Synergizing Photonics and AI: Toward Early and Accurate Cancer Diagnosis

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Abstract. The early and accurate diagnosis of cancer remains a critical challenge in modern biomedical science, demanding innovations that combine sensitivity, specificity, and speed. Photonic Crystal Fiber (PCF)-based biosensors have emerged as powerful optical platforms due to their exceptional light-guiding properties, high sensitivity, and capability to support surface plasmon resonance (SPR). In recent years, the integration of Artificial Intelligence (AI) into PCF sensor systems has shown remarkable potential to revolutionize cancer diagnostics. AI algorithms, particularly machine learning (ML) and deep learning (DL) models, have been increasingly employed to analyze complex optical signals, optimize sensor configurations, and enhance detection accuracy through pattern recognition and feature extraction. This review presents a comprehensive analysis of the synergy between AI and PCF-based biosensors for cancer diagnosis, with a particular focus on hematological malignancies, i.e. leukemia. Authors explore how AI techniques improve cancer diagnosis in conjunction with optical sensing. Furthermore, the paper discusses current trends, AI-driven sensor design strategies, data acquisition frameworks, and challenges in achieving clinical-grade performance. Finally, future prospects are outlined, emphasizing the need for standardized datasets, robust AI models, and integration into point-of-care diagnostic systems to move from proof-of-concept to real-world healthcare solutions.

Keywords: AI-driven healthcare, PCF, SPR, Cancer detection, Nanomaterials, Advanced materials, ML, DL

A. Vaidya et al. (eds.), *Proceedings of the Conference on Bioengineering for Global Health (SYMRESEARCH 2.0 2025)*, Advances in Biological Sciences Research 55,
https://doi.org/10.2991/978-94-6239-756-9_12

1 Introduction

The global burden of cancer continues to escalate at an alarming rate, with recent epidemiological data indicating a sharp rise in both incidence and mortality across various age groups. Among the multiple forms of cancer, leukemia, a haematological malignancy affecting the blood and bone marrow, is increasingly prevalent, particularly due to modern lifestyle changes, environmental pollution, exposure to carcinogenic agents, and inherited genetic mutations [1]. Factors such as prolonged exposure to benzene, ionizing radiation, dietary imbalances, and sedentary behaviour have been identified as significant contributors to leukemogenesis [2]. According to the World Health Organization (WHO) repository, estimated 277,800 cases and 208,953 deaths were reported till 2022 [3]. The mortality rate due to leukemia is ~3.5 to 4.0 per 100,00; which is very high compared to other cancers. It was also estimated that ~520,000 new cases and ~350,00 deaths may be caused due to leukemia by 2025. These figures are alarming and as a result, the demand for early, precise, and minimally invasive diagnostic tools has never been greater, especially for blood cancers that often present with ambiguous early-stage symptoms [4]. Conventional diagnostic approaches such as peripheral blood smears, immunophenotyping, cytogenetics, and Polymerase Chain Reaction (PCR) based molecular techniques, though effective, are resource-intensive and often fall short in delivering rapid, point-of-care diagnostics. This has catalyzed the exploration of next-generation sensing platforms. A variety of optical and electronic biosensing techniques developed and employed for the early detection and monitoring of leukemia and other blood cancers. Fig. 1 comprises various available optical sensors for biosensing applications including blood cancer detection. Surface plasmon resonance (SPR) sensor, planar waveguide sensor, and electrochemical sensor etc. are the most used biosensor for blood cancer detection. These platforms laid the foundation for label-free, sensitive biomolecular detection. Although the above technologies demonstrated valuable biosensing capabilities, they faced challenges such as limited sensitivity in miniaturized environments, bulky form factors, single-mode operation, and inadequate interaction lengths for weakly present leukemia biomarkers.

In this context, Photonic Crystal Fiber (PCF) based optical biosensors have emerged as powerful candidates for the detection of leukemia specific biomarkers due to their ability to guide and manipulate light with high precision. PCFs offer unique structural tunability, support for multiple sensing modalities; such as SPR, Mach-Zehnder interferometry, and evanescent field sensing, and can be engineered for high sensitivity and specificity in fluidic environments like blood plasma. The sensing capabilities of PCFs have been significantly amplified through the incorporation of nanomaterials, perovskite oxides, structural materials, and two-dimensional (2D) materials, such as graphene, molybdenum disulfide (MoS_2), MXenes, and black phosphorus, etc [5] .These advanced materials enhance the surface area for molecular interaction, facilitate selective binding of leukemia biomarkers (e.g., abnormal microRNAs, oncogenes, CD antigens), and improve plasmonic coupling when used with metallic coatings like gold (Au), silver (Ag), and copper (Cu), etc [6].

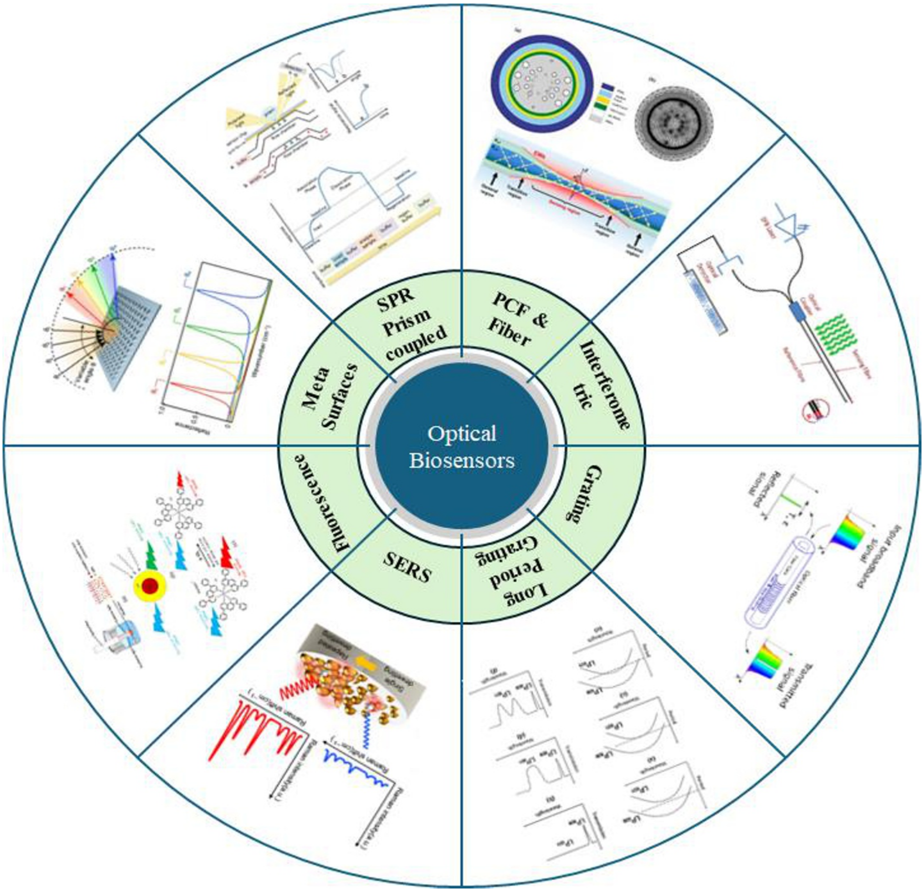

Fig. 1. Various optical sensors for biosensing applications

Complementing these optical advancements, the incorporation of Artificial Intelligence (AI), particularly Machine Learning (ML) and Deep Learning (DL) models, has proven to be a transformative strategy. AI techniques enable intelligent feature extraction, noise reduction, and automated classification of complex spectral signatures associated with leukemic biomarkers. Algorithms like support vector machines (SVMs), convolutional neural networks (CNNs), and decision trees have been successfully applied for both raw signal interpretation and sensor response optimization [7]. Moreover, AI supports the data-driven design of PCF sensor structures, guiding parameter optimization such as air-hole diameter, pitch, and coating material to maximize sensing performance [8]. In this review, authors explore the convergence of AI-enhanced PCF biosensors with nanomaterial engineering for the detection of leukemia, emphasizing their potential to address the rising cancer burden through rapid, accurate, and scalable diagnostics. The following sections delve into PCF sensor architectures, functional material integration, AI algorithmic frameworks, and leukemia-specific sensing case studies, laying the groundwork for next-generation smart diagnostics suited for clinical and point-of-care applications [9].

2 Photonic Crystal Fiber (PCF)

PCF fiber, also known as micro structured or holey fiber, is a class of optical fiber characterized by a periodic array of air holes running along its length, typically arranged in a hexagonal or square lattice. Unlike conventional step-index Fibers, PCFs guide light through two primary mechanisms: modified total internal reflection (MTIR) or photonic bandgap (PBG) guidance, depending on their structure. In index-guiding PCFs, a solid or doped silica core is surrounded by a cladding with a lower effective refractive index due to air holes, enabling light confinement through MTIR. In PBG-PCFs, light is guided in a low-index core by the photonic bandgap formed by the periodic cladding, preventing light propagation in certain wavelength ranges [10]. This offers various key advantages; such as tailorable dispersion, birefringence, modal properties, strong evanescent field exposure, wide operating bandwidth, and compatibility with nanomaterial etc. The fundamental design of PCF is governed by structural parameters such as the air hole diameter (d), pitch (Λ); the center-to-center spacing between holes and the number of air-hole rings [11]. The effective refractive index of the cladding (neff) is a key parameter in determining guidance behaviour, typically approximated by effective medium theory. This controllability allows PCFs to exhibit exotic properties not possible in standard fibers. For index-guiding PCFs, the normalized V-parameter is often used to ensure single-mode operation:

$$V = \frac{2\pi\Lambda}{\lambda}\sqrt{n_{core}^2 - n_{eff}^2} \tag{1}$$

where λ is operating wavelength, ncore is refractive index of the core (usually silica), and $n$eff is effective refractive index of the cladding [12]. PCF based sensors operate on the principle of manipulating and analyzing the interaction between guided light and external analytes within or near the fiber structure. The sensing mechanism primarily relies on changes in the effective refractive index of the guided mode or alterations in resonance conditions (e.g., SPR peaks) caused by the presence of target biomolecules or chemicals. These changes result in measurable spectral shifts, intensity modulations, or phase variations. By modifying the PCF's core geometry or coating it with functional materials for enhanced adsorption high sensitivity and specificity can be achieved. PCF-based sensing mechanisms support multiple modalities, including refractive index sensing, surface plasmon resonance, fluorescence, and Raman scattering, making them ideal for detecting biological analytes such as leukemia biomarkers. Their strong evanescent fields, tunable structures, and compatibility with advanced materials provide a robust platform for developing compact, label-free, and real-time optical biosensors. In the subsequent section, PCF based sensors are reviewed for various geometries and core materials to detect cancer [13][14].

3 Geometry

In 2023, Shweta Mittal et al. [14] used a spiral-shaped PCF to demonstrate an all-optical cancer cell detection sensor based on SPR. The following cancer cells were simulated using the finite element technique (FEM): HELA, Basal, Jurkat, MDA-MB-231, MCF7, and PC12. Within a refractive index range of 1.36–1.401, the sensor's highest sensitivity for breast cancer cells was −289 RIU^{-1} with a resolution of 2.33×10^{-4}. Multiple cancer kinds might be detected with great feasibility thanks to its robust linear sensing response.

In 2020, M. A. Mollah et al. [15] proposed a twin core PCF sensor for blood cancer detection with high sensitivity. This study is an analytical study, having two cores made of silica, with hexagonal geometry of air holes around the cores. This detailed study uses the geometric optimization for various fiber parameters to achieve high sensitivity through proposed sensor. To complete the study birefringence, coupling length, and transmission spectra have been analysed. It is concluded from the study that using simple geometry without using any advanced material high sensitivity can be achieved with the perfectly designed geometry and carefully picked biomarker. The design features a larger central air hole to improve light guidance and interacts with blood samples containing 30–70% normal cells and 80% malignant cells to mimic realistic conditions. Finite element method (FEM) simulations analyse changes in the transmitted spectrum and coupling length, showing a high sensitivity of 8571.43 nm/RIU.

In 2021, Islam and Mohammad Rakibul et al. [16] proposed a Topas-based PCF biosensor for terahertz blood detection, featuring hexagonal cladding with square-shaped air cavities in both the core and cladding to achieve highly efficient light guidance, essential for accurately detecting various blood components. It can distinguish minute changes in the refractive index of analytes such as haemoglobin, white blood cells (WBCs), plasma, water, and red blood cells (RBCs) by efficiently containing light. In COMSOL v5.3a, optical characteristics and performance metrics including sensitivity, confinement loss, effective area, birefringence, and dispersion are simulated using the finite element method (FEM). With ultra-low confinement losses (10^{-16}–10^{-15} dB/cm), the sensor reaches sensitivities of 98.79%–99.39% and provides useful benefits for biological applications.

In another study of 2021, Mahmoud MA et al. [17] highlights five important features of a PCF sensor for identifying skin and blood cancer cells. First of all, the design is unique, with a single rectangular core composed of Zeonex and an asymmetrical structure with rectangular perforations. Second, the structure is precisely modelled and simulated using the FEM with high sensitivities of 96.74% for malignant blood, 96.56% for normal Jurkat cells, 96.61% for skin cancer, 96.34% for basal normal cells, and 95.69% for water, performance validation reveals optimum detection at 2.0 THz. Fourth, the sensor operates dependably due to its low material and confinement losses. Fifth, it is easy to fabricate using current methods due to its plain shape. The uniqueness, approach, performance, efficacy, and feasible production possibilities of the sensor are highlighted in these aspects.

In 2021, Ahasan Habib et al. [18] presented a hollow-core PCF-based optical waveguide for rapid cancer cell identification by exploiting refractive index differences. Using COMSOL with an extremely fine mesh, the sensor achieved nearly 98% relative sensitivity at 2.5 THz with very low loss. Its high NA, suitable spot size, and simple, easily fabricable structure demonstrated strong potential for cancer detection.

In 2022, Shariar Mustafa et al. [19] suggested a high-sensitivity TiO_2/Au/graphene-based SPR biosensor for cancer detection utilizing refractive index analysis is proposed in this work. The sensor, which was created using ATR angular interrogation and assessed using FEM, finds changes in RI between 1.36 to 1.401 for six types of cancer cells. Along with improved field distribution and 180 nm penetration depth, it attains high sensitivities up to 292.86 deg/RIU, good FOM, detection accuracy, and SNR. In comparison to earlier research, the structure exhibits better performance and outstanding linearity ($R^2 = 0.9858$).

In another pioneering work in 2022, Baljinder Kaur et al. [20] presented a optical biosensors for the detection of cancer. These sensors can identify cancer from millions of cells rather than billions because of their high sensitivity, low detection limits, mobility, and real-time monitoring. Sensing techniques including absorbance, fluorescence, luminescence, scattering, resonance, and Fiber-based approaches were all explored in the research. The high surface-to-volume ratio, biocompatibility, and field enhancement of two-dimensional materials were emphasized. Single-molecule detection with great therapeutic potential is made possible by sophisticated techniques like surface-enhanced Raman spectroscopy (SERS) and terahertz sensing.

In 2022, Bahar Meshginqalam et al. [21] reported a highly sensitive SPR-based PCF sensor that detected six different kinds of cancer cells using optimized double gold nanowires. The full-vectorial finite element approach was used to assess the sensor response to changes in refractive index. Performance was considerably improved as compared to single-nanowire devices. High spectral and amplitude sensitivities of 53,571 nm/RIU for MCF-7 and 2582 RIU^{-1} for PC12 cells were attained by the structure. It was appropriate for early cancer diagnosis because to its high sensitivity, excellent resolution, and minimal loss.

In 2022, Bhishma Karki et al. [22] conducted another groundbreaking study using a titanium disilicide ($TiSi_2$) and black phosphorus (BP) heterostructure in the Kretschmann configuration, a SPR biosensor was demonstrated. Beyond standard SPR devices, a $TiSi_2$ layer between silver and BP improved surface sensitivity. The optical responses were confirmed by finite element simulations, and the sensor demonstrated versatility in identifying various infectiopns, including coronavirus strains and cancer cells. Additional parameters such as detection accuracy, FOM, and FWHM confirmed great efficiency for biological diagnostics, whereas reported sensitivities varied from 167.6 to 218.6 degrees/RIU.

In 2023, Shivam Singh et al. [23] suggested a SPR-based bowl-shaped bottom-side polished (BSP) single-core PCF sensor for early cancer detection. To increase stability, the design included a 40 nm gold layer with a 5 nm titanium dioxide adhesion layer. Resonance wavelength changes were used by the sensor to differentiate between healthy and malignant blood, cervical, adrenal, skin, and breast tissues. With a detection limit of 0.024 and sensitivities ranging from 22,857 to 25,000 nm/RIU, it demonstrated excellent accuracy and dependable diagnostic performance.

In another study of 2023, A. Md Tanvirul et al. [24] a PCF-SPR sensor with excellent sensitivity is created for point-of-care (POC) diagnostics with a wide range of biomedical uses. Scaled-down air pores and a u-grooved selective coating are used in the design to efficiently activate free electrons and regulate light propagation. Finite

Element Method (FEM) simulations are used to improve the structure, and perfectly matched layers (PML) are included to minimize radiation leakage. Within the range of 1.29 to 1.40 refractive indices, the sensor may identify viruses, cancer cells, proteins, carbohydrates, and nucleic acids. With a resolution of 8.0×10^{-6} RIU, an amplitude sensitivity of 1189 RIU^{-1}, and a maximum wavelength sensitivity of 12,500 nm/RIU, it is a very useful tool for precise diagnostics.

In 2023, M. Abdelghaffar et al. [25] suggested a PCF biosensor based on SPR that effectively detected cancer by using a V-shaped surface covered with zirconium nitride (ZrN). The ZrN layer improved the interaction between the plasmonic surface modes and core-guided light, increasing the sensitivity of the detection. The full vectorial finite element technique (FVFEM) was used to simulate and optimize the design. 6000, 4400, and 5333.3 nm/RIU in quasi-TE modes, and 6214.28 nm/RIU for breast cancer, 3800 nm/RIU for basal cancer, and 5008.33 nm/RIU for cervical cancer in quasi-TM modes, were the sensor's sensitivities. These findings demonstrated that the primary factors influencing performance were ZrN coating, V-shaped geometry, and parameter modification, which made the biosensor extremely sensitive, economical, and appropriate for portable cancer diagnoses in real time.

In 2023, Shivam Singh et al. [26] proposed a dual-side polished solid-core PCF sensor that uses the SPR principle to identify different kinds of cancer. Plasmonic oscillations at the gold-PCF interface were improved by the 40 nm optimized gold (Au) coating that was incorporated into the design on the etched fiber surface. Resonance wavelength changes were used to distinguish between healthy and cancerous cells in liquid biological samples. 22,857.14 nm/RIU (cervical), 19,285.71 nm/RIU (breast), 17,916.66 nm/RIU (skin), 17,857.14 nm/RIU (adrenal), and 23,214.28 nm/RIU (blood) were the reported sensitivities. High sensitivity and accuracy were made possible via dual-side polishing, gold coating, and thickness optimization. According to the study's findings, the sensor offered a straightforward, affordable, and efficient method for real-time multi-cancer detection with promising clinical applications.

In 2023, Mohmmad Y. Azab et al. [27] study examined optical biosensors for early cancer detection, emphasizing their small size, label-free functioning, and high sensitivity (varying from 1000 to 25,000 nm/RIU). It said that traditional detection techniques were costly, time-consuming, and uncomfortable, which prompted the creation of less expensive and quicker substitutes. In addition to colorimetric, OCT, SERS, and reflectometric approaches, the study covered plasmonic waveguides, photonic crystal fibers, slot waveguides, and metamaterial-based biosensors. It came to the conclusion that optical biosensors made early cancer diagnosis extremely sensitive and effective.

In another study 2023, Sapna Yadav et al. [28] used a terahertz (THz) hollow-core PCF biosensor for precise detection of breast cancer cells is presented in this work. The FEM in MATLAB was used to quantitatively examine the sensor's performance while it operated in the 1.0–2.0 THz range. strong birefringence (0.0020), low confinement loss (17.33×10^{-2} dB/cm), tiny effective area (3.04×10^{-2} μm^2), and strong relative sensitivity (65.53% on the x-axis and 53.63% on the y-axis) are all displayed in the results. With an effective refractive index of 1.376 and dispersion of 0.1588 ± 0.0121, the sensor demonstrates good feasibility for real-time, high performance, and simplicity. Diagnostics for breast cancer without labels

In another study of 2024, Md. Shahidul Hasan et al. [29] a four-channel SPR biosensor based on PCF was developed for simultaneous detection of several analytes. The square-shaped sensor was coated with Au–Ta_2O_5 and gold (Au) layers for plasmonic excitation, and it only utilized nine circular air holes. Its performance was examined via analysis using the finite element technique (FEM). In Channels 1 through 4, the sensor's maximum wavelength sensitivities were 11,000, 25,000, 11,000, and 25,000 nm/RIU, respectively. Additionally, it showed maximal figures of merit up to 352.36 RIU^{-1} and significant amplitude sensitivity. The suggested sensor has great potential for identifying chemicals, biomolecules, and carcinogenic substances with a refractive index detection range of 1.30–1.41.

In this study of 2024, Nagat A. Elmahdy et al. [30] a plasmonic gratings in a D-shaped PCF biosensor with excellent sensitivity was suggested and examined for chemical and biological detection. Using rhodium as the plasmonic material, four grating types—rectangular, triangular, circular, and elliptical—were examined. The analyte refractive index regulated the phase matching between core and plasmonic modes in the SPR-based sensing. High sensitivities of 19,750 nm/RIU, 20,428 nm/RIU, and 20,041 nm/RIU for basal, breast, and cervical cancer cells, respectively, were attained by the optimized structure. The biosensor was demonstrated to be a promising option for early cancer detection due to its high sensitivity and manufacturing tolerance.

In another study of 2024, Sanjeev Mani Yadav et al. [31] a PCF-based SPR biosensor for malaria detection and broad-range refractive index sensing was proposed in this research. With an optimum thickness of 50/12 nm, the sensor's α-AlO_3/Au contact demonstrated a maximum sensitivity of 6000 nm/RIU and a detection accuracy of 1.66 $\times 10^{-5}$ RIU. With sensitivities of 5714.28, 5263.15, and 5931 nm/RIU, it identified red blood cells infected with malaria at various stages, which proved helpful for early diagnosis.

In 2024, Shivam Singh et al. [32] presented a detection of many cancer cell types, such as those found in the adrenal gland, blood, cervical, skin, and two breast variations (MDA-MB-231 and MCF-7), was suggested using a dual-side polished PCF- based SPR biosensor. A greater region of the light–gold interaction was revealed by the side-polished design, which enhanced the coupling between the plasmon and core modes for increased sensitivity to the refractive index. Since healthy and malignant cells exhibited distinct absorption peaks, detection was accomplished by tracking resonance wavelength variations. Depending on the kind of cancer, the sensor's wavelength sensitivities ranged from 16,428.57 nm/RIU (adrenal gland) to 22,500 nm/RIU (breast type 2). These findings showed the biosensor's great potential for precise and early cancer detection.

In 2024, M F. Majeed et al. [33] suggested a dual-core PCF-based SPR biosensor for early cancer detection was examined in this study. To improve plasmonic performance and gold adherence, Au/TiO_2 films were used. Accurate optical simulations were achieved by employing COMSOL Multiphysics with FEM. Through spectral and amplitude interrogations, the differences in RI (1.36–1.401) between cancer cells were tracked. The sensor demonstrated efficacy in early, label-free cancer diagnosis with a maximum resolution of 8.75×10^{-6} RIU (basal cells) and sensitivities of 11,429 nm/RIU (MCF-7, spectral) and 1251.18 RIU^{-1} (MDA-MB231, amplitude).

In 2024, Kahlid Mohammad et al. [34] presented an early cancer detection biosensor based on SPR. To enhance light-metal interaction, the sensor included a gold coating with a hexagonal lattice of air holes. I used wavelength and amplitude interrogation techniques to examine refractive index fluctuations of cancerous cells using finite element models. The sensor has a resolution of 3.33×10^{-5} RIU for basal cells and a maximum sensitivity of 7142.86 nm/RIU for MCF-7 cells (spectral) and –4220.99 RIU^{-1} for HeLa cells (amplitude). 5These findings proved its great sensitivity, dependability, and appropriateness for accurate cancer diagnosis.

In 2024, C. S Elarmathi et al. [35] presented an innovative approach by introducing a highly sensitive PCF-SPR biosensor for early cancer detection and using dual-functionalized aptamer nanocavities and gold nano particles.The optimized design successfully identified cancer biomarkers in clinical samples, demonstrated good selectivity with negligible cross-reactivity, and had an ultralow 10-femtomolar sensitivity.

In 2024, Sumaya Arafin et al. [36] order to identify cancer cells and biomolecules in the visible to near-infrared spectrum, this study suggested a dual-core PCF-SPR biosensor coated in gold. It successfully identified six cancer cell types, including MCF-7 cells with the highest sensitivity, with a maximum sensitivity of 22,000 nm/RIU and a resolution of 4.54×10^{-2} RIU.

In 2024, T Amiri et al. [37] A dual-core PCF SPR sensor for the detection of cancer in different human tissues is presented in this work. The sensor's performance is examined using the full vectorial finite element approach. It has a straightforward circular structure with dual-sized air holes and a gold-coated coating. With 595 RIU^{-1} amplitude sensitivity for skin cancer, 16,285 nm/RIU wavelength sensitivity for adrenal gland cancer, and a high figure of merit of 571.4 RIU^{-1}, it shows impressive results. The capacity to reliably detect cancer cells is confirmed by fabrication tolerance analysis.

In another study of 2025, Sushma Swaraj et al. [38] presented a examined developments in PCF-based biosensors and demonstrated how phase matching and sensing performance were enhanced by changes in pitch, air hole diameter, and gold layer thickness. Because SPR integration improved sensitivity and allowed for label-free detection, it was adopted. In addition to immediately identifying biomarkers in blood, urine, and saliva, these biosensors also detected glucose, pH, and serum proteins, as well as pollutants and pathogens in food, water, and air. Sensitivities of 10^3–10^4 nm/RIU were reported, demonstrating their advantages over traditional biosensors. According to the study's findings, PCF–SPR biosensors are very useful for environmental monitoring and biological diagnostics.

In this research of 2025, Shrishti Singh et al. [39] the spoke about the creation of small, extremely sensitive sensors based on PCF for real-time analyte detection, especially for early cancer detection. PCFs' air-hole structure made it possible for analytes and directed light to interact precisely. SPR-based PCF sensors were chosen because of their exceptional optical qualities, flexibility, and label-free detection. Various sensing techniques, including evanescent waves, SPR, surface-enhanced Raman scattering, and interferometry, were investigated. Sensitivities ranging from 10^3 to 10^4 nm/RIU were reported, indicating their great potential for clinical and biological diagnostic applications.

In 2025, Nagavel B et al. [40] presented a dual-core PCF-based SPR biosensor with bilateral surface detection to enhance cancer cell early detection. Because the dual-core structure enhanced detection precision by enabling a stronger light–analyte interaction, it was selected. Six malignant cell types (MCF7, MDAMB231, PC12, HeLa, Jurkat, and Basal) were used to evaluate the sensor using FEM-based COMSOL simulations spanning a refractive index range of 1.360–1.401. For MCF7 and MDAMB231 cells, the sensor's greatest wavelength sensitivity was 5714.28 nm/RIU; for MCF7, its maximum amplitude sensitivity was 899.248 RIU^{-1}; and for Basal cells, its best resolution was 3.33×10^{-5} RIU. The suggested PCF-SPR sensor turned out to be a promising instrument for precise and early cancer diagnosis due to its straightforward construction and high sensitivity.

In another study of 2025, Mohammad RK Dashtmian et al. [41] a new SPR-based PCF biosensor for early, label-free cancer detection that has a gold nanowire placed in a U-shaped open channel. The U-shaped design was crucial because it made the sensor more affordable than conventional SPR-PCF devices by simplifying manufacture, facilitating simple analyte injection, and guaranteeing accurate nanowire insertion. The sensor was evaluated on six different kinds of cancer cells using FEM simulations in the near-infrared (870–1100 nm) and refractive index ranges of 1.360–1.401. For MCF-7 breast cancer cells, it obtained a maximal wavelength sensitivity of 7857.14 nm/RIU and an amplitude sensitivity of –1893.08 RIU^{-1}. The suggested sensor shown significant promise for lab-on-a-chip and real-time clinical diagnostics due to its high sensitivity, straightforward design, and label-free operation.

In 2025, Ayushman Ramola et al. [42] according to this paper detect blood biomarkers and analytical chemicals, the study offered a numerical analysis of an SPR-based biosensor that uses a hollow-core photonic crystal fiber (PCF) inspired by the kagome lattice. The sensor obtained wavelength sensitivities of 18,900 nm/RIU (TM) and 16,800 nm/RIU (TE) by evaluating both TM and TE polarizations. The amplitude sensitivities were 71,224 and 58,112 RIU^{-1}, respectively. The resolution demonstrated great accuracy, reaching the order of 10^{-6} RIU. It seemed promise for point-of-care diagnostics because of its sensitive and small design.

In 2025, Mahala A et al. [43] presented a PCF-based SPR biosensor for effective, label-free cancer detection with an open D-channel covered with titanium dioxide (TiO_2) and gold (Au). The D-channel improved performance by closing the space between the fiber core and metal, while the addition of TiO_2 improved adhesion between Au and silica. The sensor was examined for refractive index values ranging from 1.25 to 1.43, which encompassed six kinds of cancer cells, using FEM simulations in COMSOL. High accuracy was ensured by the results, which indicated a maximal spectral sensitivity of 47,000 nm/RIU, with 5214.285 nm/RIU and –1481.1 RIU^{-1} for MCF-7 and HeLa cells.

In this study 2025, Xing Wang et al. [44] demonstrated an Au-TiO_2-based bilaterally polished groove-shaped SPR sensor for early cancer cell detection. The sensor identified refractive index values (1.360–1.401) for six cancer cell types, including skin, blood, adrenal gland, cervical, and breast malignancies, using the FEM in COMSOL Multiphysics v6.2. The wavelength sensitivity ranged from 16,700 to 35,000 nm/RIU, with the blood cell exhibiting the highest (37,857 nm/RIU). The sensor showed excellent precision and great promise for early cancer screening with a resolution of 2.64×10^{-2} RIU and FOM of 659.

In 2025, A. B. M. Saiduzzaman Rafi et al. [45] suggested a PCF-based plasmonic sensor for identifying cancer cells in the 1.25–1.40 refractive index region is presented in this study. The sensor, which operates in the visible to near-infrared range, is examined using the finite element method (FEM) with ideally matched layers and scattering boundary conditions. Tantalum pentoxide (Ta2O3) and gold (Au) are deposited selectively to lower costs and fabrication difficulties. With an amplitude sensitivity of 853.52 RIU, a wavelength sensitivity of 21,000 nm/RIU, and a figure of merit of 233.33 RIU, the sensor performs exceptionally well, making it possible to identify cancer cells and other chemical or biological analytes with great accuracy.

Based on factors including amplitude sensitivity, wavelength sensitivity, resolution, and design, summarizes the sensitivity of the suggested sensor in comparison to base on previously researches in PCF-SPR sensors in Table 1.

Table 1. A comparison of existing PCF-SPR sensors based to parameters such as amplitude sensitivity, wavelength sensitivity, resolution, and design.

Year	Authors	Max Sensitivity (nm/RIU)	Accuracy/ Resolution	Sensor Configuration	Amplitude Sensitivity (RIU^{-1})
2020	M. A. Mollah et al [15]	8,571.43	N/R	Twin-core PCF	NA
2023	Shivam Singh et al. [23]	25,000	2.4×10^{-5}	Dual-side polished solid-core PCF	NA
2023	A. Md Tanvirul et al. [24]	12,500	8.0×10^{-6}	U-grooved PCF-SPR	1189
2023	Shivam Singh et al. [26]	23,214.28	N/R	Dual-side polished PCF-SPR	NA
2023	Md. Shahedul Hasan et al. [29]	25,000	N/R	4-channel PCF SPR	352.36
2024	M F. Majeed et al. [33]	11,429	8.75×10^{-6}	Dual-core PCF-SPR	1251.18
2024	Kahlid Mohammad et al. [34]	7,142.86	3.33×10^{-5}	Hexagonal lattice PCF-SPR	-4220.99
2025	Nagavel B et al. [40]	5,714.28	3.33×10^{-5}	Dual-core PCF-SPR	899.248
2025	M.R. Khodatars Dashtmian et al. [41]	7,857.14	N/R	U-channel PCF-SPR	-1893.08
2025	Mahala A et al. [43]	47,000	1.19×10^{-5}	Open D-channel PCF-SPR	1481.1

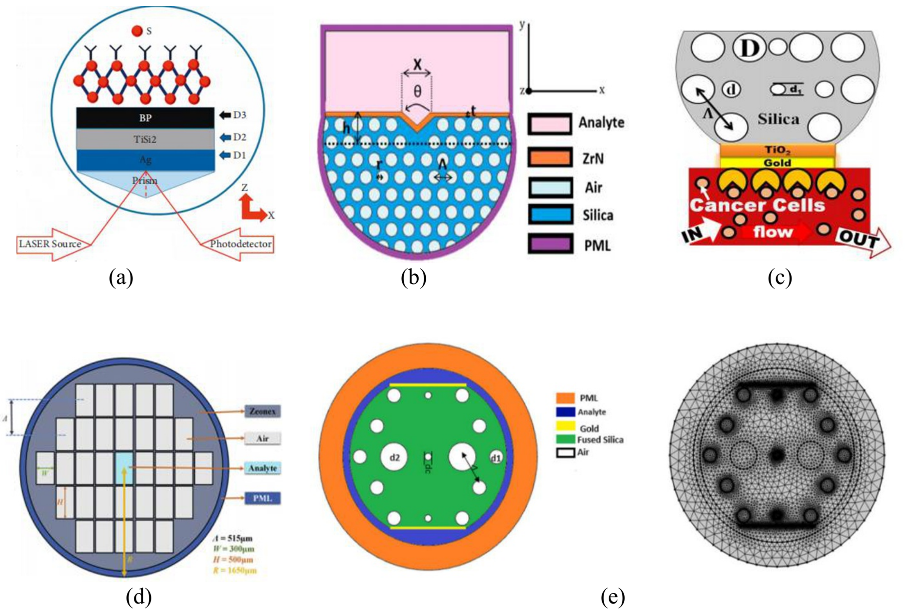

Fig. 1 (a) The schematic diagram of the proposed sensor [22]. (b) 2D cross-section of the SPR PCF sensor [25]. (c) 2D pictorial view of proposed BSP-PCF structure [23]. (d) Rectangular core-based THz sensor for breast cancer cell detection [20]. (e) Cross-sectional and meshing design of the proposed PCF sensor [40].

Advanced Materials: A significant advancement in photonic crystal fiber (PCF) biosensors is the use of two-dimensional (2D) material coatings, such as graphene, bismuthene, antimonene, hexagonal boron nitride (h-BN), black phosphorus, brophene, MXenes and TMDC. The sensitivity, specificity, and stability of the PCF are significantly improved by depositing these ultra-thin layers on its outside or inside microfluidic channels using techniques like dip-coating or optical deposition. Each substance offers unique benefits that enhance biosensor performance when used as a whole. By integrating 2D materials, PCF's capabilities for extremely sensitive and selective detection applications in biological sensing and medical diagnostics are greatly enhanced. These advance materials are given below.

Graphene is a layer of carbon atoms organized in a hexagonal lattice that is only one atom thick. Because of its powerful light-matter interaction, wide surface area, and remarkable electrical conductivity, it greatly improves performance when included into photonic crystal fiber (PCF) biosensors. These characteristics make it possible to identify biomarkers with extreme sensitivity, which makes it an essential component of next-generation biosensing systems and sophisticated, high-precision medical diagnostics.

To further improve detection sensitivity, new research has investigated graphene-based PCF biosensors with unique structural alterations. In a study 2021, Abinash Panda et al. [46] developed a graphene-embedded flaw 1D photonic crystal (PhC) biosensor for the real-time detection of breast, cervical, and basal carcinoma cells is presented in this work. It provides a straightforward, inexpensive, label-free diagnostic tool by analyzing wavelength shifts to identify cancer cells with high sensitivity (290 nm/RIU), high FOM, and poor resolution (0.0668 nm) using the transfer matrix approach.

In 2024, Khalid Mohamad et al. [47] proposed a dual-core PCF-SPR biosensor with a graphene-gold hybrid layer and C-shaped grooves. With a resolution of 4.60×10^{-5} RIU, finite element simulations demonstrated remarkable sensitivity: 2142.86 nm/RIU for MCF-7 cells and –1058.039 RIU^{-1} for HeLa cells. Through field confinement, electron mobility, and biomolecular adsorption, graphene improved performance and made accurate cancer detection possible.

In another study 2024, A.J Basha et al. [48] used a hybrid nanocomposite of gold, graphene, and TiOx-MXene, this study created an ultra-sensitive PCF-SPR sensor for early cancer detection. It produced a 15,000 nm/RIU sensitivity and a 1.2×10^{-2} RIU detection limit when simulated with FEM, providing a highly precise, non-invasive, real-time diagnostic tool for finding trace cancer biomarkers.

Bismuthene is a monolayer 2D bismuth allotrope that improves PCF-SPR biosensors through high plasmonic responsiveness, variable bandgap, and strong spin-orbit coupling. Its integration greatly enhances the sensitivity, stability, and functionalization capability of the refractive index, allowing for the ultra-sensitive, label-free detection of cancer biomarkers in clinical diagnostics with better resolution and dependability.

Novel studies have looked at bismuthene-based PCF biosensors with distinct structural modifications to increase detection sensitivity even further. In 2024, Neelesh kumar Yadav et al. [49] presented a D-shaped PCF-SPR biosensor coated with bismuthene for the detection of colorectal cancer. Within the refractive index range of 1.3433–1.3733, which corresponds to the concentrations of sick tissue scatterers, the sensor demonstrated an impressive wavelength sensitivity of 18,330 nm/RIU. Through accurate refractive index monitoring and the use of finite-element analysis and BSA-mediated cancer cell adhesion, the design allows for the high-sensitivity, label-free identification of colorectal cancer.

In 2024, Md. Ranju Sardar et al. [50] presented a gold-coated PCF based SPR sensor for the detection of cancer cells is presented in this work. To increase sensitivity, gold is applied to the fiber's two polished surfaces via chemical vapor deposition (CVD). COMSOL Multiphysics FEM simulations show a figure of merit of 900, a wavelength sensitivity of 7143 nm/RIU, and a resolution of 2.9×10^{-1} RIU. The sensor is perfect for real-time, label-free cancer diagnostics based on refractive index alterations because of its straightforward design, few air holes, and great precision.

Black phosphorus (BP) is a two-dimensional material with a puckered layered structure, integrated into PCF biosensors to leverage its tunable bandgap, high carrier mobility, and strong anisotropic optical properties. These features enhance light-matter interaction and SPR, significantly improving refractive index sensitivity. BP’s large surface area facilitates efficient biomolecular functionalization, enabling precise detection of cancer biomarkers and advancing high-performance, label-free diagnostic platforms despite challenges like environmental instability.

In 2024, Arhee Bhuyan et al, [51] suggested a D-shaped slotted PCF and SPR sensor for detecting malignant cells. Gold (50 nm), TiO_2 (12 nm), and black phosphorus monolayers were applied to the PCF to increase sensitivity, and it employed circular and oblong air holes. A detectable change in the confinement loss wavelength was brought about by the refractive index difference between healthy and malignant cells. High wavelength sensitivity was attained by the sensor, peaking for a form of breast cancer at 11,429 nm/RIU. For sensitive, multi-analyte cancer detection, the results validated the superiority of the suggested sensor over current designs.

MXenes is a class of two-dimensional transition metal carbides, nitrides, or carbonitrides, is $Mn+1XnTx$, where M is a transition metal, X is carbon/nitrogen, and T_x are surface groups such as –O, –OH, or –Fs. The "A" layer is removed from MAX phases to create MXenes, which have strong electrical conductivity, mechanical flexibility, hydrophilicity, and surface tunability. Because of these characteristics, they hold great promise for advanced materials science applications such as energy storage, sensors, catalysis, electromagnetic shielding, and medicinal uses.

In 2022, Farhan Mumtaz et al. [52] developed a D-shaped PCF-based SPR biosensor for the early detection of bio-analytes, including viruses, proteins, cancer cells, and DNA/RNA, was presented in this study. For improved analyte interaction, the sensor employed an open-channel architecture and modified rhombus cladding. Sensitivity and performance were improved with a hybrid Au/Ti_3C_2Tx MXene layer. Using the FEM, the sensor obtained a maximum refractive index sensitivity of 47,260 nm/RIU and a detection resolution of 2.11×10^{-6} RIU, almost 1.7 times higher than single Au-layer sensors. It was very successful for biological and biochemical applications due to its wide RI range (1.30–1.43).

In 2025, Md Tanveer Rana et al. [53] suggested a high sensitivity (7000–10,000 nm/RIU) for cancer detection is achieved via a photonic crystal fiber-based SPR biosensor that incorporates machine learning. GBR and XGBR provide the best prediction accuracy, cutting calculation time and increasing design efficiency for basal cancer cell sensing, while simulations and machine learning models maximize performance.

In 2024, Yimin Mao et al. [54] presented a hybrid D-type PCF sensor based on SPR for the detection of cancer cells was proposed in this paper. To improve sensitivity and specificity, the design included gold, graphene, and MXene using the full vector finite element method (FVFEM). SPP coupling and plasma wave interaction were enhanced by modified hexagonal air-hole cladding. Wavelength sensitivities of 3000–9286 nm/RIU were attained by the optimized sensor for Basal, HeLa, Jurkat, PC12, MDA-MB-231, and MCF-7 cells. A straightforward, inexpensive, and extremely sensitive optical biosensor was presented in this study, providing a viable substitute for traditional chemical and surgical cancer detection techniques.

In 2024, S. Praveena et al. [55] suggested a SPR- PCF sensor for malaria diagnosis. It utilized a dual square groove coated with cost-effective silver and an optimized five-layer MoS_2 overlayer. The sensor achieved high sensitivities of up to 12,428 nm/RIU for different malaria phases and featured ultra-low loss. The authors highlighted that their design avoided the use of costly gold and unstable 2D materials like MXENE used in other sensors. By selecting stable and cost-effective materials, the proposed sensor fulfilled the need for a high-performance, fabricable, and low-power malarial diagnostic tool.

In 2022, Amit Kumar et al. [56] suggested a very sensitive surface plasmon resonance (SPR) sensor for the detection of cancer cells was reported in the study. It is based on photonic crystal fiber (PCF) coated with gold/TiC_2Tx. The resonant wavelength changes of the sensor between healthy and malignant cells were examined using the finite element approach. With a low resolution of 10^{-6} RIU, it was able to detect breast cancer (MCF-7) cells with maximal wavelength sensitivities of 10,714 nm/RIU (x-polarization) and 13,071 nm/RIU (y-polarization). The TiC_2Tx (MXene) layer improved sensitivity, and machine learning optimization produced an MSE of 0.01525 and an error of less than 2%, making the device effective, quick, and economical for cancer diagnosis.

TMDC (Transitional Metal Dichalcogenides) are an intriguing family of two-dimensional layered materials with the general formula MX_2, in where X is a chalcogen element (like sulphur or selenium) and M is a transition metal (like tungsten or molybdenum). Strong covalent bonds hold the single plane of metal atoms in each layer between two planes of chalcogen atoms, while weak van der Waals forces hold the layers together and facilitate simple exfoliation into monolayers. WS_2 (tungsten disulfide), MoS_2 (molybdenum disulfide), and $MoSe_2$ (molybdenum diselenide) are notable examples. Monolayer MoS_2 displays a direct bandgap, and these materials have adjustable electronic characteristics ranging from metallic to semiconducting. Transistors, sensors, photodetectors, catalysts, and energy storage devices all make extensive use of TMDCs because of its great versatility, stability, and optical responsiveness.

TMDCs are useful in cutting-edge technology because of their exceptional benefits. Materials such as MoS_2, WS_2, and $MoSe_2$ are perfect for transistors, sensors, and photodetectors because of their configurable bandgap, which permits efficient semiconductor behaviour. Their great mechanical flexibility, strong light-matter interaction, and high carrier mobility allow their usage in transparent and flexible electronics. Moreover, TMDCs are suitable for harsh environments due to their chemical and thermal stability. They are also useful as materials for battery electrodes and in hydrogen evolution processes due to their catalytic activity and energy storage capabilities.

In another study 2020, Akash Srivastava et al. [57] a SPR biosensor presented in this study uses a BK7 prism integrated with MXene (Ti_3C_2Tx), BP, TMDCs, and gold as the plasmonic material for visible light sensing. When the sensitivity of the sensor was examined, a single layer of each nanomaterial produced a maximum value of 190.22 RIU^{-1}. Additionally, compared to traditional sensors, the suggested design showed a 1.52× deeper penetration depth. The study demonstrated the tremendous potential of BP, MXene, and TMDCs for high-performance SPR biosensing applications by highlighting their synergistic effect.

In 2024, Elham Jalili Tazekande janze et al. [58] suggested a SPR biosensor that uses two-dimensional materials to identify cancer cells quickly and sensitively. To improve performance, a new plasmonic structure was created that includes ZnO, Si_3N_4, and TMDCs (MoS_2, $MoSe_2$, WS_2, WSe_2). For the detection of blood cancer, the BK7/ZnO/Ag/Si_3N_4/WS_2/sensing medium configuration demonstrated the highest sensitivity (342.14°/RIU) and Figure of Merit (124.86 RIU^{-1}). Simulations using the Finite Element Method (FEM) verified enhanced light absorption and electric field confinement. Although more tuning was advised for clinical applications, the SPR biosensor showed excellent potential for early and precise cancer diagnosis overall with its high sensitivity, specificity, and quick detection.

In 2023, Shouvik K Nandy et al. [59] according to this paper TMDCs in high-sensitivity detection, biosensing, and cancer treatment. It clarified that cancer, which is brought on by genetic abnormalities, is still challenging to cure using conventional techniques that damage healthy cells. Because of its superior photoelectric qualities, adjustable bandgap (1–2 eV), and biocompatibility, researchers looked into 2D TMDC nanomaterials. According to the study, TMDC-based nanoplatforms were created with both therapeutic and diagnostic capabilities in mind, enabling intelligent and responsive cancer treatment. Their high sensitivity range (up to 340°/RIU), large surface area, and strong absorption of near-infrared light (700–1100 nm) made them ideal for biosensing, drug delivery, photothermal therapy, and biomedical imaging.

AI Algorithms: AI is a multidisciplinary domain of computer science focused on developing systems that can perform tasks typically requiring human intelligence, such as reasoning, learning, problem-solving, perception, and language understanding. At its core, AI leverages mathematical models and algorithmic frameworks to analyze complex data, identify patterns, and make informed decisions, often in dynamic and uncertain environments. AI can be broadly categorized into several subfields, including ML, DL, Natural Language Processing (NLP), Computer Vision, and Reinforcement Learning. Among these, ML and DL have gained significant traction in scientific and engineering disciplines due to their ability to learn from data without being explicitly programmed for each specific task [60]. ML models operate by building a functional mapping between input features and output targets using historical data, enabling both regression and classification tasks. DL, a subset of ML, employs artificial neural networks with multiple hidden layers to model intricate and high-dimensional data representations, particularly useful for tasks involving large datasets or complex signal structures. One of the key strengths of AI lies in its ability to capture nonlinear and multi-variable relationships that are difficult to describe analytically [61]. This capability makes AI exceptionally powerful for predictive analytics, anomaly detection, and pattern recognition across domains such as healthcare, finance, energy, and materials science. Additionally, AI algorithms can continuously improve their performance through iterative learning (as in online learning or reinforcement learning frameworks), enabling adaptability and robustness to new, unseen data.

The AI model development pipeline typically involves stages such as data collection, preprocessing, feature extraction, model selection, training, validation, and testing. Supervised learning models like SVMs, Decision Trees, and Random Forests (RF) are widely used when labelled datasets are available. In contrast, unsupervised learning techniques like K-means clustering and Principal Component Analysis (PCA) are used to uncover hidden structures in unlabelled data [62]. Deep architectures, such as CNNs and Recurrent Neural Networks (RNNs), offer enhanced capacity for learning complex temporal or spatial dependencies and are commonly used in high-dimensional data applications. As computational power and access to large datasets continue to grow, AI is rapidly transitioning from theoretical exploration to practical implementation across diverse sectors. Its integration into modern systems enables not just automation, but intelligent decision-making, real-time adaptation, and predictive control, marking a paradigm shift in how complex problems are approached and solved in science and engineering [63].

A wide range of AI models are employed in intelligent sensing systems, each offering unique advantages depending on the task complexity, data type, and computational constraints. SVMs are widely used for classification tasks in high-dimensional spaces and perform well with small to medium-sized datasets, although they can be sensitive to kernel selection and computationally expensive with large datasets. RF, an ensemble learning method, are highly robust to overfitting, capable of handling noisy and incomplete data, and offer good interpretability, though they may be slower on large-scale problems. K-Nearest Neighbours (KNN) is a simple and non-parametric algorithm ideal for small datasets and real-time classification but suffers from scalability issues and sensitivity to noise. In contrast, Artificial Neural Networks (ANNs) provide a flexible modeling framework capable of learning complex nonlinear relationships, making them suitable for both classification and regression tasks. However, ANNs can overfit and require careful tuning and training data preparation [64].

For applications involving spatial or spectral feature extraction from large and complex datasets, CNNs are preferred due to their deep layered architecture and ability to learn hierarchical representations. CNNs, however, require significant computational resources and large labelled datasets for effective training. PCA, an unsupervised dimensionality reduction technique, is often used for feature extraction or noise filtering, although it does not capture nonlinear relationships in the data. Gradient Boosting algorithms like XGBoost are powerful supervised learning methods known for their high accuracy and ability to handle heterogeneous data, but they can be computationally intensive and less interpretable compared to simpler models [65].

In summary, model selection in AI-assisted sensing depends on the trade-off between accuracy, computational cost, interpretability, and data availability, with each model suited for different stages of the sensing pipeline, ranging from design optimization and signal classification to feature extraction and real-time decision-making. A comparative table (Table 2) has been developed for better understanding of the AI models especially for sensing applications.

Table 2. Comparative analysis of various AI models based on their strengths and weaknesses with their sensing applications

Model	Type	Strengths	Weaknesses	Applications in Sensing
SVM	Supervised ML	Effective in high-dimensional space, good with small datasets	Less effective for large datasets, sensitive to kernel selection	Classification of spectral shifts, anomaly detection
RF	Supervised ML (Ensemble)	Robust to overfitting, interpretable, handles missing data	Slower with large datasets, less precise in regression	Feature importance ranking, spectral signal classification
KNN	Supervised ML	Simple, no training phase, good for small data	Sensitive to noise, inefficient with large datasets	Real-time classification of bio-signals
CNN	Deep Learning	Excellent at learning spatial and spectral features, scalable	Requires large dataset and high computation	Spectral image classification, pattern recognition in optical outputs
ANN	Deep Learning	Flexible function approximation, good for regression tasks	Prone to overfitting, lacks transparency	Sensor response prediction, inverse design
PCA	Unsupervised (Dimensionality Reduction)	Simplifies data, reveals hidden trends	Does not handle nonlinearity, unsupervised	Preprocessing for pattern detection and clustering
Gradient Boosting (e.g., XGBoost)	Supervised ML (Ensemble)	High accuracy, handles complex datasets	Computationally expensive	Classification and regression in noisy optical data

In the realm of optical biosensing, especially with complex platforms like PCF-based sensors, AI plays a pivotal role in overcoming longstanding challenges related to spectral interpretation, real-time detection, and sensor performance optimization. AI encompasses a broad spectrum of computational approaches, including ML, DL, and evolutionary algorithms, which are designed to learn from data without being explicitly programmed for each task. These algorithms are particularly valuable in biomedical sensing, where the response of optical sensors is often nonlinear, multi-parametric, and influenced by environmental noise and biological variability. Traditional analytical models struggle to interpret such high-dimensional datasets efficiently, which is where AI exhibits clear superiority. In PCF based sensors, light analyte interactions produce complex outputs such as spectral shifts, intensity changes, and interference patterns that encode biochemical information. These outputs are often subtle, especially in early-stage diseases like leukemia, where biomarker concentrations are extremely low. AI algorithms can be trained to recognize these weak signals, extract meaningful features, and classify or quantify analyte presence with high accuracy. Furthermore, AI significantly enhances the sensor design process. Techniques such as Bayesian optimization, genetic algorithms, or ANN based surrogate modeling allow for inverse design, where desired performance metrics (e.g., sensitivity, limit of detection) are used to predict optimal PCF structures, air-hole geometry, and nanomaterial configurations. This reduces dependence on time-consuming numerical simulations (e.g., FEM, FDTD), accelerating development and prototyping. In the next section use of AI with PCF sensors is reviewed.

4 AI with PCF Sensors

In this work, linked photonic sensing systems for sophisticated biological diagnostics are developed step-by-step. In order to improve air-hole diameters, pitch, and Au/TiO_2 coating thicknesses, the Taguchi L27(3^5) design was used to optimize a circular photonic crystal fiber PCF-SPR biosensor. Over a refractive index (RI) range of 1.29–1.40, this first adjustment produced spectral and amplitude sensitivities of 18,000 nm/RIU and 681.655 RIU^{-1}, respectively. A multilayer perceptron artificial neural network (MLP-ANN) and multiple linear regression were used for performance modeling, which validated the neural model's higher prediction accuracy and highlighted the usefulness of AI in exploring design space for early cancer diagnosis [66]. The design was transformed into a fabrication-ready D-type PCF-SPR sensor with a semicircular groove and dual Au/TiO_2 coatings in the second step by utilizing these optimization findings. It is suitable for compact, high-throughput screening because finite-element simulations showed an operational RI range of 1.355–1.395, a peak wavelength sensitivity of 54,000 nm/RIU, an exceptional resolution of 1.85×10^{-6} RIU, and cancer-marker sensitivities ranging from 2,500 to 24,285 nm/RIU—all within a standard 125-µm single-mode fiber form factor [67]. The third stage added a silicon photonic crystal (PhC) sensor with periodic air holes for metabolic monitoring in order to broaden the platform's applications beyond cancer. With Q-factors of 7,480–7,487, sensitivities of 1,428–2,592 nm/RIU, figures of merit (FOM) of 7,140–12,960, and limits of detection (LOD) ranging from 7×10^{-6} to 1.4×10^{-5} RIU, the device made use of photonic bandgap effects to enable label-free, real-time invasive glucose quantification from small blood samples. These three successive developments—AI-driven optimization, fabrication-feasible fiber sensor realization, and complementary planar PhC glucose sensing—combine to create a comprehensive, precision biosensing framework that can assist with ongoing metabolic monitoring as well as early-stage cancer screening [68]. An improved PCF-SPR biosensor for the detection of cancer cells was provided in this research. In order to improve electromagnetic interaction between surface plasmon and core modes and increase sensitivity, the sensor included a V-shaped groove. Important factors like air hole diameter, V-channel depth, and gold layer thickness were adjusted using the Box-Behnken Design (BBD) technique. Maximum spectrum sensitivity of 2142.86 nm/RIU, amplitude sensitivity of 632.50 RIU^{-1}, and resolution of 4.66×10^{-1} RIU were all attained by the sensor. Furthermore, a Multi-Layer Perceptron (MLP)-based ANN model demonstrated the usefulness of machine learning in biosensor optimization by properly predicting sensor performance [69].

5 Future Perspective

Future studies in PCF-SPR biosensors for cancer detection should focus on improving sensor geometries, especially open-channel and multi-channel designs, in order to get even greater frequency response and sensitivity. A combination of hybrid optical layers with cutting-edge nanomaterials might enhance detection efficiency and selectivity considerably. Additionally, efficiency may be increased and real-time, medical diagnoses made possible through the combination of these sensors with artificial intelligence analysis and large, standardized records. Exploring small and affordable manufacturing methods will enable real-world medical implementation, elevating these high-performing PCF-SPR devices from lab demonstrations to extensive healthcare applications.

6 Conclusion

This study finds that the rapid and precise identification of cancers, especially leukemia, can be greatly improved by combining the use of AI with PCF-based biosensors. Further enhancing plasmonic performance, sensitivity, and precision in detection is the use of advanced 2D materials such as MXenes, TMDCs, Black Phosphorus, Bismuthene, and Graphene. The proposed method effectively analyzes challenging optical signals with the use of machine learning and deep learning methods. All things examined, the AI-assisted PCF biosensor combined with the latest technologies has outstanding potential for creating fast, reliable, and clinically useful cancer detection systems.

Acknowledgement: This work is supported through the CST UP sponsored project (id: 3402).

Conflict of Interest: The authors declare that they have no conflict of interest.

Ethics Declaration: Not applicable.

Clinical Trials: Not applicable.

Data Availability Statement: Data will be available upon reasonable request.

References

1. Sung, Hyuna, Jacques Ferlay, Rebecca L. Siegel, Mathieu Laversanne, Isabelle Soerjomataram, Ahmedin Jemal, and Freddie Bray. "Global cancer statistics 2020: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries." *CA: a cancer journal for clinicians* 71, no. 3 (2021): 209-249.
2. Smith MT, Zhang L, McHale CM, Skibola CF, Rappaport SM. Benzene, the exposome and future investigations of leukemia etiology. Chem Biol Interact. 2011 Jun 30;192(1-2):155-9. doi: 10.1016/j.cbi.2011.02.010. Epub 2011 Feb 17. PMID: 21333640; PMCID: PMC3461963.
3. Filho, Adalberto M., Mathieu Laversanne, Jacques Ferlay, Murielle Colombet, Marion Piñeros, Ariana Znaor, Donald M. Parkin, Isabelle Soerjomataram, and Freddie Bray. "The GLOBOCAN 2022 cancer estimates: data sources, methods, and a snapshot of the cancer burden worldwide." *International Journal of Cancer* 156, no. 7 (2025): 1336-1346.
4. Ortega-Ortega, Marta, Paul Hanly, Alison Pearce, Isabelle Soerjomataram, and Linda Sharp. "Projected impact on labour productivity costs of cancer-related premature mortality in Europe 2018–2040." *Applied Health Economics and Health Policy* 21, no. 6 (2023): 877-889.
5. Balaji, V. R., MA Jahan, T. Sridarshini, S. Geerthana, Arun Thirumurugan, Gopalkrishna Hegde, R. Sitharthan, and Shanmuga Sundar Dhanabalan. "Machine learning enabled 2D photonic crystal biosensor for early cancer detection." *Measurement* 224 (2024): 113858.
6. Yadav, Prateek Kumar, Awadhesh Kumar, Satyam Upadhyay, Anil Kumar, Amit Srivastava, Monika Srivastava, and S. K. Srivastava. "2D material–based surface plasmon resonance biosensors for applications in different domains: an insight." *Microchimica Acta* 191, no. 7 (2024): 373.
7. Algorithms like support vector machines (SVMs), convolutional neural networks (CNNs), and decision trees have been successfully applied for both raw signal interpretation and sensor response optimization.
8. Nobahari, Hadi, and Saeed Nasrollahi. "A terminal guidance algorithm based on ant colony optimization." *Computers & Electrical Engineering* 77 (2019): 128-146.

9. Khatun, Mst Rokeya, and Md Saiful Islam. "Design optimization of high-sensitivity PCF-SPR biosensor using machine learning and explainable AI." *Plos one* 20, no. 9 (2025): e0330944.
10. Anbazhagan, Lavanya, P. Sudhanya, and R. Jansi. "Characteristics analysis of different photonic crystal fiber lattice structures." *Journal of Optics and Photonics Research* 1, no. 2 (2024): 67-73.
11. Singh, Sandhir Kumar, Syed Sadique Anwer Askari, and Zeba Akhter. "Recent Advancement in Photonic Crystal Fiber Based Sensors: A Review." *Indian Journal of Pure & Applied Physics (IJPAP)* 62, no. 11 (2024): 1040-1049.
12. Saad, Naira M., and El-Sayed M. El Rabaie. "A review of recent developments in photonic crystal fibers (PCFs)-based biomedical and chemical sensing applications." *Journal of Electrical Systems and Information Technology* 12, no. 1 (2025): 71.
13. Goswami, Mayank, Prasunika Khare, and Snehlata Shakya. "AI algorithm for mode classification of PCF-SPR sensor design." *Plasmonics* 19, no. 1 (2024): 363-377.
14. Mittal, Shweta, Ankur Saharia, Yaseera Ismail, Francesco Petruccione, Anton V. Bourdine, Oleg G. Morozov, Vladimir V. Demidov, Juan Yin, Ghanshyam Singh, and Manish Tiwari. "Spiral shaped photonic crystal fiber-based surface plasmon resonance biosensor for cancer cell detection." In *Photonics*, vol. 10, no. 3, p. 230. MDPI, 2023.
15. Mollah, Md Aslam, Md Yousufali, Istihad Mahmud Ankan, Md Mahabubur Rahman, Hasan Sarker, and Kisalaya Chakrabarti. "Twin core photonic crystal fiber refractive index sensor for early detection of blood cancer." *Sensing and bio-sensing research* 29 (2020): 100344.
16. Islam, Mohammad Rakibul, A. N. M. Iftekher, Farhana Akter Mou, Md Moshiur Rahman, and Mohammed Imamul Hassan Bhuiyan. "Design of a Topas-based ultrahigh-sensitive PCF biosensor for blood component detection." *Applied Physics A* 127, no. 2 (2021): 109.
17. Eid, Mahmoud MA, Ahmed Nabih Zaki Rashed, Abdullah Al-Mamun Bulbul, and Etu Podder. "Mono-rectangular core photonic crystal fiber (MRC-PCF) for skin and blood cancer detection." *Plasmonics* 16, no. 3 (2021): 717-727.
18. Habib, Ahasan, Ahmed Nabih Zaki Rashed, Hazem M. El-Hageen, and Aadel M. Alatwi. "Extremely sensitive photonic crystal fiber–based cancer cell detector in the terahertz regime." *Plasmonics* 16, no. 4 (2021): 1297-1306.
19. Mostufa, Shahriar, Tarik Bin Abdul Akib, Md Masud Rana, and Md Rabiul Islam. "Highly sensitive TiO2/Au/graphene layer-based surface plasmon resonance biosensor for cancer detection." *Biosensors* 12, no. 8 (2022): 603.
20. Kaur, Baljinder, Santosh Kumar, and Brajesh Kumar Kaushik. "Recent advancements in optical biosensors for cancer detection." Biosensors and Bioelectronics 197 (2022): 113805.
21. Meshginqalam, Bahar, and Jamal Barvestani. "High performance surface plasmon resonance-based photonic crystal fiber biosensor for cancer cells detection." The European Physical Journal Plus 137, no. 4 (2022): 417.

22. Karki, Bhishma, Arun Uniyal, Amrindra Pal, and Vivek Srivastava. "Advances in Surface Plasmon Resonance-Based Biosensor Technologies for Cancer Cell Detection." International Journal of Optics 2022, no. 1 (2022): 1476254.
23. S. Singh and Y. K. Prajapati, "Novel Bottom-Side Polished PCF-Based Plasmonic Biosensor for Early Detection of Hazardous Cancerous Cells," in *IEEE Transactions on NanoBioscience*, vol. 22, no. 3, pp. 647-654, July 2023, doi: 10.1109/TNB.2023.3233990. keywords: {Cancer;Optical fiber sensors; Sensitivity; Gold; Cells (biology);Biosensors;Breast cancer;Cancer cell;cervical cancer;sensitivity ;surface plasmon resonance}
24. Hoque, Abdullah Mohammad Tanvirul, Kusay Faisal Al-Tabatabaie, Md Eakub Ali, Asad Muhammad Butt, Sheikh Sharif Iqbal Mitu, and Khurram Karim Qureshi. "U-grooved selectively coated and highly sensitive PCF-SPR sensor for broad range analyte RI detection." *IEEE Access* 11 (2023): 74486-74499.
25. Abdelghaffar, M., Yusuf Gamal, Reda A. El-Khoribi, Wafaa Soliman, Y. Badr, Mohamed Farhat O. Hameed, and S. S. A. Obayya. "Highly sensitive V-shaped SPR PCF biosensor for cancer detection." *Optical and Quantum Electronics* 55, no. 5 (2023): 472.
26. Singh, Shivam, Bhargavi Chaudhary, Anurag Upadhyay, and Sofyan A. Taya. "Bottom side partially etched D-shaped PCF biosensor for early diagnosis of cancer cells." *The European Physical Journal Plus* 138, no. 6 (2023): 511.
27. Azab, Mohammad Y., Mohamed Farhat O. Hameed, and Salah SA Obayya. "Overview of optical biosensors for early cancer detection: fundamentals, applications and future perspectives." *Biology* 12, no. 2 (2023): 232.
28. Yadav, Sapana, Pooja Lohia, and D. K. Dwivedi. "Quantitative analysis of highly efficient PCF-based sensor for early detection of breast cancer cells in THz regime." *Journal of Optics* 53, no. 3 (2024): 2642-2655.
29. Hasan, Md Shahedul, Md Anas Ebna Kalam, and Mohammad Faisal. "PCF based four-channel SPR biosensor with wide sensing range." *IEEE Transactions on NanoBioscience* 23, no. 2 (2023): 233-241.
30. Elmahdy, Nagat A., Mohamed Farhat O. Hameed, S. S. A. Obayya, and B. M. Younis. "Highly sensitive plasmonic-grating PCF biosensor for cancer cell detection." *Optical and Quantum Electronics* 56, no. 4 (2024): 688.
31. Yadav, Sanjeev Mani. "Au-Al 2 O 3-Coated Highly Sensitive Broad-Range Refractive Index Sensor for Detecting Malaria Disease in Human Blood." *IEEE Sensors Journal* 24, no. 15 (2024): 23754-23763.
32. Singh, Shivam, Rajeev Kumar, Bhargavi Chaudhary, Priyanka Bhardwaj, Vipin Kumar Upaddhyay, Anurag Upadhyay, and Malek G. Daher. "Gold immobilized SPR-Enhanced PCF biosensor for detection of cancer cells: a numerical simulation." *Plasmonics* 20, no. 6 (2024): 3535-3544.
33. Majeed, Mohammed F., and Ahmad K. Ahmad. "Design and analysis of a dual-core PCF biosensor based on SPR for cancerous cells detection." *Optical and Quantum Electronics* 56, no. 6 (2024): 1030.
34. Ibrahimi, Khalid Mohd, R. Kumar, and Writtick Pakhira. "Early detection of cancer cells using high-sensitivity dual-side polished photonic crystal fiber

biosensors based on surface plasmon resonance." *Optical and Quantum Electronics* 56, no. 5 (2024): 888.
35. Elarmathi, S., P. Rishabavarthani, M. Sindhuja, P. Elayaraja, Malathi Murugesan, S. Kumarganesh, K. Martin Sagayam, Binay Kumar Pandey, and Digvijay Pandey. "Novel manufacturing systems for cancer diagnosis using ultra-sensitive photonic crystal fiber biosensor with dual-functionalized aptamer-nanocavity." *Microsystem Technologies* (2024): 1-20.
36. Arafin, Sumaya, Tazin Fatema, and Md Sohanur Rahman. "Numerical analysis and detection of cancer cells using a dual-core gold coated plasmonic biosensor." *Optical Materials Express* 14, no. 6 (2024): 1603-1619.
37. Amiri, Tayobeh, Erfan Kadivar, and Sajad Ghajarpour-Nobandegani. "Cancer cell detection using a dual-core photonic crystal fiber based on surface plasmon resonance." *Sensing and Imaging* 25, no. 1 (2024): 42.
38. Sawraj, Sushma, Dharmendra Kumar, Ram Pravesh, Vijay Shanker Chaudhary, Bramha Prasad Pandey, Sneha Sharma, and Santosh Kumar. "PCF-based sensors for biomedical applications-a review." *IEEE transactions on nanobioscience* (2025).
39. Singh, Srishti, Dharmendra Kumar, Anupam Sahu, Vijay Shanker Chaudhary, Ghanshyam Singh, and Santosh Kumar. "Photonic crystal fiber based sensors for various cancer detection in human body-a review." *IEEE Sensors Journal* (2025).
40. Dagar, Hitesh, and Prabu Krishnan. "High-performance dual-core bilateral surface optimized PCF SPR biosensor for early detection of six distinct cancer cells." *Plasmonics* 20, no. 7 (2025): 4799-4809.
41. Khodatars Dashtmian, Mohammad Reza, Vahid Fallahi, Mahmood Seifouri, and Saeed Olyaee. "Gold Nanowire-Enhanced SPR-PCF Biosensor for High-Throughput Cancer Cell Detection in Near-Infrared." *Plasmonics* (2025): 1-13.
42. Ramola, Ayushman, Amit Kumar Shakya, Ali Droby, and Arik Bergman. "Numerical Study of a Novel Kagome-Inspired Photonic Crystal Fiber-Based Surface Plasmon Resonance Biosensor for Detection of Blood Components and Analytical Targets." *Biosensors* 15, no. 8 (2025): 539.
43. Ashrafian, Mahla, Saeed Olyaee, and Mahmood Seifouri. "Highly sensitive cancer detection using an open D-channel PCF-based SPR biosensor." *Scientific Reports* 15, no. 1 (2025): 10168.
44. Wang, Xing, Ailing Zhang, Honggang Pan, Qingcheng You, Yukun Zhu, Licui Ji, Xu Gao, Xinjie Zhao, and Yating Tang. "Highly Sensitive Early Cancer Cell Detection Biosensor Based on Au-TiO 2 Coated Dual Groove PCF-SPR." *Plasmonics* (2025): 1-15.
45. Rafi, ABM Saiduzzaman, Hasan Sarker, Shahriar Amin, Priyanka Das, Md Arafat Rahman, Md Sakib Ikbal, and Shajjad Hossen. "Cancer Detection Using Au-Ta 2 O 5-Coated PCF-Based SPR RI Sensor." *Plasmonics* (2025): 1-11.
46. Panda, Abinash, Puspa Devi Pukhrambam, Feng Wu, and Walid Belhadj. "Graphene-based 1D defective photonic crystal biosensor for real-time detection of cancer cells." *The European Physical Journal Plus* 136, no. 8 (2021): 809.

47. Ibrahimi, Khalid Mohd, R. Kumar, and Writtick Pakhira. "C-grooved dual-core PCF SPR biosensor with graphene/au coating for enhanced early cancer cell detection." *Applied Physics A* 130, no. 6 (2024): 439.
48. Basha, A. Jameer, R. Uma Maheshwari, Binay Kumar Pandey, and Digvijay Pandey. "Ultra-sensitive photonic crystal fiber–based SPR sensor for cancer detection utilizing hybrid nanocomposite layers." *Plasmonics* 20, no. 7 (2025): 4943-4957.
49. Yadav, Neelesh Kumar, and Jitendra Bahadur Maurya. "Bismuthene-coated-silver based D-shaped photonic crystal fiber biosensor for colorectal cancer detection." *Journal of Optics* (2024): 1-10.
50. Sardar, Md Ranju, and Mohammad Faisal. "Dual-core dual-polished PCF-SPR sensor for cancer cell detection." *IEEE Sensors Journal* 24, no. 7 (2024): 9843-9854.
51. Bhuyan, Arhee, Akash Khamaru, and Ajeet Kumar. "Black phosphorus-based slotted D-shaped PCF SPR sensor for cancer detection." *Plasmonics* (2024): 1-13.
52. Mumtaz, Farhan, Muhammad Roman, Bohong Zhang, Lashari Ghulam Abbas, Yutang Dai, Muhammad Aqueel Ashraf, Muhammad Arshad Fiaz, and Amit Kumar. "MXene (Ti3C2Tx) coated highly-sensitive D-shaped photonic crystal fiber based SPR-biosensor." *Photonics and Nanostructures-Fundamentals and Applications* 52 (2022): 101090.
53. Sobur, Md Tanver Rana, Md Mehedi Hasan, Mst Rokeya Khatun, Md Manik Mia, Wahidul Islam, Md Sadiq Iqbal, and Muhammad Minoar Hossain. "Machine learning-enhanced spr-based optical biosensor for cancer cell detection." *Optics & Laser Technology* 192 (2025): 113796.
54. Mao, Yimin, Fang Ren, Deyang Zhou, and Yidan Li. "Highly sensitive PCF-SPR RI sensor for cancer detection using gold/graphene/Ti3C2Tx-MXene hybrid layer." *Plasmonics* 20, no. 4 (2025): 2279-2290.
55. Praveena, S., and K. Senthilnathan. "Ultra low loss dual square groove incorporated SPR-based PCF sensor for malaria diagnosis." *Plasmonics* 20, no. 7 (2025): 4637-4655.
56. Kumar, Amit, Pankaj Verma, and Poonam Jindal. "Surface plasmon resonance sensor based on MXene coated PCF for detecting the cancer cells with machine learning approach." *Microelectronic Engineering* 267 (2023): 111897.
57. Srivastava, Akash, Alka Verma, Ritwick Das, and Y. K. Prajapati. "A theoretical approach to improve the performance of SPR biosensor using MXene and black phosphorus." *Optik* 203 (2020): 163430.
58. Janze, Elham Jalili Tazekande, Sholeh Alaei, and Bahar Meshginqalam. "On the sensing performance improvement in SPR biosensor using ZnO and TMDCs architecture for cancer detection." *Scientific Reports* 15, no. 1 (2025): 28349.
59. Nandy, Shouvik Kumar, Sattwik Das, Sadanand Pandey, Pallab Kalita, Manoj K. Gupta, Atul Kabra, Pankaj Wadhwa, and Deepak Kumar. "The futuristic applications of transition metal dichalcogenides for cancer therapy." *Luminescence* 39, no. 5 (2024): e4771.

60. Strohmeier, Stefan. "Artificial intelligence in human resources-an introduction." In *Handbook of research on artificial intelligence in human resource management*, pp. 1-22. Edward Elgar Publishing, 2022.
61. Ramesh, K., M. N. Indrajith, Y. S. Prasanna, Sandip S. Deshmukh, Chandu Parimi, and Tathagata Ray. "Comparison and assessment of machine learning approaches in manufacturing applications." *Industrial Artificial Intelligence* 3, no. 1 (2025): 2.
62. Hossain, Delower, and Jake Y. Chen. "A Study on Neuro-Symbolic Artificial Intelligence: Healthcare Perspectives." *arXiv preprint arXiv:2503.18213* (2025).
63. Dong, Shi, Ping Wang, and Khushnood Abbas. "A survey on deep learning and its applications." *Computer Science Review* 40 (2021): 100379.
64. Arifin, Nurhikma, and Chairi Nur Insani. "Comparative Analysis of CNN, SVM, Decision Tree, Random Forest, and KNN for Maize Leaf Disease Detection Using Color and Texture Feature Extraction." *Jurnal Teknik Informatika (Jutif)* 6, no. 5 (2025): 3572-3586.
65. Hussain, Muhammad Afaq, Zhanlong Chen, Ying Zheng, Yulong Zhou, and Hamza Daud. "Deep learning and machine learning models for landslide susceptibility mapping with remote sensing data." *Remote Sensing* 15, no. 19 (2023): 4703.
66. L. Guedri-Knani, S. Kaziz and C. Dridi, "Performance Prediction of a Highly Sensitive Optimized PCF-SPR Biosensor for Cancer Cell Detection Using MLP-Based ANN Model," in IEEE Sensors Journal, vol. 25, no. 10, pp. 17136-17143, 15 May15, 2025, doi: 10.1109/JSEN.2025.3556292.
67. Sun, Yuan, Jingwei Lv, Famei Wang, Wei Liu, Jianxin Wang, Zao Yi, Miao Liu, Qiang Liu, Paul K. Chu, and Chao Liu. "Ultra-sensitive D-Type PCF-SPR Biosensor with Dual-layer Au/TiO_2 Coating for Early Cancer Cell Detection." Plasmonics (2025): 1-12.
68. Karami, Pouya, and Fariborz Parandin. "Design and Simulation of a Photonic Crystal-Based Optical Sensor with Low Detection Limit and High Sensitivity for Blood Glucose Measurement." Results in Engineering (2025): 106416.
69. Khemiri, Randa, and Sameh Kaziz. "Novel Optimization Approach and AI Performance Prediction of a Highly Sensitive V-Shaped PCF-SPR Sensor for Cancer Cell Detection." *Sensing and Imaging* 26, no. 1 (2025): 76.