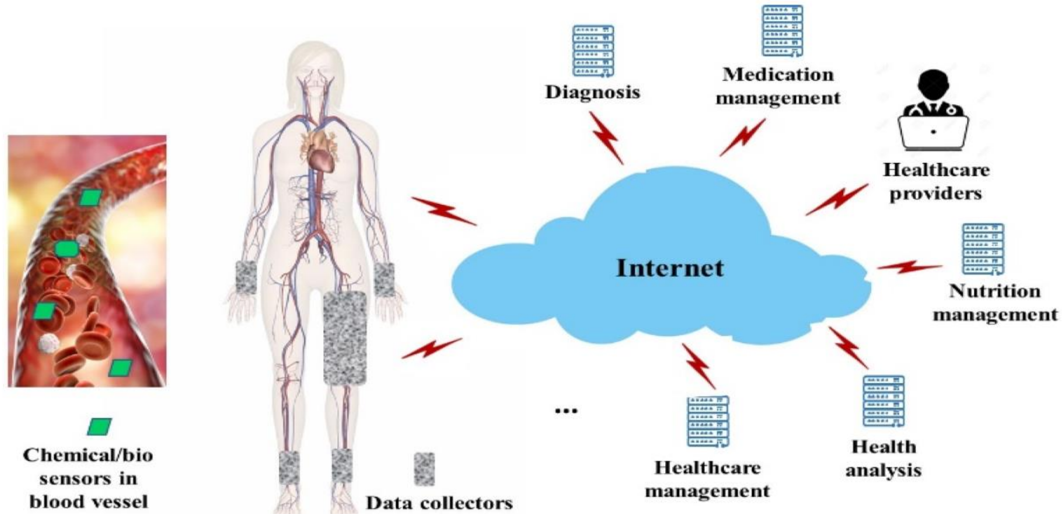

Fig 1. Graphical Abstract of Chemical Sensors for Environmental and Medical Diagnost **1.**

Introduction:

Chemical sensors have had a transformative impact on the areas of environmental monitoring and medical diagnosis. These sensors, which are specifically engineered to identify particular chemical substances with great sensitivity and accuracy, have become indispensable instruments in our endeavours to ensure public health and preserve the environment (1). Amidst a time characterised by increasing pollution and the rising occurrence of chronic illnesses, it is of utmost importance to possess the capability to observe and react to alterations in the chemical composition of our environment and our bodies.

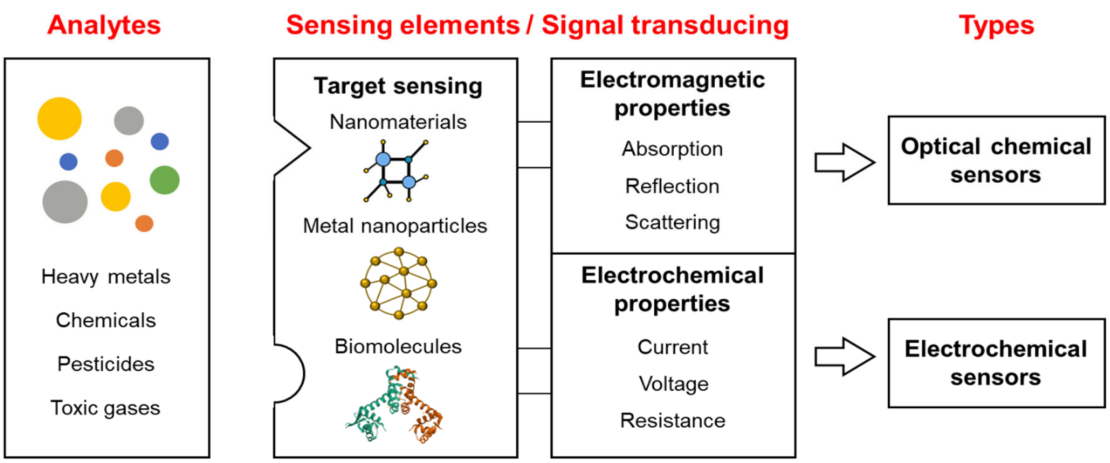

Fig 2. Types of chemical sensors based on sensing and transducing elements

The progress in chemical sensor technologies has significantly enhanced environmental monitoring. Conventional techniques for identifying contaminants typically require intricate and time-intensive laboratory examinations. Chemical sensors provide a more effective option by offering immediate information about the existence of pollutants such volatile organic compounds (VOCs), heavy metals, and particle matter. The prompt response is extremely helpful for ensuring adherence to regulations, conducting environmental research, and mitigating health problems caused by pollution (2). By incorporating these sensors into wireless networks and IoT systems, their functionality has been significantly improved, allowing for extensive and uninterrupted monitoring of air and water quality.

Chemical sensors have become influential diagnostic instruments in the medical field. They have the ability to identify biomarkers that indicate the existence of illnesses, allowing for early detection and prompt action. Electrochemical sensors utilised in glucose monitoring have revolutionised the care of diabetes, enabling patients to effortlessly and precisely monitor their blood sugar levels. Moreover, the utilisation of biosensors capable of identifying cancer biomarkers might greatly enhance the early identification of cancer, hence leading to substantial enhancements in patient outcomes. The emergence of wearable and implanted sensors has created new opportunities for ongoing health monitoring, offering immediate information on different physiological indicators and facilitating individualised healthcare.

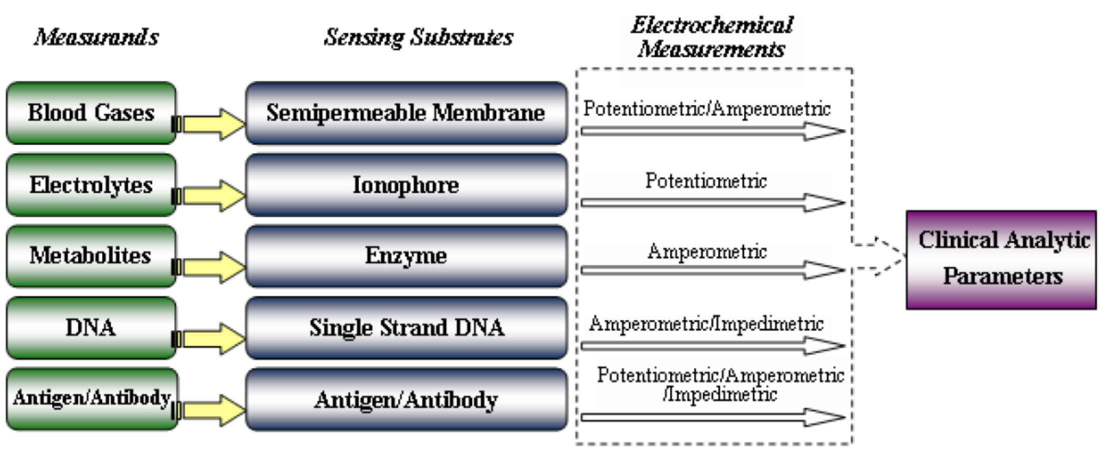

Fig 3. Clinical analysis procedures based on electrochemical sensors.

This study article seeks to offer a comprehensive assessment of the present condition and future potential of chemical sensors in the fields of environmental and medical diagnostics. The text will examine many categories of chemical sensors, such as electrochemical, optical, and mass-sensitive sensors, and provide an analysis of their operational principles and practical uses. The paper will also discuss the obstacles encountered in the advancement and implementation of chemical sensors, including the requirement for enhanced selectivity, stability, and miniaturisation. In addition, it will emphasise the potential of multidisciplinary methodologies, integrating innovative materials, biotechnology, and data analytics, to stimulate innovation in chemical sensor technology.

This paper aims to emphasise the crucial significance of chemical sensors in tackling the most urgent concerns of our day by analysing their improvements and applications. By engaging in ongoing research and development, chemical sensors possess the capacity to greatly improve environmental protection and healthcare results, so making a substantial contribution to a healthier and more sustainable future.

2. Literature Review

Chemical sensors are now essential instruments in environmental monitoring and medical diagnostics because they can detect and measure chemical compounds with great sensitivity and accuracy. These sensors transform chemical data into quantifiable signals, which can be examined for many purposes. Significant progress in material science, nanotechnology, and electronics has propelled the invention and enhancement of these sensors.

The inception of chemical sensors may be traced back to the early 20th century when the first gas detectors and pH sensors were created. An important achievement occurred in the 1950s with the development of the ion-selective electrode, which allowed for more accurate and specific measurements of ions (3). Subsequently, the field has experienced significant growth, embracing emerging materials like semiconductors, polymers, and nanomaterials. These materials have improved the performance and widened the range of applications for chemical sensors.

Chemical sensors can be classified according to their transmission process into electrochemical, optical, mass-sensitive, and thermal sensors. Electrochemical sensors quantify the electrical signals produced by chemical reactions occurring on the surface of an electrode. Optical sensors utilise the interaction between light and the target analyte, employing techniques such as absorption, fluorescence, and surface plasmon resonance. Mass-sensitive sensors, such as quartz crystal microbalances (QCM) and surface acoustic wave (SAW) sensors, are capable of detecting alterations in the mass or viscoelastic characteristics of a sensing layer when analyte adsorption occurs (4). temperature sensors detect alterations in temperature characteristics caused by chemical reactions, with catalytic combustion sensors being a prominent illustration.

The advancement of chemical sensors has been greatly improved by the innovation of new materials. Nanomaterials, including carbon nanotubes, graphene, and metal nanoparticles, possess distinctive electrical, optical, and catalytic characteristics that render them exceptionally efficient for chemical sensing purposes. These materials possess expansive surface areas and heightened responsiveness, resulting in better sensor performance. Conducting polymers and polymer composites offer the advantages of flexibility, simplicity in manufacturing, and adjustable characteristics for the purpose of sensor design (5). Metal oxide semiconductors such as ZnO, SnO_2, and TiO_2 are extensively utilised in gas sensors because of their large surface area and reactivity, which makes them highly efficient in detecting pollutants and harmful gases.

Chemical sensors are crucial in environmental monitoring as they offer immediate information on the quality of air and water. Air quality monitoring involves the use of sensors to detect various pollutants, including carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), ozone (O_3), and volatile organic compounds (VOCs). The progress in reducing the size of sensors and improving wireless connectivity has made it possible to create portable devices for monitoring air quality. Sensors are employed in water quality monitoring to identify contaminants such as heavy metals, nitrates, phosphates, and organic pollutants. Electrochemical sensors are highly useful in monitoring water quality because they possess both high sensitivity and selectivity.

Chemical sensors are utilised in the medical field to detect and measure biomarkers, which offer vital insights for illness diagnosis and management. Electrochemical glucose sensors are now widely used by diabetic patients as a reliable means of properly monitoring blood glucose levels. Continuous glucose monitoring devices offer immediate and ongoing information, greatly enhancing patient care and results. Advanced sensors have been created to identify various infections and biomarkers, such as proteins, nucleic acids, and tiny molecules. These sensors play a crucial role in detecting diseases at an early stage, enabling personalised medical treatments, and facilitating point-of-care diagnostics. Continuous health monitoring has been made possible by incorporating chemical sensors into wearable devices. These sensors have the ability to analyse physiological characteristics, such as the composition of perspiration, which can provide valuable information about hydration levels, electrolyte balance, and stress signs (6). This technology has the potential to revolutionise healthcare by offering non-invasive and real-time monitoring capabilities.

Chemical sensors encounter several obstacles, despite notable progress. Attaining a high level of selectivity for particular analytes in complex matrices continues to be a significant obstacle, as sensitivity to other chemicals might result in imprecise measurements. It is crucial to guarantee the long-term stability and endurance of sensors, particularly under challenging climatic circumstances, as the deterioration of sensor materials might impact their performance over time. The current movement towards making sensors smaller and incorporating them into portable and wearable devices brings about difficulties in maintaining performance levels while simultaneously reducing size and battery usage.

Future research aims to tackle these issues by exploring new materials, pioneering sensor designs, and employing sophisticated production techniques. The amalgamation of chemical sensors with digital technologies, such as artificial intelligence (AI) and the Internet of Things (IoT), is anticipated to transform environmental monitoring and medical diagnostics by providing unparalleled levels of sensitivity, specificity, and real-time data analysis (7).

Chemical sensors have shown great promise in tackling important issues in environmental monitoring and medical diagnostics. Further progress in material science, sensor technology, and data analytics will boost their performance and expand their applications, leading to better public health and environmental protection. This literature review focuses on the development, classifications, uses, and future prospects of chemical sensors, with a particular emphasis on their significance in contemporary scientific and technological domains.

3. Categories of Chemical Sensors

3.1 Electrochemical Sensors

Electrochemical sensors are instruments that identify and quantify chemical compounds by transforming them into electrical impulses via chemical reactions. These sensors function by relying on the idea that a chemical reaction takes place on the electrode's surface, resulting in an alteration in electrical characteristics such as voltage, current, or resistance. Common electrochemical sensors include potentiometric sensors, which detect voltage changes; amperometric sensors, which detect current changes; and conductometric sensors, which detect changes in electrical conductivity.

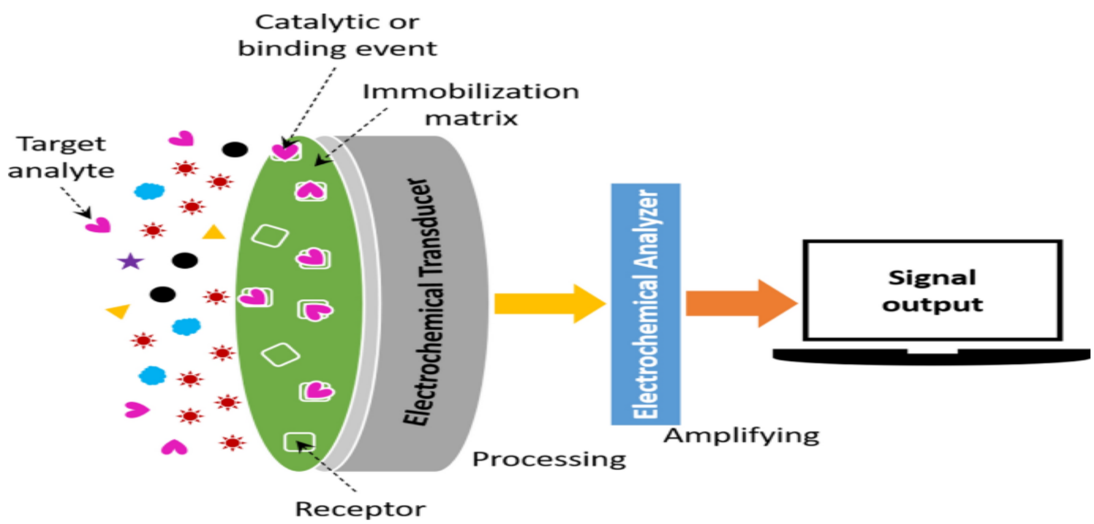

Fig 4. Electrochemical Sensors basic Principles

The Nernst equation is frequently employed to elucidate the potential of an electrochemical cell when it is subjected to conditions that deviate from the standard.

$$E=E∘−nFRTlnQ$$

Where E is the electrode potential, E∘is the standard electrode potential, R is the gas constant, T is the temperature in Kelvin, n is the number of moles of electrons transferred, F is the Faraday constant, and Q is the reaction quotient.

These sensors are extensively utilised in several applications, including glucose monitoring for individuals with diabetes, environmental monitoring of pollutants, and detection of dangerous gases, owing to their exceptional sensitivity, selectivity, and capability to deliver real-time data.

3.2 Optical Sensors

Optical sensors are instruments that employ light and its interaction with chemical compounds to detect and quantify them. These sensors function based on the idea that the existence of an analyte can induce alterations in the optical characteristics of a sensing material, such as absorption, fluorescence, or luminescence (8). Optical sensing often employs techniques such as absorption spectroscopy, fluorescence spectroscopy, and surface plasmon resonance.

The Beer-Lambert law is employed in absorption spectroscopy to establish a correlation between the absorption of light and the concentration of the analyte.

$$A=\epsilon cl$$

Where A is the absorbance, ϵ epsilonϵ is the molar absorptivity, c is the concentration of the analyte, and l is the path length of the light through the sample.

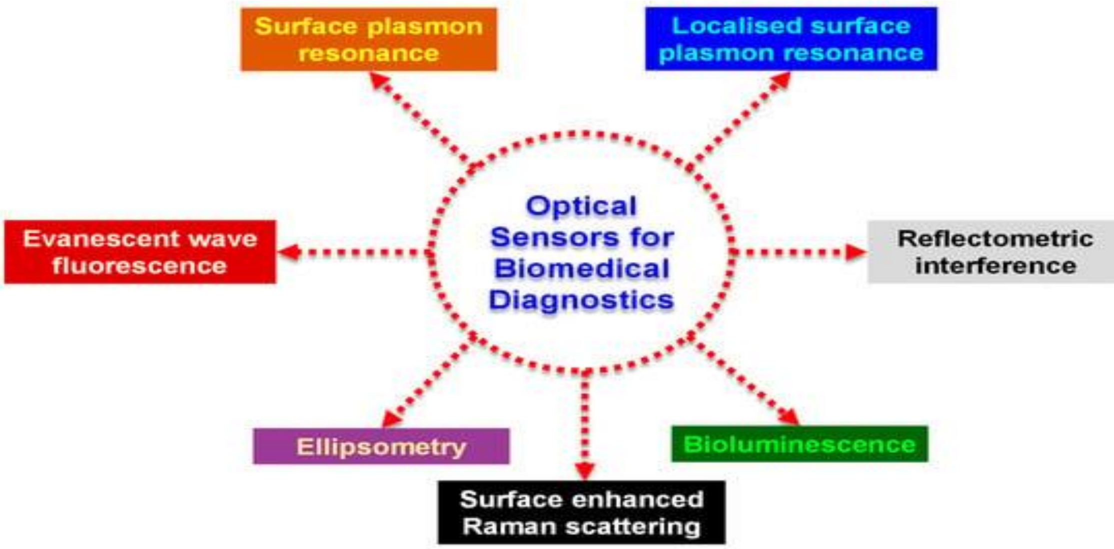

Fig 5. Different types of sensors classified on the basis of the underlying optical phenomenon arising from receptor-analyte interactions

Optical sensors are esteemed for their exceptional sensitivity, rapid response time, and capacity to conduct non-intrusive and remote sensing. They are widely employed in environmental monitoring to identify contaminants and in medical diagnostics for detecting biomarkers and infections.

3.3 Mass-Sensitive Sensors

Mass-sensitive sensors are instruments that identify and quantify chemical compounds by detecting alterations in mass. These sensors commonly employ a resonating component, such as a quartz crystal microbalance (QCM) or a surface acoustic wave (SAW) device. The resonant frequency of this component alters when mass is either added to or subtracted from its surface. The magnitude of mass alteration can be directly linked to the quantity of the analyte. The change in frequency (Δf) of a QCM can be described by the Sauerbrey equation:

$$\Delta f = -2f02\Delta mA\mu\rho$$

Where f0 is the fundamental frequency of the crystal, Δm is the change in mass per unit area, A is the area of the electrode, μ is the shear modulus of the quartz, and ρ is the density of the quartz.

Mass-sensitive sensors are renowned for their exceptional sensitivity and specificity, rendering them well-suited for the detection of minute quantities of analytes (9). They are utilised in several applications, including the detection of contaminants in the air and water, the monitoring of biological interactions, and the investigation of surface adsorption processes.

3.4 Thermal Sensors

Thermal sensors, or temperature sensors, identify and quantify chemical compounds by detecting alterations in thermal characteristics caused by chemical reactions. These sensors function based on the idea that chemical reactions can either emit or absorb heat, resulting in a temperature change that can be quantified.

The heat generated or absorbed (Q) during a chemical reaction can be described by the equation:

$$Q = mc\Delta T$$

Where m is the mass of the substance, c is the specific heat capacity, and ΔT is the change in temperature.

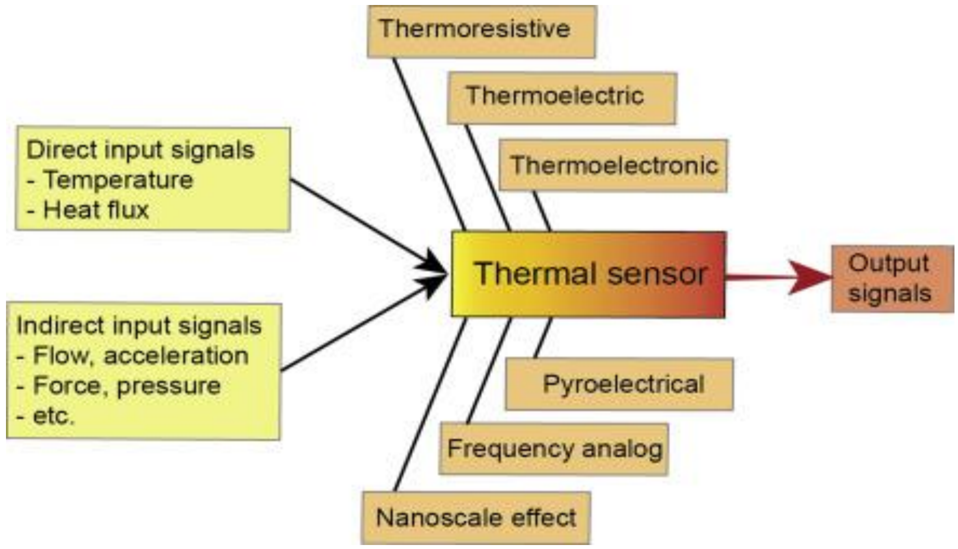

Fig 6. Concept of thermal sensors Physical signals (e.g., temperature, heat flux, flow and acceleration) are measured by thermal sensors.

Catalytic combustion sensors are a prevalent form of thermal sensor that measures the heat produced by the catalytic combustion of a flammable gas on a detecting device. The temperature change is directly proportional to the gas concentration.

Thermal sensors are highly regarded for their durability, straightforwardness, and capability to function in challenging conditions. They are utilised in several applications, including the detection of flammable gases, monitoring of industrial processes, and measurement of pollutant levels in environmental monitoring.

The various types of chemical sensors showcase the wide range of mechanisms and applications in which chemical sensing technologies are utilised, emphasising their crucial role in monitoring the environment and diagnosing medical conditions.

4. Chemical Sensor Materials

4.1 Nanomaterials, including Carbon Nanotubes and Graphene:

The field of chemical sensors has been significantly transformed by nanomaterials, thanks to their distinctive characteristics and impressive surface-to-volume ratio. Carbon nanotubes (CNTs) and graphene are widely utilised nanomaterials in chemical sensing applications.

1. Carbon nanotubes (CNTs): are cylindrical structures made of carbon atoms. Carbon nanotubes (CNTs) possess exceptional electrical, mechanical, and thermal characteristics, rendering them very suitable for sensor applications. CNT-based sensors possess exceptional electrical conductivity and exhibit remarkable sensitivity to environmental changes, enabling them to detect a wide range of chemical species even at exceedingly low concentrations. Both single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) have been used to create gas sensors for substances such as ammonia, carbon dioxide, and nitrogen dioxide (10). By adding specific chemical groups to CNTs, their ability to selectively and sensitively detect target analytes is improved. The variation in resistance (Delta R) of carbon nanotube (CNT)-based sensors with exposure to a certain gas can be characterised by:

ΔR=R0(P0P)α

Where R0 is the initial resistance, P is the partial pressure of the target gas, P0 is the reference pressure, and α is a constant dependent on the interaction between the gas and the CNTs.

Fig 7. Currently used methods for synthesising carbon nanotubes (CNTs).

2.Graphene: Graphene, a monolayer of carbon atoms organised in a hexagonal lattice, has received considerable focus because of its remarkable electrical conductivity, mechanical robustness, and extensive surface area. Graphene-based sensors utilise these characteristics to detect a broad spectrum of chemical substances with exceptional sensitivity and quick reaction times. Graphene oxide (GO) and reduced graphene oxide (rGO) have extra functions since they contain oxygen-containing groups that can interact with different analytes (11). The conductance shift (Delta G)of graphene-based sensors resulting from the adsorption of gas molecules can be represented by the following model:

ΔG=G0(1+n0Δn)

Where G0 is the initial conductance, Δn is the change in carrier concentration due to gas adsorption, and n0 is the initial carrier concentration.

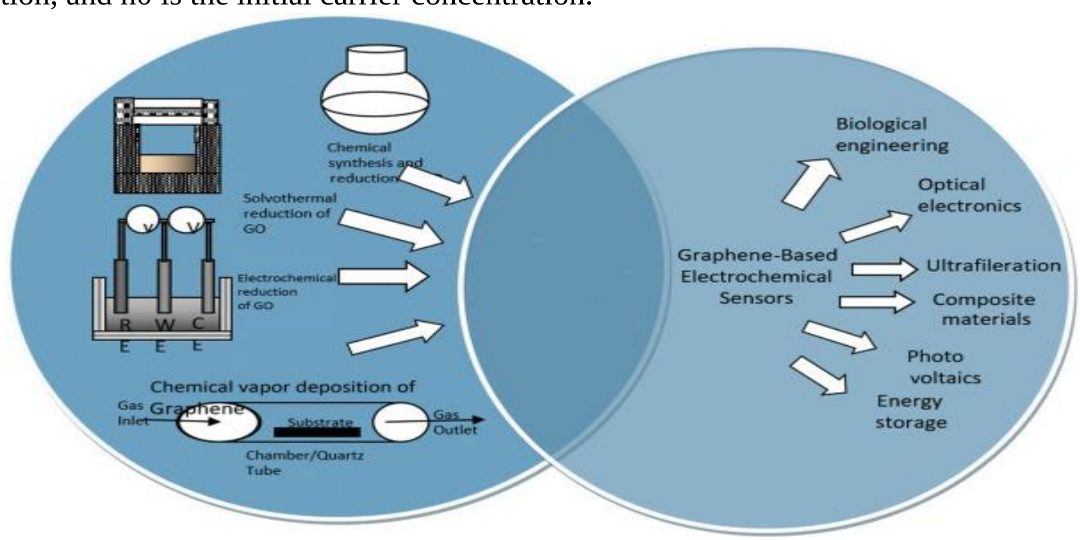

Fig 8. Applications of graphene-based electrochemical sensors

4.2 Polymers and Composites

Polymers and their composites are highly adaptable substances employed in chemical sensors because of their convenient manipulation, adjustable characteristics, and capacity to create discerning sensing layers.

Conducting polymers: Chemical sensors extensively utilise conducting polymers, including polyaniline (PANI), polypyrrole (PPy), and polythiophene (PTh). These materials have the ability to undergo reversible doping and dedoping processes when exposed to analytes, resulting in detectable alterations in their electrical conductivity. This characteristic renders them well-suited for the detection of gases, ions, and organic molecules.

$$\Delta\sigma=\sigma0(C0C)\beta$$

Where σ0 is the initial conductivity, C is the concentration of the analyte, C0 is the reference concentration, and β is a constant related to the polymer-analyte interaction.

1. Polymer composites: are materials made by combining two or more different types of polymers to create a new material with improved properties. The incorporation of polymers with other substances, such as nanomaterials, metals, or metal oxides, results in composites that possess improved sensing capacities (12). These composites utilise the combined effects of its components to provide enhanced sensitivity, selectivity, and stability. For instance, the addition of carbon nanotubes (CNTs) or graphene to polymer matrices improves the electrical characteristics of the resulting composite, rendering it more sensitive to environmental fluctuations. The variation in resistance (Delta R) in a polymer composite sensor can be mathematically represented as:

$$\Delta R=R0(1+k\cdot\Delta T)$$

Where R0 is the initial resistance, k is the temperature coefficient of resistance, and ΔT is the change in temperature due to the analyte interaction.

4.3 Metal Oxides - Alternative and Novel Materials

Metal oxides are widely employed in chemical sensors because of their exceptional catalytic capabilities, stability, and sensitivity to alterations in the chemical surroundings.

1. Traditional metal oxides: Typical metal oxides utilised in chemical sensors comprise zinc oxide (ZnO), titanium dioxide (TiO_2), and tin oxide (SnO_2). These materials are highly efficient in detecting gases such as carbon monoxide, hydrogen, and volatile organic compounds (VOCs).

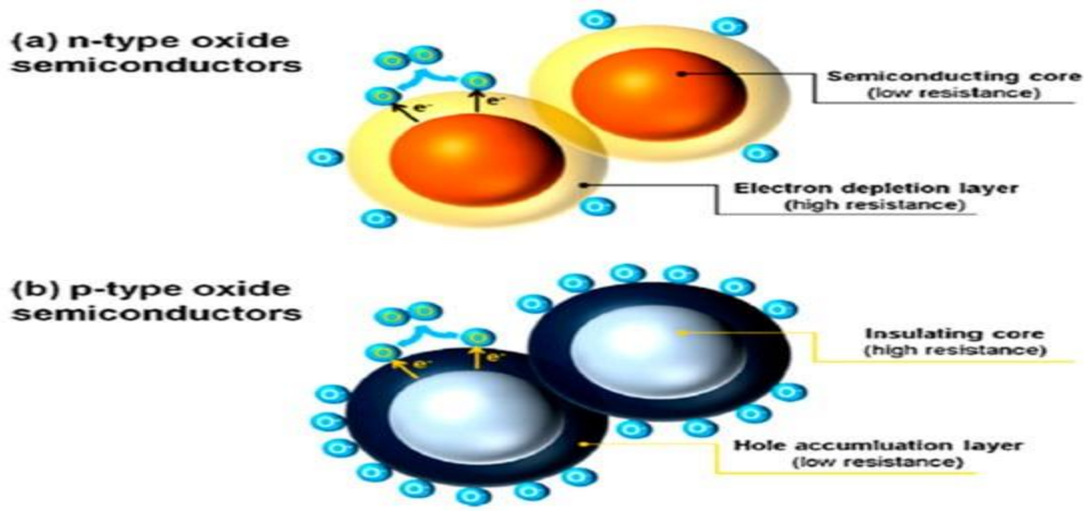

Fig 9. The electronic core-shell structures formation in metal oxide semiconductors

Metal oxide sensors function by detecting alterations in their electrical resistance upon exposure to specific analytes. The sensitivity (S) of a metal oxide sensor can be defined by:

S=RairRgas

Where Rgas is the resistance in the presence of the target gas, and Rair is the resistance in air.

2.Unconventional and Innovative Metal Oxides:

Current studies have concentrated on investigating unconventional and innovative metal oxides in order to enhance the capabilities of sensors. Tungsten oxide (WO_3), indium oxide (In_2O_3), and molybdenum oxide (MoO_3) have demonstrated potential in several sensing applications. These materials possess distinctive characteristics, such as the capacity to selectively adsorb certain gases, a high level of catalytic activity, and stability under various environmental conditions (13). Researchers are currently studying the use of mixed metal oxides and doped metal oxides to improve the selectivity and sensitivity of metal oxide-based sensors. The response (R) of a new metal oxide sensor can be represented by the Freundlich adsorption isotherm.

R=kf·C1/n

Where kf is the Freundlich constant, C is the concentration of the analyte, and n is the adsorption intensity.

5. Applications in Medical Diagnostics

5.1 Monitoring Glucose Levels - Advancements and Developments in Glucose Sensors

Regularly monitoring blood glucose levels is essential for effectively controlling diabetes. The accuracy, simplicity, and affordability of glucose monitoring devices have been greatly enhanced by advancements in glucose sensor technology. Conventional glucose monitoring utilises electrochemical sensors, in which glucose oxidase facilitates the oxidation of glucose, resulting in a detectable electrical signal that is directly proportional to the concentration of glucose. The fundamental response in these sensors is:

Recent advancements include the development of continuous glucose monitoring (CGM) systems that offer instantaneous glucose readings. These systems utilise subcutaneously implanted sensors that are minimally invasive and communicate data to an external device. The integration of nanomaterials such as gold nanoparticles and carbon nanotubes has significantly improved the sensitivity and reaction time of glucose sensors in the field of nanotechnology.

5.2 Pathogen and Biomarker Detection - Infectious Disease Sensors

The identification of pathogens and biomarkers is crucial for the diagnosis of infectious disorders. Chemical sensors are crucial in this domain as they offer quick and precise identification of pathogens, including bacteria and viruses. The detection process frequently entails capturing distinct biomarkers, such as proteins or nucleic acids, that are linked to the disease. One often used method involves utilising antigen-antibody interactions, which can be stated as:

Electrochemical, optical, and piezoelectric sensors are extensively employed for the purpose of pathogen detection. Electrochemical impedance spectroscopy (EIS) quantitatively detects changes in impedance resulting from the attachment of biomarkers to the sensor surface, allowing for the determination of pathogen concentration (14). The sensitivity and specificity of these sensors have been further improved through advancements in nanomaterials and surface functionalization.

5.3 Detection of Cancer Biomarkers - Wearable Body Sensors

Identifying cancer biomarkers is crucial for timely detection and therapy. Wearable sensors with the ability to detect cancer biomarkers provide a non-intrusive and uninterrupted monitoring solution. These sensors frequently depend on the detection of particular proteins, nucleic acids, or metabolites that are linked to cancer. The relationship between the biomarker and the sensor can be characterised as:

Notable advancements involve the use of wearable electrochemical sensors capable of detecting biomarkers present in sweat, saliva, or interstitial fluid. These sensors are incorporated into pliable materials, enabling them to adapt to the body and offer uninterrupted monitoring. The progress in microfabrication and nanotechnology has facilitated the creation of wearable cancer biomarker sensors that are both highly sensitive and selective.

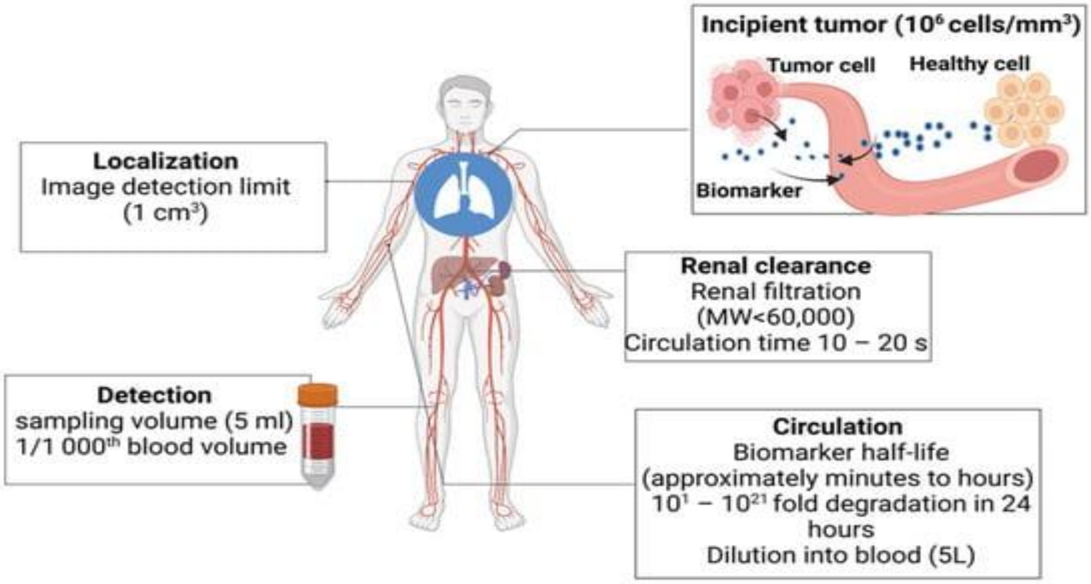

Fig 10. Difficulties related to the identification of tumors in their early stages. Due to their tiny size and the difficulties in transferring biomarkers from the tumor microenvironment to the bloodstream, early-stage cancers are challenging to detect.

5.4 Monitoring of Physiological Parameters

Chemical sensors are widely employed to monitor physiological characteristics, offering vital information about an individual's health condition. Various sensor technologies can be used to measure parameters such as pH, electrolyte levels, and oxygen saturation. For instance, pH sensors are used to quantify the concentration of hydrogen ions ([H^+]) in physiological fluids, a crucial factor in the diagnosis of metabolic and respiratory disorders. The Nernst equation provides the sensor response (E).

E=E0+nFRTln[H+]

Where E0 is the standard electrode potential, R is the gas constant, T is the temperature, n is the number of electrons transferred, and F is the Faraday constant.

Electrolyte sensors, including those that measure sodium and potassium ions, play a vital role in monitoring hydration and maintaining electrolyte equilibrium. Oxygen sensors, commonly utilising optical or electrochemical principles, gauge oxygen concentrations in blood or tissues, yielding insights into respiratory function and tissue perfusion. Integrating these sensors into wearable devices enables uninterrupted and non-intrusive tracking of vital physiological data, facilitating prompt medical interventions and enhancing patient outcomes (15).

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Chemical sensors are crucial in medical diagnostics since they provide advanced methods for monitoring glucose levels, identifying viruses and cancer biomarkers, and surveilling physiological factors. By incorporating these sensors into wearable devices, their usefulness is enhanced, allowing for immediate health monitoring and tailored healthcare solutions.

6. Result

The progress and use of chemical sensors in medical diagnostics have demonstrated substantial advancements, revolutionising healthcare by offering precise, instantaneous monitoring of diverse health indices. The subsequent passage provides a concise overview of the primary results obtained from employing chemical sensors in medical applications:

6.1 Improved Precision and Sensitivity

The utilisation of sophisticated materials, such as nanomaterials and metal oxides, has resulted in the development of exceptionally sensitive and precise sensors. These materials offer a substantial surface area for interacting with analytes, leading to enhanced detection limits and quicker reaction times. For example, the addition of carbon nanotubes and graphene to glucose sensors has improved their sensitivity, enabling accurate monitoring of glucose levels even at lower concentrations. The sensitivity (S) of these sensors can be measured using the equation:

$$S=I0\cdot\Delta C\Delta I$$

Where ΔI is the change in current, I0 is the initial current, and ΔC is the change in analyte concentration.

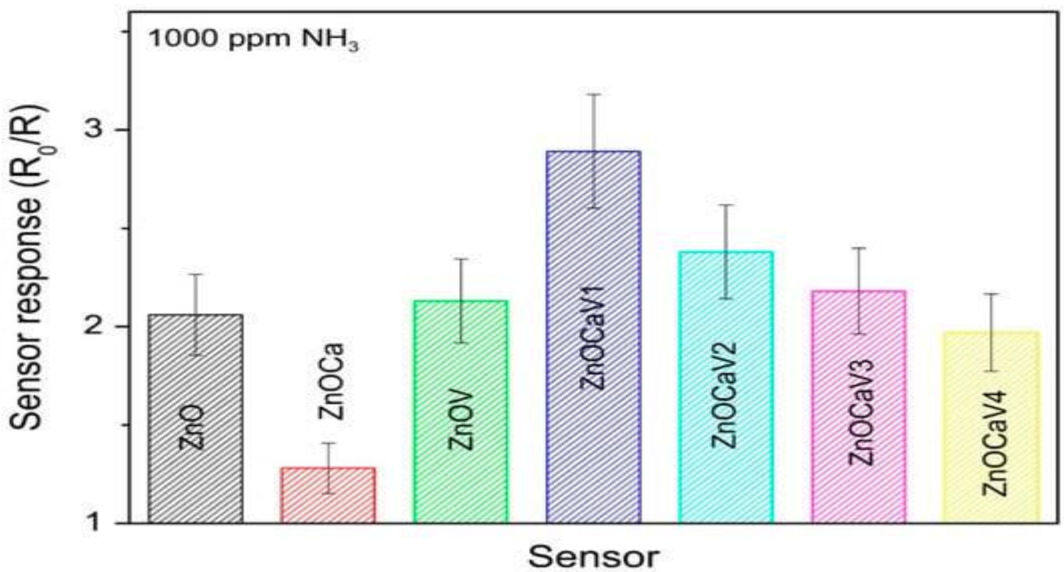

Fig 11. Detection response of 1000 ppm of ammonia for the investigated sensors.

6.2 Non-invasive and Continuous Monitoring

Chemical sensors incorporated into wearable devices allow for uninterrupted and non-intrusive tracking of vital health parameters. As a result, there has been an enhancement in patient adherence and satisfaction, along with prompt identification of anomalies. Continuous glucose monitors (CGMs) and wearable sensors for detecting cancer biomarkers exemplify the ways in which these technologies have improved patient care (16). The capability to observe physiological markers such as glucose levels, electrolyte equilibrium, and oxygen saturation without the necessity for regular blood extractions or clinical appointments signifies a noteworthy progression in medical diagnostics.

6.3 Early Detection and Intervention

Timely identification of disorders, such as diabetes, cancer, and infectious diseases, is essential for efficient therapy and enhanced patient results. Chemical sensors with the ability to identify particular biomarkers linked to various illnesses facilitate early diagnosis, enabling timely medical intervention. For instance, specialised sensors that are created to detect cancer biomarkers in bodily fluids have the ability to identify the existence of cancer at an initial phase, hence enabling prompt treatment and perhaps enhancing survival rates.

6.4 Incorporation of Telemedicine and Remote Monitoring

The use of chemical sensors into telemedicine platforms has enabled the remote monitoring and control of chronic illnesses. Patients have the ability to send real-time data to healthcare providers, which allows for continuous monitoring and timely actions without the requirement of frequent visits to the clinic. This is especially advantageous for individuals with chronic illnesses like diabetes, as it allows for the sharing of continuous glucose monitoring data with healthcare providers to enhance disease management.

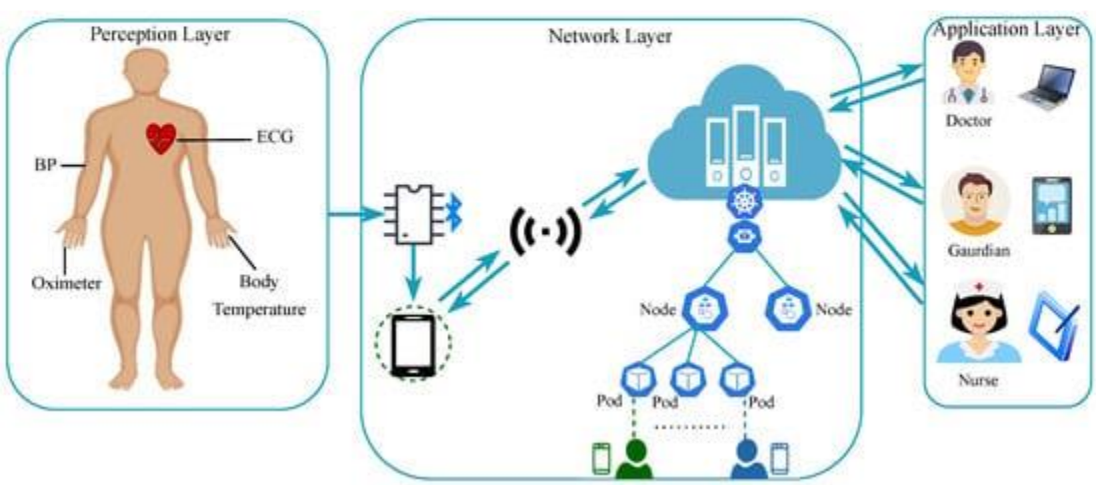

Fig 12. System model of the proposed scalable digital health framework.

6.5 Customised Healthcare

Chemical sensors capture data that allows for personalised healthcare by providing detailed information about an individual's health condition and patterns. By employing a personalised approach, healthcare providers are able to customise treatment programmes according to the individual requirements and circumstances of each patient (17). An example of this is the ongoing surveillance of glucose levels, which can assist in promptly modifying insulin dosages, resulting in improved glycemic control for those with diabetes.

6.6 Cost-Effectiveness and Accessibility

The progress in sensor technology has resulted in the creation of affordable diagnostic instruments that can be used by a wider range of people. The decrease in sensor expenses, combined with its incorporation into commonly utilised products such as smartphones and wearables, has made healthcare more accessible to the general public. This is particularly crucial in areas with low resources, where there may be restrictions on accessing advanced diagnostic facilities.

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