Research Article

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A deep dive into AI integration and advanced nanobiosensor technologies for enhanced bacterial infection monitoring

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Abstract: The emergence of smart and nanobiosensor (NB) technologies has transformed the monitoring and management of bacterial infections. These developments offer remarkable accuracy and precision for detecting infectious pathogens. Smart artificial intelligence (AI)-assisted and NB-based methods are used as powerful tools in biomedicine for bacterial detection, combatting multidrug resistance, and diagnosing infections. In this study, we delve into the advancements in these technologies, focusing on AI-based techniques for NBs in detecting bacterial infections from 2019 to 2024. We analyze the contributions of machine learning and deep learning techniques to enhance performance and reliability. The new approaches to improve the effectiveness and versatility of antibacterial treatments are critically analyzed. Our study includes the observations of carbon nanoparticles that selectively target bacteria using photothermal properties and the production of hybrid hydrogel composites with capabilities. Furthermore, the study emphasizes the crucial significance of NBs in propelling the progress of diagnostic methods, biosensing technologies, and treatments, thereby transforming the healthcare industry and the way diseases are managed. In addition, we explore pathogen-based infections, bacterial diagnosis, and treatment using engineered NBs enhanced with various modalities such as electrochemistry, acoustics, electromagnetism, and photothermal resonance. Our comprehensive review highlights the potential and throws light on future research directions for effective management and control of bacterial infections.

Keywords: nano-biosensors, bacterial infection, smart diagnosis, diagnostic tools, biosensing technologies

1 Introduction

Bacterial resistance to antibiotics has emerged as a critical contemporary concern in human health, posing significant challenges to disease management and treatment outcomes. To present historical information on bacterial losses, the research determined the number of fatalities linked to 33 bacterial genera or species spanning 11 infectious syndromes in 2019. Furthermore, estimations demonstrate that the prevalence of infections caused by bacteria will continue to rise to almost 10 million cases yearly in the next years, more than cancer cases [1]. This trend emphasizes the urgent need for innovative technologies to detect and control bacterial infections. Bacterial infections harm patients and pose significant economic consequences for medical facilities. Continuous antibiotic therapy is frequently necessary to treat diseases caused by multidrug-resistant bacteria, especially in serious cases when tissue ablation may also be desired. Nevertheless, the successful outcome of these treatment options is hindered by disproportionate healthcare expenditures and poor patient compliance, culminating in a projected

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yearly total of social and health expenses surpassing USD 55 billion in the United States alone [2].

Antibiotic resistance leads to higher antibiotic use, which complicates the outbreak by promoting the spread of resilient varieties of bacteria. Studies indicate a high degree of antimicrobial resistance, with a significant percentage of bacterial types, such as *Staphylococcus aureus* (*S. aureus*), displaying resistance to several antimicrobial agents, including methicillin, vancomycin, and carbapenems [3]. Bacterial resistance to frequently employed antibiotics is a complex phenomenon that demands the contribution of several processes, including suppression of cell walls, production of proteins, and alterations in DNA and structures. Bacteria possess inherent mechanisms to endure the negative consequences of antimicrobials, such as change and spreading of genetic material. The emergence of genes such as NDM-1, which have been linked to high levels of resistance to particular beta-lactam antibiotics, poses substantial obstacles to the efficacy of antibiotics [4]. Furthermore, it is well established that microorganisms that cause diseases such as tuberculosis exhibit multidrug resistance, hence complicating the growth of effective treatment strategies [5]. Considering these challenges, there is an urgent requirement to find robust smart and nanobiosensor (NB)-based effective antibiotic strategies to successfully combat diseases caused by highly resistant bacteria [6].

Bacterial infections, drug resistance, and biofilm development present significant barriers, emphasizing the need for innovative identification, tracking, and treatment methods. Conventional approaches are often time-consuming, resource-intensive, and less effective due to emerging multidrug-resistant bacterial strains. Overuse and misuse of antibiotics further exacerbate resistance, prolong hospital stays, increase medical costs, and pose global public health threats. Biofilms add complexity by protecting bacteria from immune responses and antibiotics, leading to chronic infections. Advanced biosensor technologies, ingenious and NBs, offer promising solutions by providing rapid, sensitive, and specific pathogen detection, allowing timely and targeted treatment. Integrating artificial intelligence (AI) specifically machine learning (ML) and deep learning (DL) enhances these sensors' capabilities with real-time data analysis and accurate bacterial monitoring and control. These intelligent sensors can detect specific biomarkers and patterns, monitor treatment effectiveness, and prevent biofilm formation. Nanotechnology in biosensing enables multifunctional platforms for diagnostic and therapeutic use, releasing antimicrobial agents in response to pathogen detection. Advanced smart and NB tools can revolutionize bacterial infection management by providing rapid, accurate, and cost-effective options, mitigating bacterial infections and resistance, and improving public health. The traditional dependence on these approaches necessitates significant financial and human capital and might unintentionally worsen antibiotic resistance due to overuse and improper usage [7].

This research investigates the significant capacity for change that smart NBs possess, particularly with or without cutting-edge technologies like ML- and DL-based smart approaches. These innovative approaches provide a potential substitute for conventional approaches, offering improved sensitivity, specificity, and efficiency in the treatment of bacterial infections. The integration of AI into the monitoring of bacterial infections and NBs represents significant progress, allowing rapid and precise analysis that surpasses conventional diagnostic methods. This facilitates the development of more precise forecasts about infection patterns and treatment outcomes and the availability of real-time and ongoing monitoring data [8]. Intelligent NBs can provide customized therapy interventions and real-time surveillance, leading to a significant influence on the management of bacterial infections. These technological advancements make previous approaches outdated by enabling accurate identification of bacterial infections even at very low levels [9]. These technologies provide enhanced data collection and management, facilitating more precise identification and tracking of bacterial infections, hence resulting in more effective treatment approaches. To efficiently control illnesses caused by various bacterial strains, address contamination issues, and overcome antibiotic-resistant microorganisms, it is essential to use this strategy [10]. The potential use of photothermal effects as well as electromagnetic resonances is being explored to enhance the diagnostic and treatment processes for NB. The advanced methods shown here illustrate the adaptability and capacity of intelligent NBs to transform the treatment. The aim is to emphasize the substantial potential of smart NBs in enhancing diagnostic accuracy, customizing treatments, decreasing healthcare expenses, and ultimately addressing the growing problem of antibiotic resistance [11]. This will be critically analyzed and achieved by thoroughly examining these cutting-edge technologies and their practical uses. In this study, we address several critical questions to understand the advancements and challenges in integrating AI, biosensor technology, and nanotechnology for bacterial infection management. Our research questions are as follows.

1.1 Research questions

- What are the main developments in integrating AI, biosensor technology, and nanotechnology that have improved the ability to monitor, identify, and manage bacterial infections?

- In what ways have AI methods, especially ML and DL approaches, enhanced the capability of sensors to deal with bacterial infections efficiently?
- How have integrated biosensor technologies and nanotechnology-based treatments advanced the detection and control of bacterial infections, considering factors such as contamination by bacterial agents, resistance mechanisms, and biofilm formation?
- How does the combination of biosensor technologies and nanotechnology-based solutions improve the identification and management of bacterial infections, taking into account aspects such as bacterial contamination, resistance mechanisms, and the emergence of biofilms?
- How have several improvements, such as the use of photodynamics, electrochemistry, acoustics, electromagnetism, and photothermal resonance, enhancing the diagnostic and therapeutic powers of designed NBs in the treatment of bacterial infections?
- What are the challenges and future paths in advancing and utilizing intelligent nanobots for managing bacterial infections, and how can these improvements be applied to overcome these challenges for more accurate and customized diagnostic and therapeutic interventions?

1.2 Contributions

- This article offers an in-depth and comprehensive analysis of the latest advancements in AI-integrated technology and nanotechnology tools that significantly enhanced the monitoring, detection, and control of bacterial infections. By examining the specific applications of smart NBs, the study offers a detailed understanding of how these technologies have evolved and their overall impact on bacterial infection management.
- Our study explores how AI-based techniques, particularly ML and DL approaches, have improved the performance of sensors in effectively monitoring bacterial infections inside the specified period.
- We investigate how integrated biosensor and nanotechnology-based treatments advance the control and detection of bacterial infections, addressing contamination, resistance, and biofilm formation. A detailed analysis of contamination by bacterial agents, resistance mechanisms, and microorganism bio-curtains, offering insights into pathogen-based infection complexities and dynamics.
- We examined various enhancements, including photodynamics, electrochemistry, acoustics, electromagnetism, and photothermal resonance, that have improved the diagnostic and therapeutic capabilities of engineered NBs in bacterial infection management. This analysis demonstrates the multifaceted approaches used to enhance the effectiveness and functionality of NBs.
- The article identifies the current challenges in the development and application of smart NBs. We also discuss potential solutions and future directions, emphasizing the advancements that can be leveraged to address the highlighted challenges. We provided a roadmap for future research and development, aiming for more precise and tailored diagnostic and therapeutic interventions.

2 Overview of biosensor technologies in bacterial infection management

Biosensors offer innovative approaches to efficiently detect, monitor, and control bacterial pathogens. This overview encompasses conventional methods and cutting-edge advancements such as AI-integrated biosensor technology and the utilization of smart NBs. In addition, it explores the role of nanotechnology in biosensing applications, underscoring its significance in enhancing sensitivity, specificity, and overall performance in bacterial infection management.

2.1 Conventional methods

The challenge of treating infections is significantly compounded by bacterial survival in biofilms, where populations are encased in a protective matrix, leading to heightened resistance against antimicrobial agents. Biofilms contribute to the persistence and severity of bacterial infections, particularly in healthcare settings. Despite extensive research on bacterial resistance mechanisms, the complex dynamics of biofilm formation and development have not been thoroughly explored. Traditional techniques for identifying and managing bacterial infections, such as smear microscopy, isolation cultures, biochemical tests, and histiocyte cultures, are becoming less prevalent due to their limitations. Synthetic peptides derived from natural host-defence peptides demonstrate antibiofilm activity. Combined with traditional antibiotics, these peptides exhibit a synergistic effect, reducing the required antibiotic concentration to eradicate specific bacterial strains effectively [12,13]. These methods often suffer from restricted sensitivity, prolonged processing times, and complex handling procedures, leading to inaccurate diagnoses and ineffective treatments [14]. As a result,

healthcare-associated infections are frequently mismanaged. There is an urgent need to develop innovative techniques to address the challenges posed by bacterial infections, biofilm formation, and antibiotic resistance. Advanced tools and methodologies are required to combat bacterial infections and mitigate the global impact of antibiotic resistance. Researchers are leveraging AI tools, nanotechnology, and bioinformatics to develop more effective diagnostic procedures and treatments for bacterial infections [15]. Integrating advanced technologies and multidisciplinary research efforts is essential in this endeavor. Collaboration between academia, industry, and healthcare sectors is crucial for the development and implementation of specific strategies to combat bacterial infections and safeguard public health.

2.2 AI-integrated biosensor technology

The integration of AI with biosensor technology is becoming an influential factor in the constantly shifting healthcare industry, transforming the way diseases get diagnosed and managed. The use of computer-aided diagnostics and AI technologies in clinical practice is an important achievement, though it comes with major challenges [16]. It is observable that medical imaging approaches [17], such as X-ray, magnetic resonance imaging, computed tomography, and positron emission tomography, are crucial methods in detecting different diseases [18]. They offer important information about different pathological situations. The diversity of openly available imaging and biological resources improves the abilities of AI systems, making it simpler to adapt them for medical purposes. Pioneering platforms like PathAI [19], Viz.ai, and Freenome harness the power of AI to augment the diagnostic capabilities of pathologists, enhance clinical diagnostics, aid clinical trial support, and advance translational research. Moreover, entities like Freenome revolutionize cancer screening, diagnostics, prevention, and overall disease management. The pervasive adoption of AI-powered tools underscores a commitment to leveraging cutting-edge technologies across various medical domains, from diagnostic imaging to biosensors [20,21]. In tandem with the burgeoning utilization of AI in medical imaging, biosensor technology emerges as a pivotal frontier in disease detection and management. The amalgamation of AI algorithms with biosensors heralds a paradigm shift in disease diagnostics, empowering clinicians with enhanced sensitivity, specificity, and accuracy in detecting biomarkers indicative of diverse health conditions. This joint coordination not only enhances diagnostic capabilities but also paves the way for personalized healthcare, offering tailored treatment methods adapted to the unique features of each patient [22].

Applications of biosensors in conjunction with AI Figure 1 enable lightning-fast detection of diseases, enabling proactive therapy prior to the appearance of clinical symptoms. AI-enabled NBs have continuous monitoring capabilities and offer up-to-the-minute data on the progression of diseases and the effectiveness of treatments. This enables doctors to enhance therapeutic tactics and improve patient outcomes. Furthermore, the use of AI-powered inspection of biosensor data enables clinicians to promptly evaluate the efficacy of medicines in real-time [23]. This allows clinicians to promptly modify treatment regimens, and the likelihood of antibiotic resistance may be reduced, leading to enhanced patient care. The development of powered by AI biosensors that easily connect with current healthcare systems represents a new age of improved communication among medical professionals and efficient clinical operations. AI researchers may provide tailored solutions to boost diagnostic precision, optimize workflow effectiveness, and improve patient care by comprehending the specific challenges and requirements encountered by doctors in various clinical roles. The combination of AI and biosensor technology is poised to significantly alter the management of illnesses and the delivery of healthcare. This confluence has a chance to result in a substantial transformation toward more efficient, customized, and patient-centric care models. The combination of AI with biosensor innovations in health care has the promise to usher in a new age of precise treatment. This would include timely identification, customized treatment, and enhanced results for patients, eventually reshaping the criteria for achieving healthcare performance.

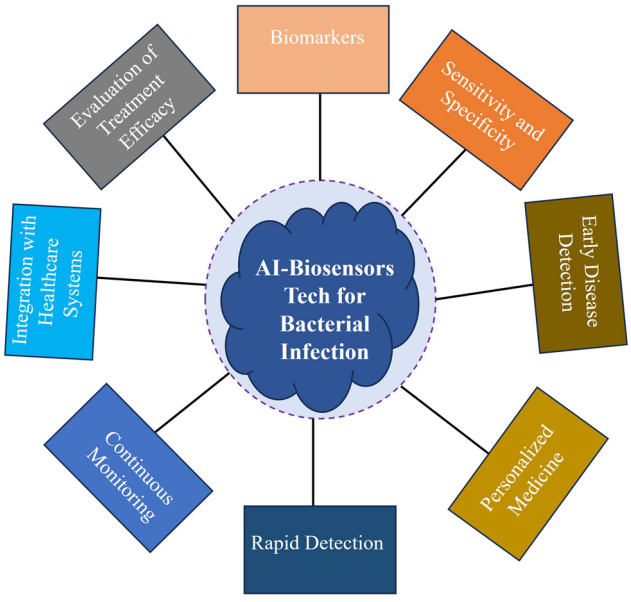

Figure 1: Key nanotechnology techniques in biosensing for bacterial infections.

2.3 Smart NBs in bacterial infection management

The smart NB solution is a modern invention that revolutionizes the detection and management of infections caused by bacteria. These sensors are designed to instantly and accurately detect the existence and behavior of microorganisms. Smart NBs are pivotal in diagnosing infectious diseases, offering sensitivity, selectivity, and rapid detection capabilities. Combining nanomaterials and biosensing technology, these sensors provide versatile tools for disease diagnosis, including point-of-care methods for swift pathogen detection. While offering promise in controlling disease spread, the ongoing research focuses on optimizing these sensors and exploring new opportunities for enhanced diagnosis using nanotechnology [24]. Smart NB methods are frequently employed to detect bacteria instantaneously, enabling ongoing surveillance of their development [25,26]. Smart nanobots for bacterial infection prevention can be grouped into many broad categories and have an extensive list of functions. Table 1 presents an overview of many different uses together with the corresponding NB technology. It is observable that fluorescent NBs can quickly detect the existence of microorganisms, allowing medical professionals to react immediately as necessary. Point-of-care diagnostics use paper-based NBs to swiftly and precisely identify infections caused by bacteria at the patient's bedside. Smart nanobots play a vital role in preventing antimicrobial resistance as they examine the variables that contribute to resistance in strains of bacteria. DNA-based NBs demonstrate exceptional accuracy in detecting such markers, enabling accurate administration of antibiotics and monitoring developments in resistance. Furthermore, they suggest potential methods for destroying bacterial biofilms, which are notoriously tough to eliminate and are frequently associated with chronic infections and resistance to antibiotics. Electrochemical nanobots are designed specifically to detect and eliminate features unique to biofilms, with the capacity to avoid the emergence of permanent diseases by addressing these resilient bacterial populations as highlighted by [27]. In addition, these small devices enable remote detection of bacterial infections in individuals, utilizing functional NBs that have wireless connectivity for transmitting real-time data to medical professionals. This allows for swift intervention and personalized treatment plans tailored to the unique attributes of each patient. The researchers deeply focused on this era, however, on enhancing the versatility and specificity of detection methods, as well as exploring novel approaches for targeted treatment and prevention strategies that need to be tailored to individual patient needs. In addition, research efforts could aim to further integrate wireless connectivity and remote monitoring capabilities into smart NBs for real-time disease surveillance and personalized healthcare interventions.

2.4 Nanotechnology for biosensing

The rapid evolution of molecular biological science has propelled nanotechnology into a dynamic field characterized by continuous innovation and refinement. Leveraging nanotechnology, the scientific community has achieved remarkable breakthroughs, particularly in the realms of biomedical engineering, food safety management, and environmental health monitoring [28]. Nanotechnology presents a promising avenue for addressing challenges associated with bacterial infections, antimicrobial resistance, and biofilms [29]. With its unique chemical, biological, and physical properties, nanotechnology has emerged as an indispensable tool across various medical domains [30,31]. In light of the widespread application of nanomaterials and nanotechnology in diagnosing and treating bacterial infections, a comprehensive examination of recent research findings becomes imperative. This article endeavors to scrutinize the latest advancements in crafting tailored NBs for the detection and management of bacterial diseases. These innovative biosensors harness a

Table 1: Broad categories and applications of smart NBs for bacterial infection management

Category/application	Description	NBs technologies
Real-time detection	Continuous monitoring of bacterial presence and activity in real time.	Fluorescent
Point-of-care diagnostics	Rapid detection of bacterial infections at the point of care.	Paper based
Antibiotic resistance monitoring	Detection of antimicrobial resistance markers.	DNA based
Biofilm detection and disruption	Detection and disruption of bacterial biofilms.	Electrochemical
Remote monitoring	Remote monitoring of bacterial infections in patients.	Wearable
Environmental surveillance	Monitoring bacterial contamination in various environmental settings.	Microfluidic
Smart medical devices	Detection of bacterial infections in medical implants.	Implantable
Personalized treatment strategies	Tailoring treatment strategies based on individual characteristics.	Smartphones

diverse array of nanotechnology methodologies, encompassing electrochemistry, acoustic dynamics, electromagnetism, photothermal responses, and surface plasmon resonance. The multidisciplinary nature of NB techniques holds pivotal importance in unraveling intricate facets of bacterial responses and guiding innovative approaches in diagnosis and therapy. Ongoing research endeavors in nanotechnology are dedicated to exploring novel frontiers and enhancing the efficacy of NBs for precise and efficient diagnosis and treatment of bacterial infections. Through rigorous scientific inquiry and technological advancement, the field of nanotechnology continues to pave the way for transformative solutions in biomedical science and healthcare (Table 2).

3 ML and DL analysis for in bacterial monitoring and control

Researchers utilized different applications of ML and DL techniques in improving nano biosensors for detecting bacterial infections. Subsection 2.1 analyzes ML methods, while Subsection 2.2 focuses on DL approaches, highlighting their contributions to enhancing performance.

3.1 ML approaches for detecting bacterial infections

ML methods have greatly improved biosensor technologies by increasing their sensitivity, accuracy, and efficiency. Significant progress has been made in the development of customized integrated sensor arrays that combine 2D nanomaterials with fluorescently labeled single-stranded DNA. The arrays can precisely identify different bacteria, including those that are resistant to drugs, by examining the unique patterns of response that occur when bacteria contact with the sensing components. The technique has a remarkable level of accuracy, with a detection rate of 97.9%, in recognizing pathogens such as *S. aureus* and *Escherichia* at various levels of concentration. Moreover, the integration of Surface-Enhanced Raman Scattering (SERS) with ML techniques like support vector machine (SVM) and random forest has greatly enhanced the ability to identify viruses [32,33].

This combination enables the rapid and accurate identification of respiratory viruses, such as SARS-CoV-2, common human coronaviruses, and influenza viruses. By using the enhanced sensitivity of SiO2-coated silver nanorod substrates, these systems can accurately differentiate and classify virus species and strains with an accuracy above 99%. This makes them a powerful tool for managing viral epidemics. In addition, the combination of optical biosensors, nonlinear optics, and ML enhances viral detection by using multiphoton interactions to boost both sensitivity and specificity. This makes them very effective in identifying a variety of viruses, including the SARS-CoV-2 virus [47]. Through the use of ML Figure 2, these biosensors can examine complex biological data and detect mobile entities inside the human body, facilitating rapid detection of possible health problems and quick intervention [43]. ML-enhanced biosensor technologies have revolutionized pathogen detection and virus identification, offering unprecedented levels of sensitivity and accuracy. Customized integrated sensor arrays, combining nanomaterials with DNA labeling, enable precise identification of bacteria, including drug-resistant strains, with high detection accuracy.

3.2 DL techniques for detecting bacterial infections

DL algorithms have significantly transformed biosensor technology by offering advanced data analysis and prediction capabilities. Carbon nanotube (CNT)-based biosensors, when combined with deep neural networks (DNNs), have shown substantial promise in the realm of medical diagnostics, namely, for the detection of heart failure [39]. These biosensors utilize electrochemical impedance spectroscopy (EIS) data to accurately forecast B-type natriuretic peptide (BNP) levels, hence eliminating the necessity for conventional error-prone analytical methods. This method improves both the accuracy of diagnosis and the availability of the technology for point-of-care testing. Nonenzymatic electrochemical biosensors, employing a back-propagation neural network, exhibit exceptional selectivity in the detection of glucose and lactate. These sensors utilize specialized working electrodes that are incorporated into arrays of electrochemical microdroplets. When combined with neural network analysis, they can accurately forecast the levels of analytes, even in complicated biological samples, simplifying the detection process and reducing the need for sophisticated material production and selection [58].

Figure 3 illustrates the general features of DL models, such as DNN and CNNs, which have achieved great success in recognizing and measuring vitamin B6 molecules through 3D fluorescence spectra [52]. These models may attain accuracy levels of up to 100%, showing their effectiveness in distinguishing between molecules with very similar

Table 2: Application of ML and DL for bacterial infection monitoring and control

References & year	ML/DL technique	Detection mechanism	Target bacteria	Applications	Advantages
Rawson *et al*. [32] 2019	SVM	Classification using six blood parameters (C-reactive protein, white cell count, bilirubin, creatinine, ALT, and alkaline phosphatase).	Community-acquired bacterial infections	Diagnosing bacterial infection in hospital-admitted patients.	Utilizes routinely available blood parameters for accurate diagnosis with high ROC AUC 84%
Agbaria *et al*. [33] 2019	SVM, principal component analysis, LDA	Infrared spectroscopy of white blood cell (WBC) samples	Differentiation between bacterial and viral infections	Rapid identification of infection type within less than 1 h after blood sample collection	High sensitivity (93%) and specificity (85%); fast, accurate, sensitive, and low-cost method
Gadalla *et al*. [34] 2019	Random forest, SVM coupled with recursive feature elimination.	Identification of clinical and urinary immunological predictors	Urinary tract infections (UTIs)	Diagnosis of uncomplicated UTIs in women	Improved accuracy in ruling in/out UTIs using urine cloudiness and specific urinary biomarkers. potential development of a point-of-care test
Oh *et al*. [35] 2019	Convolutional neural network (CNN)	Embedding disease diagnosis and antibiotic prescriptions in electronic health records (EHR) and using a DL model for prediction	Antibiotic-resistant bacteria	Prediction and estimation of antibiotic resistance for preemptive measures	Improved f1-score from 0.525 to 0.617 by incorporating disease and antibiotic information; DL model outperformed traditional ML models
Ho *et al*. [36] 2019.	CNN, logistic regression and SVM	Raman optical spectroscopy for label-free bacterial detection, identification, and antibiotic susceptibility testing	30 common bacterial pathogens, including *S. aureus* (both methicillin resistant and methicillin susceptible)	Culture-free pathogen identification and antibiotic susceptibility testing	Achieves high accuracies even on low signal-to-noise spectra; distinguishes between methicillin-resistant and -susceptible isolates with high accuracy
Hattori *et al*. [37] 2020	Ensemble-learning algorithm for data classification in high-dimensional feature space	Oulter principle measuring transient drops in ionic current as bacteria translocate through a low aspect ratio pore	*S. aureus*, *Pseudomonas fluorescens*, *Salmonella enterica*, *Escherichia coli*, and *Bacillus cereus*	Rapid screening of pathogens for infection control in healthcare and environmental settings	Label-free single-cell identifications, high-spatiotemporal resolution, real-time detection of pathogenic bacteria
Nehal *et al*. [38] 2020	CNN	Photonic crystal-based optical biosensor detecting spectral changes due to bacterial presence	*E. coli*	Prediction of bacterial contaminants in water	High accuracy (95%) in detecting bacterial presence; lightweight, small, portable, and low-noise optical biosensors that work without electric power
Iriya *et al*. [39] 2020	Long short-term memory (LSTM) network	Optical imaging-based method to track motion patterns of single bacterial cells	*E. coli*	Rapid antibiotic susceptibility testing	Accurately determines antibiotic susceptibility within 30 min for five commonly used antibiotics
Brown *et al*. [40] 2020	Neural network	Optical intensity information from an array of fiber optic cables to detect bacterial growth	*S. aureus*	Rapid and automated antimicrobial susceptibility testing (AST)	Faster results (within 5.72–10.5 h), cost-effective, eliminates human error, compatible with standard phenotypic assays, meets FDA criteria for essential and categorical agreements

(Continued)

Table 2: *Continued*

References & year	ML/DL technique	Detection mechanism	Target bacteria	Applications	Advantages
Draz *et al*. [41] 2020	CNN	Nanoparticle-enabled smartphone system with platinum nanoprobes inducing gas bubble formation	Hepatitis B virus (HBV), HCV, and Zika virus (ZIKV)	Rapid and sensitive virus detection	High sensitivity (98.97%) for detecting viral-infected samples, no need for optical hardware smartphone attachment
Alafeef *et al*. [42] 2020	SVM in ML is used with wireless communication	Nanotechnology-based smart sensors using nanomaterials like carbon nanoparticles, metallic nanoparticles, metal oxide nanoparticles, and nanocomposites	Pathogenic bacteria, including antibiotic-resistant bacteria	Early and rapid detection of bacterial pathogens at the point-of-care	Enables real-time and continuous monitoring, potentially providing valuable information for outbreak prevention and containment
Zhang *et al*. [43] 2021	CNN, SVM, PCA	Noninvasive biosensors collecting physiological signals	Physiological signals and bacterial data	Clinical practice, health monitoring, and food safety	Improved accuracy and efficiency in healthcare, bringing a digital revolution
Ding *et al*. [44] 2021	Multi-scale CNN	SERS	*Salmonella enteritidis*, *Salmonella typhimurium*, and *Salmonella paratyphi*	Efficient detection and distinction of Salmonella serovars	High recognition accuracy (over 97%) for serovar identification
Yu *et al*. [45] 2021	LSTM neural network and CNN	Raman spectroscopy	Pathogens isolated from the marine organism *Urechis unicinctus*	Efficient and accurate identification of pathogens in seafood and the environment	LSTM methods achieved average isolation-level accuracies exceeding 94%, faster and more accurate than normal CNN models
Li *et al*. [46] 2022.	MRDP was applied to LDA algorithm	Interaction-induced release of ssDNA from 2D-n	Pathogenic microorganisms including *E. coli*, *S. aureus*, methicillin-resistant *S. aureus* (MRSA)	Rapid and accurate microbial taxonomic identification	High overall accuracy of 97.9%
Yang *et al*. [47] 2022	SVM, k-nearest neighbor, random forest	SERS with SiO_2 coated silver nanorod array substrates	Thirteen respiratory virus species, including SARS-CoV-2, common human coronaviruses, and influenza viruses	Rapid and accurate detection and classification of respiratory viruses, aiding medical diagnosis and therapeutic intervention	High differentiation accuracy (>99%) and ability to quantify virus concentrations in buffer and saliva
Arano-Martinez *et al*. [48] 2022.	Linear regression, SVM, navie Bayes, decision trees, and KNN	Optical biosensors enhanced by nonlinear optics and multiphoton interactions	SARS-CoV-2 and other viruses	Detecting biological information, predicting urgent situations, and identifying viruses and harmful entities in living organisms	Enhanced sensitivity, expanded application range, and improved identification of complex agents
Verma *et al*. [49] 2022	SVM, RF	Biosensors utilize ML to interpret environmental changes, detect biomarkers, and integrate sensing modalities for system understanding	Lung cancer-related exosomes or prostate cancer biomarkers	ML-enhanced biosensors monitor physiological parameters, diagnose diseases, and detect pathogens in healthcare settings	These biosensors offer improved accuracy, sensitivity, and personalized diagnostics
Guo *et al*. [50] 2022	Deep neural network	EIS data from carbon nanotube thin film (CNT-TF) biosensors	BNP for heart failure diagnosis		High sensitivity, fast response, enhanced reliability, and

(Continued)

Table 2: *Continued*

References & year	ML/DL technique	Detection mechanism	Target bacteria	Applications	Advantages
				Diagnosis and management of heart failure in point-of-care settings	applicability without advanced hardware
Zhou *et al.* [51] 2022	CNN	Nonenzymatic electrochemical biosensing with chronoamperometry data analysis	Glucose and lactate	Point-of-care detection for glucose and lactate in biological samples	High sensitivity, low cost, long-term stability, enhanced selectivity without complex material synthesis, accurate prediction in real samples
Noreldeen *et al.* [52] 2022	DNN, CNN	Intrinsic fingerprint of 3D fluorescence spectra	Five Vitamin B6 derivatives (VB6Ds)	Qualitative and quantitative analysis of VB6Ds	High accuracy in identifying and quantifying VB6Ds, effective transfer learning, broad concentration range detection
Wang *et al.* [53] 2022	Neural networks and PCA	MEMS microcantilever structures	Various MEMS biosensors for automation, consumer electronics, industrial manufacturing, defence, medical equipment,	Development of high-sensitivity sensors and intelligent sensing systems	Small size, high sensitivity, mass production capability, simple arraying, and integration
Kumar *et al.* [54] 2022	LSTM, Bi-LSTM with Bahdanau attention, CNN-LSTM, Convolutional-LSTM	Prediction of respiratory rate using ECG, PPG, and sEMG data	Respiratory rate prediction in a body sensor network	Monitoring and predicting respiratory rates for health monitoring	High prediction accuracy; Bi-LSTM with Bahdanau attention showed best results
Rahmani *et al.* [55] 2023	CNN	Near-infrared (NIR) and RGB imaging analyzed with a SWCNT sensor and DNA aptamer	Bacteria detection using biosensor imaging	Early detection and prevention of crop diseases in agriculture	High accuracy (98.72%) and computational efficiency; effective classification of biosensor images
Ramalingam *et al.* [56] 2023	KNN, SVM, NB, DT, GBT, RF, feedforward ANN, RNN and CNN	Nanotechnology-enhanced biosensors leveraging nanomaterials for improved performance	Viruses and pathogens detection	Virus detection, improving biosensor performance, facilitating efficient detection of viruses and pathogens	Enhanced sensitivity, high surface-to-volume ratio, quantum size effects, improved biosensor performance
Kang *et al.* [10] 2024	1D CNN with binary labeling	3D nanostructure swab captures pathogens, and portable Raman instrument collects Raman signals for classification by the DL algorithm	Multiple foodborne bacterial species	Rapid identification of foodborne pathogens on contaminated surfaces and kitchen utensils for food safety monitoring	Rapid detection (≈5 min), high accuracy close to 100%, practical application with blind tests, and enhanced sensitivity using DL and Raman spectroscopy
Zhou *et al.* [57] 2024	YOLOv7	Portable lens-free holography microscope for digital single-particle counting and nucleic acid detection without pre-amplification	*Salmonella typhimurium*	Point-of-care testing for nucleic acids, food safety inspection, environmental monitoring, and in vitro diagnostics	High sensitivity (72 CFU/mL), low cost ($70), lightweight (~318 g), wide field of view, and no need for pre-amplification

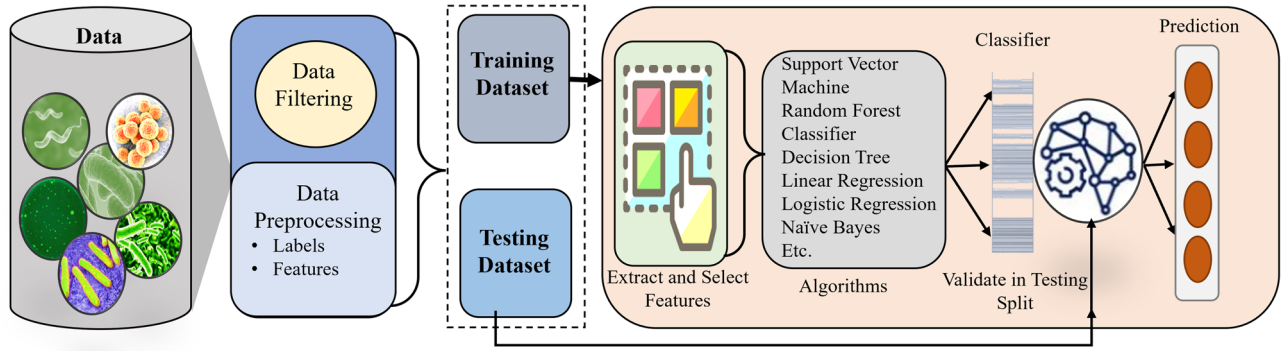

Figure 2: Generic overflow of ML approaches for bacteria diagnosis.

chemical structures. Possessing this skill is essential for precise medical diagnosis and treatment. In addition, advanced DL models such as LSTM networks and bidirectional LSTM (Bi-LSTM) with Bahdanau attention have demonstrated high accuracy in predicting respiratory rate using data from biosensors such as ECG, PPG, and surface electromyogram (sEMG) [54]. The Bi-LSTM with attention mechanisms offers very precise predictions, which are essential for monitoring patient health in real time [37]. A novel lens-free holography microscope, which incorporates DL techniques, has been created for digital single-particle counting in nucleic acid detection, without the need for pre-amplification. This cost-effective and portable technology collects three-dimensional images of small spherical objects and uses an enhanced YOLOv7-based algorithm to effectively and precisely identify minuscule items [57,59].

The combination of powerful ML and DL algorithms with state-of-the-art biosensor technology is resulting in significant progress in pathogen detection. ML approaches improve the sensitivity and accuracy of biosensors in identifying different pathogens, such as viruses and bacteria, by evaluating intricate data patterns and enhancing the efficiency of detection procedures. However, the ML-based approaches are not robust in complex problems as the features engineering is often manual. DL algorithms provide advanced data processing and prediction capabilities, allowing for precise diagnoses and real-time health monitoring. These technological advancements are improving the accuracy, efficiency, and accessibility of diagnostic techniques, which are vital for managing public health, detecting diseases early, and providing timely medical treatment. The integration of machine learning, deep learning, and nanotechnology is revolutionizing biosensor development, leading to diagnostic instruments that are more efficient, precise, and accessible. This advancement has substantial implications for healthcare, food safety, and disease prevention. The progress in this discipline is enhancing the existing state of pathogen detection and also creating opportunities for future study and application in other areas, such as environmental monitoring, food safety inspection, and clinical diagnostics.

4 Pathogen-based infection

Infectious diseases, including the outbreak of COVID-19, represent a constant and widespread danger to public health. According to the World Health Organization, there

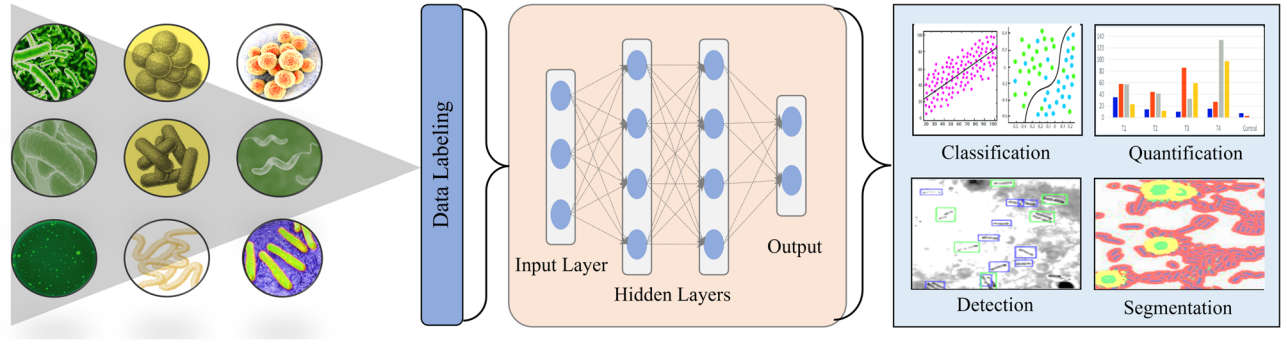

Figure 3: Technical overflow of DL techniques for the identification and monitoring of bacteria.

Table 3: Frequently employed methods for identifying pathogenic viruses

Concept	Methodology	Benefits	Time Span	References
Nuclic acid	PCr	Clearly established limited quantity of test specimens	Hourly	[67]
Viral defense	Elisa	Extremely particular	Hourly	[68]
Infectiousness test	Cellular culture	Appropriate for virus subtyping and divergent strain recovery Quite affordable	Conversion from days to weeks	[69]
Viral components	The use of electron microscopes	Expeditious technique	Hourly	[70]
Thoracic imaging	Computerized tomography (CT)	Solid foundation for clinical diagnosis and therapy	Hourly	[71]

have been over 76,382,044 confirmed cases of COVID-19 and more than 1,702,128 deaths in over 200 countries or territories worldwide as of 23 December 2020 [60,61]. The lack of adequate point-of-care detection tools is a significant factor contributing to the high incidence of these disorders. Hence, the development of fast and dependable health technologies for the diagnosis of numerous viruses is crucial to protect ourselves from serious dangers. The current approaches for diagnosing viral infections involve detecting viruses or viral antigens in human bodily fluids and conducting lung computerized tomography scans of patients, focusing on specific imaging abnormalities. Common virus detection techniques encompass viral culture, a method called reverse transcription-polymerase chain reaction (RT-PCR), and enzyme-linked immunosorbent test (ELISA) [62–64]. However, the majority of these diagnostic procedures have disadvantages in terms of being time-consuming and requiring a lot of effort. Table 3 presents a comprehensive analysis of the advantages and limitations of current virus detection techniques. Virus culture is a laborious task that requires skilled individuals and particular procedures. To conduct the RT-PCR experiment, the viral RNA is initially extracted and then converted into complementary DNA (cDNA) using reverse transcription. The cDNA is subsequently amplified by PCR, or polymerase chain reaction, to facilitate detection.

The RT-PCR approach exhibits a high level of sensitivity; however, it requires costly specialist equipment, intricate primer design for sequence alignment, and tuning of assay conditions. In addition, the testing procedure of the RT-PCR technology is time consuming because it involves multiple cycles of heating. ELISA is a fast detection technique that uses a solid-phase enzyme immunoassay to identify viral antigens. However, its usefulness for on-site detection is limited due to its relatively poor sensitivity and the requirement for high-quality sample preparation [65]. Due to the initial shortage of testing kits and the high probability of false negative results from RT-PCR, chest CT scans were temporarily employed as a means of clinically diagnosing COVID-19 during the early stages of the illness outbreak. The CT scan is a non-invasive technology that requires the patient to lie still. The patient's chest is subjected to several X-ray scans from various angles to generate cross-sectional images that vary depending on the stage of infection following the start of symptoms. CT scan for COVID-19 detection has a significant drawback in terms of low specificity (25%), as its imaging features are similar to those of other viral pneumonia. Molecular diagnostic techniques are more appropriate for precise diagnoses compared to syndromic testing and CT scanning. This is because they can directly focus on and identify specific infections [66].

4.1 Contamination by bacterial agents

It is generally acknowledged that once bacteria enter the body, they reproduce, multiply, and release toxic substances. Infection with bacteria or, in extreme circumstances, intoxication caused by germs can manifest in various pathogenic ways in the body. Bacterial infections commonly appear in two main forms: acute and persistent. The effects of different pathogenic bacteria on the host organism can differ [72]. During acute infections, bacteria trigger an immediate inflammatory reaction in the host, typically marked by symptoms such as redness, swelling, increased temperature, discomfort, and reduced functionality. In contrast, chronic infections develop slowly as bacteria gradually create biofilms, which make them more resistant to antimicrobial treatments and the host immune system. It is important to mention that although self-limiting bacterial infections might happen, most bacterial infections present considerable difficulties in terms of therapy [73]. The outcome and intensity of bacterial infections depend on the interaction between human immunity and bacterial pathogenicity. Several variables significantly

Table 4: Possible nanotechnology-based treatments for the control of bacterial infections

References	Microorganisms	Nanoparticles	Anti-bacterial solution	Operations
[74]	*E. coli* and *S. aureus*	PLGA-poly(L-histidine)- PEG	Vancomycin	Increasing binding of antibiotic to bacteria
[75]	Multidrug-resistant *P. aeruginosa*	AgNPs	Polymyxin B	Three-fold higher biofilm reduction than the neat Ag nanoparticles
[76]	*P. aeruginosa*	PLGA/chitosan nanoparticles	Colistin	Inhibition of biofilm with a 90% reduction in biomass
[77]	Methicillin-resistant *S. aureus* (MRSA)	Chitosan	Daptomycin	Antibacterial effect
[78]	*E. coli*	Chitosan/heparin	Ciprofloxacin	A synergistic effect of drug and biopolymer on the disruption of bacterial membranes
[79]	*P. aeruginosa*	AuNPs	Esculentin-1a (antimicrobial pep- tide)	Fifteen-fold increase in anti-*P. aeruginosa* activity of free esculentin-1a without toxic effect on human keratinocytes
[80]	Gram-negative bacteria	Graphene oxide, Ag	Ciprofloxacin	Eradicating of Gram-negative bacteria
[81]	*M. tuberculosis*	PLGA	Rifampicin	Bactericidal activity against *M. tuberculosis*
[82]	MRSA	TiO_2	Erythromycin	Decreasing the MIC of erythromycin

impact the infection's progression, including the infecting agent's dosage, environmental conditions, co-infections, and associated factors. A thorough comprehension of these aspects is essential in ascertaining the result of bacterial infections and directing efficient approaches for prevention and therapy. Current research efforts strive to understand the complicated dynamics of bacterial infections, leading to progress in developing treatments and improving our capacity to deal with the intricacies of bacterial pathogenesis (Table 4).

4.2 Resistance to bacterial agents

Antibiotic use is known to promote the evolution of bacteria that are resistant to their effects, which in turn leads to their eventual dominance. A major global health concern, the rise of antibiotic-resistant microorganisms has made the significant shift toward viable therapies seem like a distant dream. It is crucial to acknowledge that antibiotic resistance is an inherent and unavoidable occurrence. Bacteria have undergone ongoing evolution over billions of years, acquiring adaptations to counteract the effects of antimicrobial treatments. Bacterial resistance is influenced by a confluence of environmental and intrinsic factors. The quick spread of bacterial drug resistance is greatly influenced by environmental mechanisms, specifically the protracted process of ecological evolution. Alterations to the DNA sequence, such as genetic transfer across bacterial species, can occur when bacteria colonize or infect hosts in the environment [83,84]. Gaining a deep comprehension of the complex mechanisms behind antibiotic resistance is essential for formulating comprehensive approaches to tackle this rapidly developing worldwide health crisis. Current research efforts are focused on discovering innovative strategies to reduce antibiotic resistance, providing possible solutions to the difficulties posed by this intricate problem.

4.3 Microorganism bio-curtain

The process of bacterial biofilm formation might be described as a gripping narrative, resembling a symphony with four distinct stages. In Figure 4, microorganisms adhere to surfaces using mechanisms such as the cell's surface charge of everything, the van der Waals force, its hydrophobicity, as well as electrostatic force [85], similar to artists using charged brushes. The story then transitions to a complex dance, as microorganisms move through liquid environments or gather on solid surfaces, resembling artists on a canvas, using the coordinated movements of rotating flagella [86]. The climax occurs during the maturity phase, where biofilm micro-

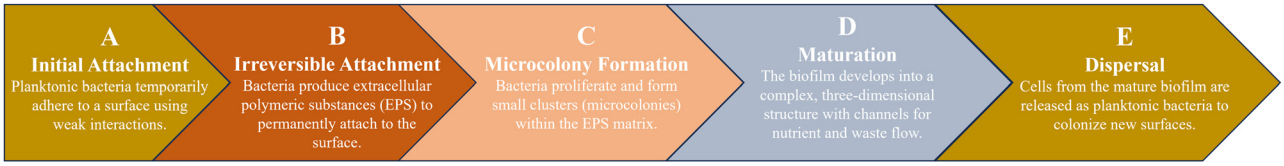

Figure 4: Phases overview of the biofilm cycle.

colonies, resembling masterpieces, are surrounded by water transport channels. These channels facilitate the movement of nutrients and coordinate quorum sensing and gene regulation [87]. In the last stage, known as dispersion, bacteria elegantly transition between floating states and biofilm states within a complex community of many cells [88]. The fully developed biofilm serves as a channel for the transfer of energy, chemicals, and information, strengthening microorganisms underneath against unpredictable external conditions. This biofilm development pattern serves as evidence of the ability of cells to thrive in challenging conditions and spread out into new ecological habitats, similar to innovative explorers [89,90]. The composition's subtleties are meticulously adjusted by factors such as bacterial density, duration of life, temperature, fluid flow characteristics, nutrient concentration, and the interplay of surface material qualities. The complex flagella and fimbriae on the bacterial canvas are additional decorations that play important functions in the development of biofilms. Continuing research efforts, similar to innovative composers, aim to enhance our comprehension and develop tactics for modulating or regulating the formation of biofilms in various environments. The life cycle of a microbial biofilm is illustrated with relevant features (Figure 4). where the process begins with initial attachment, where planktonic bacteria temporarily adhere to a surface through weak interactions. This progresses to irreversible attachment, where bacteria produce extracellular polymeric substances (EPS) to secure permanent adhesion. In the microcolony formation phase, bacteria proliferate, forming small clusters within the EPS matrix. During maturation, the biofilm evolves into a complex, three-dimensional structure with channels facilitating nutrient and waste flow. Finally, in the dispersal phase, cells from the mature biofilm are released as planktonic bacteria, ready to colonize new surfaces. This iterative process guarantees the persistence, expansion, and dissemination of bacterial populations across many habitats.

5 Bacterial diagnosis and treatment using engineered NBs

The era of bacterial diagnosis and treatment using engineered NBs involves the integration of nanotechnology with photodynamic therapy (PDT) to accurately and efficiently control bacterial infections. The incorporation of PD into novel NBs capitalizes on the ongoing advancements in optical technology and photosensitive compounds, enabling the generation of reactive oxygen species inside bacterial cells to eliminate infections. Nanomaterials are crucial in the delivery of phototherapeutic drugs, since they may specifically target and eliminate bacterial cells *via* PD mechanisms. Zeolite L-nanocrystals and other nanoparticles are particularly effective in this procedure. By combining the use of photonic synergy with drugs such as metronidazole (MNZ), the efficiency of PDT against biofilm infections is improved [91]. This is achieved by stimulating anaerobic metabolism in bacteria, namely, MRSA. NBs are activated by NIR light irradiation. These biosensors use nanocomposite films and hierarchically constructed nanoparticles to generate reactive oxygen species and nitric oxide, resulting in strong antibacterial effects. Moreover, the use of gold and silver nanocages in precision phototherapy exploits their specific surface plasmon reflection properties, allowing for the efficient elimination of drug-resistant biofilms and infections *via* the aggregation-induced photothermal (AIP) effect. Together, these categories emphasize the revolutionary capability of merging nanotechnology with PD principles to provide advanced biosensing technologies and therapeutic approaches for addressing bacterial resistance and infections.

5.1 Integration of photodynamics into innovative NBs

The emergence of PDT represents a notable advancement in the targeted treatment of bacteria, propelled by the continuous advancement of technology for optics. In recent years, there has been tremendous interest in the continual development of new photosensitive substances, which offer a novel and inventive approach to antibacterial treatments. This innovative antibacterial medication employs PD principles to induce the production of reactive oxygen compounds within microbial cells, leading to their eradication. The utilization of nanotechnologies in bacterial detection and therapy by PD is becoming increasingly popular due to its advantages, such as fewer adverse effects and decreased vulnerability to

medication resistance [91,92]. PDT, as a burgeoning therapeutic method, exhibits immense potential in the accurate and efficient management of bacterial infections. As research progress continues, the combination of optical technologies and nanomaterials is increasingly enabling new opportunities, enhancing the field of bacterial therapy and strengthening human defenses against infectious pathogens.

5.1.1 Nanomaterials for phototherapeutic drug delivery

The use of phototherapeutic medicinal materials has significant therapeutic promise, and nanotechnology is crucial in exploiting this potential to develop multifunctional structures that can selectively target and destroy cells. The integration of these two domains presents new possibilities, especially in fighting microorganisms that are resistant to many drugs [93]. Scientists employ nanometer-scale particles derived from zeolite L-nanocrystals to affix a chemical component onto the bacterial coat using a simple and economical approach. These particles possess the capacity to incorporate dye molecules that generate a green fluorescence when examined under a microscope, permitting simple identification of the microorganisms. PD processing involves exposing bacteria to light to trigger a response that effectively kills them. In focused studies, researchers have enhanced micron-sized crystals with a third element. Because of their red light sensitivity, these crystals release specific molecules of reactive oxygen species. Oxygen molecules, even a single oxygen molecule, can set off a chain reaction that damages bacterial cells [94].

Integrating nanotechnology with phototherapeutic materials to improve bacterial therapy precision is the goal of the ongoing investigation in this area. The potential for these flexible structures to concentrate on specific markers and their adaptability bode well for the fight against bacterial infections, especially those that defy standard treatment methods. In the never-ending quest for effective treatments for bacterial infections, researchers are always looking for new ways to improve these procedures.

5.1.2 Photonic synergy in combined therapy

To treat bacterial biofilm infections, scientists are pioneering a method that combines PDT with the MNZ, which amplifies the effects of low oxygen levels. Hyaluronic acid (HA)-Ce6-MNZ nanoparticles (HCM NPs) are synthesized by combining chlorin e6 (Ce6) with MNZ in a unique way. The release of Ce6 and MNZ occurs when the HCM NPs are broken down by the hyaluronidase (Hyal) secreted by MRSA biofilm when they reach sites contaminated with this biofilm. Utilizing atmospheric pressure and the principles of PD treatment, laser irradiation of Ce6 starts a reaction that generates the singlet oxygen (1O2), effectively killing any bacteria in the biofilm. As PD therapy consumes oxygen, the oxygen deprivation within the biofilm intensifies, leading to the creation of nitroreductase by MRSA. The enzymatic response triggers the activation of MNZ, resulting in the elimination of bacteria in low-oxygen settings [95]. Table 5 summarizes the advantages, disadvantages, applications, and general usage of antimicrobial nanoparticles in this context.

This innovative incorporation of PD treatment not only enhances the oxygen-deficient microclimate but also eradicates this MRSA swarm even in the absence of hypoxic conditions. This method induces anaerobic metabolism in MRSA and enhances the antimicrobial effects of MNZ, showing the potential of this adaptable strategy in addressing complex bacterial infections. As scientific research progresses, these innovative methods create opportunities for the development of precise treatments that utilize the interaction between nanotechnology and PD principles to effectively address antibiotic-resistant biofilm infections.

5.1.3 NIR light irradiation activates NBs

The wide range of organic and inorganic nanomaterials that emit NIR light are being utilized in antibacterial approaches to address bacterial resistance. A inventive strategy entails creating nanocomposite films for NIR irradiation that utilize nitric oxide (NO)-assisted PD treatment. This approach is based on nanoparticles that are built hierarchically, namely composed of upconversion nanoparticles (UCNPs) and porphyrinic metal-organic frameworks (PCN-224). To enhance their efficiency, the particles are impregnated with the amino acid L- (LA) and subsequently bonded to a polyvinylidene fluoride (PVDF), structure, leading to the creation of an electrically spun nanocomposite material membrane (UCNP@PCN@LA-PVDF) [96]. When exposed to NIR light at a wavelength of 980 nm, this novel membrane enhances the production of reactive oxygen species (ROS). In addition to its ability to kill bacteria in PDT, the creation of ROS also activates loaded LA, leading to the formation of nitric oxide (No). This dynamic collaboration provides an innovative antibacterial effect through NO-assisted PDT. The employment of NIR light for irradiating nanoparticles holds potential for application in medical engineering biosensors, particularly for the detection and treatment of bacteria. The combination of nanotechnology and light-based therapies shows great potential for enhancing antibacterial interventions and biosensing technologies in

the field of biomedical engineering. Current research efforts are focused on improving and broadening existing techniques, introducing innovative approaches to address bacterial resistance, and improving the functionality of biosensors in the field of biomedicine.

5.1.4 Nanocages for precise phototherapy using biosensing technology

In addressing bacterial biofilms, the utilization of tailored phototherapy technology is commonly employed. This approach is often paired with nanomaterials to induce microenvironmental regulation of the antimicrobial effects of drugs by photodynamic therapy. Extensive studies have been conducted in the past on metal nanoparticles, particularly gold and silver, because of their distinct local surface plasmon reflection (LSPR) characteristics. The utilization of gold and silver nanoparticles is credited to their remarkable durability, safety for biological systems, and adaptable capacity for modification, making them more helpful in various applications including highly sensitive detection, imaging, and diagnosis and therapy of bacterial infections. This technique involves the integration of abundant quantities of silver-loaded golden silver nanocages (GSNCs) with thiolate. The whole treatment utilizing the rapid release of silver from GSNCs and the thermal action of NIR radiation shows effectiveness in completely removing biofilms produced by bacteria that are resistant to several drugs in a controlled laboratory setting, as well as eradicating drug-resistant *S. aureus* in mice with the disease. This approach offers a hopeful pathway in the fight against stubborn multidrug-resistant bacterial illnesses [97].

Tan proposes a distinct method that utilizes red phosphorus and NIR irradiation to swiftly eliminate biofilms on phototube implants. This method makes use of the favorable biocompatibility and exceptionally effective photothermal properties of red phosphorus [98]. Continuing research is demonstrating the possibility of combining targeted phototherapy with nanomaterials to effectively tackle the challenges presented by bacterial biofilms and infections that are resistant to several drugs. These novel approaches signify crucial progress in the quest for efficacious remedies against resilient bacterial illnesses.

Table 5: Advantages, disadvantages, applications, and general usage of antimicrobial nanoparticles

Usage	Advantages	Applications of antimicrobal nanoparticles	Disadvantages
Precision drug delivery to infection sites, reducing systemic side effects.	Nano-biosensors enhance drug delivery precision, ensuring antimicrobial nanoparticles accumulate at infection sites.	Enhanced precision in treating bacterial infections with NBs.	Risk of nanoparticle accumulation in nontarget tissues.
Localized drug release to specific sites, reducing off- target effects.	Smart biosensors control and localize drug release, minimizing side effects.	Smart biosensors offer solutions for multidrug-resistant bacteria.	Keeping nanoparticles localized is challenging.
Early detection and intervention of bacterial contamination, preventing device-associated infections.	Nano-biosensor techniques help reduce bacterial resistance by enabling timely interventions.	Nano-biosensors monitor and control bacterial contamination in devices.	Potential toxicity in vital organs.
Facilitates drug delivery to the brain, enabling the treatment of neurological infections.	Nano-biosensors facilitate nanoparticle transport across barriers like the blood-brain barrier.	Biosensors aid in delivering nanoparticles across the blood brain barrier.	Limited safety data; biosensors collect essential long-term information.
Real-time monitoring of therapeutic levels, optimizing treatment efficacy.	Biosensors provide real- time feedback for sustained therapeutic levels.	Continuous monitoring ensures effective chronic infection treatment.	Accurate nano-particle characterization is crucial.
Enhanced drug formulation and water purification, improving drug efficacy and environmental safety.	Nano-biosensors improve drug formulation, increasing solubility and bioavailability.	Nano-biosensors detect and eliminate bacterial contaminants in water.	Stability and environmental impact issues.
Safe administration of higher doses, improving treatment efficacy.	Biosensors ensure safe administration of higher nanoparticle doses.	Enhanced sterilization techniques with antimicrobial nanoparticles and biosensors.	Nanoparticles can induce stress. biosensors detect early responses.
Reduced immune response and improved compatibility, extending product shelf life.	Nano-biosensors minimize immune detection and improve compatibility.	Smart packaging with NBs controls bacterial contamination, extending shelf life.	Production is costly.

5.2 NBs enhanced with electrochemistry

There has been considerable interest in using bioelectric nanotechnology techniques to address resistance genes and biofilms of bacterial species. Specifically, researchers have focused on surface modification methods that disrupt the bio-electric balance within bacteria, both internally and externally [25,99]. Moreover, the inherent benefits of electrochemical sensors, which include affordability, little energy usage, lack of intricate automation, and micro-miniaturization, make them well suited for the quick and precise detection of bacteria. When combined with microfluidic technology and nanotechnology, this becomes especially important since it allows for rapid and extremely accurate identification of intricate bacterial samples directly at the location. Furthermore, the simplicity with which electrochemical detection can be scaled down and rendered portable increases its appropriateness for swift and economical identification of bacteria in areas with restricted medical facilities. The purpose of this flexibility is to avoid significant public health incidents caused by delays in detection, highlighting the essential contribution of bioelectric nanotechnology in improving accessible and prompt bacterial detection methods. Continual research efforts are being made to improve these methods, guaranteeing their effectiveness and availability for general use in various healthcare environments. While this section focuses on bacterial detection, Table 6 provides a summarized review of advancements in NBs for the detection of transmissible and nontransmissible diseases, highlighting the broader applications of this technology. Figure 5 illustrates the integrated biosensors technology for bacterial infection management.

5.2.1 3D electrode scaffold design

It is observable that to understand disease mechanisms and drug responses, researchers have looked into the possibility of creating electrochemical cells that can identify bacteria with multidrug resistance. First, a glass carbon electrode is attached to a custom-made electrochemical cell. At the same time, as adding the soluble electron transfer agent phenazine methosulfate (PMS) to the growth medium, the bacterial culture is placed into the specified battery configuration. Electrons are generated during bacterial respiration, leading to a reduction in PMS and resulting in its oxidation on the surface of the electrode. This process allows the current to be recorded. The electrochemical antibiotic sensitivity test yielded consistent findings, accurately classifying bacteria as either antibiotic resistant or sensitive. This classification was accomplished not only within a 90 min

Table 6: Review on the advancements in NBs for the detection of nontransmissible diseases

Various disorder	Mechanisms used for biosensors	Biomarkers of health	minimum detectable levels	Nanotechnologies and biological factors are incorporated	References
Diabetes	Amperometric	Glucose	0.1 M	Glucose oxidase that has been fixed or attached to a material called rGO-Fe_3O_4	[100]
Lung cancer	Electrochemical	Cancer miRNA-182	0.43 fM	The combination of MoS_2 (molybdenum disulfide)/Ti_3C_2 nanohybrids and a modified glassy carbon electrode (GCE)	[101]
Second type diabetes	Fluorescence	Vaspin	39 pg mL^1	Upconverting nanoparticles	[102]
Jaundice	Voltammetric	Bilirubin	2.0 µM	Coating of reduced graphene oxide (rGO) and polystyrene sulfonate (PSS) on an electrode composed of glassy carbon	[103]
Alzheimer's illness	Voltammetric analysis	Acetylcholine	10 µmol l^1	A gold electrode with a high level of porosity that has been modified with acetylcholinesterase	[104]
E. coli and *Vibrio cholerae*	Colorimetric assay	Bacterial receptor-binding protein	The detection limit is approximately 100 cells	AuNPs	[105]
Neoplasm of the breast	Electrochemical processes	HER-2	Two cells in one milliliter	Functionalized graphene and nanostructured polyaniline (PANI) with attached AuNPs	[106]
Malaria	EIS stands for electrochemical impedance spectroscopy	pldh	0.5 fm	A glassy carbon electrode is a type of electrode made from glassy carbon material	[107]

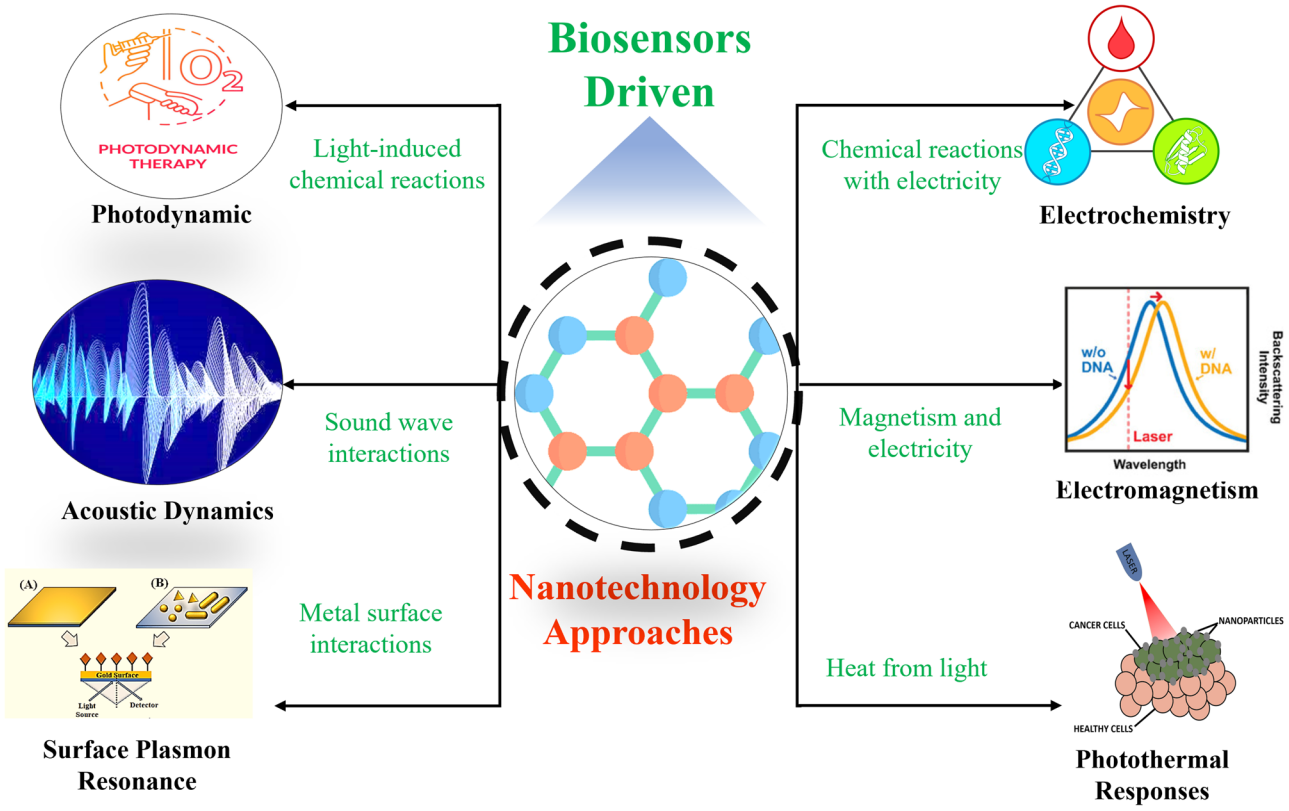

Figure 5: Applications of integrated biosensors technology for bacterial infection management.

timeframe of research on methods but also within a 150 min timeframe of blind testing. Future developments are expected to significantly reduce the detection time [108]. This study represents a significant achievement in the advancement and verification of electrochemical diagnostic methods for detecting the susceptibility of antibiotics. It allows for the rapid and precise classification of infections as either sensitive or resistant to antibiotics. The mechanism of action of three-dimensional electrode scaffolds involves their use in electrochemical coupling with intracellular metabolism and transforming extracellular redox. The three-dimensional electrode holder can host bacteria that are capable of producing a reference current density. The utilization of three-dimensional electrode scaffolds in solar-powered biochemical processes offers significant benefits. This adaptable platform can be utilized in the creation of environmentally friendly chemicals, forming a strong connection with the inherent physiological processes of bacteria, resembling a partially biological system. Because it contains a porous hydrophilic IO-ITO electrode structure, the three-dimensional electrode scaffold can easily integrate that produce electricity [109]. The incorporation allows for the real-time and ongoing tracking of bacterial infections, showing how this innovative method has the potential to improve our understanding and management of bacterial processes. Numerous three-dimensional electrode scaffolds are the subject of ongoing research due to their promising applications in green chemical processes and enhanced real-time bacterial infection monitoring.

5.2.2 Platforms for biosensing at a small scale

A novel microfluidic impedance biosensor has been created for bacterial isolation and detection. It integrates immunomagnetic nanoparticles for bacterial isolation, urease for bio-signal amplification, and microfluidic chips for electrochemical capacitance sensing. The aforementioned biosensor provides a cutting-edge platform for the rapid, uninterrupted, and responsive monitoring of *E. coli* O157:H7 in continuous flow systems. The sensor's rate of impedance change was directly correlated with the frequencies of *E. coli* O157:H7, which were found in percentages ranging from 10^1 to 10^5 CFU/mL. In about 2 h, the biosensor demonstrated astonishing sensitivity by detecting *E. coli* O157:H7 levels as low as 1.2×10^1 CFU/mL [110]. Yang made a significant breakthrough by introducing the ATP-binding box transporter pathway, which enables various bacteria to independently absorb gold nanoparticles. The

process was expedited by altering the gold nanoparticle with a glucose polymer and then subjecting it to laser irradiation, which caused aggregation within the bacterial cells. The approach exhibited exceptional lucidity, successfully identifying roughly 10^7 colony-forming units (CFUs) of bacteria present in malignancies or the gastrointestinal tract. The integration of imaging detection and complete treatment is highly significant. This technique allows for both the viewing and therapeutic intervention of various bacteria, representing a significant advancement in the study of microbial ecosystems [111] As research progresses in this field, the incorporation of multifunctional methods demonstrates the ability to tackle intricate issues in bacterial detection and treatment, leading to additional improvements in microbiological research and clinical applications.

5.3 Acoustic signal-enhanced NBs

Sonodynamic therapy is a treatment method that is based on PDT. It primarily employs low-frequency ultrasound (LFU) to activate sensitizers and stimulate the production of reactive oxygen species (ROS). Sonodynamic treatment involves using ultrasonic sound stimulation to activate acoustic sensitizers, resulting in the production of reactive oxygen species. These ROS have strong lethal effects on certain multidrug-resistant microbes without the establishment of resistance [112,113]. Ultrasound, a noninvasive therapeutic technique, shows great potential for use in clinical settings. This is because it has the unique capacity to deeply penetrate tissues, even when faced with difficult obstacles [114,115]. Currently, the precise mechanism of sonodynamic treatment remains unidentified. However, the prevalent viewpoint highlights ROS as the key agent responsible, independent of the specific mechanism involved. Antimicrobial sonodynamic therapy (SDT) is an advanced and revolutionary technology that has the ability to effectively combat bacterial infections. The current study in this area seeks to decipher the complexities of the sonodynamic treatment mechanism, leading to better knowledge and a wider range of applications in the field of antimicrobial therapies. The inherent nonresistance characteristic of an SDT, along with its nonintrusive nature and exceptional tissue penetration capability, establishes it as a highly promising approach in the ongoing fight against bacterial diseases.

5.3.1 Sonodynamic nanozyme system

The nanoplatform, known as Pd@Pt-T790, is named after the enzymatic creation of a Pd@Pt nanoplate that is intimately linked to tetra-(4-carboxyphenyl) porphyrin, which acts as an organic acoustic sensitizer. Specifically, the conversion of the substance is carefully regulated during ultrasonic activation, which enables the efficient production of both catalytic oxygen and reactive oxygen species through the use of the acoustic sensitizer. The ongoing buildup of reactive species reduces obstacles associated with a lack of oxygen, ultimately improving the effectiveness of SDT. The ultrasound-switchable nanozyme system is notable for its active, adjustable, and precise features, as well as its enhanced acoustic properties. This technology effectively eliminates deeply entrenched bacterial infections [116].

The Pd@Pt-T790-based SDT nanosystems effectively employ ultrasound-switchable enzyme activity, together with substantial accumulation at the infection site and exceptional biological compatibility, to eradicate myositis caused by MRSA. Furthermore, they enable the unobtrusive monitoring of the progress of sonodynamic therapy by the utilization of both photoacoustic scanning and MRI [117]. The ultrasound switchable nano-enzyme system reported in this study presents a highly promising method to actively, precisely, and selectively boost the efficacy of sonodynamic therapy for eradicating bacterial infections situated in deep anatomical regions. Continuing research seeks to enhance and broaden the possible uses of this groundbreaking nanozyme technology in the field of therapeutic interventions.

5.3.2 Ultrasonic sterilization at low frequencies

Sonodynamic technology employs ultrasonography for stimulation allowing for deeper penetration into physiological tissues compared to the photodynamic technique. This can help overcome the limits typically associated with PD therapy. Acoustic power utilizes LFU, namely, in the range of 20 kHz to 3 MHz, to efficiently treat deep-seated lesions within the body. This technology has a maximum depth of tissue penetration of 10 cm. A LFU is defined as sound waves with frequencies ranging from 20 kHz to 1 MHz [118]. Further research on ultrasound capabilities has revealed that LFU exhibits robust penetration, precise targeting, and substantial efficacy, enabling the eradication of bacterial biofilms and the successful elimination of germs.

The established research research demonstrates that the use of LFU at specific parameters (40 kHz, 600 mW/cm^2, 30 min, duty cycle 1:9) leads to a noteworthy reduction in the population of bacteria within biofilms, whether used alone or in conjunction with a single agent. This significantly improves the effectiveness of the treatment in killing microorganisms. Significantly, when colistin was used in conjunction with larger concentrations, the combination treatments exhibited a more pronounced ultrasound-enhanced antimicrobial impact. The time-kill curves conducted over 24 h

showed that the combination of colistin (8 mg/mL) and vancomycin (4 mg/mL) with LFU. After 8 h, there was a substantial decrease in the total bacteria count in biofilms over time The decrease persisted and gradually diminished until reaching the 24 h point [119]. The results emphasize the capability of LFU to enhance antibacterial approaches, particularly in addressing bacterial biofilms and maximizing treatment results. The current study is exploring the various ways in which LFU can be used to improve therapeutic approaches.

5.3.3 UltraSonic activation of chemokinetic therapeutic response

Ultrasound-activated chemokinetic therapy (SCDT) is a method for using ultrasound to drive therapeutic interventions. SCDT possesses remarkable features that enable noninvasive operations and deep tissue penetration, making it a highly successful approach to combat bacterial resistance and diseases. This innovative therapy utilizes the catalytic production of superoxide anions, along with the harmful hydroxyl radicals [120].

The SCDT open platform was developed by incorporating Fe3+ over polyethylenimide-modified bismuth oxybromide (BiOBr) nanoplates. Simultaneously, ultrasonic catalysis efficiently segregated the positive holes (h+) and the minus electrons (e−) of BiOBr, B nanomaterials. The electron transport pathway is disturbed by this isolation, which triggers redox and Fenton reactions, resulting in the generation of an excessive amount of reactive oxygen species. This increase in ROS successfully competes with and fights against MRSA infections [121]. The unique characteristics of SCDT are that in addition to its ability to utilize ultrasound, this therapy technique has the potential to effectively and flexibly manage bacterial infections, particularly those caused by strains that are resistant to many drugs. Ongoing research is dedicated to exploring and enhancing the applications of SCDT to achieve more effective outcomes in combating microorganisms.

5.4 Acoustic-responsive nanostructure for bacterial capture

An innovative approach that combines antibacterial acoustic-dynamic treatment with antivirulent immunotherapy, drawing inspiration from biological processes. A experiment was conducted to modify an antibody that specifically targets the alpha-toxin of MRSA, enabling it to attach to the outer surface of cell membrane nanovesicles. These nanovesicles were then enclosed with a substance that is responsive to sound. This novel approach goes beyond traditional passive absorption of virulence by utilizing natural red blood cell (RBC) membranes [114]. It takes advantage of the strong antiboil-toxin interaction to enhance the efficiency of nanovesicles in capturing virulence in laboratory conditions.

When ultrasound is used, acoustic sensitizers are crucial in producing reactive oxygen species, which effectively eradicate microorganisms and accelerate the removal of harmful effects. The efficacy of our antibody-based nanotrap in detecting MRSA infections and distinguishing between lesions and sterility has been validated by in vivo optical imaging. This novel combination of antimicrobial sonodynamic therapy and antivirulent immunotherapy provides a potent and antibiotic-free nanotherapeutic approach to combat multidrug-resistant bacterial infections, thereby paving the way for cutting-edge medical interventions. The generic visual overflow of the three main parts of biosensor is shown in Figure 6. Continuing research endeavors to enhance and broaden the uses of this combined treatment approach to have a more extensive and significant effect in clinical settings.

5.5 Nano-biotechnological sensors operating on electromagnetic forces

Magnetic nanoparticles are small, uniform particles with a size between 1 and 100 nm. Particles with these unusual properties exhibit features seen in other nanomaterials as well as those associated with quantum size and surface effects. Through the integration of superpara magnetization with the inherent magnetic conductivity of magnetic materials, and more especially magnetic nanoparticles, exhibit extraordinary characteristics. Their advantages also include a straightforward preparation process, high surface reactivity, and exceptional compatibility with living things. Conductive nanoparticles [122], magnetic iron oxide (Fe_3O_4) particles, for example, which are nanometer-sized, have lately garnered a lot of attention from scientists. The surface effects and superparamagnetism of magnetic Fe_3O_4 nanoparticles make them very interesting and have great potential for many uses in fields as diverse as biomedicine and sewage treatment. At room temperature, an external magnetic field improves the surface modification of Fe_3O_4 which allows it to incorporate distinct functionalities like adsorption and separation. In addition, Fe_3O_4 nanoparticles find widespread application in the realm of water and food safety monitoring.

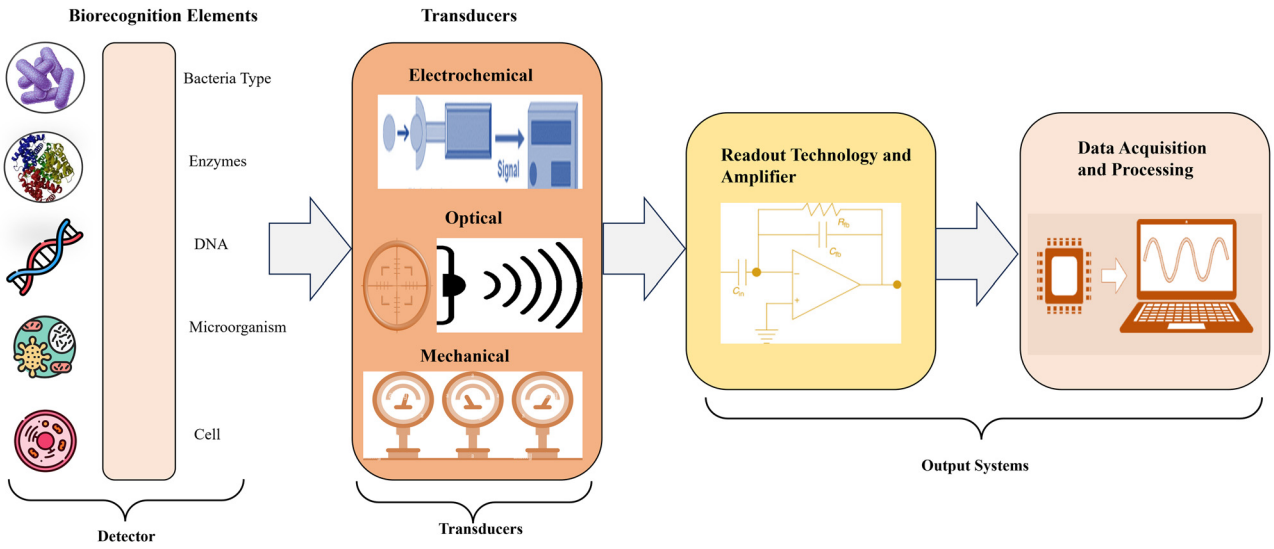

Figure 6: The three parts of a biosensor – the detector, the transducer, and the output system.

To aid in bacterial enrichment and separation in complex substrates, magnetic nanoparticles are frequently employed. In addition, they make it possible to directly test clinical specimens for microorganisms with low abundance. The distinctive properties of Fe_3O_4 nanoparticles make them stand out among the other magnetic nanophase materials. Their magnetic field reactivity and surface modifiability make them very flexible tools. Their adaptability and practicality in various scientific fields are evident from this [123,124].

5.5.1 Microscale motor governed by magnetism

An innovative tool for combating bacterial biofilms and illnesses, this micromotor is both magnetically controlled and extremely adaptable. The micromotor employs hydrogen peroxide (H_2O_2) as a fuel and manganese oxide (MnO_2) as a catalyst to self-propel using oxygen microbubbles generated by the H_2O_2. The distinctive propulsion method enables the micromotor to infiltrate the EPSs of biofilms, resulting in their total eradication with the aid of bubbles. The process reaches its climax with the eradication of vulnerable bacteria, which succumb to the extremely poisonous (OH) generated. The focused strategy has exceptional efficacy, successfully eliminating microbial infections in a brief period of around 10 min. The micromotor holds promising implications in clinical medicine, particularly in tackling complicated infection sites on a large scale [125]. The micro/nano hybrid multifunctional motor demonstrates remarkable precision, manipulation, and profound infiltration, leading to improved antibacterial efficacy and potent effectiveness against challenging infections caused by biofilm.

5.5.2 Attractive cantilever structures

The attractive cantilever, which is essential for its operation, needs to be attached to a substrate that can be controlled from a distance. Based on the laws of electromagnetism, the magnetic cantilever experiences a self-driven and periodic vertical deflection from its original position when it is subjected to an alternating magnetic field. It is noteworthy that the frequency of this deflection is extremely modest, usually approximately 0.16 Hz. The deflection and periodic motion of the magnetic cantilever beam have demonstrated remarkable efficacy in preventing the adherence of bacterial biofilms and impeding their subsequent growth. The researchers' liquid culture experiments with *E. coli* yielded empirical evidence showing a substantial decrease, reaching 70%, in the formation of microbe biofilms. The decrease in bacterial bio-film development is credited to the efficient magneto-mechanical driving of micro-structure construction [126].

5.5.3 Nano-magnetic bacterial navigators

The magnetotactic bacterium is a distinct category of bacteria that can align themselves with a magnetic field as a result of their magneto-sensitivity. The electron

microscopy analysis demonstrates the existence of magnetite magnetosomes, a magnetic material, within these magnetotactic bacteria [127] developed a pioneering method to isolate *S. aureus* by altering the surface of magnetotactic bacteria MO-1 cells using a rabbit anti-MO-1 polyclonal antibody. This study is the initial evidence of bacterial microrobots that are capable of transporting infections, namely *S. aureus*, to a specified place by using a magnetic field. The utilization of magnetotactic bacteria in the creation of magnetic-guided, self-propelled microrobots for pathogen isolation highlights their significant potential. This achievement establishes a strong basis for future efforts in the detection of pathogenic bacteria. Further experiments were conducted to evaluate the deadly effects of *S. aureus* using MO-1. The utilization of both alternating electromagnetic-field erythema and the mechanical force generated by an oscillating magnetic field exhibited a substantial bactericidal effect in animal experiments. highlighting the versatility and effectiveness of this technique [128,129]. This research not only enhances our comprehension of magnetotactic bacteria but also creates opportunities for novel applications in pathogen manipulation and detection.

5.5.4 Nano-magnetic alloy fluid particles

A research team conducted investigation on the application of magneto-responsive gallium-based liquid metal (LM) droplets as antimicrobial agents to assess their ability to kill germs. The nanometer-sized droplets exhibited the capacity to physically harm, dissolve, and eradicate bacteria present in fully developed biofilms. When subjected to a weak magnetic field, the droplets experienced a change in shape, resulting in the creation of nanoscale sharp edges. Upon encountering bacterial biofilms, these droplets, with their motion and jagged contours, effectively perturbed the biofilm structure, resulting in the complete annihilation of bacterial cells. The technique's effectiveness against two forms of bacterial biofilms, both Gram-positive and Gram-negative, was assessed in a recent study. After being exposed to the liquid metal nanoparticles for 90 min, both biofilms were completely eradicated, leading to a significant decrease of 99% in bacterial survival. Importantly, laboratory experiments verified that these droplets, which can kill bacteria, did not cause any harmful effects on human cells [130,131]. This novel methodology exhibits potential for creating antibacterial remedies that target specific bacteria while minimizing harm to human cells, demonstrating its versatility for various applications in biomedical research and healthcare.

5.6 Nano-biosensing with photothermal resonance

Photothermal therapy (PTT) is a highly regarded and extensively studied method for identifying and treating bacterial infections. It is noninvasive and has the ability to selectively target the disease. PTT, utilizes physical mechanisms along with chemical approaches [132,133]. Microorganisms, as living organisms with complex cellular structures, experience protein denaturation and subsequent death when exposed to high temperatures. The sterilizing process based on this idea is widely known as heat sterilization technology. This innovative approach has significant promise for revolutionizing bacterial diagnostic and treatment protocols, marking a pivotal advancement in the realm of medical technologies.

5.6.1 NBs exploiting photothermal effects

Many researchers demonstrated fast and comprehensive methods for killing germs using MXene and light, known as photothermal ablation. This refers to a rapid, thorough, and multilevel approach to using light-induced heat to destroy microorganisms. Ti3C2 MXenes had a highly effective antibacterial activity against 15 diverse bacterial strains when subjected to 808 nm light for only 20 min. The potential of this revolutionary photothermal technique is immense. In addition, the rapid antibacterial approach demonstrates efficacy against MRSA biofilms by disrupting their structures and eradicating bacteria present within the biofilms [134]. This innovative research not only broadens the possible uses of photothermography but also provides a method to completely eliminate bacteria and biofilms without promoting medication resistance, representing notable progress in antibacterial technologies.

5.6.2 Interwoven sheath

Devised a method to alter the surface of a substance with the aim of improving its ability to combat microorganisms and facilitate several functionalities. The surface of functionalized polyurethane (PU), a frequently used biomedical material for hernia recovery, was modified (PU-Au-PEG) to provide intrinsic properties that prevent fouling and can kill bacteria through photothermal means. The change was made possible by applying a coating that reacts to near-infrared (NIR) light and contains both organic and inorganic components. The coating is made up of polyethylene glycol and gold nanorods (Au NRs). When subjected to 808

nm NIR irradiation, the PU-Au-PEG material showed remarkable bactericidal properties, especially against MDR bacteria, and was highly effective in preventing bacterial attachment. In addition, PU-Au-PEG showed the ability to inhibit biofilm formation for an extended period of time. By conducting cytotoxicity and hemolysis assays, the biocompatibility of PU-Au-PEG was confirmed, demonstrating its potential as a versatile and biocompatible alternative for antibacterial uses [135,136].

5.6.3 Bacterial-selective photothermal carbon nanoparticles

A bacterial affinity is the propensity of bacteria to attach themselves to a particular surface or substance. Photothermal carbon dots (BAPTCDs) are specifically engineered to target MurD ligase, an enzyme that plays a crucial role in the manufacture of peptidoglycan (PG) in bacteria. These carbon dots demonstrate outstanding performance by effectively and accurately detecting bacterial organisms with enhanced specificity and sensitivity. BAPTCDs exhibit a unique chiral arrangement and display a particular attraction to bacteria. The enzyme's biological activity is greatly diminished by the competitive interaction with D-glutamate and simultaneous attachment to MurD ligase. This dual mechanism hinders the production of bacterial cell walls, hence enhancing the effectiveness of therapy with lasers for microorganisms. The synergistic impact of these mechanisms enhances the remarkable antibacterial effectiveness of the photothermal carbon dots, especially when directed towards specific bacteria [137,138].

5.6.4 Smart hybrid hydrogel composites

Wang created a complex hydrogel that can both visually detect bacterial infections and provide PTT. The use of a conjugated polymer (PTDBD) that absorbs NIR light- and pH-sensitive bromothymol blue (BTB) is the major way that bacteria are killed using thermotherapy. A chitosan (CS) thermosensitive hydrogel incorporates these components. Biofilms and infected wounds can be more easily detected with the help of the BTB/PTDBD/CS hydrogel, which can visually detect the acidic microenvironment of *S. aureus* by going through noticeable color shifts. Upon rapid diagnosis, the hydrogel precisely targets the affected area by generating localized high temperatures in response to near-infrared laser (808 nm) light. This method efficiently eliminates even the most resistant biofilms that are persistent and hard to remove [139].

5.7 Bacterial disease theranostics facilitated by nano-sensors assembled *in situ*

One new way to image and identify cancer cells, tissues, and microbes is with *in situ* synthesis technology. Incorporating metal elements chemically into live organisms to form functional nanocluster probes accomplishes this [140]. Among these methods is fluorescence *in situ* hybridization (FISH), a new tool for determining the spatial distribution of microbes in biofilms and quantifying microbial communities. There is no need to extract nucleic acids while using FISH, which differs from previous approaches. To conduct *in situ* hybridization, it substitutes fluorescent oligonucleotide probe labeling. Multiple populations can be identified at once by marking the probes with fluorescent dyes with distinct excitation and emission spectra [141]. Using *in situ* synthesis extends beyond enhancing antimicrobial permeability in biofilms and has wider implications. It may cause biochemical or physical processes, like photothermal conversion, that compromise biofilm integrity. Chemically linking nanoclusters of gold with the antibacterial peptide daptomycin demonstrated the production of a very efficient antibacterial molecule. The synthesized conjugated structure significantly boosts the synergistic impact by fusing the two parts' best qualities. The structure effectively eliminates bacterial biofilms by creating membrane holes through localized daptomycin action [142,143]. By using *in situ* chemical synthesis techniques, the authors created bioresponsive nanocomposite materials for disinfection and bacterial bioimaging. The novel biofilm microenvironment was used to construct a nanoheating platform with multiple applications. The nanoclusters, which were sensitive to the microenvironment, were able to detect bacteria and promote sterilization through electrostatic interactions, breakdown of the cell membrane, suppression of biofilm formation, and accumulation of reactive oxygen species (ROS) [144]. The particular interactions with bacteria emphasize the promise of *in situ* synthesis as a versatile instrument for accurate detection and treatment of bacterial infections [145].

6 Discussion and future directions

The increasing danger presented by bacterial infections, resistance to therapy, and the creation of biofilms requires the immediate development of novel treatment solutions. The significance of this progress is underscored by the growing occurrence of antibiotic-resistant bacterial strains and the creation of enduring biofilms, which complicate therapy and contribute to protracted illnesses. Conventional antimicrobial medications and diagnostic technologies,

while necessary, frequently have limitations in terms of their sluggish procedures and unintentional promotion of antibiotic resistance. Improper use of these compounds may exacerbate the challenge of managing biofilms and also facilitate the establishment of resistance. Traditional techniques for identifying bacteria and managing infections with antibiotics need significant resources, in both terms of finances and personnel. These approaches usually need substantial time and resources, resulting in treatment delays and higher healthcare expenses. The dependence on conventional antibiotics further worsens the issue of resistance, as organisms adapt to tolerate these treatments, making them progressively less efficient.

However, recent breakthroughs in nanotechnology, including the creation of intelligent NBs, provide encouraging options. These state-of-the-art biosensors provide increased sensitivity, specificity, and effectiveness in the detection and treatment of germs. These sensors have the ability to identify bacterial infections at very low concentrations, making them far more efficient than traditional approaches. Currently, there are ongoing clinical evaluations of many innovative methods that include NBs. These evaluations have shown enhanced sensitivity, high specificity, and efficacy in both monitoring and therapy. This work also emphasizes the substantial potential of combining smart NBs with AI and nanotechnology to transform bacterial infection management. By using methods such as PDT, electrochemical sensors, acoustic dynamics, electromagnetic forces, photothermal responses, and surface plasmon resonance, these biosensors have the capability to provide individualized and accurate therapies. The use of modern methods allows for the creation of individualized treatment plans using nanotechnology, which are specifically designed for individual patients. This improves the accuracy of diagnosis and the efficiency of therapy.

Through a comprehensive examination of these cutting-edge technologies, we highlight the increasing danger of antibiotic resistance and its effect on healthcare expenses, emphasizing the need for proactive actions to tackle these difficulties. The article provides a comprehensive analysis of bacterial resistance to antibiotics and its impact on illness management, treatment, and overall results. It highlights the need for novel methodologies to precisely detect and treat bacterial infections. We emphasizes the need to promote interdisciplinary cooperation and undertake translational research, while also investigating the possibilities offered by advanced technologies like smart NBs and AI. The use of a collaborative and interdisciplinary approach is crucial in the development of efficient ways to address bacterial infections and antibiotic resistance.

To ensure the practical and widespread application of smart NBs, particularly in local and community settings, future research and development should focus on several key areas:

- Develop AI and ML algorithms customized to the particular bacterial diseases patterns that are common in local populations. Improving the accuracy and efficacy of NBs would enable a quick and precise analysis of intricate data for immediate monitoring and predictive modeling of bacterial infections.
- Develop affordable and easy-to-use NBs specifically tailored for use in nearby clinics and by community health practitioners. These devices should possess multifunctionality, enabling them to concurrently diagnose, monitor, and cure bacterial infections. Their design should guarantee that only a little training is necessary, thereby enabling the provision of sophisticated care at the community level.
- Carry out comprehensive clinical studies in nearby communities to evaluate the safety, effectiveness, and cost-efficiency of NB technologies in real-life environments. Engaging in partnerships with local healthcare practitioners and community groups will guarantee that the results are relevant and can be implemented, therefore promoting the incorporation of new technologies into regular clinical procedures.
- Tackle the obstacles associated with the large-scale manufacturing and dissemination of NBs to guarantee their affordability and broad accessibility, especially in distant and underserved regions. Establishing resilient distribution networks will be essential to aid this process, guaranteeing that the advantages of these advances are accessible to all communities.
- Utilize nanomaterials to optimize medication delivery systems, ensuring precision, efficacy, and customization of therapies. This focused strategy strives to optimize therapeutic results while avoiding adverse effects, guaranteeing that therapies are both secure and efficacious for a wide range of patient demographics.
- Evaluate the environmental impact of nanomaterials used in biosensors and address ethical considerations, particularly regarding data privacy and patient consent, within local communities. Ensuring that these technologies are developed and deployed responsibly will help mitigate potential negative impacts and build public trust.
- Incorporate NB technology with community-based public health methods to actively monitor and manage bacterial outbreaks in realtime. Inform community members on the advantages and correct use of these technologies to promote acceptance and optimize their efficiency.

Providing communities with information and tools will improve their capacity to proactively control bacterial illnesses.

By prioritizing these specific areas, researchers can formulate efficient tactics to address bacterial infections and protect public health. The use of cutting-edge technology, such as smart NBs and AI, shows significant potential in transforming the process of diagnosing and treating bacterial infections. This strategy will guarantee that the advantages of these state-of-the-art advancements are available to everyone, regardless of their location or resources, resulting in a substantial enhancement in public health results and a decrease in the worldwide impact of bacterial diseases.

7 Conclusion

The urgency of developing effective treatment strategies is highlighted by the threat posed by bacterial infections, medication resistance, and the formation of bacterial biofilms. Although traditional antimicrobial agents are frequently used, their incorrect usage can worsen the difficulty of controlling biofilms and contribute to the spread of resistance. Traditional methods for detecting microorganisms and treating infections with antibiotics require substantial resources, including financial and human resources. Nevertheless, recent progress in nanotechnology provides encouraging opportunities for addressing multidrug-resistant bacteria and eliminating antimicrobial biofilms. These novel methods demonstrate increased sensitivity, strong specificity, and effectiveness in monitoring and treatment, with several currently undergoing clinical evaluation. This study presents an in-depth examination of bacterial resistance to antibiotics and its effects on the management and treatment of diseases and their ultimate outcomes. By thoroughly analyzing the tools and state-of-the-art technologies accurately diagnose and manage infections caused by bacteria. The study emphasizes the increasing risk of antibiotic resistance and its effect on costs associated with healthcare, underscoring the need to take action to tackle highlighted limitations. In addition, we explore the potential of modern technologies such as smart NBs and AI to transform the management of bacterial infections. Our objective is to highlight the reliability of diagnosis and the developed nano-based personalized treatment strategies for individual patients by incorporating advanced techniques such as PDT, electrochemical sensors, acoustic dynamics, electromagnetic forces, photothermal responses, and surface plasmon resonance. By fostering collaboration across disciplines and conducting translational research, we technically analyze the techniques to control bacterial diseases and protect public health in the future.

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References

[1] Cai P, Jia T, Zhang L, Jiang Y, Wang S, Liu G, et al. Multifunctional antibacterial materials for inhibiting bacterial surface growth and triggering release of bacterial resistance genes. Nature Commun. 2018;9:4865. https://www.nature.com/articles/s41467-018-07226-7.

[2] Prestinaci F, Pezzotti P, Pantosti A. Antimicrobial resistance: A global multifaceted phenomenon. Pathogens Global Health. 2015;109:309–18.

[3] Ventola CL. The antibiotic resistance crisis: Part 1: Causes and threats. Pharm Ther. 2015;40:277.

[4] Wang L, Hu C, Shao L. The antimicrobial activity of nanoparticles: present situation and prospects for the future. Int J Nanomed. 2017;12:1227. doi: https://doi.org/10.2147/IJN.S121956.

[5] Lee NY, Koooo WC, Hsueh PR. Nanoparticles in the treatment of infections caused by multidrug-resistant organisms. Front Pharmacol. 2019;10:1153. doi: https://www.frontiersin.org/articles/10.3389/fphar.2019.01153.

[6] Mubeen B, Ansar AN, Rasool R, Ullah I, Imam SS, Alshehri S, et al. Nanotechnology as a novel approach in combating microbes providing an alternative to antibiotics. Antibiotics. 2021;10:1473. https://www.mdpi.com/2079-6382/10/12/1473.

[7] Singh A, Amod A, Pandey P, Bose P, Pingali MS, Shivalkar S, et al. Bacterial biofilm infections, their resistance to antibiotics therapy and current treatment strategies. Biomed Materials. 2022;17(2):022003.

[8] Darwish MA, Abd-Elaziem W, Elsheikh A, Zayed AA. Advancements in nanomaterials for nanosensors: a comprehensive review. Nanoscale Adv. 2024.

[9] Ahangari A, Mahmoodi P, Mohammadzadeh A. Advanced nano biosensors for rapid detection of zoonotic bacteria. Biotechnol Bioeng. 2023;120(1):41–56.
[10] Kang H, Lee J, Moon J, Lee T, Kim J, Jeong Y, et al. Multiplex detection of foodborne pathogens using 3D nanostructure swab and deep learning-based classification of Raman spectra. Small. 2024:2308317.
[11] Chauhan N, Saxena K, Tikadar M, Jain U. Recent advances in the design of biosensors based on novel nanomaterials: An insight. Nanotechnol Precision Eng (NPE). 2021;4(4):045003.
[12] De La Fuente-Núñez C, Cardoso MH, de Souza Cândido E, Franco OL, Hancock RE. Synthetic antibiofilm peptides. Biochim Biophys Acta, Biomembr. 2016;1858(5):1061–9.
[13] Rudilla H, Fusté E, Cajal Y, Rabanal F, Vinuesa T, Viñas M. Synergistic antipseudomonal effects of synthetic peptide AMP38 and carbapenems. Molecules. 2016;21(9):1223.
[14] Tse BN, Adalja AA, Houchens C, Larsen J, Inglesby TV, Hatchett R. Challenges and opportunities of nontraditional approaches to treating bacterial infections. Clin Infect Diseases. 2017;65(3):495–500.
[15] Anandaram H. Role of bioinformatics in nanotechnology: An initiation towards personalized medicine. In: Data analytics in medicine: concepts, methodologies, tools, and applications. Hershey, Pennsylvania, United States: IGI Global; 2020. p. 1875–94.
[16] Bhambri P, Khang A. AI-integrated biosensors and bioelectronics for healthcare. AI-driven innovations in digital healthcare: emerging trends, challenges, and applications. Hershey, Pennsylvania, United States: IGI Global; 2024. p. 82–96.
[17] Ullah N, Hassan M, Khan JA, Anwar MS, Aurangzeb K. Enhancing explainability in brain tumor detection: A novel DeepEBTDNet model with LIME on MRI images. Int J Imag Syst Technol. 2024;34(1):e23012.
[18] Rasheed Z, Ma YK, Ullah I, Ghadi YY, Khan MZ, Khan MA, et al. Brain tumor classification from MRI using image enhancement and convolutional neural network techniques. Brain Sci. 2023;13(9):1320.
[19] Shimizu H, Nakayama KI. Artificial intelligence in oncology. Cancer Sci. 2020;111(5):1452–60.
[20] Nasir N, Kansal A, Barneih F, Al-Shaltone O, Bonny T, Al-Shabi M, et al. Multi-modal image classification of COVID-19 cases using computed tomography and X-rays scans. Intelligent Syst Appl. 2023;17:200160.
[21] Chatterjee A, Somayaji NR, Kabakis IM. Abstract WMP16: artificial intelligence detection of cerebrovascular large vessel occlusion-nine month, 650 patient evaluation of the diagnostic accuracy and performance of the Viz. ai LVO algorithm. Stroke. 2019;50(Suppl_1):AWMP16–AWMP16.
[22] Antony A. Flexible and wearable biosensors: revolutionizing health monitoring. in: Biosensors: developments, challenges and perspectives. Singapore: Springer; 2024. p. 237–58.
[23] Dave S, Dave A, Radhakrishnan S, Das J, Dave S. Biosensors for healthcare: an artificial intelligence approach. Biosensors Emerging Re-Emerging Infect Diseases. 2022:365–83.
[24] Deng J, Zhao S, Liu Y, Liu C, Sun J. Nanosensors for diagnosis of infectious diseases. ACS Appl Bio Materials. 2020;4(5):3863–79.
[25] Xia Q, Jiang H, Liu X, Yin L, Wang X. Advances in engineered nanobiosensors for bacteria diagnosis and multidrug resistance inhibition. Biosensors. 2024;14(2):59.
[26] Ghafouri P, Kasaei B, Aghili S, Monirvaghefi A, Hosseini AM, Amoozegar H, et al. Application of nanobiosensors in detection of pathogenic bacteria: an update. Res Biotechnol Environ Sci. 2023;2(4):65–74.
[27] Markandan K, Tiong YW, Sankaran R, Subramanian S, Markandan UD, Chaudhary V, et al. Emergence of infectious diseases and role of advanced nanomaterials in point-of-care diagnostics: a review. Biotechnol Genetic Eng Rev. 2022:1–89.
[28] Ramesh M, Janani R, Deepa C, Rajeshkumar L. Nanotechnology-enabled biosensors: A review of fundamentals, design principles, materials, and applications. Biosensors. 2022;13(1):40.
[29] Pelgrift RY, Friedman AJ. Nanotechnology as a therapeutic tool to combat microbial resistance. Adv Drug Delivery Reviews. 2013;65(13–14):1803–15.
[30] Munir MU, Ahmad MM. Nanomaterials aiming to tackle antibiotic-resistant bacteria. Pharmaceutics. 2022;14(3):582.
[31] Liu H, Liu Z, Wang Y, Xiao J, Liu X, Jiang H, et al. Intracellular liquid-liquid phase separation induces tunable anisotropic nanocrystal growth for multidimensional analysis. Adv Funct Materials. 2023;33:2302136.
[32] Rawson T, Hernandez B, Moore L, Blandy O, Herrero P, Gilchrist M, et al. Supervised machine learning for the prediction of infection on admission to hospital: a prospective observational cohort study. J Antimicrob Chemotherapy. 2019;74(4):1108–15.
[33] Agbaria AH, Salman A, Beck G, Lapidot I, Rich DH, Kapelushnik J, et al. Potential of bacterial infection diagnosis using infrared spectroscopy of WBC and machine learning algorithms. In: European Conference on Biomedical Optics. Optica Publishing Group; 2019. p. 11073_40.
[34] Gadalla AA, Friberg IM, Kift-Morgan A, Zhang J, Eberl M, Topley N, et al. Identification of clinical and urine biomarkers for uncomplicated urinary tract infection using machine learning algorithms. Sci Rep. 2019;9(1):19694.
[35] Oh SW, Lee H, Shin JY, Lee JH. Antibiotics-resistant bacteria infection prediction based on deep learning. J Soc e-Business Stud. 2019;24(1):105–20.
[36] Ho CS, Jean N, Hogan CA, Blackmon L, Jeffrey SS, Holodniy M, et al. Rapid identification of pathogenic bacteria using Raman spectroscopy and deep learning. Nature Commun. 2019;10(1):4927.
[37] Hattori S, Sekido R, Leong IW, Tsutsui M, Arima A, Tanaka M, et al. Machine learning-driven electronic identifications of single pathogenic bacteria. Sci Rep. 2020;10(1):15525.
[38] Nehal SA, Roy D, Devi M, Srinivas T. Highly sensitive lab-on-chip with deep learning AI for detection of bacteria in water. International J Inform Technol. 2020;12:495–501.
[39] Iriya R, Jing W, Syal K, Mo M, Chen C, Yu H, et al. Rapid antibiotic susceptibility testing based on bacterial motion patterns with long short-term memory neural networks. IEEE Sensors J. 2020;20(9):4940–50.
[40] Brown C, Tseng D, Larkin PM, Realegeno S, Mortimer L, Subramonian A, et al. Automated, cost-effective optical system for accelerated antimicrobial susceptibility testing (AST) using deep learning. ACS Photonics. 2020;7(9):2527–38.
[41] Draz MS, Vasan A, Muthupandian A, Kanakasabapathy MK, Thirumalaraju P, Sreeram A, et al. Virus detection using nanoparticles and deep neural network-enabled smartphone system. Sci Adv. 2020;6(51):eabd5354.

[42] Alafeef M, Moitra P, Pan D. Nano-enabled sensing approaches for pathogenic bacterial detection. Biosensors Bioelectronics. 2020;165:112276.
[43] Zhang K, Wang J, Liu T, Luo Y, Loh XJ, Chen X. Machine learning-reinforced noninvasive biosensors for healthcare. Adv Healthcare Materials. 2021;10(17):2100734.
[44] Ding J, Lin Q, Zhang J, Young GM, Jiang C, Zhong Y, et al. Rapid identification of pathogens by using surface-enhanced Raman spectroscopy and multi-scale convolutional neural network. Analytic Bioanalytic Chem. 2021;413(14):3801–11.
[45] Yu S, Li X, Lu W, Li H, Fu YV, Liu F. Analysis of Raman spectra by using deep learning methods in the identification of marine pathogens. Analytic Chem. 2021;93(32):11089–98.
[46] Li Z, Jiang Y, Tang S, Zou H, Wang W, Qi G, et al. 2D nanomaterial sensing array using machine learning for differential profiling of pathogenic microbial taxonomic identification. Microchim Acta. 2022;189(8):273.
[47] Yang Y, Xu B, Murray J, Haverstick J, Chen X, Tripp RA, et al. Rapid and quantitative detection of respiratory viruses using surface-enhanced Raman spectroscopy and machine learning. Biosens Bioelectron. 2022;217:114721.
[48] Arano-Martinez JA, Martínez-González CL, Salazar MI, Torres-Torres C. A framework for biosensors assisted by multiphoton effects and machine learning. Biosensors. 2022;12(9):710.
[49] Verma S, Shukla RP, Dutta G. Machine learning-enabled biosensors in clinical decision making. In: Next-generation nanobiosensor devices for point-of-care diagnostics. Singapore: Springer; 2022. p. 163–94.
[50] Guo Z, Tian R, Xu W, Yip D, Radyk M, Santos FB, et al. Highly accurate heart failure classification using carbon nanotube thin film biosensors and machine learning assisted data analysis. Biosens Bioelectron X. 2022;12:100187.
[51] Zhou Z, Wang L, Wang J, Liu C, Xu T, Zhang X. Machine learning with neural networks to enhance selectivity of nonenzymatic electrochemical biosensors in multianalyte mixtures. ACS Appl Mater Interfaces. 2022;14(47):52684–90.
[52] Noreldeen HA, Huang KY, Wu GW, Peng HP, Deng HH, Chen W. Deep learning-based sensor array: 3D fluorescence spectra of gold nanoclusters for qualitative and quantitative analysis of vitamin B6 derivatives. Analytic Chem. 2022;94(26):9287–96.
[53] Wang J, Xu B, Shi L, Zhu L, Wei X. Prospects and challenges of AI and neural network algorithms in MEMS microcantilever biosensors. Processes. 2022;10(8):1658.
[54] Kumar AK, Ritam M, Han L, Guo S, Chandra R. Deep learning for predicting respiratory rate from biosignals. Comput Biol Med. 2022;144:105338.
[55] Rahmani MKI, Ghanimi HM, Jilani SF, Aslam M, Alharbi M, Alroobaea R, et al. Early pathogen prediction in crops using nano biosensors and neural network-based feature extraction and classification. Big Data Res. 2023;34:100412.
[56] Ramalingam M, Jaisankar A, Cheng L, Krishnan S, Lan L, Hassan A, et al. Impact of nanotechnology on conventional and artificial intelligence-based biosensing strategies for the detection of viruses. Discover Nano. 2023;18(1):58.
[57] Zhou Y, Zhao J, Chen R, Lu P, Zhao W, Ma R, et al. A portable deep-learning-assisted digital single-particle counting biosensing platform for amplification-free nucleic acid detection using a lens-free holography microscope. Nano Today. 2024;56:102238.
[58] Iqbal S, Qureshi AN, Aurangzeb K, Alhussein M, Haider SI, Rida I. AMIAC: adaptive medical image analyzes and classification, a robust self-learning framework. Neural Comput Appl. 2023:1–29.
[59] Wang Y, Wang Z, Shang Y, Wang J, Zhu Z, Xi L, et al. Next-generation pathogen detection: Exploring the power of nucleic acid amplification-free biosensors. Coordination Chem Rev. 2024;513:215895.
[60] Yi Y, Lagniton PNP, Ye S, Li E, Xu RH. COVID-19: What has been learned and to be learned about the novel coronavirus disease. Int J Biologic Sci. 2020;16:1753–66.
[61] Singhal T. A review of coronavirus disease-2019 (COVID-19). Indian J Pediatrics. 2020;87:281–6.
[62] Deee la Rica R, Stevens MM. Plasmonic ELISA for the ultrasensitive detection of disease biomarkers with the naked eye. Nature Nanotechnol. 2012;7:821–4.
[63] Leland DS, Ginocchio CC. Role of cell culture for virus detection in the age of technology. Clin Microbiol Rev. 2007;20:49–78.
[64] Killian ML. Hemagglutination assay for the avian influenza virus. In: Spackman E, editor. Avian Influenza Virus. Totowa, New Jersey, United States: Humana; 2008. p. 47–52.
[65] Lequin RM. Enzyme immunoassay (EIA)/enzyme-linked immunosorbent assay (ELISA). Clin Chem. 2005;51(12):2415–8.
[66] Udugama B, Kadhiresan P, Kozlowski HN, Malekjahani A, Osborne M, Li VY, et al. Diagnosing COVID-19: the disease and tools for detection. ACS nano. 2020;14(4):3822–35.
[67] Payungporn S, Chutinimitkul S, Chaisingh A, Damrongwantanapokin S, Buranathai C, Amonsin A, et al. Single step multiplex real-time RT-PCR for H5N1 influenza A virus detection. J Virological Methods. 2006;131(2):143–7.
[68] Munch M, Nielsen LP, Handberg K, Jørgensen PH. Detection and subtyping (H5 and H7) of avian type A influenza virus by reverse transcription-PCR and PCR-ELISA. Arch Virol. 2001;146:87–97.
[69] Hematian A, Sadeghifard N, Mohebi R, Taherikalani M, Nasrolahi A, Amraei M, et al. Traditional and modern cell culture in virus diagnosis. Osong Public Health Res Perspectives. 2016;7(2):77–82.
[70] Bishop R, Davidson G, Holmes I, Ruck B. Detection of a new virus by electron microscopy of faecal extracts from children with acute gastroenteritis. Lancet. 1974;303(7849):149–51.
[71] Xing Y, Mo P, Xiao Y, Zhao O, Zhang Y, Wang F. Post-discharge surveillance and positive virus detection in two medical staff recovered from coronavirus disease 2019 (COVID-19), China, January to February 2020. Eurosurveillance. 2020;25(10):2000191.
[72] Sahu T, Ratre YK, Chauhan S, Bhaskar L, Nair MP, Verma HK. Nanotechnology based drug delivery system: Current strategies and emerging therapeutic potential for medical science. J Drug Delivery Sci Technol. 2021;63:102487.
[73] Krishnan Y, Seeman NC. Introduction: nucleic acid nanotechnology. Washington DC, United States: ACS Publications; 2019.
[74] Radovic-Moreno AF, Lu TK, Puscasu VA, Yoon CJ, Langer R, Farokhzad OC. Surface charge-switching polymeric nanoparticles for bacterial cell wall-targeted delivery of antibiotics. ACS Nano. 2012;6(5):4279–87.
[75] Lambadi PR, Sharma TK, Kumar P, Vasnani P, Thalluri SM, Bisht N, et al. Facile biofunctionalization of silver nanoparticles for enhanced antibacterial properties, endotoxin removal, and biofilm control. Int J Nanomed. 2015:2155–71.
[76] d'Angelo I, Casciaro B, Miro A, Quaglia F, Mangoni ML, Ungaro F. Overcoming barriers in *Pseudomonas aeruginosa* lung infections: engineered nanoparticles for local delivery of a

cationic antimicrobial peptide. Colloids Surf B Biointerfaces. 2015;135:717–25.
[77] Silva NC, Silva S, Sarmento B, Pintado M. Chitosan nanoparticles for daptomycin delivery in ocular treatment of bacterial endophthalmitis. Drug Delivery. 2015;22(7):885–93.
[78] Kumar GV, Su CH, Velusamy P. Ciprofloxacin loaded genipin cross-linked chitosan/heparin nanoparticles for drug delivery application. Mater Lett. 2016;180:119–22.
[79] Casciaro B, Moros M, Rivera-Fernandez S, Bellelli A, de la Fuente JM, Mangoni ML. Gold-nanoparticles coated with the antimicrobial peptide esculentin-1a (1-21) NH2 as a reliable strategy for anti-pseudomonal drugs. Acta Biomater. 2017;47:170–81.
[80] Kooti M, Sedeh AN, Motamedi H, Rezatofighi SE. Magnetic graphene oxide inlaid with silver nanoparticles as antibacterial and drug delivery composite. Appl Microbiol Biotechnol. 2018;102:3607–21.
[81] Rani S, Gothwal A, Pandey PK, Chauhan DS, Pachouri PK, Gupta UD, et al. HPMA-PLGA based nanoparticles for effective in vitro delivery of rifampicin. Pharmaceutic Res. 2019;36:1–12.
[82] Ullah K, Khan SA, Mannan A, Khan R, Murtaza G, Yameen MA. Enhancing the antibacterial activity of erythromycin with titanium dioxide nanoparticles against MRSA. Current Pharmaceutic Biotechnol. 2020;21(10):948–54.
[83] Feynman R. There is plenty of room at the bottom. In: Feynman and computation. Boca Raton, Florida, United States: CRC Press; 2018. p. 63–76.
[84] Al-Shuj'a O, Obeid A, El-Shekeil Y, Hashim M, Al-Washali Z, et al. New strategy for chemically attachment of imine group on multi-walled carbon nanotubes surfaces: synthesis, characterization and study of DC electrical conductivity. J Materials Sci Chem Eng. 2017;5(02):11.
[85] Bayda S, Adeel M, Tuccinardi T, Cordani M, Rizzolio F. The history of nanoscience and nanotechnology: from chemical-physical applications to nanomedicine. Molecules. 2019;25(1):112.
[86] Thostenson ET, Ren Z, Chou TW. Advances in the science and technology of carbon nanotubes and their composites: a review. Composites Sci Technol. 2001;61(13):1899–912.
[87] Wang H, Agarwal P, Jiang B, Stewart S, Liu X, Liang Y, et al. Bioinspired one cell culture isolates highly tumorigenic and metastatic cancer stem cells capable of multilineage differentiation. Adv Sci. 2020;7(11):2000259.
[88] Duuuuu G, Moulin E, Jouault N, Buhler E, Giuseppone N. Muscle-like supramolecular polymers: integrated motion from thousands of molecular machines. Angew Chem. 2012;124(50):12672–6.
[89] Campbell EK, Holz M, Gerlich D, Maier JP. Laboratory confirmation of C60+ as the carrier of two diffuse interstellar bands. Nature. 2015;523(7560):322–3.
[90] Song T, Cai X, Tu MWY, Zhang X, Huang B, Wilson NP, et al. Giant tunneling magnetoresistance in spin-filter van der Waals heterostructures. Science. 2018;360(6394):1214–8.
[91] Larue L, Myrzakhmetov B, Ben-Mihoub A, Moussaron A, Thomas N, Arnoux P, et al. Fighting hypoxia to improve PDT. Pharmaceuticals. 2019;12(4):163.
[92] Liu H, Guo Z, Mo L, Sun Y, Zhang J, Liu X, et al. Quantitative label-free optical technique to analyze the ultrastructure changes and spatiotemporal relationship of enamel induced by Msx2 deletion. J Biophotonics. 2021;14(10):e202100165.
[93] Guo Z, Chen Y, Wang Y, Jiang H, Wang X. Advances and challenges in metallic nanomaterial synthesis and antibacterial applications. J Materials Chem B. 2020;8(22):4764–77.
[94] Kwiatkowski S, Knap B, Przystupski D, Saczko J, Kedzierska E, Knap-Czop K, et al. Photodynamic therapy-mechanisms, photosensitizers and combinations. Biomed Pharmacother. 2018;106:1098–107.
[95] Xiu W, Wan L, Yang K, Li X, Yuwen L, Dong H, et al. Potentiating hypoxic microenvironment for antibiotic activation by photodynamic therapy to combat bacterial biofilm infections. Nature Commun. 2022;13(1):3875.
[96] Sun J, Fan Y, Ye W, Tian L, Niu S, Ming W, et al. Near-infrared light triggered photodynamic and nitric oxide synergistic antibacterial nanocomposite membrane. Chem Eng J. 2021;417:128049.
[97] Qin Z, Zheng Y, Du T, Wang Y, Gao H, Quan J, et al. Cysteamine: A key to trigger aggregation-induced NIR-II photothermal effect and silver release booming of gold-silver nanocages for synergetic treatment of multidrug-resistant bacteria infection. Chem Eng J. 2021;414:128779.
[98] Tan L, Li J, Liu X, Cui Z, Yang X, Zhu S, et al. Rapid biofilm eradication on bone implants using red phosphorus and near-infrared light. Adv Mater. 2018;30(31):1801808.
[99] Sun J, Wang K, Hao R, Zhang Z, Feng Z, Shi Z, et al. Disregarded free chains affect bacterial adhesion on cross-linked polydimethylsiloxane surfaces. ACS Appl Mater Interfaces. 2023;15(30):36936–44.
[100] Pakapongpan S, Poo-Arporn RP. Self-assembly of glucose oxidase on reduced graphene oxide-magnetic nanoparticles nanocomposite-based direct electrochemistry for reagentless glucose biosensor. Mater Sci Eng: C. 2017;76:398–405.
[101] Liu L, Wei Y, Jiao S, Zhu S, Liu X. A novel label-free strategy for the ultrasensitive miRNA-182 detection based on MoS_2/Ti_3C_2 nanohybrids. Biosens Bioelectron. 2019;137:45–51. Elsevier.
[102] Ali M, Sajid M, Khalid MA, Kim SW, Lim JH, Huh D, et al. A fluorescent lateral flow biosensor for the quantitative detection of Vaspin using upconverting nanoparticles. Spectrochim Acta Part A: Mol Biomol Spectrosc. 2020;226:117610. Elsevier.
[103] Balamurugan T, Berchmans S. Non-enzymatic detection of bilirubin based on a graphene–polystyrene sulfonate composite. RSC Adv. 2015;5(62):50470–7. Royal Society of Chemistry.
[104] Moreira FT, Sale M, Goreti F, Di Lorenzo M. Towards timely Alzheimer diagnosis: A self-powered amperometric biosensor for the neurotransmitter acetylcholine. Biosens Bioelectron. 2017;87:607–14.
[105] Peng H, Chen IA. Rapid colorimetric detection of bacterial species through the capture of gold nanoparticles by chimeric phages. Acs Nano. 2018;13(2):1244–52. ACS Publications.
[106] Salahandish R, Ghaffarinejad A, Naghib SM, Majidzadeh-A K, Zargartalebi H, Sanati-Nezhad A. Nano-biosensor for highly sensitive detection of HER2 positive breast cancer. Biosens Bioelectron. 2018;117:104–11. Elsevier.
[107] Krampa FD, Aniweh Y, Kanyong P, Awandare GA. Recent advances in the development of biosensors for malaria diagnosis. Sensors. 2020;20(3):799. MDPI.
[108] Tibbits G, Mohamed A, Call DR, Beyenal H. Rapid differentiation of antibiotic-susceptible and-resistant bacteria through mediated extracellular electron transfer. Biosens Bioelectron. 2022;197:113754.
[109] Fang X, Kalathil S, Divitini G, Wang Q, Reisner E. A three-dimensional hybrid electrode with electroactive microbes for efficient electrogenesis and chemical synthesis. Proc National Acad Sci. 2020;117(9):5074–80.
[110] Yao L, Wang L, Huang F, Cai G, Xi X, Lin J. A microfluidic impedance biosensor based on immunomagnetic separation and urease

catalysis for continuous-flow detection of E. coli O157: H7. Sensors Actuators B Chem. 2018;259:1013–21.
[111] Yang Y, Chu B, Cheng J, Tang J, Song B, Wang H, et al. Bacteria eat nanoprobes for aggregation-enhanced imaging and killing diverse microorganisms. Nature Commun. 2022;13(1):1255.
[112] Qian X, Zheng Y, Chen Y. Micro/nanoparticle-augmented sonodynamic therapy (SDT): breaking the depth shallow of photoactivation. Adv Mater. 2016;28(37):8097–129.
[113] Xuuuu M, Zhou L, Zheng L, Zhou Q, Liu K, Mao Y, et al. Sonodynamic therapy-derived multimodal synergistic cancer therapy. Cancer Lett. 2021;497:229–42.
[114] Sun D, Pang X, Cheng Y, Ming J, Xiang S, Zhang C, et al. Ultrasound-switchable nanozyme augments sonodynamic therapy against multidrug-resistant bacterial infection. ACS Nano. 2020;14(2):2063–76.
[115] Gong Z, Dai Z. Design and challenges of sonodynamic therapy system for cancer theranostics: from equipment to sensitizers. Adv Sci. 2021;8(10):2002178.
[116] Ouyang J, Tang Z, Farokhzad N, Kong N, Kim NY, Feng C, et al. Ultrasound mediated therapy: Recent progress and challenges in nanoscience. Nano Today. 2020;35:100949.
[117] Huang H, Ali A, Liu Y, Xie H, Ullah S, Roy S, et al. Advances in image-guided drug delivery for antibacterial therapy. Adv Drug Delivery Reviews. 2023;192:114634.
[118] Mitragotri S, Kost J. Low-frequency sonophoresis: a review. Adv Drug Deliv Rev. 2004;56(5):589–601.
[119] Liu X, Yin H, Weng CX, Cai Y. Low-frequency ultrasound enhances antimicrobial activity of Colistin-Vancomycin combination against Pan-Resistant Biofilm of Acinetobacter baumannii. Ultrasound Med Biol. 2016;42(8):1968–75.
[120] Song M, Cheng Y, Tian Y, Chu C, Zhang C, Lu Z, et al. Sonoactivated chemodynamic therapy: a robust ROS generation nanotheranostic eradicates multidrug-resistant bacterial infection. Adv Funct Mater. 2020;30(43):2003587.
[121] Erriu M, Blus C, Szmukler-Moncler S, Buogo S, Levi R, Barbato G, et al. Microbial biofilm modulation by ultrasound: current concepts and controversies. Ultrason Sonochem. 2014;21(1):15–22.
[122] Wu MC, Deokar AR, Liao JH, Shih PY, Ling YC. Graphene-based photothermal agent for rapid and effective killing of bacteria. ACS nano. 2013;7(2):1281–90.
[123] Ibarra IS, Rodriguez JA, Galán-Vidal CA, Cepeda A, Miranda JM, et al. Magnetic solid phase extraction applied to food analysis. J Chem. 2015;2015.
[124] Wang H, Wang J, Xu L, Zhang Y, Chen Y, Chen H, et al. Selection and characterization of thioflavin T aptamers for the development of light-up probes. Anal Methods. 2016;8(48):8461–5.
[125] Ji H, Hu H, Tang Q, Kang X, Liu X, Zhao L, et al. Precisely controlled and deeply penetrated micro-nano hybrid multifunctional motors with enhanced antibacterial activity against refractory biofilm infections. J Hazard Mater. 2022;436:129210.
[126] Leulmi Pichot S, Joisten H, Grant A, Dieny B, Cowburn R. Magneto-mechanically actuated microstructures to efficiently prevent bacterial biofilm formation. Sci Rep. 2020;10(1):15470.
[127] Blakemore R, Maratea D, Wolfe R. Isolation and pure culture of a freshwater magnetic spirillum in chemically defined medium. J Bacteriol. 1979;140(2):720–9.
[128] Chen CY, Chen CF, Yi Y, Chen LJ, Wu LF, Song T. Construction of a microrobot system using magnetotactic bacteria for the separation of Staphylococcus aureus. Biomed Microdevices. 2014;16:761–70.
[129] Chen C, Chen L, Wang P, Wu LF, Song T. Magnetically-induced elimination of Staphylococcus aureus by magnetotactic bacteria under a swing magnetic field. Nanomed Nanotechnol Biol Med. 2017;13(2):363–70.
[130] Ye P, Li F, Zou J, Luo Y, Wang S, Lu G, et al. In situ generation of gold nanoparticles on bacteria-derived magnetosomes for imaging-guided starving/chemodynamic/photothermal synergistic therapy against cancer. Adv Funct Materials. 2022;32(17):2110063.
[131] Liu H, Chen C, Chen H, Mo L, Guo Z, Ye B, et al. 2D-PROTACs with augmented protein degradation for super-resolution photothermal optical coherence tomography guided momentary multimodal therapy. Chem Eng J. 2022;446:137039.
[132] Han HS, Choi KY. Advances in nanomaterial-mediated photothermal cancer therapies: toward clinical applications. Biomedicines. 2021;9(3):305.
[133] Chen Y, Gao Y, Chen Y, Liu L, Mo A, Peng Q. Nanomaterials-based photothermal therapy and its potentials in antibacterial treatment. J Controlled Release. 2020;328:251–62.
[134] Wu F, Zheng H, Wang W, Wu Q, Zhang Q, Guo J, et al. Rapid eradication of antibiotic-resistant bacteria and biofilms by MXene and near-infrared light through photothermal ablation. Sci China Mater. 2021;64(3):748–58.
[135] Zhao YQ, Sun Y, Zhang Y, Ding X, Zhao N, Yu B, et al. Well-defined gold nanorod/polymer hybrid coating with inherent antifouling and photothermal bactericidal properties for treating an infected hernia. Acs Nano. 2020;14(2):2265–75.
[136] Liu H, Mo L, Chen H, Chen C, Wu J, Tang Z, et al. Carbon dots with intrinsic bioactivities for photothermal optical coherence tomography, tumor-specific therapy and postoperative wound management. Adv Healthcare Materials. 2022;11(6):2101448.
[137] Qie X, Zan M, Gui P, Chen H, Wang J, Lin K, et al. Design, synthesis, and application of carbon dots with synergistic antibacterial activity. Front Bioeng Biotech. 2022;10:894100.
[138] Liu H, Chen H, Liu X, Mo L, Chen C, Guo Z, et al. Dual-responsive ultrathin 1T-phase niobium telluride nanosheet-based delivery systems for enhanced chemo-photothermal therapy. J Materials Chem B. 2021;9(38):8109–20.
[139] Wang H, Zhou S, Guo L, Wang Y, Feng L. Intelligent hybrid hydrogels for rapid *in situ* detection and photothermal therapy of bacterial infection. ACS Appl Mater Interfaces. 2020;12(35):39685–94.
[140] Wang M, Chen Y, Cai W, Feng H, Du T, Liu W, et al. In situ self-assembling Au-DNA complexes for targeted cancer bioimaging and inhibition. Proc National Acad Sci. 2020;117(1):308–16.
[141] Singh MP, Singh P, Li HB, Song QQ, Singh RK. Microbial biofilms: development, structure, and their social assemblage for beneficial applications. In: New and future developments in microbial biotechnology and bioengineering: microbial biofilms. Amsterdam, Netherlands: Elsevier; 2020. p. 125–38.
[142] Zheng Y, Liu W, Chen Y, Li C, Jiang H, Wang X. Conjugating gold nanoclusters and antimicrobial peptides: From aggregation-induced emission to antibacterial synergy. J Colloid Interface Sci. 2019;546:1–10.
[143] Guo Z, Zeng J, Liu W, Chen Y, Jiang H, Weizmann Y, et al. Formation of bio-responsive nanocomposites for targeted bacterial bioimaging and disinfection. Chem Eng J. 2021;426:130726.
[144] Zeng J, Guo Z, Wang Y, Qin Z, Ma Y, Jiang H, et al. Intelligent bioassembly imaging-guided platform for real-time bacteria sterilizing and infectious therapy. Nano Res. 2022;15(5):4164–74.
[145] Wang J, Xia Q, Huang K, Yin L, Jiang H, Liu X, et al. Ultrafast cancer cells imaging for liquid biopsy via dynamic self-assembling fluorescent nanoclusters. Biosensors. 2023;13(6):602.