Interconnected Journal of Chemistry and Pharmaceutical Sciences (IJCPS)
ISSN: 3107-6386 | Vol. 02, Issue 02, May-Aug., 2026 | pp. 51-66

Nanomaterials in Analytical Chemistry: Applications and Future Perspectives

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Abstract:

Nanomaterials revolutionize analytical chemistry owing to their outstanding optical, electrical, magnetic, and catalytic properties, increasing sensitivity, selectivity, and analytical speed of the methods applied in human clinical diagnostics. The current review presents a detailed description of the main types of nanomaterials used in analytical chemistry and their application in human biological sample analysis. These include gold nanoparticles, silver nanoparticles, carbon nanotubes, graphene-based nanomaterials, quantum dots, and magnetic nanoparticles. In addition, the review considers their analytical characteristics, procedures, advantages and limitations, as well as the role of nanomaterials in cancer biomarker detection, infectious diseases diagnostics, cardiovascular and metabolic biomarkers testing, drug therapeutic concentrations measurement, and many others. Moreover, it is important to discuss the current progress made in the area of nano-biosensors, lab-on-a-chip, microfluidic, wearable diagnostic platforms, and analytical techniques assisted with artificial intelligence regarding their contribution to rapid, sensitive and noninvasive diagnostics. Based on the currently available data, it can be said that nanomaterial-based analytical systems provide significantly higher analytical performance compared with the traditional ones owing to lower detection limits, faster response time, better diagnostic accuracy, and the ability to work with low amounts of human biological samples. Nevertheless, issues such as variability in nanomaterial preparation, absence of standardized analytical procedures, potential toxicity and regulatory problems, as well as insufficient large-scale human clinical trials hinder their clinical application. Further research should be conducted in the field of standardization of nanomaterial fabrication, multicenter human clinical trials, integration of nanomaterials with artificial intelligence and digital healthcare technologies, and the creation of safe, economical, and portable diagnostic systems. Overall, it can be concluded that nanomaterials represent an excellent basis for future analytical technologies.

Keywords: Nanomaterials; Analytical Chemistry; Clinical Diagnostics; Biosensors; Human Biomarkers; Personalized Medicine.

Received: May 16, 2026 **Revised: June 17, 2026** **Accepted: July 25, 2026** **Published: August 08, 2026**

DOI: https://doi.org/10.64474/3107-6386.Vol2.Issue2.4

https://ijcps.nknpub.com/1/issue/archive

1. INTRODUCTION

Nanomaterials have turned out to be one of the greatest achievements in analytical chemistry because of their special physicochemical properties, such as high ratio of surface area to volume, excellent conductivity, superior optical properties, and great catalytic ability. Such properties have contributed considerably to an increase in the sensitivity, selectivity, and speed of analytical techniques, making it possible to detect biological molecules at extremely low concentrations that cannot be analyzed by traditional analytical techniques[1]. The combination of nanotechnology and analytical chemistry resulted in creation of highly sophisticated biosensors, imaging systems, electrochemical sensors, and point-of-care diagnostic devices, which allow for quick and reliable analysis of various biological samples obtained from human body, including blood, serum, plasma, saliva, urine, and tissues. Consequently, nanomaterials have become indispensable tools in modern clinical diagnostics, biomedical research, pharmaceutical analysis, and personalized healthcare.

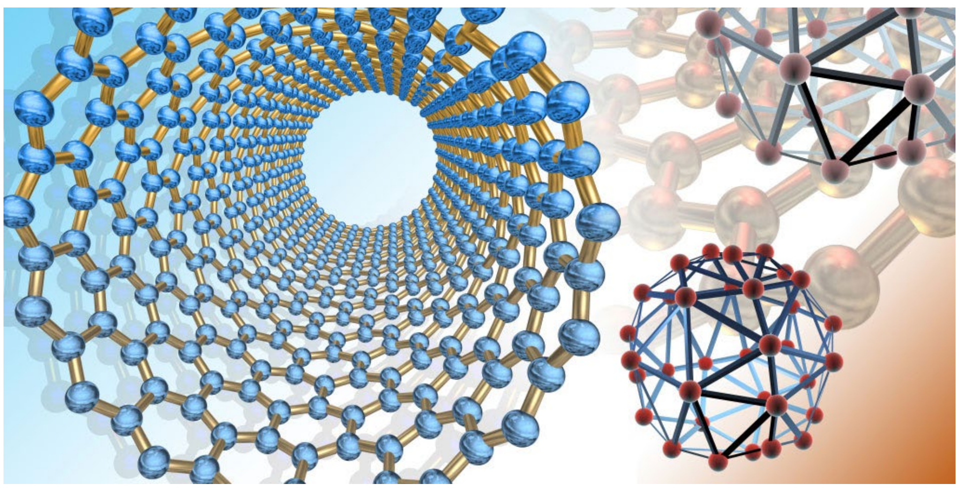

Figure 1: Nanomaterials[2]

Recent developments in nanotechnology have increased the utility of different nanomaterials like gold nanoparticles, silver nanoparticles, carbon nanotubes, graphene, quantum dots, and magnetic nanoparticles in human analytical chemistry. These nanomaterials have been found to show exceptional capabilities in the detection of cancer biomarkers, infectious agents, cardiovascular biomarkers, metabolites, and drug concentrations with better analytical precision and sensitivity. Moreover, incorporation of artificial intelligence, microfluidics, wearable biosensors, and lab-on-a-chip technology along with the use of nanomaterials for developing analytical methods has facilitated the development of point-of-care testing platforms[3]. Although these systems have accomplished great heights in the field, there are certain issues associated with reproducibility, standardization, biocompatibility, regulation, and clinical validation continue to limit their routine implementation in healthcare.

1.1 Background Information and Context

There are several aspects where analytical chemistry is of key importance in diagnosing diseases, evaluating the treatment process, and conducting biomedical studies because of its ability to provide accurate identification and quantification of the biological molecules involved[4]. The conventional methods of analytical chemistry are usually unable to overcome the problem of low sensitivity and high processing time along with the detection of biomarkers with low abundance levels. This problem was solved due to the use of nanomaterials that provide better signal amplification, rapid electron transfer, better optical response, and flexible surface modification.

1.2 Objectives of the Review

The key aims of this review are:

- To present an outline of the main types of nanomaterials employed in analytical chemistry along with their analytical characteristics.
- To assess the utilization of nanomaterials for the detection of clinically significant biomarkers based on human biological samples.
- To analyze the latest developments in the analytical technologies based on nanomaterials, such as biosensors, microfluidics, artificial intelligence, and wearables diagnostics.
- To assess the advantages, drawbacks, and existing problems related to the clinical implementation of analytical technologies based on nanomaterials.
- To reveal research gaps and future prospects related to the development of nanotechnologies in analytical chemistry and precision healthcare.

1.3 Importance of the Topic

The ever-growing prevalence of cancer, infectious, cardiovascular, metabolic, and other types of diseases around the globe has increased the need for fast, accurate, and non-invasive diagnostic techniques[5]. The use of nanomaterials has considerably boosted the efficiency of current diagnostic techniques by allowing sensitive, specific, and real-time detection of biomarkers associated with various diseases. Incorporation of nanomaterials into portable diagnostic equipment, point-of-care diagnosis platforms, and personalized medicine holds great promise for the enhancement of medical diagnostics, treatment optimization, and improvement of patients' outcomes. That is why the knowledge of contemporary uses of nanomaterials in analytical chemistry, the obstacles related to this sphere, and future perspectives in this field become vitally important[6].

2. NANOMATERIALS IN ANALYTICAL CHEMISTRY: TYPES AND ANALYTICAL PROPERTIES

The application of nanomaterials has revolutionized the field of analytical chemistry due to the increased sensitivity, selectivity, and efficiency in detection of biomarkers in human biological specimens. The properties of the materials in terms of optics, electronics, and catalysis have led to the fabrication of sophisticated diagnostic devices for clinical purposes[7]. This chapter highlights some of the commonly applied nanomaterials in analytical chemistry.

2.1 Gold Nanoparticles in Human Clinical Analysis

The gold nanoparticles (AuNPs) have been extensively employed in the field of analytical chemistry due to their excellent biocompatibility and optical characteristics. Several recent research papers have described their use for cancer biomarker sensing, cardiac marker sensing, and infection sensing by employing human blood, serum, and plasma samples[8]. Techniques such as colorimetric methods, electrochemical biosensing, and SERS have been used to achieve high analytical performance and fast sensing.

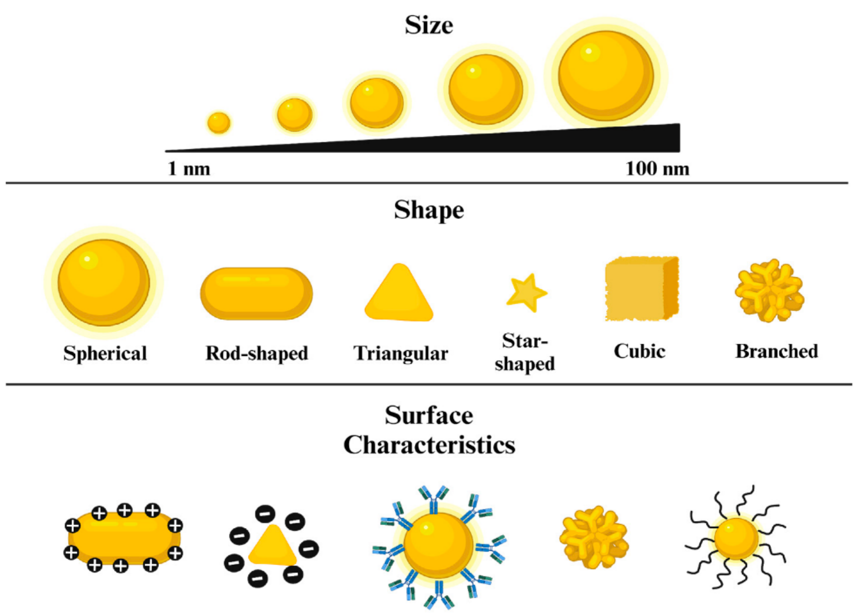

Figure 2: Gold Nanoparticles[9]

Strengths

- High sensitivity and specificity
- Excellent biocompatibility
- Easy surface functionalization

- Suitable for point-of-care testing

Weaknesses

- High production cost
- Particle aggregation may affect accuracy
- Need for standardized analytical protocols

2.2 Silver Nanoparticles in Analytical Applications

Silver nanoparticles have strong plasmonic and catalytic characteristics, which render them applicable in biosensors and clinical diagnostic applications[10]. They have been found to be effective in the detection of glucose, inflammatory biomarkers, and biomarkers for infectious diseases in human serum and urine. The techniques used by the researchers for the detection were mainly electrochemical and colorimetric in nature.

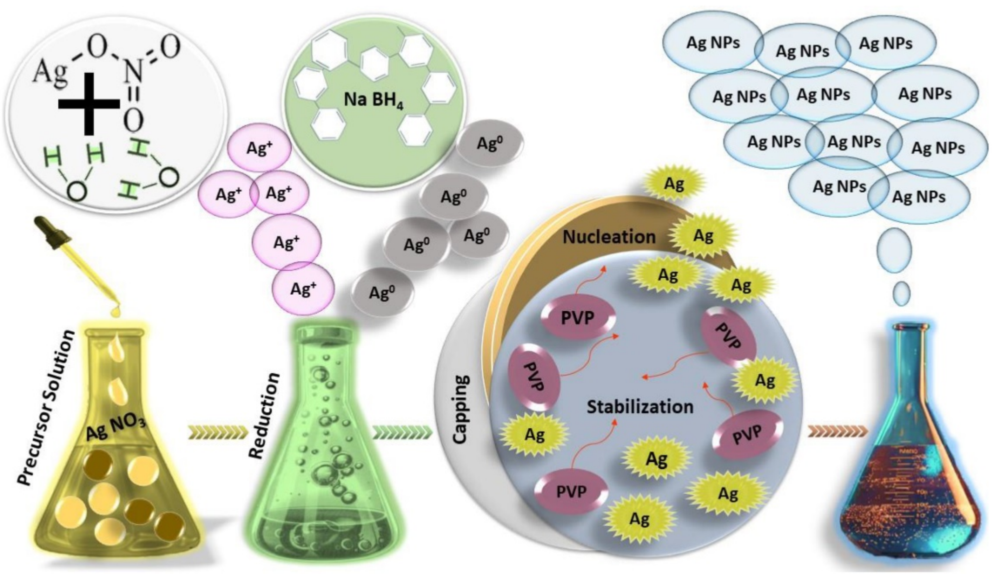

Figure 3: Silver Nanoparticles[11]

Strengths

- High sensitivity in analysis
- Economical
- Fast detection properties

Weaknesses

- Oxidizable
- Low stability
- Cytotoxicity in high concentration

2.3 Carbon Nanotubes and Graphene-Based Nanomaterials

The carbon nanotubes (CNTs) and graphene nanomaterials have found extensive use in electrochemical biosensors owing to their high electrical conductivity and large surface area. Some of the published works have employed the use of these nanomaterials in detection of glucose, cancer biomarkers, and cardiovascular biomarkers from the human biological fluids utilizing voltammetry and impedimetric approaches[12].

Strengths

- Outstanding electrical conductivity
- Great sensitivity
- Compatible with wearable biosensors

Weaknesses

- Complicated manufacturing
- Varied material quality
- Difficult to produce on an industrial scale

2.4 Quantum Dots and Magnetic Nanoparticles

The application of quantum dots and magnetic nanoparticles for fluorescence imaging and biomarker detection has been gaining importance in recent times[13]. Quantum dots (QDs) and magnetic nanoparticles (MNPs) have been used to detect cancer biomarkers and pathogens in human samples by fluorescence assay methods and magnetic separations techniques.

Strengths

- High fluorescence sensitivity
- Effective separation of samples
- Multiplex analysis capabilities

Weaknesses

- Possibility of toxicity for some quantum dots

- Expensive equipment cost
- Limited long-term clinical testing

Generally, the existing studies show that the analytical techniques based on nanomaterials have greater sensitivity and specificity as well as are able to detect disease-causing molecules faster than the conventional analytical techniques[14]. These techniques need smaller amount of sample and help in early detection of diseases through human samples. But there are some problems such as no standardization, problems of reproducibility, regulatory challenges, and a lack of large clinical studies that prevent their routine use in clinics. Future research should focus on standardization, multicentre human studies, and the integration of nanomaterials with artificial intelligence and portable diagnostic technologies.

3. APPLICATIONS OF NANOMATERIALS IN HUMAN ANALYTICAL CHEMISTRY

Nanomaterials have brought about a transformation in human analytical chemistry, where the detection of clinically important biomarkers has been made easy, rapid, sensitive, and accurate. This has led to better diagnosis and treatment for disease management[15]. This topic deals with the clinical application of nanomaterials in human analytical chemistry.

3.1 Cancer Biomarker Detection

The early detection of cancer is a very important factor in ensuring good health results for patients, and nanomaterials have made significant contributions to increasing the sensitivity of biomarker identification[16]. The most common nanomaterials used in detecting biomarkers like PSA, CEA, AFP, and circulating tumor DNA are gold nanoparticles, quantum dots, graphene, and carbon nanotubes. Research has demonstrated that biosensors incorporating nanomaterials offer low detection limit, rapid analysis, and high specificity compared with many other conventional diagnostic techniques.

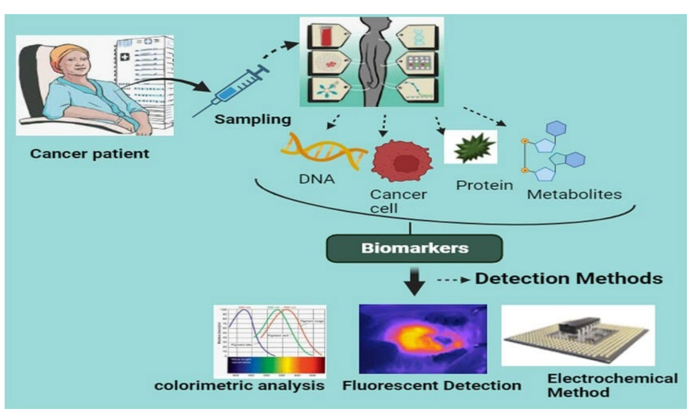

Figure 4: Biomarker Detection Methods For Cancer Diagnostics[17]

3.2 Infectious Disease Diagnosis

The use of nanomaterials has greatly contributed to the fast diagnoses of infections through the enhancement of biosensor and immunoassay performances[18]. Gold and silver nanoparticles, magnetic nanoparticles, and graphene nanosensors have been used to detect viruses and bacteria such as SARS-CoV-2, HIV, hepatitis viruses, and TB, using human blood and saliva. They can detect these infectious pathogens within a short time due to their high analytical sensitivity and detection time.

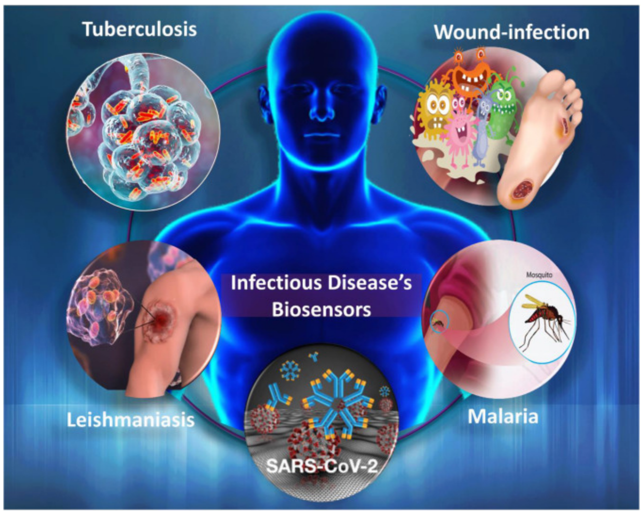

Figure 5: Infectious Disease[19]

3.3 Cardiovascular and Metabolic Biomarker Analysis

The development of nanotechnology has contributed to the enhancement of the detection of biomarkers for cardiovascular and metabolic diseases in terms of analytical precision and the shortened duration of assays[20]. Electrochemical biosensors utilizing carbon nanotubes, graphene, and gold nanoparticles have been used for detecting cardiac troponins, C-reactive protein (CRP), glucose, cholesterol, and other metabolic biomarkers in human samples. These analytical platforms support early diagnosis, disease monitoring, and improved clinical decision-making through rapid and reliable biomarker assessment.

3.4 Therapeutic Drug Monitoring and Personalized Medicine

Analytical systems using nanomaterials have improved drug monitoring therapies due to their ability to accurately measure the concentration of drug levels in human serum and plasma[21]. Gold nanoparticles, magnetic nanoparticles, and biosensors based on graphene have found application in monitoring antibiotic drugs, anti-cancer drugs, and others in the pharmaceutical field, with increased sensitivity. These systems play an important role in personalized medicine.

3.5 Point-of-Care Testing and Human Biosensing

Point-of-care testing is one of the most important fields in which nanomaterials have found an application in analytical chemistry[22]. Biosensors based on nanomaterials, lateral flow devices, wearable devices, and microfluidic systems allow for fast and non-invasive detection of various components in human biological fluids like blood, saliva, sweat, and urine. Such diagnostic tools deliver immediate results by processing a very small volume of the analyzed samples and help increase access to healthcare services, especially in distant and underserved regions. Improvements in nanotechnology and artificial intelligence will lead to further improvements in diagnostic instruments[23].

4. EMERGING ADVANCES IN NANOMATERIAL-BASED ANALYTICAL TECHNOLOGIES

The recent technological innovations in the use of nanomaterials in analytical systems have revolutionized the field of clinical diagnosis through the development of techniques that offer fast, sensitive, and highly accurate identification of disease markers in humans[24]. The use of nano-biosensors that make use of gold nanoparticles, graphene, carbon nanotubes, quantum dots, and magnetic nanoparticles has been found to be effective in the identification of cancer markers, infectious agents, cardiovascular markers, and metabolic markers. Moreover, the invention of lab-on-a-chip technology and microfluidics technology has resulted in miniaturization of the process and reduction in the use of the sample and reagents[25].

In addition to increasing the level of accuracy of diagnosis, the incorporation of artificial intelligence (AI) into nanomaterial-enabled analytical systems allows for automated analysis and pattern recognition[26]. Machine learning algorithms may be able to process analytical data obtained from nanosensors and thus help in biomarker detection and reduction of human errors. It is obvious that AI-powered analytical systems are likely to make a significant contribution to predicting diseases, personalized diagnostics, and clinical monitoring. The combination of nanotechnology and AI is expected to play an increasingly important role in precision medicine by supporting early diagnosis and individualized treatment strategies.

Another significant achievement is the development of wearable and portable diagnostic equipment which can constantly analyze physiological markers in the body using minimally invasive techniques on blood, sweat, saliva, and other bodily fluids[27]. Wearable biosensors powered by nanomaterials not only offer fast, continuous monitoring of health but also play an extremely useful role in chronic disease management and patient monitoring in remote locations. This portability and convenience have allowed analytical chemistry to be used outside of laboratories and increase access to healthcare facilities in poor settings[28].

However, despite all these advancements in technology, there still are several problems that need to be solved prior to making clinical application of these nanomaterials possible. Problems include inconsistencies in synthesis process of these nanomaterials, lack of standardized testing protocols, biocompatibility and toxicity concerns, regulatory issues, and absence of large-scale validation in humans are just some of the issues preventing from translating these technologies into the clinic[29]. Resolving these issues is important for the safe use of these technologies in practice.

Table 1: Summary of Selected Literature on Nanomaterials in Analytical Chemistry and Related Biomedical Applications[30]

Author(s) & Year	**Study Focus**	**Methodology/Model**	**Key Findings**
Nile et al. (2020)[31]	Applications of nanotechnology in food science, food safety, packaging, and analytical detection systems	Comprehensive review of published studies on nanomaterials, including metal nanoparticles, nanocomposites, and nanosensors used in food science and analytical applications	The review found that nanomaterials significantly enhanced analytical sensitivity and enabled rapid detection of contaminants and pathogens. However, toxicity assessment, regulatory approval, consumer acceptance, and commercialization remained major challenges for wider implementation.
Alshawwa et al. (2022)[32]	Nanocarrier drug delivery systems, characterization, artificial intelligence integration, and future perspectives	Systematic review of nanocarrier characterization techniques, clinical applications, limitations, and AI-based optimization models	The review reported that AI improved nanocarrier design, drug release prediction, and therapeutic efficiency while supporting personalized medicine. Standardization, regulatory frameworks, data quality, and clinical validation were identified as important barriers to clinical implementation.

Vallabani & Singh (2018)[33]	Biomedical and diagnostic applications of iron oxide nanoparticles	Review of biomedical research on iron oxide nanoparticles focusing on diagnostic imaging, biosensing, and targeted drug delivery	The review demonstrated that iron oxide nanoparticles exhibited excellent magnetic properties, high biocompatibility, and strong diagnostic potential. Nevertheless, issues related to toxicity, biodistribution, biodegradation, and clinical translation required further investigation before routine medical use.
Mittal et al. (2020)[34]	Nanoparticle-based sustainable agriculture, food science, environmental monitoring, and analytical technologies	Review of recent advances in nanoparticle applications for agriculture, food quality assessment, and analytical sensing	The review showed that nanoparticle-based sensing platforms improved the detection of pesticides, contaminants, pathogens, and nutrients with greater sensitivity and precision than conventional methods. Environmental safety, ecological risks, regulatory concerns, and commercialization remained significant limitations.
Azzouz et al. (2018)[35]	Nanomaterials as sorbents in solid-phase extraction for environmental analytical chemistry	Review of nanomaterial-based solid-phase extraction techniques using carbon nanomaterials, metal nanoparticles, magnetic nanoparticles, and nanocomposites	The review concluded that nanomaterial-based sorbents enhanced adsorption capacity, analytical sensitivity, selectivity, and extraction efficiency during sample preparation. However, sorbent reusability, synthesis cost, reproducibility, and large-scale application remained key challenges requiring further research.

5. DISCUSSION

This discussion presents a summary of the results derived from the literature reviewed, emphasizing the use of nanomaterials to enhance the quality of analysis in relation to clinical diagnostics of human biological samples[36]. The discussion also sheds light on the significance of such nanomaterials in terms of their clinical importance, research gaps and limitations, and outlines future directions for advancing nanomaterial-based analytical technologies in healthcare.

5.1 Interpretation and Analysis of Current Findings

The research results discussed in this literature review prove that nanomaterials have greatly contributed to the improvement of analytical chemistry, especially the detection of clinically significant biomarkers from human samples. Gold nanoparticles, silver nanoparticles, carbon nanotubes, graphene, quantum dots, and magnetic nanoparticles have constantly provided better sensitivity, selectivity, and fast response than traditional analytical techniques[37]. Their distinctive optical, electrical, and magnetic features have allowed researchers to create efficient biosensors and diagnostic devices for detecting cancer, identifying infectious diseases, analyzing cardiovascular biomarkers, therapeutic drugs, and conducting point-of-care tests. In addition, the combination of nanomaterials with artificial intelligence, microfluidics, and wearable technologies has increased the area of applicability of analytical chemistry for clinical diagnostics.

5.2 Clinical Implications and Significance

Application of nanomaterials on an extensive scale has great effects on health care and precision medicine. The use of nanomaterials in analytical devices offers early disease diagnosis, quick clinical decisions, and patient monitoring through the analysis of minimal quantities of biological human specimens without compromising the effectiveness of the analytical process[38]. Their integration in portable biosensors, lab-on-a-chip technology, and wearable diagnostics has led to greater access to health care especially at the point-of-care settings. In addition, developments in drug monitoring and precision medicine show the possibilities of nanotechnology in improving treatment techniques.

5.3 Research Gaps and Limitations

Even with all the advances made, there still exist various problems that prevent the use of nanomaterials on a regular basis in clinical settings. Several scientific studies done using nanomaterials have used small numbers of human subjects, which make their results not very universal[39]. Various issues like differences in the production, surface modification, methods of analysis, and validation procedures for nanomaterials may lead to inconsistencies in the performance of different studies. Biocompatibility, toxicity, reproducibility, scaling up, and the regulatory approval of these nanomaterials pose significant obstacles to their successful implementation.

5.4 Future Research Directions

The future research should aim at conducting clinical investigations involving large cohorts of human subjects to demonstrate the reliability of nanomaterials-based detection platforms. More efforts should be made towards establishing reproducible approaches in terms of the fabrication procedures and quality controls of nanomaterials. It is also important to establish the international regulations for the use of nanomaterials in clinical settings[40]. In addition, the integration of nanotechnology with such approaches as artificial intelligence, microfluidics, biosensors, and digital health care is expected to lead to the development of highly sensitive, real-time, and personalized diagnostics. Furthermore, interdisciplinary collaboration among analytical chemists, clinicians, biomedical engineers, and regulatory agencies will be essential for accelerating the safe and effective translation of nanomaterial-based analytical technologies into routine healthcare applications.

6. CONCLUSION

the present study proves that nanomaterials have a revolutionary influence on analytical chemistry by providing increased sensitivity, selectivity, speed and accuracy of analytical methods applied to diagnose various diseases in human clinical settings. From the perspective of the current review, gold nanoparticles, silver nanoparticles, carbon nanotubes, graphene-based nanomaterials, quantum dots and magnetic nanoparticles possess significant potentials for the detection of cancer biomarkers, infectious diseases, cardiovascular and metabolic disorders, drugs in therapeutics and point-of-care testing. Besides, modern techniques, which include nano-biosensors, lab-on-a-chip technology, wearable diagnostic devices, microfluidics and AI-assisted analytical systems, further develop the field of analytical chemistry and provide a possibility to obtain fast, accurate and minimally invasive diagnostics. Although there are still many obstacles that should be overcome by researchers in the sphere of standardization, reproducibility, biocompatibility, regulatory approval and clinical validation, continuous scientific progress provides hope that these issues will soon be resolved. All in all, the current review shows the great possibilities of nanomaterials for developing analytical technology.

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