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Original Article

Review on Smart Surface Plasmon Resonance: Taxonomy, Applications, and Trends

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ABSTRACT

Surface Plasmon Resonance (SPR) has become an emerging powerful label-free sensing technology for the real-time detection in biomedical application, environmental monitoring and industrial application. In recent years, combining SPR with optical fiber platforms has gained more and more research interest because of its benefits such as the compact sensor design, remote sensing, high sensitivity, and in-situ measurement capability. In parallel, new possibilities of signal interpretation and sensing performance have been opened up by recent advances in artificial intelligence (AI), in particular machine learning (ML) and deep learning (DL). Despite the recently increasing number of studies focusing on fiber-integrated SPR sensors, as well as AI-assisted sensing approaches, there is still a lack of systematic and critically comparative analysis that can link these studies. This review is dedicated to this lack of information and aims to give a structured overview of the optical fiber-integrated SPR sensing technologies and the emerging integration of these technologies with intelligent data-driven methods. A taxonomy-based framework is proposed to classify the existing studies based on different methodological approaches, application domains, material platforms, system integration strategies and performance optimization methods. Representative sensor architectures are compared with one another for sensitivity, detection limit, robustness and structural complexity to find out the important design trends and performance trade-offs. In addition, the review discusses some of the major technical challenges in fiber-integrated SPR systems, such as noise sensitivity, complexity in signal interpretation, multiplexing limitations, and fabrication limitations. The role of ML and DL techniques in enhancing signal processing, reliability of sensing together with intelligent optimization of sensing platforms is also discussed. Overall, this review opens the possibility of the combination of complex plasmonic sensing architectures with artificial intelligence for the next-generation smart SPR sensing systems.

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Keywords: Surface Plasmon resonance, Optical fiber sensors, Artificial intelligence, Machine learning, Deep learning, Biosensing.

1 Introduction

Surface Plasmon Resonance (SPR) is a powerful analytical method that will help the researchers to examine the interactions of the molecules in real-time without labelling the molecules. It can be commonly used in biochemistry, drug development and materials research, The SPR lies on the coherent vibration of the electrons at the boundary of a metal and a dielectric substance, in a system where the polarized light is incident on this contact in a specific angle, it excites the surface Plasmon that will create resonance. An SPR system comprises of a monochromatic light source, a prism, a thin metal sheet, and a detector which measures changes in the intensity of reflected light [1].

The incident light causes collective oscillations of the electrons in the metal when the incident light is perpendicular to the metal surface and is known as surface Plasmon waves, this vibration is very much sensitive to the change in the immediate environment. Molecules, including proteins or small ligands, binding to the surface change the surrounding refractive index and this results in a change in the surface Plasmon wave and hence the reflected light. Using the changes of these alterations, SPR provides overall knowledge of the dynamics and strength of molecular interactions [2].

In addition, the integration of AI and SPR technology enhances data processing, which is sensitive and selective to a broad variety of uses, such as environmental monitoring and medical diagnostics. This connection allows real time tracking and computer controlled operation that makes it possible to respond fast to dynamic changes in biological or environmental factors. Moreover, AI algorithms reveal trends and concealed patterns in SPR data and provide valuable information to find new biomarkers or trends in the environment [3]. The general SPR sensor is presented in Figure 1.

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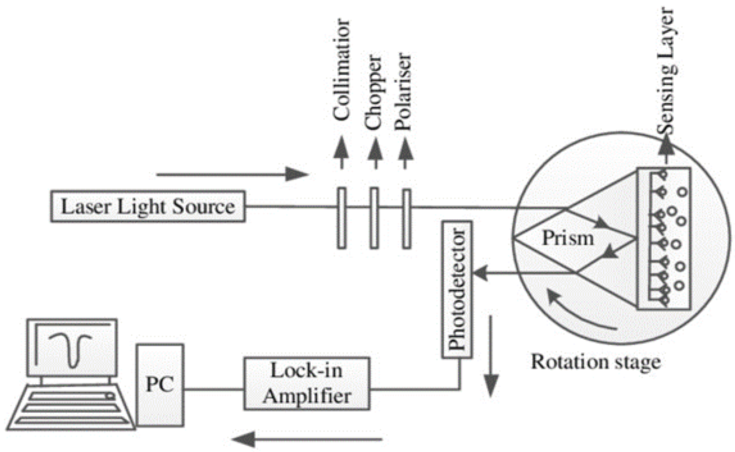

Figure 1: Typical Surface Plasmon Resonance (SPR) sensor [4].

This paper will give a close and descriptive review of SPR technology, specifically optical fiber-integrated designs and new AI-based sensing approaches. Besides outlining the main principles and the recent achievements in this field, this review also critically evaluates the current trends in research and outlines the main challenges that determine the performance, reliability and scalability of smart SPR systems.

Several review articles have discussed important aspects of SPR technology such as conventional prism-based systems, localized surface plasmon resonance (LSPR), material optimization strategies and biosensing applications. While these studies have promoted the understanding of plasmonic sensing mechanism, the majority are dedicated to the study of traditional architectures or enhancement of materials, and there is little attention given to the optical fiber-integrated SPR as a distinct and fast evolving platform.

In addition, while artificial intelligence (AI) especially machine learning (ML) and deep learning (DL) has been proposed to improve sensing performance, it has not been systematical analyzed on the integration with fiber-based SPR systems within a unified framework. Therefore, it is timely and necessary to make a comprehensive review to link the fiber-integrated SPR architectures with AI-assisted optimization and performance evaluation. This work fills this gap by proposing a structured taxonomy and providing some comparative insights to aid the development of smart SPR sensing systems.

2 Taxonomy of Studies

The current advancement of studies on fiber-integrated Surface Plasmon Resonance (SPR) systems has led to a range of design solutions, materials platforms, and applications. To offer a systematic and consistent insight in this dynamic environment, the literature is divided into five of the complementary dimensions, namely, methodology-based studies, application-based studies, material-based studies, integration-based studies, and performance-based studies.

These dimensions were chosen with references to the common research patterns that were identified in the recent publications, and their direct impact on sensor architecture, functionality, and deployment potential. This classification does not only classify the extant body of work but also allows the comparative understanding of the trade-offs in design, optimization of performance, and research gaps in the emergent research in smart SPR systems. The taxonomy is shown in Figure 2.

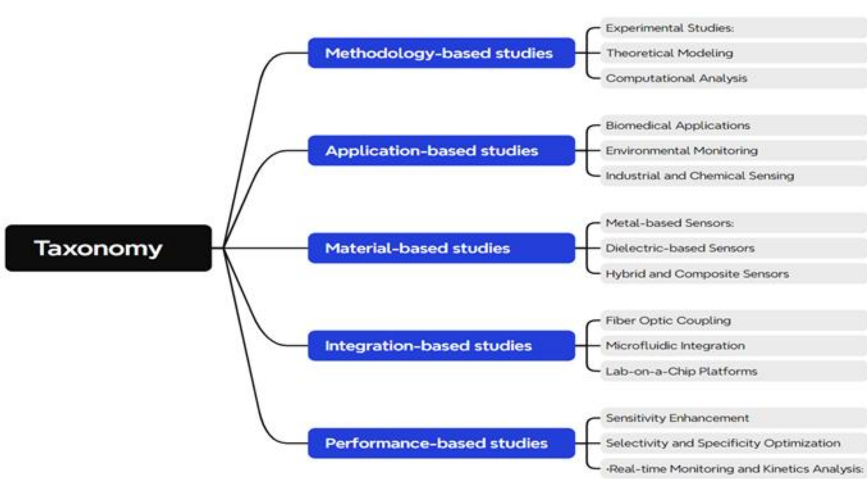

Figure 2: Taxonomy of studies.

2. 1 Methodology-based Studies

This section comprises of three sets of studies. The former is concerning experimental studies, which refers to a research that has a specific focus on conducting experiments to investigate and study numerous things, including developing sensors, analyzing them, and validating them. It is a type of research that involves the development of well-thought experiments to test hypotheses and gather empirical data. This is aimed at providing empirical facts to support scientific hypotheses or practical applications [5].

The second category of the studies is regarding Theoretical modelling: The subject of the study is the theoretical modelling and simulation of SPR events, sensor behavior, and optical characteristics. These investigations usually employ the mathematical and computational analysis to forecast sensor performance, and also enhance design parameters. The experimental data and theoretical models would be able to provide the researchers with more in-depth knowledge regarding the essential principles that regulate sensor functionality [6].

The third category of research studies is on computational analysis which is defined as the application of computational analysis i.e. finite element analysis (FEA) or numerical simulation to study the performance of SPR sensors and optimize the design of these sensors. Such computational tools enable the researchers to predict the behavior of sensors in different conditions and investigate the different design options. The use of empirical data in conjunction with the computational Analysis could be used to make well-informed decisions to improve the sensors sensitivity and specificity [7].

Altogether the experimental validation, theoretical modelling and computational optimization are the most interdependent elements of fiber-integrated SPR studies as shown by methodology-based studies. Although experimental research has the benefit to give practical viability and practical validation, theoretical and computational research can be used to allow predictive optimization and sensitivity analysis of parameters before fabrication. Nevertheless, most of the reported works focus on either the accuracy of simulation or the experimental performance without a combination of the two, which suggests that more unified modelling-experiment frameworks can be utilized in the future development of smart SPR systems.

2. 2 Application-based Studies

This part will consist of three sets of studies. The former is the Biomedical Applications: Research which takes place the investigation of SPR sensors into the biomedical field, to analyze the bimolecular interaction, diagnose medical conditions and identify new drugs. The sensors are extremely sensitive and can be tracked in real-time which makes them invaluable tools in the world of biomedicine. Researchers are also looking at the potential of SPR sensor to improve personalized medicine by rapid and accurate biomarker detection [8].

The second category is Environmental Monitoring: Research: The focus of the research is on the use of SPR sensors to monitor pollutants, poisons and contaminants in air, water and soil. Their high sensitivity and ability to provide real-time monitoring make SPR sensors appropriate in the detection and quantification of small amounts of pollutants in the environment in a short period of time. The technology can greatly increase our capacity to monitor and address environmental problems in a timely manner [3].

The third one is regarding Industrial and Chemical Sensing: Research The use of SPR sensors in the monitoring and controlling of industrial processes, chemical analysis, and quality assurance in the fields of pharmaceutical, food and manufacturing. The SPR sensors have demonstrated the capabilities to provide accurate and reliable measurements in a range of industrial applications resulting to increased efficiency and low costs [9].

On the whole, according to application-based studies, performance requirements vary widely across domains. Biomedical uses are normally defined by very low detection limits, high selectivity and high stability in complicated biological matrices. Robustness, long term stability, and resistance to change in temperature and humidity are often the requirements of environmental monitoring. The application of industrial and chemical sensors is focused upon reliability, scalability and low cost. These contrasting needs highlight the need to design sensors in a domain-specific manner, in which the choice of architecture and material should be made in accordance with domain-specific performance requirements.

2. 3 Material-based Studies

This part is divided into three groups of studies. The former category is the Metal-based sensors that mean the application of metal nanostructures, i.e., gold or silver, in SPR sensors. These plasmonic material are metal nanostructures, which increase the sensitivity and amplify the signal in sensor [10].

The second category of discussion provides the Dielectric-based sensors which are studies that focus on the application of dielectric materials e.g. silicon and silicon nitride in SPR sensors [11]- [12].

The third category is the Hybrid and Composite Sensors: The paper discusses the application of the hybrid or composite materials in SPR sensors to achieve better stability and multi-functionality [13].

Studies based on materials focus on the importance of plasmonic and dielectric platforms on sensor sensitivity, stability and bandwidth. Noble metals like gold and silver are still preferred as they have favorable plasmonic characteristics but problems regarding oxidation, roughness on surfaces and stability over time still exist. Graphene-based and multilayer versions of hybrid and composite materials have been shown to have better field confinement and increased sensitivity, although typically add complexity and reproducibility problems to fabrication. These observations indicate that the choice of the materials involves a performance-pragmatic tradeoff that works well particularly with scalable and portable SPR systems.

2. 4 Integration-based Studies

This section is comprised of 3 groups of studies. The first group is pointing to the Fiber Optic Coupling: Research efforts are being made to connect surface Plasmon resonance (SPR) sensors with optical fiber to enhance the light transmission and light signal collection, and to enable the remote sensing function [14].

The second group is Microfluidic integration, which is the research to combine microfluidic systems and SPR sensors. This Integration is to achieve regulated sample delivery, mixing and analyze concentration, which eventually leads to improved sensitivity and selectivity of the system [15].

The third group discusses the Lab-On-A-Chip: Research is being done on lab-on-a-chip systems to investigate the Integration of SPR sensors. The main objectives are to achieve miniaturization, automation and high throughput sensing capabilities [16].

Studies involving integration show that the combination of SPR sensors and optical fiber platforms, microfluidic systems, or lab-on-chip technologies can greatly improve portability, remote sensing and precision of sample handling. Specifically, fiber-optic coupling allows small and versatile sensor designs to be used in in-situ and real-time monitoring. Integration, however, can also cause other issues, such as the sensitivity of coupling efficiency, and modal interference, sensitivity to alignment, and complexity of fabrication. All these affect directly the stability and reproducibility of signals and it is important to have optimized integration strategies to balance miniaturization and measurement reliability.

2. 5 Performance-based studies

This section is comprised of three sets of studies. The first category is Sensitivity Enhancement: Research is being conducted on improving the sensitivity of SPR sensors by devising innovative sensor designs, surface functionalization techniques and signal amplification techniques [17].

The second group is about Selectivity and Specificity Optimization: Research has been done to enhance the selectivity and specificity of SPR sensors by reducing the non-specific binding, enhancing molecular recognition, and developing better signal processing algorithms [18].

The third group is referred to as the Real-time Monitoring and kinetics analysis. Investigations are being carried out on the real-time tracking of dynamic processes, kinetics analysis and transient event detection using SPR sensors with excellent temporal resolution and responsiveness [19].

Studies based on performance underline that sensitivity improvement is not a sufficient condition of overall system effectiveness. Although many studies are concerned with maximizing the sensitivity of refractive index or minimizing detection limits, the real-world application demands all other aspects of selectivity, stability, response time, and long-term repeatability to be optimized. Enhanced sensitivity could in most instances be achieved at the cost of enhanced noise vulnerability or fabrication complexity. Thus, the challenge of the balanced performance of smart fiber-integrated SPR systems is a key issue to attain the success of the system in the applications that need to be characterized by the dependable real-time and field-deployable sensing.

The following literature review is presented in the framework of the five dimensions that enable each study to be analyzed not only due to their technical contribution but also based on their methodological approach, integration strategy, and performance characteristics.

3 Literature Review

Many studies have considered studying, developing, and analyzing the SPR sensor, SPR system, and other components related to SPR. These studies reviewed in this section are analyzed in the context of the taxonomy that has been previously defined, which helps to clearly locate each work based on its methodological approach, integration strategy, material platform, and performance contribution.

Despite the fact that the sensitivity of fiber-integrated SPR sensors has been enhanced due to the improved structural design and material optimization, a number of constraints are present in the traditional sensing techniques. Numerous systems still use the basic spectral peak tracking to measure resonance changes. Nevertheless, this technique can be inaccurate in cases where the signals are influenced by noise, environmental fluctuations or when you have many parameters being recorded at a time. With increasingly complicated sensor structures the spectral responses can also be nonlinear and harder to interpret. The more sophisticated methods of data analysis are needed, then. In this regard, machine learning (ML) and deep learning (DL) have become the prospective solutions to enhance the signal interpretation and increase the reliability of the SPR sensing systems.

In [20], the authors developed a susceptible refractive index sensor based on Surface Plasmon Resonance (SPR), utilizing a microfluidic channel and Graphene-Ag composite nanowires. The sensor has a microfluidic channel which enables it to deliver samples more precisely and have a better contact with the substances under analysis. The enhancement of the SPR signal by the addition of graphene and Ag composite nanowires enhances the capability to detect and measure the alteration of the refractive index of the SPR sensor, and researchers have improved it by improving its architecture and composition of nanomaterials. Such advancement in technology demonstrates the possibility of applications in environmental analysis, biomedical diagnostics, as well as chemical analysis, which demonstrates the potential of the sensor in these fields.

In a different study [21], a specific and vulnerable sensor has been developed to identify the presence of Baohuoside-I, which is a biologically active chemical found in medicinal herbs. The sensor uses SPR configuration to attain real-time, label-free detection specifically developed towards Baohuoside-I. The effectiveness of the sensor is demonstrated by looking at its response to the varying concentrations of Baohuoside-I solutions. The sensor has a very high sensitivity and specificity, which makes it a promising tool in detecting bioactive substances in complex biological samples, which may be used in pharmaceuticals, quality monitoring of herbal medicine and biomedical research.

A biosensor based on the SPR technology using PCF has been developed in [22] to identify Escherichia coli, some bacteria that causes foodborne diseases and water pollution. The sensor has a PCF structure that allows it to guide light practically and detect biomolecules in real-time and without labeling. The effectiveness of the system is demonstrated through the analysis of the reaction to various samples of E. coli, which can enhance food safety, water quality monitoring, and clinical diagnostics.

A new microfluidic chip, the All-Fiber SPR chip, has been developed in [23] to detect the biologically active chemical Arctigenin, which is found in plants and herbal remedies. When a microfluidic chip is used in conjunction with a biosensor, the biosensor utilizes specialized recognition elements (antibodies or aptamers) to bind and detect specifically Arctigenin molecules in a sample. This can enhance the application of biosensors in pharmaceuticals, herbal medicine quality control and biomedical research.

A new Double Helical Loopback Fiber SPR sensor to measure chromium ions (commonly occurring in industrial effluent and environmental samples as a common pollutant) has been developed in [24]. The sensor has a unique design with a loopback fiber of a double helix that enhances the sensitivity and amplification of the signal and the SPR sensing mechanism that allows the target ions to be detected in real-time without any label. In order to make the sensor selective to the Cr ions, the surface of the sensor is altered with specific recognition properties, e.g. chelating ligands or ion-selective membranes. The sensor has been demonstrated to be effective through the measurement of various concentrations of Cr ions to which it responds. The biosensing technological innovation can be applied in a number of ways, which include environmental monitoring, industrial processes and water quality.

Here, [25] the S-taper structure is used to improve the sensitivity of the sensor to changes in the environment by increasing the overlap between the light mode guided and the plasmonic field around the sensor surface. This is mainly done to detect the presence of nickel ions in solutions that may have major effects on the environment and health due to their wide use in industrial processes.

In [26], The work includes experimental validation, fabrication, characterization, testing with Pb2+ solutions, and comparison with other sensing methods; the main idea of the sensor is the detection of lead ions (Pb2+), which is a dangerous heavy metal pollutant capable of causing great damage to people and the environment. Hybrid Electrochemical-Surface Plasmon Resonance Microfiber Sensor to Pb2+ Detection is a new sensor design which combines electrochemical sensing and SPR technology. Furthermore, the device employs microfiber optics in order to obtain a high degree of sensitivity and selectivity. It also uses SPR technology such that it can do real time and label free detection.

A different study [27] proposes a new technique of temperature measurement by adopting an Optical Fiber Sensor of No-core that is based on SPR. The sensor design depicted below offers a compact and high-responsive temperature sensor design based on no-core optical fiber structure and the SPR phenomena. The temperature sensitivity of the sensor is increased by direct contact of directed light with the environment. The viability and effectiveness of the sensor are demonstrated, with a high level of sensitivity, quick response, and compatibility with miniature and portable sensor devices.

In [28] the paper has created a refractive index sensor based on Photonic Crystal Fiber (PCF) and films composed of silver and titanium dioxide that uses SPR. The sensor uses thin layers of silver and titanium dioxide to enhance the SPR effect and it has a PCF structure to direct light effectively. The sensor sensitivity and performance are evaluated through the study of changes in SPR spectrum; they improved the metal and dielectric layer thickness and composition, demonstrating the capability of the sensor to determine and measure changes in the refractive index with high sensitivity and precision.

In [29], A special curvature sensor has been developed in structural health monitoring, robotics and biomechanics. The sensor uses the fiber-optic structure and SPR technology to sense the changes in the three-axis curvature. To measure the curvature variation along three axes, they improved sensor architecture and signal processing techniques in order to determine the variations accurately and sensitively. The technological advancement in the field of curvature sensing can be applicable in various applications, including structural monitoring, robotics, and wearable devices. Incorporation of fiber SPR technology enables the development of small and light weight sensors capable of effectively measuring complex changes in curvature in real time.

The purpose of the work [30] is to create cost-effective optoelectronic biosensor systems capable of detecting biological analyses in medical diagnostics and environmental monitoring. The key characteristics include smart functions of automated working, low cost of large scale production, real time and non-labelled detection, power saving, targeted detection, flexibility to diverse types of samples, and seamless Integration of data collection and Analysis with smart gadgets. This study aims to increase the availability and practicability of biosensing technologies.

In [31], the authors examine a novel sensing technique involving the use of SPR in Photonic Crystal Fiber (PCF) systems made up of U-shaped nanowires, and two parameters are measured. The aim is to make SPR sensors more sensitive and efficient so that changes of the environment are detected. The technique makes use of two-parameter PCF to control optical characteristics and uses of U-shaped nanowires to offer sufficient interactions between light and nanowires. The capability of the sensor to identify and react to the environmental variables like refractive index and temperature is demonstrated, which implies a high degree of accuracy and precision. This paper presents a future advancement in the SPR sensing technology that can be used in many applications. A summary of the literature is presented in Table 1.

Table 1: Quantitative Performance Comparison of Representative Fiber-Integrated SPR Sensors.

Ref.	Year	Fiber Type	Plasmonic Material	Sensitivity	Detection Limit (LOD)	Target	Key Structural Feature	Remarks
[20]	2021	Microfluidic-assisted fiber	Graphene–Ag	13700 nm/RIU	Not reported	RI sensing	Microfluidic channel + graphene–Ag nanowires	Enhanced field interaction and stability
[21]	2024	Fiber SPR	Gold	0.66 nm/(µg/ml)	0.15 µg/ml	Baohuoside-I detection	Bio-recognition surface functionalization	High specificity biosensing
[22]	2023	PCF	Gold	3472 nm/RIU	Not reported	E. coli detection	PCF structure + immobilized bioreceptors	Real-time label-free detection
[23]	2023	All-fiber + Microfluidic	Gold	0.205 nm/(µg/mL)	0.49 µg/mL	Arctigenin detection	Fully integrated fiber-microfluidic chip	High integration and sample precision
[24]	2024	Double helical loopback fiber	Gold	6356 nm/RIU	0.15 ng/mL	Cr^{3+} detection	Helical loopback geometry	Increased interaction length and sensitivity
[25]	2024	S-taper fiber	Gold	3244.62 nm/RIU	8.65 pg/mL	Ni^{2+} detection	S-taper enhancement	Improved light–plasmon overlap
[26]	2022	Microfiber	Hybrid electrochemical-SPR	Not reported	≈ pM level	Pb^{2+} detection	Electrochemical + SPR hybrid	High selectivity and sensitivity
[27]	2021	No-core fiber	Gold	2.882 nm/% (glucose)	Not reported	Temperature sensing	No-core configuration	Compact and high responsiveness
[28]	2021	PCF	$Ag + TiO_2$	7400 nm/RIU	1.35×10^{-6} RIU	RI sensing	Multilayer thin films	Improved spectral sensitivity
[29]	2023	Fiber SPR	Gold	2.89 nm/m^{-1}	Not reported	Three-axis curvature sensing	Multi-axis configuration	Structural health monitoring capability
[30]	2022	Optoelectronic SPR	Gold	Not reported	µM level	Biosensing systems	Low-cost optoelectronic integration	Focus on scalability and automation
[31]	2023	PCF	Gold (U-shaped nanowires)	12300 nm/RIU	Not reported	Dual-parameter sensing	Embedded nanowires	Simultaneous RI and temperature detection

The quantitative analysis in Table 1 clearly shows that there are major differences in performance between fiber-integrated SPR designs. The greatest wavelength sensitivity of refractive index-based sensors was found with the Graphene-Ag composite microfluidic setup [20] (13700 nm/RIU), then the U-shaped nanowire PCF setup [31] (12300 nm/RIU), which has been shown to have a strong effect of nanostructured plasmonic enhancement and optimised light-plasmon coupling. D-shaped and helical structural changes [28], [24] are also highly sensitive (7400 and 6356 nm/RIU, respectively) and thus geometric tailoring is an important factor in confining the field and extending the interaction length.

In applications of heavy metal detection, they reported ultra-low detection limits, especially in the S-taper nickel ion sensor [25] (8.65 pg/mL) and a double helical chromium sensor [24] (0.15

ng/mL) using structural engineering with surface functionalization as a key factor in improving detection limits. Even greater is the pico-molar level detection [26] with hybrid electrochemical-SPR systems, which underscores the advantage of multi-modal sensing approaches.

Conversely, biosensing platforms that make use of a particular biomolecule as a target [21], [23], [30] focus on selectivity and application-relevant sensitivity measures instead of maximizing RI sensitivity. Moreover, dual-parameter sensors [27], [31] also show the significance of cross-sensitivity effects, especially temperature interference, compensation, which has a direct effect on the stability of the measurements.

In general, the comparative analysis indicates that an increased evanescent field interaction, nanostructured plasmonic materials, and optimized fiber geometries are the most important consideration to realizing high sensitivity, but practical implementation must put a balance between detection performance and structural stability, selectivity, and complexity of integration.

4 Integration of SPR with Optical Fiber

Combining technology with optical fiber poses a number of issues including high sensitivity, which is necessary in sensing applications in the biological and environmental fields with low concentrations. Various optical fiber designs are also significant in ascertaining the sensing performance of systems with fiber-integrated SPR. As a case in point, tapered fiber designs enhance the coupling between the evanescent field and the media surrounding, and these could be useful in improving sensitivity, but could also augment fabrication complexity [25]. The designs of photonic crystal fibers offer high levels of confinement, and flexibility of structure, as well as allow high sensitivity and multi-parameter sensing, [22], [31] , whereas D-shaped or polished fibers enhance plasmonic coupling by reducing the distance between the guided optical mode and the metal layer, [28]. The problem is to realize increased sensitivity of the SPR sensors, especially when they are combined with optical fiber. Sensitivity can be improved by increasing the design to achieve the most appropriate interaction of light and analyses, and minimize noise. Additionally, the design of smaller SPR systems involves application of innovative manufacturing processes and materials, signal processing algorithm advancement to achieve high sensitivity and accuracy in small sensing systems. There is need to introduce complex optical elements, light sources, and detectors into a hand-held device, and at the same time a high level of sensitivity and accuracy [32].

In addition to this, the multiplexed sensing should be used so that the high throughput screening can be conducted and the complete Analysis can be achieved. Yet, it must overcome such challenges as crosstalk, signal interference, and spatial resolution in order to proceed. Advanced signal processing methods and optimized sensor design can be used to enhance the performance. Specific coating or the alteration of the surface can improve the possibility of detection and distinction. The multiplexed SPR sensors can be enhanced with advanced signal processing algorithms and methods of analyzing the data. Besides, non-specific binding, matrix effects and sample heterogeneity are among the challenges the complexity of biological samples in biomedical applications presents, and thus, it is not easy to develop robust sensing platforms to detect the accurate analyses of the samples [33]. Moreover, real-time monitoring is necessary in various applications, including drug development and molecular biology because it enables observing dynamic processes and rapid kinetics. However, the real-time monitoring with the high temporal resolution made using the surface SPR sensors that are integrated with the optical fiber requires the solution of the impediments related to the speed of signal acquisition, data processing, and reaction time of the system. The practical solution to improve the real-time monitoring with the accurate time resolution is the development of efficient signal processing algorithms that will be able to process and interpret the data collected by SPR sensors very fast. However, traditional signal processing methods are frequently constrained in nonlinear spectral response, multiplexed sensing signal and cross-sensitivity effects in complex environments. Thus, machine learning and deep learning methods are becoming increasingly researched in order to represent complicated dependencies in SPR sensing data and enhance signal detection and prediction rates. Moreover, the efficiency and accuracy of real-time monitoring systems can be enhanced significantly with the help of the integration of artificial intelligence techniques.

Also, high selectivity and specificity in analyze detection are essential and they require high selectivity and specificity in analyze detection. Background interference discrimination and selective binding are a challenge to SPR sensors especially in complex samples. The long-term monitoring and continuous operation relies on stability and reliability of sensor which requires improvement and repeatability measures to be developed. The other important issue is that the integration of SPR technology with optical fiber is still expensive and technically difficult and therefore limiting its access among the researchers and practitioners. Financial barriers should be broken and the procedure of using and maintaining instruments simplified so as to promote greater acceptance. Standardization and commercialization can play key role in bridging the gap between research prototype and commercial products in order to ensure scalability, maneuverability, regulatory compliance and acceptance in the market [34]. To address the mentioned problems, there is a need to work with a wide range of disciplines, adopt innovative technological solutions and engage in critical research to improve the integration of SPR technology with optical fiber to serve various functions. Successful management of these challenges would help in the development of advanced sensing platforms which would delineate enhanced performance, adaptability and versatility in different fields.

The SPR sensing method have better sensitivity because it is able to couple and transmit light through optical fiber, which is able to detect low concentrations of analytes and biomolecule interactions that are weak. It allows the development of small and easily portable devices, which is ideal when it comes to the diagnostics that can be completed in the field [33]. However, it requires complex optical designs and a large number of components and may be problematic in design, calibration, and maintenance, limiting its access to researchers and practitioners. Besides, cost of SPR sensing technology can be a hindrance to some facilities and it will hinder its overall adoption. Despite these challenges, ongoing advances in the industry are aimed at simplifying the technology and making it more effective to be used in a wider range of applications. The advantages and limitations associated with optical fiber–integrated SPR systems are summarized in table 2 indicates the pros and cons.

Table 2: Advantages and Disadvantages.

Advantages based on Enhanced Sensitivity	Disadvantage based on Complexity of Instrumentation
Enhancing the efficiency of light coupling and transmission over optical fibers enhances the signal-to-noise ratio [33].	It demands intricate optical configurations for the functioning of the sensor and the collection of data [9].
Facilitates the identification of analyses with low concentrations and the measurement of weak interactions between biomolecules [35].	It comprises many elements, such as sources of light, devices that detect light, and electronics that process signals.
Enables the creation of small and easily transportable SPR sensing devices [36].	Designing, calibrating, and maintaining intricate systems can pose difficulties [37].
Perfect for situations where onsite and diagnostics are needed [38].	Enhanced system intricacy and expenditure may restrict the availability of researchers and practitioners.

5 Applications of Optical fiber-integrated SPR Sensors

SPR technology is used together with optical fiber in many industries such as biomedical sensing, environmental monitoring, food safety, drug discovery, bioprocess monitoring, chemical and gas sensing, diagnostics, materials science and nanotechnology. Biomedical sensing is the continuous detection of biomolecular interactions, such as protein-protein interactions, antibody-antigen binding, DNA hybridization [39], and enzyme-substrate reactions. In addition, environmental monitoring involves the detection and quantification of pollutants, toxins, and contaminant in a very sensitive and precise manner [40]. Also, SPR makes use of food safety and quality control that demand prompt and precise identification of foodborne pathogens, allergies and pollutants without labelling [41]. Pharmaceutical research also uses SPR to screen potential drugs, study how drugs interact with their targets, and determine the kinetics of the therapeutic binding. Besides that, SPR is used in Bioprocess monitoring to make the processes of bioproduction efficient in companies involved in biopharmaceuticals, biofuels, and biotechnology. Besides, the term of diagnostics can be defined as the development of small and portable devices which can detect biomarkers, infections, and signs of diseases rapidly [42]. SPR is also used to advance the field of material science and nanotechnology through the investigation of optical and electrical properties of materials on a nanoscale basis. The applications of SPR sensor are summarized in figure 3.

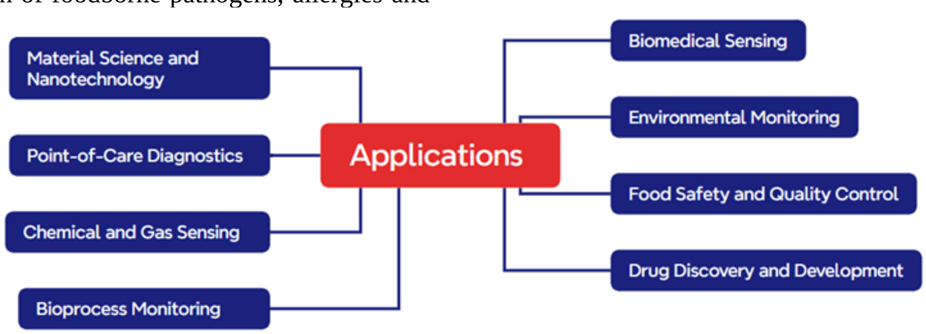

Figure 3: Applications of Optical Fiber-Integrated SPR Sensors.

Performance requirements of fiber-integrated SPR sensors are considerably different in various areas of application. The high sensitivity and selectivity of a biomedical sensing application are normally needed to be extremely high in order to detect low concentrations of biomolecules in complex biological environments [21], [23]. As opposed to this, robustness, long-term stability and the ability to detect trace levels of pollutants or heavy metal ions in varying environmental conditions is often a priority in environmental monitoring [24], [25]. The focus of industrial sensing applications, including structural monitoring, often goes towards rapid response, durability of the system and the capability to conduct continuous real time measurements [29].

Despite the fact that several recent fiber-based SPR sensors have outstanding sensitivity and a high detection limit, it is still a big challenge to find a balance between sensitivity, selectivity, stability, and real-time application. As a result, more studies are needed to streamline sensor architecture, surface functionalization as well as data analysis procedures to suit a wide range of sensors in practice.

The optical fiber-based and integrated SPR sensors have a number of benefits over the traditional sensing technologies in the applications where high sensitivity, compact system design, and remote or in situ measurements are needed. They are especially applicable to the biomedical diagnostics and environmental monitoring that require the ability to detect trace concentrations of analytes due to their capability to offer label-free detection, real-time monitoring, and high sensitivity [24], [25]. Moreover, optical fibers are small and flexible, allowing measurement of a small or inaccessible space.

Nevertheless, SPR-based sensors can be still not as competitive as other sensing technologies in certain applications. As an example, some of the large-scale industrial monitoring systems might be constrained by the complexity of the system, cost, and stability over time, which could reduce its pervasiveness. Moreover, other electrochemical or spectroscopic methods of sensing can provide easier instrumentation and reduce the cost of operation in regular measurements [29].

6 Recent Advances in Research and Development

Integrating the SPR technology and the optical fiber is a new multidisciplinary field that may potentially offer solutions to more basic problems in sensing and diagnostics elsewhere. The direction that researchers are moving to discover the new capabilities and uses of optical fiber integrated SPR sensors is through advancements in materials science, photonics, and bioengineering.

There have been some integration solutions discussed like mounting the SPR-active materials on the optical fiber cores, incorporation of microfluidic channel to carry out the samples and tapering the fiber shapes to allow increase in sensitivity. Considering such aspects as the shape of sensors, the material used in them, surface functionalization method, and signal transduction systems, sensor design and engineering is considered rather attentively. Optical fiber-integrated SPR sensors are being used in several fields, such as in biomedicine, environmental protection, food safety and in monitoring processes of industries [43].

Limitations in the optical fibers optical fibers such as the lack of sensitivity, complications of using instruments and sensitivity to the outside environment are weaknesses to the potential of optical fiber integrated SPR sensors. In the absence of these concerns, researchers are considering more sophisticated signal processing environments, emerging sensor fabric and miniature sensor technologies to make these sensors more useful and applicable in several applications. Moreover, attempts are underway to stabilize and reproducible fiber integrated SPR sensors to enable reliable and accurate measurements. It is also trying to come up with new sensor designs and production processes to break the current limitations and improve the capabilities of these sensors [44].

Recent trends in fiber-based SPR sensors prove to represent both true technology break even and advances. Major advances have been made in the form of introducing nanostructured plasmonic materials, hybrid sensing systems, and multi-parameter sensing systems. Indicatively, sensors based on nanowires, tapered fiber geometries, and photonic crystal fiber (PCF) have been shown to enhance sensitivities significantly and set extremely low detection limits that can be used in trace-level biochemical and environmental detection [31].

Conversely, most of the studies that are reported are incremental advancements that mainly aim at optimizing existing designs, including changing the thickness of metal layers, altering the material used in the coating, or making slight improvements in the sensitivity by changing the structure. These refinements do help achieve optimization of performance, but they usually do not change the sensing mechanism or system architecture. The difference between these two kinds of developments is significant to comprehend the real technological development in fiber-integrated SPR sensing studies.

Despite major progress in laboratory-scale demonstrations of fiber-integrated SPR sensors, there are still limitations in their laboratory-to-commercial translation that affect fiber-based SPR sensors in general. Many high performance sensor designs are based on complex nanostructures and high precision fabrication process which make the production cost high and could not be easily reproduced. In addition, long term stability, calibration reliability and environmental robustness are also major challenges for sensing applications in the real world. Furthermore, to combine optical sensing components and compact electronic systems to acquire data and control the sensor in real-time poses other engineering challenges. These limitations suggest that there is a large difference between the prototypes demonstrated in laboratories and the commercialization of SPR sensing platforms, with the challenge of scaling of fabrication methods as well as effectively employing system integration strategies therefore highlighted herein [25].

7 Machine Learning and Deep Learning

Machine learning and deep learning methods can greatly improve sensors in terms of sensitivity, accuracy and efficiency. A variety of data obtained by SPR sensing systems can be processed with the assistance of machine learning and deep learning tools. Spectral data is the most typically used where changes in refractive index or concentration of an analyte are determined by analyzing resonance wavelength shifts or intensity changes. Besides that, angular interrogation data, temporal response signal, and image-based measurements of SPR can be also useful to gather the data on the basis of which the data analysis may be performed. The generation of these datasets is usually done by experimental measurements on the basis of SPR sensing platforms or by numerical simulation of optical responses in a variety of sensing conditions. To verify reliability, the obtained datasets are usually checked on the calibration samples, reference measurements, and statistical evaluation procedures and then utilized to train and test machine learning models.

The above principles can be applied in an infinite number of activities that may affect SPR sensors such as analysis of data, signal processing, reduction of noise, and predictive modelling. These machine learning algorithms can examine high amounts of data and determine trends and make a prediction regarding sensor behavior. This assists the scientists to learn the principle mechanics of SPR sensing and sensor performance maximization [45].

Deep learning methods can be used to further develop the performance of SPR sensors through the use of a neural network that has many interconnected layers to train. The models have the capability of detecting certain biomolecules or analyses in complex mixtures which leads to better precision and specificity of detection. Deep learning has the ability to enhance the resolution and sensitivity of SPR sensors, automate data analysis processes, and reduce the need to involve the user [46].

Through the application of the power of artificial intelligence, SPR sensing devices will be equipped with the capacity to analyze complex biological samples quickly and accurately, leading to faster and more accurate diagnostics of diseases and increased monitoring of the effectiveness of treatment. Besides, machine learning algorithms can provide useful information about the dynamics between molecules, which can contribute to the understanding of biological processes and the creation of new therapeutic strategies by researchers [47].

Although the potential of machine learning and deep learning in SPR sensing system has a significant potential, a number of computation and hardware limitations still exist. Some state of the art ML/DL models have huge computational and memory needs as well as processing capabilities, which can restrict their use in portable or point-of-care SPR measurements. Moreover, real-time sensing applications require low latency prediction and real-time processing of large data volumes, which may be challenging if a complicated neural network model is employed. Thus, the implementation of AI-assisted SPR sensing systems requires lightweight algorithms and devices integration that would allow the practical use of the innovative approach.

Within the near future, a number of AI-assisted SPR applications seem to be realistically attainable, especially in such fields as automated signal interpolation, noise-removal, and smart-calibration of sensing-systems. Machine learning models can help detect resonance changes, counteract environmental changes, and enhance true-to-life detection of the analytes in a complex sensing scenario. Nevertheless, not all applications put forward are very practical at the present because of the technical limitations and data-related ones. To illustrate, more generalized AI models that can effectively record the response of SPR to a range of sensing platforms and analytes need large, high-quality datasets that are not common at present. Moreover, the application of deep learning models in handheld SPR instruments is still limited by hardware limitations and the computational energy.

The integration of machine learning and deep learning methods in SPR sensing technology will help revolutionize the field of biomedical research and make significant advances in healthcare. Table 3 below presents various that are related to the application of machine learning to the SPR.

Table 3: The use of machine learning and deep learning for the SPR system/sensor.

Ref.	AI Techniques	Method	Objective	Strength	Software /Hardware
[48]	Machine learning algorithms and genetic.	The work utilizes the Taguchi methodology, a rigorous optimization method, to systematically assess and enhance the design parameters of sensors	To advance the working of PCF-SPR sensors to locate the most considerable design factors and optimize them to produce peak sensitivity, accuracy and reaction time.	The optimized sensor design exhibits heightened sensitivity, higher accuracy, and accelerated reaction times in comparison to early designs or conventional optimization techniques.	Taguchi approach and ANOVA analysis
[49]	Machine learning and deep learning,	This entails training the AI model with data sets that accurately depict various patterns of behavior. Subsequently, the model is employed to forecast the mode categorization in real-time applications.	To improve the mode categorization of PCF-SPR sensors with artificial intelligence (AI) techniques. Mode categorization is necessary to optimize the sensitivity and specificity of the sensor in identification of different analyses.	Enhanced mode categorization enhances the precision of sensor responses, hence boosting the sensitivity and reliability of the PCF-SPR sensors.	COMSOL™ Multiphysics and neural network (CNN)
[50]	Deep learning	The study outlines the process of creating and educating deep learning	The objective of the work is to improve the accuracy of measuring SPR-based	Application of deep learning in SPR measurement enables	CMOS camera (MT9P006, Huatengvision).

		models using a dataset produced from SPR angular scanning studies. Multiple neural network designs are investigated to identify the most efficient model for improving measurement accuracy.	angular scanning detection by utilizing deep learning methods.	better detection of changes in refractive index and therefore enhances the sensitivity and performance of the sensor.	And A gas flow control system
[51]	Machine learning in combination with localized surface Plasmon resonance (LSPR)	The researchers utilize machine learning methods to analyze the intricate data produced by LSPR sensors when exposed to samples containing SARS-CoV-2 particles.	To improve the sensitivity and precision of LSPR sensors in identifying SARS-CoV-2 by incorporating machine learning techniques into the sensing process.	These strategies facilitate the discovery of distinct patterns or signatures linked to the existence of the virus, hence enhancing detection capabilities.	CellSens software and spectrometer (iHR320 HORIBA
[52]	Deep learning	They subsequently developed and instructed a sophisticated deep neural network, most likely a convolutional neural network (CNN), to acquire knowledge of the intricate patterns and characteristics linked to phase changes in SPR pictures	To enhance the precision and effectiveness of phase imaging in SPR microscopy by integrating a deep learning system.	The model underwent training to directly predict phase information from input photos, eliminating the necessity for conventional phase extraction procedures.	UNet (ANNs)

The use of ML and DL techniques in SPR optical fiber sensors may significantly improve their performance in several aspects. Figure 4 list the significant advantages of using ML and DL in SPR optical Sensor.

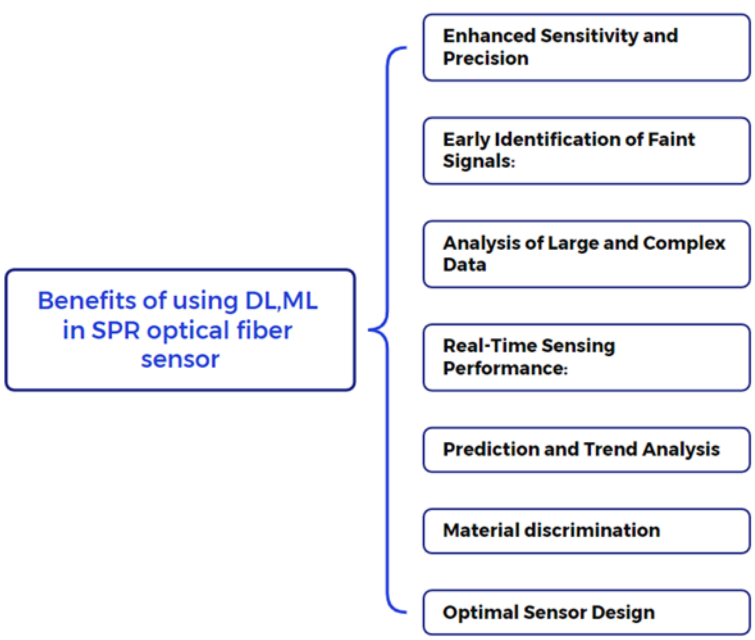

Figure 4: Benefits of using DL and ML in SPR Sensors.

Improved Response Models: (Enhanced Sensitivity and Precision) (ML) and (DL) methods can increase the accuracy of sensor data analysis by effectively identifying complex relationships between signal and physical variables. This can improve the sensitivity of the sensor to detect small changes around the environment. In addition, noise can be reduced through the application of convolutional neural networks (CNNs) that can be used to filter undesired noise and enhance sensor signal quality.

Early Detection of Weak Signals: DL can identify weak trends in the data, and this enables it to identify signals that would otherwise go unnoticed through the conventional method. Detecting small changes in refractive index or concentration is critical, and can detect highly complicated trends in the data that would otherwise be missed by standard analysis methods [53].

Large and Complex Data Analysis: SPR sensors produce large volumes of data. This data can be optimally analyzed by ML and DL and the results may yield useful insights that can be not easily detected by conventional methods of analysis.

Real-Time Sensing Performance: ML has a high response rate, as it provides quick sensor data processing, which provides instant feedback to applications requiring immediate response [54].

Prediction and Trend Analysis: ML models can be applied to predict environmental changes in the future based on the current and historical data. This enhances the ability of the sensor to respond to changes that are about to take place [45].

Discrimination of materials: DL methods can discriminate fine differences between different materials and can discriminate substances in SPR sensors with high accuracy [55].

Ideal Sensor Design: With automated data analysis, machine learning can help to create more efficient SPR sensors through optimization of the sensor structure or components to improve performance based on some criteria.

Alongside the mentioned methods, smart sensing systems and sensor data analysis methods have recently been studied to enhance the performance of monitoring and detection.

Recent research has been focused on the development of fiber optic sensing systems for environmental and structural parameter monitoring using advanced sensor configuration. Such sensing platforms are able to sense small variations of physical parameters and can be combined with modern data analysis techniques to enhance measurement accuracy and reliability in measurement and monitoring applications [56].

Another study discussed the intelligent sensor-based monitoring systems for the performance improvements of the wireless sensing networks. The results showed that optimized sensing and data transmission strategies can improve the efficiency of monitoring and the reliability of the system in distributed sensing environments, indicating the increasing importance of smart sensing technologies in the applications of modern engineering [57].

8 Future Directions and Emerging Trends

Scientists are in the process of developing miniature devices that can be easily integrated into portable and handheld devices. These mini-sized devices are supposed to be used in diagnostics as well as in field applications. In addition, multiplexing and high-throughput screening are equally gaining interest. Multiplex SPR instruments are currently being engineered to examine multiple analyses simultaneously within the same experiment. Also, there is the use of high throughput screening technologies to screen large libraries of chemicals at a rapid rate [58].

One of the promising studies nowadays is nanoparticle-enhanced SPR, which should enhance the sensitivity and selectivity of SPR sensors. The study can be used in a number of fields, including detection, environmental monitoring, and clinical diagnostics. Researchers are now exploring novel methods of data processing, such as machine learning and deep learning algorithms and artificial intelligence in general to increase the sensitivity, specificity, and accuracy of SPR measurement, [59].

Surface modification on SPR: To enhance the sensitivity and specificity of the SPR based assays, surface modifying of the SPR surfaces with special ligands, antibodies or other biomolecules can enhance the detection of target analyses [60]. The integration of SPR with other sensory systems such as electrochemical sensors, optical sensors and microfluidics are known as hybrid sensory systems. This performance can be enhanced by such a combination because this will provide more information and will enhance the overall performance of sensing platforms. In conclusion, the future directions and research directions, in SPR, are focused on expanding the prospects of the SPR technology to be used in the biological, environmental and industrial field.

9 Conclusion

In conclusion, this review provides a comprehensive insight into the recent developments regarding fiber-integrated Surface Plasmon Resonance (SPR) sensing technology, and the enhanced potential in biomedical diagnostics, environmental and industrial sensing. The literature reviews reveal that the advances in optical fiber arrangements, nanostructured plasmonic materials and hybrid architectures of sensing have improved significantly the sensitivity of sensors, detection limit and capabilities of system integration. Certain comparative reviews of current designs indicate that structural engineering, material optimization as well as better sensing configuration is an important component of improving the overall sensor performance. Even with these developments, the large-scale implementation of fiber-integrated SPR systems is limited by a number of issues, which include the complexity of fabrication, system robustness and cost and a combination of complex sensing signals interpretation in the conditions of real-world usage. Here, combination of machine learning and of deep learning techniques has potential prospects of improving signal interpretation, increasing noise resistance, and being able to optimize sensing platforms intelligently and using smart (data-driven) methods. The trend in upcoming studies is expected to be the evolution of scalable fabrication process, better methodology of surface functionalization and the standardization of sensory data used to enable feasible application of intelligent SPR systems. It is expected that the combination of sophisticated plasmonic sensing technologies and artificial intelligence will speed up the achievement of next-generation smart SPR sensing systems that can work autonomously, make decisions in a real-time fashion, and ensure reliable work under various working conditions.

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Authors contribution

The initial author generated the concept of the review, performed a literature search, structured and interpreted the acquired studies, and wrote the paper. The research was conducted under the supervision of the second and third authors, who assisted with technical and scientific advice, reviewed the manuscript critically, and helped to increase the quality and clarity of the paper. The final manuscript was read and approved by all authors.

Conflict of interests

The authors declare no conflicts of interest.

References

[1] Ghosh, S. K. & Pal, T. Interparticle coupling effect on the surface plasmon resonance of gold nanoparticles: from theory to applications. *Chem. Rev***.** **107**, 4797–4862 (2007).

[2] Pattnaik, P. Surface plasmon resonance: applications in understanding receptor–ligand interaction. *Appl. Biochem. Biotechnol*. **126**, 79–92 (2005).

[3] Hasan, A. S., Al-Azawi, R. J. & Alwahib, A. A. Theory and modeling of slab waveguide based surface plasmon resonance. *Eng. Technol. J.* **40**, 1–8 (2022).

[4] Usman, F., Dennis, J. O., Ahmed, A. Y., Meriaudeau, F., Ayodele, O. B. & Rabih, A. A. S. A review of biosensors for non-invasive diabetes monitoring and screening in human exhaled breath. *IEEE Access* **7**, 5963–5974 (2018).

[5] Byun, K. M., Yoon, S. J., Kim, D. & Kim, S. J. Experimental study of sensitivity enhancement in surface plasmon resonance biosensors by use of periodic metallic nanowires. *Opt. Lett.* **32**, 1902–1904 (2007).

[6] Salahuddin, M., Jothilingam, S., Alam, M. K., Uniyal, A. & Pal, A. Theoretical model for glucose detection in urine samples using heterogeneous layered surface plasmon resonance sensor. (2022).

[7] Abraha, K. & Utomo, A. B. S. Computational study of sensitivity enhancement in surface plasmon resonance biosensors using core–shell inclusion for biomaterial detection. *Biosensors* **8**, 75 (2018).

[8] Houari, F., Akjouj, A., Mir, A. Engineering and optimization of $ZnO/Ag/WO_3/Ni$/2D-nanomaterial SPR device for biomedical detection. *Opt. Mater.* **149**, 115019 (2024).

[9] Singh, P. SPR biosensors: historical perspectives and current challenges. *Sens. Actuators B Chem.* **229**, 110–130 (2016).

[10] Shi, H., Zhu, X., Zhang, S., Wen, G., Zheng, M. & Duan, H. Plasmonic metal nanostructures with extremely small features: new effects, fabrication and applications. *Nanoscale Adv.* **3**, 4349–4369 (2021).

[11] Yesudasu, V., Neelaveni, P., Bhuvaneswari, B., Mukesh, S., Ramkumar, G., Kannagi, L. & Hossain, M. A. Silver–dielectric–black phosphorus based surface plasmon resonance biosensor for alcohol detection. *Plasmonics* **19**, 2129–2139 (2024).

[12] Yadav, A., Kumar, A., Sharan, P. & Mishra, M. Highly sensitive bimetallic-metal nitride SPR biosensor for urine glucose detection. *IEEE Trans. Nanobiosci***.** **22**, 897–903 (2023).

[13] Hu, S., Chen, J., Liang, J., Luo, J., Shi, W., Yuan, J., & Luo, Y. Hyperbolic-metamaterials-based SPR temperature sensor enhanced by nanodiamond–PDMS hybrid. *ACS Appl. Mater. Interfaces* **14**, 42412–42419 (2022).

[14] Caucheteur, C., Voisin, V. & Albert, J. Near-infrared grating-assisted SPR optical fiber sensors. Opt. *Express* **23**, 2918–2932 (2015).

[15] Tokel, O., Yildiz, U. H., Inci, F., Durmus, N. G., Ekiz, O. O., Turker, B., & Demirci, U. Portable microfluidic integrated plasmonic platform for pathogen detection. *Sci. Rep*. **5**, 9152 (2015).

[16] García-Hernández, L. A., Martínez-Martínez, E., Pazos-Solís, D., Aguado-Preciado, J., Dutt, A., Chávez-Ramírez, A. U., & Oza, G. Optical detection of cancer cells using lab-on-a-chip. *Biosensors* **13**, 439 (2023).

[17] Shalabney, A. & Abdulhalim, I. Sensitivity-enhancement methods for surface plasmon sensors. *Laser Photonics Rev*. **5**, 571–606 (2011).

[18] Haes, A. J. & Van Duyne, R. P. A nanoscale optical biosensor based on localized surface plasmon resonance. *J. Am. Chem. Soc*. **124**, 10596–10604 (2002).

[19] Wang, D., Loo, F. C., Cong, H., Lin, W., Kong, S. K., Yam, Y., & Ho, H. P. Real-time multi-channel SPR sensing based on DMD-enabled angular interrogation. *Opt. Express* **26**, 24627–24636 (2018).

[20] Pathak, A. K., Viphavakit, C., Rahman, B. M. A. & Singh, V. K. Highly sensitive SPR refractive index sensor using graphene–Ag nanowire microfluidic channel. *IEEE Photonics J*. **13**, 1–8 (2021).

[21] Wei, Y., Tang, Y., Zhang, Y., Liu, C., Liu, C., Shi, C., & Liu, Z. A novel high sensitivity fiber SPR sensor for the specific detection of Baohuoside-I. *IEEE Sens. J.* **24**, 7947–7953 (2024).

[22] Shrivastava, P., Mittal, S., Saharia, A., Singh, G. & Tiwari, M. Photonic crystal fiber based SPR biosensor for escherichia coli detection. *In Proc. MoSICom,* 544–547 (2023).

[23] Wei, Y., Liu, C., Zhang, Y., Shi, C., Tang, Y., Liu, C., & Liu, Z. All-fiber SPR microfluidic chip for arctigenin detection. *IEEE Sens. J.* **23**, 12838–12844 (2023).

[24] Liu, C., Zhang, Z., Shao, Y., Wei, Y., Ren, P., Tang, Y., & Liu, Z. Double helical loopback fiber SPR sensor for chromium ion detection. *IEEE Sens. J.* **24**, 7932–7938 (2024).

[25] Wei, Y., Cheng, J., Shao, Y., Liu, C., Ren, P., Tang, Y., & Liu, Z. Fiber SPR sensor based on S-taper sensitivity enhancement for nickel ion detection*. IEEE Sens. J.* **24**, 6272–6278 (2024).

[26] Peng, X., Ren, Z., Lu, C., Guo, P., Chen, W., You, D., & Li, J. Hybrid electrochemical–surface plasmon resonance microfiber sensor for Pb^{2+} detection. *J. Lightwave Technol.* **41**, 4307–4314 (2022).

[27] Li, B., Yan, X., Zhang, X., Wang, F., Li, S., Suzuki, T., & Cheng, T. No-core optical fiber sensor based on surface plasmon resonance for glucose solution concentration and temperature measurement. *Opt. Express* **29**, 12930–12940 (2021).

[28] Liu, C., Shen, T., Liang, H., Chen, J. J. & Yang, T. Surface plasmon resonance refractive index sensor based on photonic crystal fiber with silver and titanium dioxide films. *In Proc. OGC,* 47–51 (2021).

[29] Liu, C., Liu, C., Wei, Y., Shi, C., Ren, P., Tang, Y., & Liu, Z. Three-axis curvature sensor based on fiber SPR. *IEEE Sens. J.* **23**, 30413–30419 (2023).

[30] Cennamo, N., Arcadio, F., Zeni, L., D'Agostino, G., Perri, C., Porto, G., & Rizzetti, M. Towards ON/OFF smart and low-cost optoelectronic biosensor systems. *In Proc. ICECCME,* 1–5 (2022).

[31] Ying, Y., Yan, X., Shan, D. & Gao, Z. Research on SPR two-parameter PCF sensing technology based on U-shaped nanowires. *In Proc. CYBER,* 976–981 (2023).

[32] Wang, X., Deng, H. & Yuan, L. Ultra-high sensitivity SPR temperature sensor based on a helical-core fiber. *Opt. Express* **29**, 22417–22426 (2021).

[33] Jing, J., Liu, K., Jiang, J., Xu, T., Wang, S., Ma, J., & Liu, T. Performance improvement approaches for optical fiber SPR sensors and their sensing applications. *Photonics Res.* **10**, 126–147 (2022).

[34] Leitao, C., Pereira, S. O., Marques, C., Cennamo, N., Zeni, L., Shaimerdenova, M., & Tosi, D. Cost-effective fiber optic solutions for biosensing. *Biosensors* **12**, 575 (2022).

[35] Safina, G. Application of surface plasmon resonance for the detection of carbohydrates and glycoconjugates: A critical review. *Anal. Chim. Acta* **712**, 9–29 (2012).

[36] Daems, D., Knez, K., Delport, F., Spasic, D. & Lammertyn, J. Real-time PCR melting analysis with fiber optic SPR enables multiplex DNA identification of bacteria. *Analyst* **141**, 1906–1911 (2016).

[37] Masson, J.-F. Portable and field-deployed surface plasmon resonance and plasmonic sensors*. Analyst* **145**, 3776–3800 (2020).

[38] Rasheed, S., Kanwal, T., Ahmad, N., Fatima, B., Najam-ul-Haq, M. & Dussain, D. Advances and challenges in portable optical biosensors for onsite detection and point-of-care diagnostics. *TrAC Trends Anal. Chem.,* 117640 (2024).

[39] Englebienne, P., Van Hoonacker, A. & Verhas, M. Surface plasmon resonance: principles, methods and applications in biomedical sciences. *Spectroscopy* **17**, 255–273 (2003).

[40] Baeumner, A. J. Biosensors for environmental pollutants and food contaminants. *Anal. Bioanal. Chem.* **377**, 434–445 (2003).

[41] Hasan, A. S., Alwahib, A. A. & Al-Azawi, R. J. Review of surface plasmon resonance phenomenon applied in different applications. *In AIP Conf. Proc.* 2660 (2022).

[42] Soler, M., Huertas, C. S. & Lechuga, L. M. Label-free plasmonic biosensors for point-of-care diagnostics: A review. *Expert Rev. Mol. Diagn.* **19**, 71–81 (2019).

[43] Wang, W., Xia, L., Xiao, X. & Li, G. Recent progress on microfluidics integrated with fiber-optic sensors for on-site detection. *Sensors* **24**, 2067 (2024).

[44] Li, X., Yu, Q., Zhou, X., Zhang, Y., Lv, R. & Zhao, Y. Magnetic sensing technology of fiber optic interferometer based on magnetic fluid: A review. *Measurement* 112929 (2023).

[45] Chowdhury, S., Abdulrazak, L. F., Mitu, S. A., Ahmed, K., Bui, F. M., Smirani, L. K., & Chen, L. A highly sensitive multi-channel SPR-PCF based biosensor with deep learning prediction approach. *Alexandria Eng. J.* **77**, 189–203 (2023).

[46] Khonina, S. N., Kazanskiy, N. L., Skidanov, R. V. & Butt, M. A. Exploring types of photonic neural networks for imaging and computing: A review. *Nanomaterials* **14**, 697 (2024).

[47] Ansari, G., Pal, A., Srivastava, A. K. & Verma, G. Machine learning approach to surface plasmon resonance biochemical sensor based on nanocarbon allotropes for formalin detection in water. *Sens. Bio-Sens. Res.* **42**, 100605 (2023).

[48] Kaziz, S., Echouchene, F. & Gazzah, M. H. Optimizing PCF-SPR sensor design through taguchi approach, machine learning, and genetic algorithms. *Sci. Rep.* **14**, 7837 (2024).

[49] Goswami, M., Khare, P. & Shakya, S. AI algorithm for mode classification of PCF-SPR sensor design. *Plasmonics* **19**, 363–377 (2024).

[50] Thadson, K., Sasivimolkul, S., Suvarnaphaet, P., Visitsattapongse, S. & Pechprasarn, S. Measurement precision enhancement of surface plasmon resonance based angular scanning detection using deep learning. *Sci. Rep*. **12**, 2052 (2022).

[51] Liang, J., Zhang, W., Qin, Y., Li, Y., Liu, G. L. & Hu, W. Applying machine learning with localized surface plasmon resonance sensors to detect SARS-CoV-2 particles. *Biosensors* **12**, 173 (2022).

[52] Pechprasarn, S., Sasivimolkul, S., Sukkasem, C., Suvarnaphaet, P. & Thongpance, N. Surface plasmons phase imaging microscopy using deep learning. *In Photoptics,* 33–39 (2020).

[53] Oh, S., Kim, H. K., Jeong, T.-E., Kam, D.-H. & Ki, H. Deep-learning-based predictive architectures for self-piercing riveting process*. IEEE Access* **8**, 116254–116267 (2020).

[54] Mulchan, N. M., Rodriguez, M., O'Shea, K. & Darici, Y. Application of a high-resolution SPR technique for monitoring real-time metal/dielectric interactions. *Sens. Actuators B Chem.* **88**, 132–137 (2003).

[55] Liu, W., Liu, Z., Zhang, Y., Li, S., Zhang, Y., Yang, X., & Yuan, L. Specialty optical fibers and 2D materials for sensitivity enhancement of fiber optic SPR sensors: A review. *Opt. Laser Technol.* **152**, 108167 (2022).

[56] Johni, R. A., Tariq, K. R., Ahmadhamdi, R. T., & Forsyth, D. I. Investigation into fiber optic seismic sensor incorporating fiber Bragg grating array. *Passer J Basic Appl Sci* **4**, 92–99 (2022).

[57] Kakarash, Z. A., Karim, S. H. T., Ahmed, N. F., & Omar, G. A. New topology control base on ant colony algorithm in optimization of wireless sensor network. *Passer J Basic Appl Sci* **3**, 123–129 (2021).

[58] Drozd, M., Kobylska, E., Żmieńko, M. & Chudy, M. Sensitive and label-free SPR biosensing platforms for high-throughput screening of plasma membrane receptor interactions. *Talanta* **274**, 125914 (2024).

[59] Sun, R., Zhou, Y., Fang, Y., Qin, Y., Zheng, Y. & Jiang, L. DNA aptamer-linked sandwich structure enhanced SPRi sensor for rapid and quantitative detection of SARS-CoV-2 spike protein. *Anal. Bioanal. Chem.* **416**, 1667–1677 (2024).

[60] Erkek, M., Akgönüllü, S., Denizli, A. & Bereli, N. Surface plasmon resonance biosensors for detection of allergen-specific immunoglobulin *E. IEEE Sens. J.* **24**, 17410–17417 (2024).