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REVIEW

A Comprehensive Review on Sensor Materials, Sensing Mechanism and their Applications

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The advancement of sophisticated sensing tools in the present days is made easier by sensor materials, which have grown in importance across a number of industries. These materials are essential for collecting critical data in order to control, monitor and make well-informative decisions since they are specifically designed to convert physico-chemical or biological inducements into computable signals. Understanding the challenges and opportunities associated with sensor materials is crucial, as the necessity for operational and pliable sensor systems continues to grow. A material's sensory capabilities include its ability to recognize and measure changes in its environment. A variety of techniques are covered by these characteristics, including as resistive, capacitive, optical, chemical and piezoelectric interactions. Even though these materials are used in different industries, including environmental observing, transportation, agriculture, medical and industrial operations. There are still recurring problems with increased sensitivity, selectivity and reaction speed. However, there appears to be hope for sensor materials since ongoing research and development is expected to produce things with improved enactment, robustness and energy efficacy. The possibility of developing highly sensitive and selective sensors with novel functions is made possible by the development of nanomaterials and advanced fabrication techniques. This development pays homage to the increase of the Internet of Things (IoT) and their uses in gathering vast amounts of data, which improve automation and decision-making. The current improvements, applications and research in sensor materials are reviewed in this review article along with the challenges they face and the prospects that could allow them to have a big impact on society and a variety of industries.

Keywords: Sensor materials, Computable signals, Sensor systems, Sensory capabilities, Internet of Things (IoT).

INTRODUCTION

These days, sensor materials are vital because they enable the development of advanced sensing technologies which are necessary for a wide range of industries [1,2]. These materials are designed to convert biological, physical or chemical stimuli into optical or electrical or any other signals that may be measured [3]. Moreover, they have exceptional electrical or electrochemical capacities which permit it to supply the important data for different functions like controlling, monitoring or decision making [4]. As the demand for efficient and flexible sensor systems increases, it is imperative to understand the opportunities and challenges associated with sensor materials [5,6]. The sensing properties of a substance are defined by its ability to detect and quantify changes in its physical or chemical surroundings [7]. The structural properties of sensing materials can be studied by various sophisticated analytical techniques. A variety of sensing methods are employed, depending on the stimulus type and component design [8]. These sensing methods involve optical, chemical and piezoelectric interactions. When exposed to specific gases or liquids, chemical sensors change their electrical properties, but piezoelectric things produce electrical signals while they experience mechanical strain. It is necessary to examine the mechanisms behind sensing processes before selecting the best materials for a given application [9].

Many fields including transportation, industrial processing and agricultural sector, medical and environmental field employs sensor materials for various controlling and monitoring systems [10-12]. For instance, in the medical fields, biosensors provide precise biomarker identification for early sickness diagnosis and therapy, environmental sensors assist in monitoring the quality of the air and water, while automotive sensors enable security and autonomous driving systems [13-15]. The vast array of uses enabled by the versatility of sensing materials will increase as technology advances. Even though sensor materials offer many benefits, they must meet specific needs such as improved sensitivity, selectivity and response speed. Sensor materials must be resilient to harsh operating conditions in addition to being long-lasting, affordable and environmentally benign [16-18]. As the internet of things (IoT) has grown, the network connection and interaction with information processing devices have also acquired a great importance. In order to enhance the reliability and performance of sensor materials their selectivity, sensitivity and response speed concerns must be fixed. The future of sensor materials looks hopeful by tackling certain hurdles raised during its implementations. It is important to continue researching and developing new materials that have improved performance, durability and energy efficiency [19]. Advanced production techniques and the development of nanomaterials will enable the creation of highly sensitive and selective sensors with novel capabilities. Additionally, sensor materials are anticipated to play a key role in emerging fields such as the IoT, which will be permitting the collection of vast amounts of data for enhanced automation and decision-making [20].

In this review, latest improvements, uses and research in sensor materials have been analyzed. Furthermore, it has explored the potential of these substances to shape our future, emphasizing both the obstacles and thrilling prospects they encounter. This article aims to give readers a comprehensive understanding of the evolution of sensing technologies and their profound impacts on various industries and society as they explore world of sensor material.

Materials employed as sensor: Numerous materials are employed in sensors, depending on the kind and function of the sensor. To enable their specialized operation, various sensor technologies need distinct materials. Recall that a sensor's specific requirements, including sensitivity, accuracy, ambient circumstances and so forth, influence the materials utilized in the sensor. The advancement of novel and enhanced sensor technologies is continuously facilitated by progress in materials science. Some of the popular and frequently used types of sensor are depicted in Fig. 1.

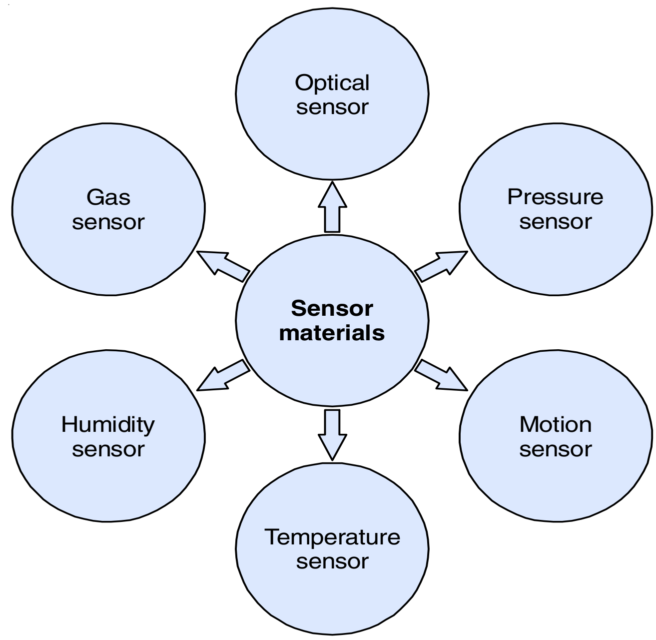

Fig. 1. Popular and frequently used types of sensor

Temperature sensors: Sensors are frequently regulated by measurements of constant current or voltage. The way voltage varies with temperature is determined by materials employed in the p-n junction [21]. Sensor design and material selection are crucial for meeting high-performance temperature sensor requirements. Materials, especially polymeric and nano-based materials, are being investigated for the construction of flexible temperature sensors [22]. They are widely used in a variety of applications, such as environmental monitoring, industrial processes, automotive systems, consumer electronics and more. The ideas used by various types of temperature sensors to detect temperature vary, as do their accuracy, sensitivity, reaction time and cost. The different types of temperature sensors are resistance temperature detectors, thermocouples, thermistors, *etc*.

Thermocouples function as thermometers, monitoring temperature and are manufactured by connecting two distinct metals at one end. Thermocouples work on the Seebeck phenomenon. When the temperature of the materials varies throughout their length, a voltage is produced, which can be used to measure temperature [23]. Thermocouples can be made from combining different metals in their correct proportions or they are also made from combination of different alloys. Thermocouples can be classified on the basis of components comprising it. The different types of the thermocouples are Type-K (Chromel/Alumel), Type-E (chrome l/constantan), Type-J (iron/constantan), Type-P (gold/palladium) and Type-N (nickel-chromium-silicon). Details of thermocouples are given in Table-1.

TABLE-1
E-TYPE, J-TYPE, K-TYPE T-TYPE AND N-TYPE COAXIAL THERMOCOUPLE MATERIALS

	Outer component	Inner component	Insulating substance	Surface intersection point materials	Ref.
Type-E thermocouples	Constantan	Chrome l	Teflon	Chrome l & constantan	[24]
Type-J thermocouples	Constantan	Iron	Teflon	Iron and constantan (Cu-Ni alloy)	[25]
Type-K thermocouples	Alumel	Chromel	Teflon	Chromel and alumel	[26]
Type-N	Constantan	Copper	Teflon		[27]
Type-T	Nisil	Nicrosil	Teflon		[28]

Resistance temperature detectors (RTDs) are sensor that measures temperature by detecting changes in resistance. RTDs are made of a material whose resistance changes predictably with temperature. An electrical current is passed through the sensor and the resistance element measures the resistance of the current. RTDs are more accurate and stable than thermocouples, especially below 600 ºC. They are also more linear over a wide range of temperatures. The most common types of RTDs are platinum, nickel and copper. The most popular RTD is the Pt100, which is known for its accuracy, repeatability and stability. Options for high temperatures includes germanium, carbon resistors, ruthenium oxide and rhodium-iron alloys [29].

Thermistors, a solid-state component with electrical resistance that rapidly varies in response to temperature changes, thermistors are also known as thermally sensitive resistors. Due of their ease of use, portability, durability, long lifespan and low maintenance requirements, they are positioned as prospective components for a range of applications, including scientific research, communication, instrumentation and military technology [30]. Thermistors can be classified as either positive (PTC) or negative (NTC) depending on their temperature coefficient. Higher temperatures result in more resistance for PTC thermistors and reduced resistance for NTC thermistors. The materials for negative temperature coefficient (NTC) thermistors are created by the chemical interaction of several transition metal oxides (CoO_2, CuO and NiO_2). This can be used for low temperature sensing (30 to 300 ºC) for domestic applications while materials like ZrO_2, Y_2O and ThO_2 are employed in high-temperature sensing (300 to 1000 ºC) mostly found in autos [31]. There are two types of thermistors or positive temperature coefficient (PTC) thermistors, which are defined by their response to changes in temperature [32]. Different types of temperature sensitive suggested sensors are given in Table-2.

TABLE-2
TEMPERATURE SENSITIVITY AND THE RANGE OF SUGGESTED SENSORS

Sensing structure	Temperature range (°C)	Temperature sensitivity (nm/°C)	Ref.
Sagnac interferometer	42-44	29	[33]
Sagnac interferometer	0-10	1.46	[34]
Sagnac interferometer	55-65	1.7	[35]
Fabry-Perot interferometer	20-60	12.5	[36]

Pressure sensors: Pressure sensors are most widely employed micro-devices for industrial, viable and therapeutic sensing [37]. These sensors are necessary for a wide range of applications, including industrial operations, consumer electronics and medical equipments. Different concepts are used by various types of pressure sensors to measure pressure and its working mechanisms enable them to be classed together.

Piezoelectric sensors: The Greek term "piezo" implies "press" or "squeeze." When a crystal is compressed to apply mechanical stress, an electrical potential is created across its sides, a phenomenon called piezoelectricity or the piezoelectric effect [38]. While the opposite phenomenon–often used in actuation–produces strain proportionate to an applied electric field, piezoelectricity, which is observed in non-centrosymmetric crystals, involves developing electric polarization under stress [39]. The former, sometimes referred to as the direct effect, is employed to identify force changes, acceleration changes caused by shock or vibration and changes in pressure dynamics. Upon applying a voltage, the opposing piezoelectric effect results in deformation by generating mechanical stress in a piezoelectric material in reaction to an external electric field. The transduction element, which is frequently apply for the sensing element, is typically made of a combination of piezoelectric ceramics and single crystals like quartz, tourmaline, orthophosphate, gallium, CGG-group crystals, lithium niobate, lithium tantalate and lithium sulphate. Crystals like quartz and organic materials like wood and silk are examples of natural piezoelectric materials. Quartz-like crystals, ceramics, polymers and composites are examples of man-made piezoelectric materials. Some crystals exhibit piezoelectric properties as a result of polarization and deformation under the influence of mechanical stress or an electric field [40]. Notable among the families of artificial ceramics are perovskite structures like barium titanate and lead zirconate titanate (PZT), which require specific preparation methods to provide desired piezoelectric activity *via* poling [41]. A piezoelectric pressure sensing material is created by combining ZnO nanomaterial with P (VDF-TrFE) co-polymer [42]. Especially in its β-phase, trifluoroethylene affords the co-polymer remarkable piezoelectric properties. ZnO is a lead-free piezoelectric material which is added to the co-polymer to further enhance its properties. The polymer nanocomposite that is produced by this mixture is then used to build a pressure sensor prototype so that its ability to detect pressure changes can be evaluated [43].

Strain gauge sensors: A popular kind of sensor, strain gauges are used in many different applications, such as force sensing and structural health monitoring, where mechanical deformation needs to be analyzed. Different types of pressure sensors with their response time, pressure limits, sensitivity and linearity range are given in Table-3.

Optical sensor: An optical sensor is a tool that counts the number of light beams and converts that number into an electrical signal that a human or electronic device can read. Numerous applications have made extensive use of them due to their adaptability and ability to deliver non-contact sensing. The optical sensor is the most sophisticated sensor for detecting volatile gases since it makes use of the ideas of reflectance, absorbance, fluorescence, luminescence and refractive index

TABLE-3
COMPARISON OF PROPERTIES AMONG VARIOUS PRESSURE SENSORS

Types	Response time	Pressure limit	Sensitivity	Linearity range	Detection limit	Ref.
Piezoelectric sensors	Medium	Wide range	High	Excellent	Medium	[44]
Strain gauge sensors	Medium	Low to moderate range	Medium-High	Good	Low	[45]

[46]. Optical sensors are employed in a wide range of fields, including consumer electronics, industrial automation, medical equipment, environmental monitoring and more.

Photodiodes: Materials used in photo-detectors, particularly organic photodetectors (OPDs), include small molecules, fullerenes, polymer compounds (like P3HT and PC 61 BM), poly(phenylene-vinylene) derivatives, polyfluorene derivatives, squaraine compounds and phthalocyanines. These materials are utilized in a variety of combinations to maximize photodetector performance at different electromagnetic spectrum wavelengths, ranging from visible to near-infrared. These substances were selected due to their capacity to absorb substances [47,48]. Photo-diodes require a wide range of materials, including crystalline inorganic semiconductors such as silicon, GaP, Ga_2O_3, GaAs, HgCdTe, Ge, ZnO and CdS. Furthermore, topics covered include halide perovskites, hetero-structure photodiodes utilizing a variety of semiconductor combinations, topological insulators such as bismuth telluride (Bi_2Te_3) and colloidal inorganic quantum dots, such as PbS or Ge [49].

Photo-transistors: Photo-transistor devices use captivation layers composed of chalcogenide materials like MoS_2, CdS and Se to enhance light absorption over certain wavelength ranges. While Se and CdS offer effective absorption in visible spectral regions, improving photo-responsivity in photo-transistors, the tiny bandgap of 2D chalcogenide MoS_2 enables the visible light detection. For improving photo-transistor enactment in a range of applications, these elements are crucial [48].

Gas sensors: Because of their low power consumption, high sensing capabilities and long-term stability, gas sensors that function at ambient temperature are far more attractive. Flexible gas sensors typically employ metal oxides, graphene, carbon nanotubes (CNTs), polymer composites and metal nanoparticles. These compounds are chosen for their unique properties and suitability for identifying specific gases [50,51]. Semiconductor gas sensors detect flammable and hazardous gases by tracking changes in the electrical resistance of a polycrystalline sensor element made of oxide materials as gases adsorb or react with its surface. These sensors are versatile and can be used to detect gases such as CO_2, NOx, O_2 and fluorocarbons. In certain situations, gasses can also be detected by changes in capacitance.

Motion sensors: A motion sensor is a gadget that can identify motion or physical movement in its environment and in reaction, can start a certain operation. These sensors are extensively used in many different applications, including as home automation, lighting control, security systems and even wearable fitness devices that use them to identify physical activity. There are many different types of motion sensors, such as passive infrared sensors that identify changes in heat signatures, ultrasonic sensors that use sound waves to identify motion and microwave sensors that generate microwave signals and analyse their reflection to identify movement [52].

Accelerometers: Accelerometer typically use materials called MEMS (Micro-Electra-Mechanical Systems) to measure acceleration [53]. Typically, accelerometers employ piezoelectric components, such as strong permanent magnets for magnetic induction-based sensors or single crystals of lithium niobate ($LiNbO_3$) for high-temperature applications. There are certain temperature ranges and sensitivity requirements for each of these materials.

Gyroscopes: The word "gyroscope" is derived from the Greek words "skopein" (to view) and "gyros" (revolving). Sensors and gyroscopes are made of a variety of materials–silicon for MEMS compatibility, quartz for high-precision applications and piezoelectric materials like PZT that produce electrical charges in response to mechanical stress depending on their intended use and performance requirements [54]. It is commonly known that quartz has piezoelectric qualities, which allow it to produce electrical impulses in reaction to vibrations or mechanical stress. Additionally, inertial materials, metals, ceramics and polymers are employed; the choice of material is contingent upon the particular gyroscope or sensor's parameters.

Sensing mechanism: The design of the sensor structures and the use of multifunctional materials are critical factors in multimodal sensors with decoupled sensing mechanisms. Highlighted are recent developments in our knowledge of the properties of the materials, the impact of their structure and sensing mechanisms for a range of input signals [55]. The resistive, capacitive, optical and piezoelectric sensing technologies are examined in this part, shedding light on how material properties impact the conversion of analyte-induced changes into measurable signals. It is crucial to comprehend the sensing principles underlying the different kinds of sensors in order to construct effective sensing devices. Analyte-induced changes are converted into detectable signals by the unique interactions of target analytes with different kinds of sensor materials and designs.

Capacitive sensing mechanism: Capacitive sensors are characterized by their capacity to modify capacitance in response to external stimuli [56]. A common kind of capacitive sensor is a parallel plate capacitor, which is usually positioned between upper and lower conducting electrodes. An insulating dielectric layer separates it from the electrodes [57]. Both the materials selected and the structure design of electrodes and core layers are critical for capacitive sensors to have superior sensing performance in terms of sensitivity, linear range, SNR ratio and stability [58]. When a voltage is given to one electrode, charge builds up in the space between two metal sheets or electrodes, according to the capacitance principle.

Piezoelectric sensing mechanism: A piezoelectric sensor is a transducer that converts mechanical stress or strain into electrical signals using materials that exhibit the piezoelectric effect. In comparison to other high-temperature sensing methods, piezoelectric sensing is becoming more and more common for use in high-temperature applications in the power, automotive, aerospace and material processing industries because of its low cost, small sensor size and simple signal conditioning.

Optical sensing mechanism: As a discriminating device, an optical sensor is adept at detecting and quantifying the physical strength of incident light beams, successfully translating this optical information into an electrical signal that can be understood by electronic devices and instruments or by human operators. Because of their versatile nature, these sensors have found extensive use in a wide range of industrial areas, including healthcare, environmental monitoring, energy, aerospace and many more [59,60]. Optical sensors are rapidly developing and becoming increasingly widespread. Optical sensors can be classified as SPR-based, SERS-based biosensors, fluorescence based, structural color-based, *etc*., according to their detection mechanisms [61]. In order to detect, quantify and track the presence of analytes of interest, label-free optical biosensors are instruments that can rapidly perform an assay with high sensitivity and specificity at the point of application. Optical sensors are widely used in biochemistry, medical diagnostics and environmental monitoring.

Electrochemical sensing mechanism: Nanomaterials are appealing for sensing applications, particularly electrochemical sensing, due to their specific properties, which include their remarkable electrochemical capabilities, high surface area and adjustable electric conductivity [62]. An electrochemical biosensor detects the concentration of the target analytes by oxidizing or reducing the analyte at an electrode and measuring the conductance, change in current or impedance [63]. Because of their unique electrocatalytic properties, large adsorption capacity, minuscule size, large surface area and simplicity of surface modification, nanomaterials have shown promise for bio-sensing applications in recent decades.

Nanomaterial-based sensing mechanism: The creation of inexpensive, portable, accurate and fast-to-identify nanosensors has been made possible in large part by nanotechnology. Developments in the creation of nanomaterials have shown the great promise of nano-sensors for explosives detection. One of the main uses for nano-sensors, which bank on the unique electrical, optical or magnetic properties of nanomaterials, is the detection of environmental viruses. Detectable signals with high sensitivity, high specificity and fast response times can be generated when viruses interact with nanoparticles (or recognition agents on the nanomaterials) [64]. Nanomaterial-based sensors have revolutionized the wearable health monitoring field of bio-electronics nano-engineering, resulting in significant advancements in ongoing and customized healthcare [65]. A nano-biosensor can detect biological substances such as metabolites, pathogens, antibodies and nucleic acids. By binding desirable bio-analytics to receptors, the approach modifies the physicochemical sign associated with binding [66]. Biosensors are employed in biological testing, forensic analysis, health monitoring, diagnostics and the treatment of mental health issues in addition to monitoring infectious diseases. In addition to offering healthcare and therapy, biosensors can track patients' states and diagnose diseases more promptly [67].

Wireless sensing mechanism: Wireless sensor networks (WSNs) are a key element of the communications sector. WSNs are usually made up of a lot of low-cost sensors that can communicate wirelessly and process data. Through one-hop or multihop routing, these sensors automatically collect environmental data in an orderly manner and send it to sinks [68,69]. A wireless sensor network is a group of many sensor nodes dispersed around a territory to monitor an area of interest. In many WSN applications, the data is useless without the exact location of sensor nodes. Understanding and applying these different sensing processes is crucial for the creation of reliable, accurate and efficient sensing devices for a variety of applications [70]. The particular requirements of the application, the kind of analyte and the required degree of sensitivity and selectivity all play a role in the choice of sensing mechanism.

Applications of sensor materials: About a decade of metamaterial research for sensing application has led to the development of smaller and more effective sensors [71]. Sensor materials are employed in many different industries because of their ability to gather data and facilitate precise analysis. Some specific applications of versatile sensor materials are shown in Fig. 2.

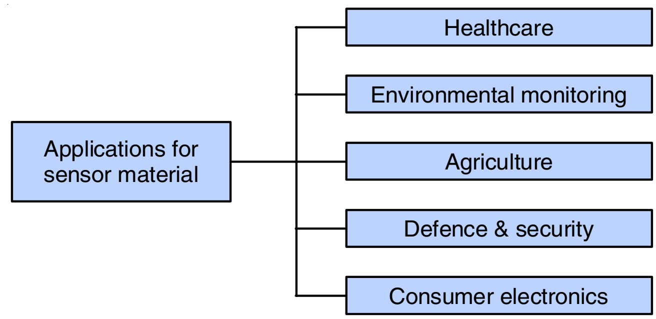

Fig. 2. Sensor materials applications

Healthcare: The healthcare industry has grown significantly in recent years and has contributed significantly to employment and income [72]. Because of their unique characteristics, these allotropes are very helpful for a range of biological applications, such as drug administration, tissue engineering, cancer treatment, medical diagnostics, bio-imaging and biosensing. Depending on the kind of physiological data collected, wearable sensors used in regulated settings like houses can be either static or very dynamic. A range of sensor networks are being used in the design of the architecture for wearable sensing applications. Some features of these networks, like cost, setup and power usage, are considered when integrating with wearable sensors [73]. For the sensor prototypes to function, the protocols of Bluetooth (IEEE 802.15.1), Wi-Fi (IEEE 802.11), ZigBee (IEEE 802.15.4) and radio-frequency identification tags (RFID) have been considered. Electronic/optical tattoos, smartwatches, head-mounted displays, hearing aids, footwear with subcutaneous sensors and electronic textiles are a few examples of wearable technology. For drug delivery and the measurement of electro-physiological or biochemical signals, they are simply applied to the epidermis and inserted through the skin or other bodily openings. Multiple wearable sensors may send data to a body area network through multiple sensor arrays [74].

Environmental monitoring: Applications for environmental monitoring are essential for obtaining information about the condition of the environment around us, such as whether it is improving, deteriorating or remaining unchanged. Environmental sensors are primary instruments for monitoring the environment and eventually, its protection. Recently, nanomaterials have been extensively studied and employed for environmental sensing due to their exceptional dimension characteristics [75]. Rapid world-wide urbanization and industrialization have resulted in huge economic welfares but also led in the exhaustion of natural resources and caused major environmental pollution problems. Inland water quality detection has made extensive use of hyperspectral remote sensing. This method uses a direct, high-resolution analysis of the electromagnetic spectrum reflected from the water surface to obtain the water quality parameters. By employing a non-contact approach, this novel approach presents the opportunity to generate real-time data from water, significantly increasing operating efficiency [76]. People using smart gadgets, cars regularly driving down city streets, buses, taxis and any other type of transportation system are a few well-known examples of the numerous crowd sensing nodes that can be utilized to assess the sources of air pollution and infer their possible effects on human exposure. This makes it possible to lessen and avoid their negative side effects. The enormous environmental issues that modern society is dealing with demand the creation of innovative technology that can provide thorough and continuous environmental monitoring in all of its aspects. With the growing availability of UAV, WSN and crowd sensing technologies, which are now recognized with significant sensing and processing abilities, a new borderline of environment monitoring has emerged, made possible by a multitude of inexpensive devices and providing a more precise coverage of the territory [77].

Defence and security: Contemporary radar sensors for defence and security must operate in a variety of dynamically shifting scenarios. The detection, tracking and classification of very small and slow air targets, such as drones in crowded areas, up to quick air targets, such as missiles and fighter aircraft, as well as an increasingly crowded and contested spectrum are essential and challenging system requirements [78]. High-performance distributed fibre-optic sensors have been used in outdoor and underground intrusion detection systems in recent years. In intrusion detection systems, fibre optic sensors are known to offer a number of well-known benefits over traditional technologies, such as high sensitivity, immunity to electromagnetic interference, no field power requirements, inherent safety in hazardous environments, high reliability and cost-effectiveness over long distances.

Agriculture: Chemical (bio) sensors for food and agricultural analysis have gained increasing interest in recent years. Chemical (bio) sensors have the potential to complement or even replace conventional analytical methods because of their advantageous features, which include simple sample preparation, mobility, downsizing and lower cost per analysis [79].

Enzyme biosensors based on cholinesterase suppression have been used to identify pesticide residues of organophosphate and carbamate. Nano-sensors may be used to diagnose soil disease (caused by infecting soil microorganisms, such as bacteria, fungus and viruses) by quantitatively measuring the fluctuating oxygen consumption in the respiration (relative activity) of good microbes and bad microbes in the soil. Using a range of transducer techniques, such as amperometric, electrochemical and optical, biosensors have been shown to be very beneficial in detecting these stressful situations (Table-4). The ability of sensor materials to satisfy a variety of needs in many contexts, enhancing safety, efficacy and data-driven decision-making in numerous industries, demonstrates their versatility.

Current challenges: Unreliability and performance gaps are ongoing problems for sensors. To get around these issues, flexible sensors have been created using conductive materials based on graphene, which have exceptional mechanical and electrical properties. Humans depend on sensors to solve major issues and to improve their quality of life in the digital era. In order to overcome the drawbacks of their usually stiff equivalents, flexible sensors are being developed for ubiquitous sensing [89]. However, a number of problems need to be fixed in order to increase the performance and reliability of sensor technology. This overview will cover some of the current problems with sensor technology and materials. The accuracy and repeatability of different measurement tools, such as sensors and measuring systems, are confirmed through a calibration procedure. Calibrated sensors are essential for precise, consistent and dependable measurement results. Among other things, calibration is necessary for effective quality assurance. Sensors with low cost (LCSs) are widely acknowledged to have caused a model shift in the additional conventional air monitoring by air regulatory agencies. Its large-scale applications have been significantly constrained due to issues with performance stability and data quality. Understanding the most current techniques, advancements and challenges related to calibration of LCS is extremely beneficial for environmental monitoring. The overview of the data presented in this study displays that worldwide sensor market is speedily growing because of growing needs. Standardized calibration procedures and standards are also necessary to preserve consistency across different sensor types and applications. Cross-sensitivity refers to the potential for a gas, other than the target gas, to influence the measurements produced by a certain electrochemical sensor. The cross-sensitivity of parameters like humidity or temperature or other inter-

TABLE-4
TYPICAL AGRICULTURAL SENSORS ARE USED IN DIFFERENT Ag-IoT APPLICATIONS

Classification	Metrical information	Principle of measurement	Typical product	Ref.
Environmental information	Oxygen	Electrochemistry	Renke, RS-O_2	[80]
	Air temperature	Pyroelectricity	METER, ECT	[81]
	Ammonia gas	Electrochemistry	Winsen, ME3-NH3	[82]
	Soil humidity	Electronics and electromagnetics	Meter, ECH2O EC-5	[83]
	Carbon dioxide	Electrochemistry	Hanwei, MH-Z19	[84]
Crop life information	Stem growth	Mechanics	AWL, SD5z	[85]
	Leaf humidity	Electromagnetism	METER, PHOTOS 31	[86]
	Electrical conductivity	Electrochemistry	METER, HYDROS 21	[87]
Animal information	Body weight	Electronics and electromagnetics	OMEGA, TQ101	[88]

fering factors to achieve precise hydrogen gas measurement in a variety of situations is one issue impeding the improvement of hydrogen sensors. The majority of commercially available hydrogen sensors are only capable of measuring at room temperature and many have a narrow temperature range of functioning. Furthermore, higher temperatures necessitate longer sensor lives and more accuracy than those needed at ambient temperature.

Several new hydrogen-sensitive materials were developed to improve the performance of sensors [90]. The advantages of the hydrogen sensor over conventional detection devices include its small size, low cost, online measurement capability and fast response time. It generates a response signal after determining the amount of hydrogen present [91-93]. Therefore, developing hydrogen sensor with great detection precision, fast reaction time, long calibration times, plus outstanding stability is now the aim of regenerative life support technology design. One of the most limiting factors for communication sensor design and application is energy consumption [94]. Power consumption is a vital aspect to consider for wireless sensor networks, whether they are powered by energy harvesters or batteries. However, both solutions require smart power-using equipment to be successful. Energy management challenges arise in real-world scenarios, such as when batteries need to be recharged and replaced. Network congestion results from several sensor nodes attempting to communicate at the same time during sensor network deployment. In real-world scenarios, low data yield is a problem because the network only offers a limited amount of information. The sensor can guarantee a real-time data conveyance rate with reasonable energy consumption [95]. In conclusion, sensor technologies still face significant challenges with regard to stability, power consumption, cross-sensitivity or calibration, even with recent significant advancements. To solve these problems, engineers, materials scientists and data specialists must collaborate across disciplines. Innovative solutions are necessary to enhance performance of sensor and boost its durability and trustworthiness through a wide range of uses.

Prospects of sensor materials: Upcoming sensors will be additionally accurate and have much advanced measurement techniques. More potent and better-networked sensing equipment is created as automation and sensing technology development. This kind of equipment helps to provide appropriate decision-making opportunities and is more successful and effective. A connected society is the result of the increasing use of sensors in many different applications. This will be helpful in many future scenarios, depending on the needs. More intelligent and accurate measurements will be made by future sensors. Sensor materials and technology have a bright future because of their significance to so many various industries and applications. Future sensors will be much more potent and capable due to the integration of cutting-edge technologies like artificial intelligence, sophisticated data analysis and Internet of Things (IoTs). We numerically calculate the electric field and surface current intensity distributions at their respective resonances in order to examine the physical mechanism behind the well-preserved absorption behaviour and enhanced sensing capabilities [96]. The sensors are sensitive to volatile organic compounds (VOCs) changes down to the ppb level with a very low power consumption of 10.5 mW. To further enhance low power intake sensing responses properties with basic stability, a novel sensor structure is proposed. The innovative application of micro-heater geometry and advanced fabrication methods has enabled the deployment of SMO gas sensors in a variety of new applications. In this work, two designs were analyzed using experimental characterization and modelling. A comparative report containing the results of the two sensors' studies is reported [97].

Tiny sensors are essential to the science of nanotechnology. Size-affected nanomaterials are promising materials for sensing due to their special properties, such as improved electrochemical, photonic and electromagnetic capabilities. Advancements in wireless communication, embedded systems, nanotechnologies, miniaturization, and sensing technology have paved the way for the creation of intelligent systems capable of continuously monitoring human activities. There have been numerous reported commercial advances and research on human activity tracking is flourishing. The emergence of attractive and robust devices capable of monitoring various activities is likely to increase substantially. The problems with the current design will also be addressed by future devices. Wearable technologies that monitor a range of human activities will be more pleasant as physiological sensors get lighter. According to a formal and informal poll, wearable technology is expected to gain popularity and be used more often in the near future. Moreover, it forecasts that device costs will reduce, increasing their social utility. Sensors are one of the most crucial components of every IoTs devices [98]. Advances in electronics, healthcare diagnostics, artificial intelligence, are being applied to IoTs applications to help manage chronic diseases and enhance quality of life. Future advancements that include data trending, machine learning are expected as a consequence of the endeavour to capitalize on developing technology and some advances have already been made. Heterogeneous integration is being employed in IoTs and healthcare for future new sensors and diagnostics. The IoTs, artificial intelligence and sophisticated data analytics will all work together to drive a major advancement in sensor technologies and materials in the years to come. These developments will outcome in sensing capabilities which are highly efficient, precise and steady through a variety of industries, enabling future smarter, more networked and environmental friendly systems.

Conclusion

In conclusion, a variety of industries, including transportation, healthcare, agriculture, industrial processes and environmental monitoring, now depend heavily on sensor materials. However, these materials also face significant challenges. The need for enhanced reaction rate and sensitivity, selectivity, along with need for robustness and ecological friendly properties, highlight the complexity of creating sensor materials for a range of applications. The importance of addressing these challenges is highlighted by the expanding reach of Internet of Things, which highlights the need for materials that can easily link and interact with information processing devices in a variety of operating scenarios. When considering the future, sensor materials seem to have a lot of promises. Materials with improved performance, increased robustness, with higher energy efficiency are expected to be developed as a result of ongoing research and innovation. The development of nanomaterials opens the door to the development of sensors with remarkable sensitivity and selectivity as well as novel functionality. It is expected that these technical advancements would not only remove current barriers but also make it easier to integrate sensor materials into upcoming industries like the Internet of Things. Large-scale data collection will be made possible by this integration, which will enhance automation and decision-making. Through an analysis of contemporary developments, applications and research, this study highlights the importance of sensor materials. It highlights the significance of these substances in influencing our future and offers valuable direction for society and industry as they navigate the constantly changing landscape of sensor technologies.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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