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Biotechnological Tools for Early Cancer Detection in Clinical and Primary Healthcare Settings: A Narrative Review

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ABSTRACT

Background: Cancer remains a major global health concern, and survival depends heavily on early diagnosis. Recent advances in biotechnology have led to the development of more efficient and less invasive tools for early detection of cancer, key for improving diagnosis in resource-limited healthcare settings.

Purpose: This paper reviews a wide range of biotechnological tools currently being explored for early cancer detection. The goal is to understand their strengths, limitations, and possible impact on both clinical practice and public health.

Methods: A narrative review was conducted using peer-reviewed, open-access articles published between 2021 and 2025. Sixteen tools were grouped into eight themes, such as microfluidics, Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) diagnostics, liquid biopsy, biosensors, organoids, breath-based tests, Artificial Intelligence (AI)-guided tools, and radiomics. Each tool was evaluated for its potential to be scaled for wider use, its ease of access, the strength of its clinical testing, and how well it can be incorporated into existing diagnostic systems.

Results: Several tools, such as wearable biosensors, breath-based tests, and paper-based microfluidics, showed strong potential for use in routine screening due to their low cost and ease of use. Others, like CRISPR and organoid models, are more complex but offer high accuracy and personalization. However, many tools still need wider validation across different populations and clinical settings.

Conclusion: While each tool has its own limitations, biotechnology is helping make cancer tests more accurate, less painful, and easier to access. If these technologies are developed carefully and adapted to local healthcare needs, they could improve early diagnosis and help reduce cancer cases around the world.

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1. Introduction

Cancer continues to be a major global health concern, with increasing incidence and mortality worldwide (Dhyani *et al.*, 2022; Sood *et al.,* 2024). According to the World Health Organization (WHO), it accounted for nearly 10 million deaths in 2020, or nearly one in six deaths. Projections based on population trends estimate that by 2050, the number of new cancer cases each year will rise to 35 million, a 77% increase compared to 20 million cases in 2022. This steady rise places immense pressure on healthcare systems, especially in regions where diagnostic services are already limited or delayed. Early identification and efficient screening strategies are more important in such places. According to the National Cancer Institute (NIC), cancer is a disease in which some of the body's cells grow uncontrollably and spread to other parts of the body. An updated definition of cancer has been proposed, describing it as the uncontrolled growth of abnormal cells shaped by evolutionary forces (Brown *et al.,* 2023). These transformed cells undergo natural selection, allowing the disease to grow, change, and become harder to treat over time. Nonetheless, the survival rate improves when cancer is detected early. Yet, ~50% of cancers are at an advanced stage when diagnosed. Early detection of cancer or precancerous change allows early intervention to try to slow or prevent cancer development and lethality (Crosby *et al.,* 2022). It reduces morbidity, mortality, and costs by minimizing the need for aggressive treatments and prolonged hospital care associated with advanced disease.

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Biotechnology has shifted early diagnostics from invasive lab procedures to simpler, clinic-friendly tools by enabling detection at the molecular level. This includes non-invasive techniques like liquid biopsy, biosensors, and rapid microfluidic devices. Innovations such as Chimeric Antigen Receptor T cells (CAR-T cells), nanotechnology, and mRNA-based methods have strengthened early cancer detection and expanded personalized treatment options (Jiménez, 2024). These approaches aim to address not just the biological complexity of cancer but also the practical limitations of existing diagnostic tools. By focusing on speed, sensitivity, and patient comfort, biotechnology plays a key role in improving early detection. While many studies explore individual biotech diagnostics, few have compared tools in both cancer and primary healthcare. A unified review of all tools highlights which technologies, such as point-of-care (POC) devices, AI, and biosensors, are advancing fastest and where translation gaps lie. Examining these tools together also helps in identifying which ones offer cross-cutting benefits and which are still confined to controlled research settings. This broader perspective is especially useful in designing systems that are both effective and scalable. Most tools originate in highincome countries and aren't well adapted to low-resource environments. In low-resource regions like India and parts of Africa, poor infrastructure, diagnostic shortages, and fragmented referral systems slow adoption. A study conducted across seven African countries identified critical shortages in services like pathology, imaging, chemotherapy, and radiotherapy, all of which are essential for early cancer detection (Bamodu & Chung, 2024). These challenges go beyond technology and point to broader issues, including a lack of infrastructure, staff shortages, and uncoordinated health policies. Without improvements in training, funding, and health system coordination, even the most advanced diagnostic innovations risk being inaccessible or underutilized in regions that need them most. Summarizing these biotechnological tools together allows for a clearer understanding of where the major gaps lie and how implementation can be improved, particularly in low-resource settings. This review explores a wide range of emerging biotechnological tools that are reshaping diagnostics in both cancer and primary healthcare. These are categorized as follows: point-of-care (POC) devices & microfluidics, liquid biopsy & exosome-based diagnostics, epigenetic markers & breathomics, radiomics & wearable biosensors, CRISPR-Cas9 & nano-sensor platforms, multi-cancer early detection (MCED) & multi-omics integration, single-cell sequencing & T-cell receptor (TCR) profiling, and organoid models & AI-driven oncology platforms.

In light of rising global cancer burdens and the persistent delays in early diagnosis, especially in underserved regions, there is an urgent need to bridge the gap between innovation and real-world application. This review highlights a variety of biotechnological tools that not only facilitate earlier detection but also aim to improve diagnostic accessibility, accuracy, and cost-effectiveness. By examining technologies ranging from portable diagnostic devices to AI-supported platforms, the review aims to capture both scientific advancements and the practical challenges that limit widespread use. A clear understanding of these technologies along with the barriers to their use is important for shaping strategies that support their integration into real-world healthcare systems. This is especially critical in regions where early diagnosis could make the biggest difference in patient outcomes. With the rise in global cancer rates, improving access to reliable and affordable diagnostics is key to making sure new innovations don't just stay in research labs but reach the people who need them most. This review aims to connect current research with on-the-ground healthcare challenges, encouraging the use of diagnostic tools that can bring meaningful change in clinical practice, especially in under-resourced settings.

To frame these innovations in a practical context, Figure 1 classifies the tools based on their functional roles in the cancer care pathway: early detection, targeted treatment, and ongoing monitoring, emphasizing their potential for impactful integration into real-world healthcare settings.

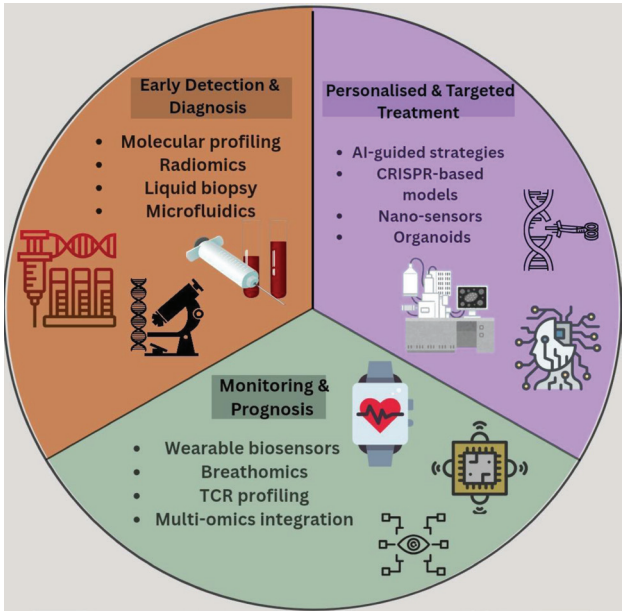

Figure 1: Classification of Emerging Biotechnological Tools based on their Role in Cancer Care: Early Detection, Treatment Support, and Disease Monitoring.

2. Methodology

2.1. Rationale and Purpose of the Study

This literature review focuses on recent advances in biotechnological tools for the early detection and diagnosis of cancer. A narrative review format was chosen to provide a flexible, theme-based understanding of the topic. It is especially useful for readers who are new to the subject, as it explores different aspects of the field instead of focusing on just one research question. The goal is to highlight key innovations, ongoing challenges, and areas needing further research.

2.2. Scope and Article Selection

The review focused on studies published between 2021 and 2025. The articles selected have been grouped into eight focused sections, ranging from biosensors and AI-based imaging to emerging approaches like breathomics and epigenetics. Sources were gathered from a range of openly accessible articles. These include peer-reviewed journals published by MDPI, platforms like PubMed Central (PMC), research collections such as Frontiers, search tools like Google Scholar, and official websites like the World Health Organization (WHO) and the National Cancer Institute (NCI). Search terms were based on tool-specific keywords. For easier understanding and discussion, the tools have been grouped into themes. Each theme covers two closely related diagnostic tools that reflect shared functions or technological approaches. Articles were included if they were relevant to biotechnology-based cancer diagnostics, clearly written in English, and openly accessible. As this is a narrative review, the article selection process was flexible and evolved alongside the structure of the review.

2.3. Data Collection and Analysis

All selected articles were read carefully, and their key findings were manually organized based on similar ideas and innovations. No statistical tools or software were used. Instead, a simple comparison method was applied to identify patterns, major developments, and how various technologies have progressed in detecting different types of cancer. Figures and tables used in this review were created by the author based on original sources, with proper citations.

The review also considered how these biotechnological tools are being used in real-life healthcare settings, such as clinics and primary care. Since this review is based entirely on publicly available literature and does not involve human or animal subjects, no ethical approval was required.

3. Results

The following section highlights selected biotechnological tools, grouped by their diagnostic approach and clinical relevance.

3.1. Theme-1: POC Devices & Microfluidics

Biomarker-based diagnostic tools have become central to early cancer detection because they can catch subtle molecular shifts at the very beginning of tumor development. Paper-based microfluidic devices offer a low-cost and user-friendly approach to detecting cancer-related molecules such as mRNA, proteins, and circulating tumor cells from saliva or blood (Das *et al.*, 2024). These devices are useful in clinics without access to advanced laboratory facilities. Another concern is that many of these tools have yet to be tested outside controlled environments, which delays their adoption in clinical practice. Even so, progress continues. For example, microfluidic systems have been used to detect methylated tumor suppressor genes, early indicators of cancer, all within just a few hours, showing how far the technology has come. Point-of-care (POC) microfluidics are extending this progress by combining core lab functions into compact, portable chips. Lab-on-a-chip systems that integrate with small fluid samples and connect to smartphones for rapid, on-site testing have been described in recent studies (Yang *et al.*, 2022). A platform has been developed to detect the ovarian cancer biomarker CA-125 from just a finger-prick blood sample (Nunna *et al.*, 2023). Even after this progress, practical barriers such as inconsistent sample handling, limited training, and lack of clear guidelines limit their use. Progress in exosome detection is also gaining ground. Research is increasingly directed towards multiplex systems that can detect multiple biomarkers like nucleic acids, proteins, and circulating tumor cells in a single test. Newer microfluidic chips are able to isolate cancer-related vesicles from fluids like urine, offering an additional, non-invasive option for early diagnosis. However, due to the lack of standardized protocols and clinical validation, these tools remain difficult to scale for routine use.

3.2. Theme-2: Liquid Biopsy & Exosomes (Non-Invasive Biomarkers)

Liquid biopsy is being studied as a less invasive way to detect and monitor cancer. It mainly focuses on circulating tumor DNA (ctDNA), which are tiny pieces of genetic material released by cancer cells into body fluids like blood. ctDNA shows strong potential in monitoring disease progression, detecting post-surgical relapse, and evaluating treatment response. Its presence in various body fluids such as blood, saliva, and urine facilitates non-invasive and flexible sample

collection (Ge *et al.*, 2024). Since samples can be taken multiple times, it allows for regular testing using methods such as droplet digital Polymerase Chain Reaction (ddPCR) and next-generation sequencing (NGS). However, spotting ctDNA in early-stage cancer is still difficult because its concentration is very low. There is also a risk of getting false results due to other genetic changes like clonal hematopoiesis. Besides that, the lack of clear testing guidelines and the high cost make it hard to use in everyday clinical practice. As of now, ctDNA may be more useful for tracking cancer over time rather than for early diagnosis, especially in places with limited medical resources. Exosomes are small extracellular vesicles released by cells into various body fluids. They are another potential tool for non-invasive cancer diagnostics. Exosomes carry DNA, RNA, proteins, and metabolites that reflect the molecular characteristics of their cells of origin (Kalluri & LeBleu, 2020). They have been found in nearly all biological fluids and are thought to participate in intercellular communication, cancer progression, immune modulation, and drug resistance, based on findings summarized by the authors. Although these tools hold strong diagnostic potential, several practical challenges remain. At present, there is no standardized protocol for isolating exosomes, and identifying cancer-specific exosomal markers continues to pose difficulties. Such limitations affect both the reproducibility of findings and their clinical reliability. Together, ctDNA and exosome-based approaches represent a growing move toward minimally invasive, real-time cancer diagnostics. If issues related to cost, standardization, and integration within healthcare systems can be resolved, their combined application may offer a more comprehensive understanding of disease progression.

3.3. Theme-3: Epigenetics & Breathomics

There is growing scientific interest in epigenetic changes like DNA methylation, histone modification, and altered non-coding RNA expression for their potential role in signaling early signs of cancer. These changes do not alter the DNA sequence itself but significantly impact gene regulation, often silencing tumor suppressor genes or activating oncogenes. Techniques such as bisulfite sequencing and chromatin immunoprecipitation have helped identify cancer-specific epigenetic signatures that could support early diagnosis and prognosis (Sherif *et al.*, 2025). Yet, challenges like high costs, complex lab procedures, and inconsistent findings across various studies limit their use in clinical settings, especially in places with limited infrastructure. Breathomics refers to the analysis of volatile organic compounds (VOCs) present in exhaled breath. Changes in metabolism caused by cancer can lead to unique patterns of VOCs, which researchers are now studying as possible early signs of the disease. Technologies such as gas chromatography–mass spectrometry and electronic noses have shown effectiveness in identifying VOC patterns linked to breast cancer (Yockell-Lelièvre *et al.*, 2025). These technologies are portable, relatively affordable, and more patient-friendly. But issues like inconsistent breath profiles, unstandardized sampling techniques, and environmental influences make consistency difficult. Still, both epigenetics and breath-based diagnostics represent a shift toward less invasive, early-stage cancer detection. With more testing and refinement, they may become useful tools alongside current diagnostic methods.

3.4. Theme-4: Radiomics & Wearable Biosensors

Radiomics allows for detailed analysis of imaging data by quantifying patterns that are often missed in visual assessments. A systematic review found that radiomics-based models, when integrated with AI in Positron Emission Tomography/Computed Tomography (PET/CT) scans, demonstrated strong diagnostic accuracy in identifying lymph node metastasis in head and neck cancers (Valizadeh *et al.*, 2025). This approach enhances breast cancer screening by extracting subtle mammographic features such as texture, shape, and brightness that may be missed during conventional visual assessment (Elahi & Nazari, 2024). Radiomics can help classify tumors and assess cancer risk by extracting measurable features from medical images. It is still not widely used in clinical settings. The adoption is slowed by inconsistent imaging protocols, the absence of standardized datasets, and practical difficulties in applying AI tools in hospitals. In some regions, limited access to high-quality imaging equipment adds to these challenges. Advancing its clinical relevance will require coordinated efforts, including shared imaging standards and institutional collaboration. Wearable biosensors are compact, skin-adhering devices designed to continuously monitor physiological signals or biochemical markers. They are used in cancer studies to detect biomarkers associated with inflammation, including IL-6 and TNF-α. Biosensors embedded in patches, mouthguards, or smart bands collect real-time data from accessible fluids such as sweat, saliva, and tears (Wu & Liu, 2025). The evolution of sensor miniaturization and the development of soft, biocompatible materials have made devices more comfortable to wear. At the same time, multiplex sensing and electrochemical transducers have enhanced their specificity. Biosensors still face issues like signal instability, interference from other molecules, and high production costs. These problems delay their clinical use. But they can support home-based cancer tracking, especially in places without centralized healthcare. Clinical trials and regulatory approvals will be needed to confirm their usefulness and safety.

3.5. Theme-5: CRISPR-Cas9 & Nano-Sensor Platforms

There is a continued rise in the use of CRISPR-Cas9, not only for gene editing but also for probing functional genetic vulnerabilities in cancer (Ravichandran & Maddalo, 2023). Researchers now use it to inactivate specific genes like TP53 in cultured cells to understand how their loss contributes to unchecked cell survival. CRISPR-Cas9, a gene-editing tool that uses guide RNA to direct the Cas9 enzyme to specific DNA sequences, is being repurposed as a platform for functional genomic screening. These approaches have deepened our understanding of how tumors evolve and respond to stress, offering pathways to discover treatment targets that were previously hard to study. CRISPR is also being used in drug resistance screening, helping to reveal why some therapies lose effectiveness in certain tumors. But its transition to clinical use remains uncertain. Off-target editing, immune responses, and inefficient delivery into human tissues continue to hinder progress. Although carriers like lipid nanoparticles and viral vectors are under development, current systems remain confined to research environments, especially where cost and safety are critical concerns.

In contrast, a nanozyme-based metasurface plasmon sensor has been developed to detect carcinoembryonic antigen (CEA), which is a glycoprotein often elevated in colorectal and pancreatic cancers (Li *et al.*, 2023). The device converts low concentrations of CEA in blood into measurable optical signals, with a detection limit of just 0.46 pg/mL. Unlike CRISPR, which investigates genetic alterations, this sensor captures biochemical changes associated with tumor development. Its compact design and high sensitivity could enable earlier detection than imaging, especially for cancers that lack early symptoms. Yet its real-world use is restricted by environmental variability, such as pH fluctuations or background proteins in samples, and by its dependence on lab-grade infrastructure. While CRISPR identifies genetic causes and nanosensors track molecular consequences, both technologies highlight different aspects of precision diagnostics. Their combined value lies in complementing each other, but wider adoption will depend on technical validation, delivery models, and cost-effectiveness in real-world care.

3.6. Theme-6: Multi-Cancer Early Detection & Multi-Omics Integration

Cancer screening is shifting from single-cancer tests to broader approaches such as MCED, which utilize circulating free DNA (cfDNA) methylation profiling to identify multiple cancers from a single blood sample (Milner & Lennerz, 2024). While promising for early detection in asymptomatic individuals, its clinical utility is limited by interpretive challenges, especially when test results suggest cancer presence without locating a specific tumor. The Galleri test, developed by the biotechnology company GRAIL, reflects both potential and concern: it detects over 50 types of cancer, but its use is constrained in settings with limited follow-up infrastructure. The authors also highlight a lack of systems to support patients who receive uncertain or inconclusive results, raising ethical concerns about the emotional and medical consequences of such findings. These gaps suggest the need for integrated diagnostic pathways that include counseling and follow-up care. Combining multiple molecular layers such as genomic, transcriptomic, and epigenomic may enhance diagnostic accuracy beyond what cfDNA alone can offer (Cai *et al.*, 2022). Despite their technical promise, multi-omics diagnostic tools often fall short in clinical settings due to inconsistent data, lack of standardized protocols, and limited population diversity. Tools using blood-based data to trace tumor origin show early potential, but their performance across healthcare systems remains unclear. Without validated methodologies and reproducible results, these models risk remaining theoretical. Furthermore, rapid innovation is outpacing healthcare infrastructure, emphasizing the need to embed such technologies within frameworks that ensure clinical readiness, equitable access, and policy support.

3.7. Theme-7: Single-Cell Sequencing & TCR Profiling in Immunotherapy

Single-cell RNA sequencing (scRNA-seq) offers detailed insights into gene expression by analyzing individual cells, which helps identify specific immune cell subsets involved in cancer therapy. Instead of combining data from mixed cell populations, this method allows scientists to examine how different immune cells behave in the tumor microenvironment. scRNA-seq has revealed immune subtypes such as exhausted CD8+ T cells, effector memory cells, and regulatory T cells, which actively influence treatment outcomes (Davis-Marcisak *et al.*, 2021). The same analysis identified elevated expression of genes like IFNG and PRF1 in patients with sustained responses to immune checkpoint inhibitors. Despite these benefits, scRNA-seq remains largely absent from clinical workflows. Its adoption is hindered by high costs, complex data interpretation, and lack of standardized protocols. To make this technology more widely usable, simplified analysis tools and better integration with clinical workflows are needed. T-cell receptor (TCR) profiling is used to study the diversity and frequency of TCR sequences, offering insights into the body's immune response against tumors. This approach

focuses on identifying T-cell clones that expand in response to cancer, especially during or after treatment. This technique has been used to track real-time immune dynamics and detect clonal expansion associated with therapeutic effects (Huang *et al.*, 2024). One advantage of TCR profiling is that it can be done with blood samples, which makes it easier to use repeatedly for monitoring patient responses. However, interpreting the results remains a challenge. Clonal expansion may sometimes be due to infections or unrelated immune activity, not necessarily tumor-specific responses. Also, differences in sequencing pipelines across studies make it difficult to compare findings. When used together with single-cell data, TCR profiling could help improve how patients are selected for immunotherapy and how their progress is monitored over time.

3.8. Theme-8: Organoid Models & AI-Driven Oncology Platforms

Organoids are three-dimensional (3D) in vitro models derived from tumors that replicate key aspects of the original tissue's structure and function. Patient-specific tumor replicas are now being used to screen drugs and predict treatment responses prior to clinical application, marking a practical advancement toward personalized therapy (Tao *et al.*, 2025). For instance, miniaturized colorectal cancer organoids have successfully predicted patient-specific drug sensitivity in preclinical settings. Even so, challenges like time-intensive culture processes, variation in growth conditions, and lack of scalable, automated systems hinder their real-time clinical utility. It is also unclear whether such models can be feasibly adopted in under-resourced clinical labs. Future efforts must focus on automation, protocol standardization, and broader clinical validation to move organoids beyond research and into frontline oncology practice. Artificial intelligence is increasingly integrated across cancer care workflows, supporting early diagnosis, treatment selection, and outcome prediction (Huhulea *et al.*, 2025). These platforms process large datasets from medical imaging, genomic sequencing, and patient records to help clinicians make faster, more informed decisions. For example, convolutional neural networks (CNNs) are increasingly used in histopathology to detect subtle tumor features missed by the human eye. Yet despite this promise, current AI systems are often developed in high-resource research settings and remain poorly validated in diverse real-world populations. Concerns over data bias, regulatory barriers, and the opaque nature of "black box" algorithms, where model decisions lack clinical interpretability, further complicate implementation. For AI to meaningfully reduce clinical workload and improve equity, future research must prioritize ease of use, ethical integration, and deployment in low-infrastructure healthcare systems.

With these insights in mind, it becomes important to compare these innovations side by side. Table 1 presents an overview of the key biotechnological tools discussed across these themes, their main purposes in early detection, and the challenges they face.

Table 1: Key Biotechnological Tools for Early Cancer Detection

Focus Area	Key Technologies	Purpose in Early Detection	Challenges
Point-of-care Devices & Microfluidics	Lateral Flow Assays (LFAs), Microfluidic Platforms	Low-cost, portable, and rapid diagnostics, especially for resource-limited settings	Limited multiplexing, integration issues, sensitivity concerns
Liquid Biopsy & Exosomes	Circulating Tumor DNA (ctDNA), Exosome Analysis	Non-invasive, real-time cancer monitoring and relapse detection	Lack of standardization, isolation complexity
Epigenetics & Breathomics	DNA Methylation Biomarkers, Volatile Organic Compounds (VOCs) in Breath	Early changes detection before tumor formation; potential for non-invasive screening	Biomarker validation, environmental contamination
Radiomics & Wearable Biosensors	AI-based Radiomic Imaging, Wearable Biochemical Sensors	Continuous monitoring and prediction of cancer risk via imaging and sweat/skin sensor	Data overload, real-time accuracy, privacy issues
CRISPR-Cas9 & Nano-Sensor Platforms	CRISPR Functional Screens, Nano-based Sensor Arrays	Functional gene editing and ultra-sensitive biomarker detection	Off-target effects, reproducibility, biosecurity concerns
Multi-Cancer Detection & Multi-Omics Integration	Multi-analyte Blood Tests, Integrated Omics Platforms	Detect multiple cancers simultaneously using layered molecular insight	High cost, data harmonization, false positives
Single-Cell Sequencing & TCR Profiling	scRNA-seq, T-cell Receptor Sequencing	Immune profiling at single-cell level for precise therapy design	Data complexity, high cost, technical expertise required

Focus Area	Key Technologies	Purpose in Early Detection	Challenges
Organoid Models & AI in Oncology	Patient-Derived Tumor Organoids, AI Prediction Platforms	Personalized therapy design and drug screening	Scalability, computational bias, limited clinical validation

4. Discussion

As biotechnology races ahead, it's worth pausing to ask what progress truly means for patients. Are these innovations simply faster and smarter, or are they meaningfully accessible, ethical, and trusted? Tools can transform detection, but only if they also fit into the realities of human care. This review brought together a range of biotechnological tools aimed at early cancer detection, each representing diverse innovations in sensitivity, usability, and diagnostic scope. While no single approach offers a perfect solution, the combined landscape shows evidence of improvement. From rapid point-of-care microfluidics to advanced models like organoids and AI-driven platforms, the analysis highlights tools that significantly enhance early detection. These innovations also show strong potential for integration into clinical workflows, particularly within primary healthcare settings. Notably, multi-cancer detection platforms and CRISPR-based screening showed the highest potential for scalability, while breathomics and wearable biosensors emphasized patient comfort and accessibility. Taken together, the reviewed technologies show how biotechnology is improving cancer diagnosis in ways that are both practical and patient-focused. The integration of molecular tests, biosensors, and AI-based tools marks a shift from relying on single types of tests toward creating connected and adaptable diagnostic systems.

This review highlights not only the benefits of these approaches but also the hurdles to adopting them, especially in primary care and in settings with limited resources. By comparing technologies in a clinical context, it provides clearer insight into how different tools may be matched to the needs of various patients and healthcare environments. This thematic analysis also draws attention to gaps in current testing and the pressing need for collaboration among researchers, clinicians, and policymakers. In future work, studies should aim for larger, more diverse populations and prioritize fair, ethical access to new diagnostics. Continuing development and validation will be important to ensure these biotechnological tools meet real-world standards. With further improvement, these advances could help close the gap between new discoveries and meaningful patient impact.

Compared to earlier research, the review reaffirms and extends several findings. Paper-based microfluidic platforms have been shown to reliably detect tumor markers such as mRNA and CTCs using minimal samples, supporting the broader conclusion that POC tools offer diagnostic speed and simplicity but face challenges in reproducibility and scalability (Ajikumar & Lei, 2024). Similarly, ctDNA detection has shown promise for longitudinal monitoring, supporting the observation that liquid biopsy, though promising, still lacks early-stage sensitivity (Neriya Hegade *et al.*, 2025). MCED technologies such as Galleri have raised concerns due to their tendency to produce ambiguous results without anatomical context. This reinforces the argument that, despite their futuristic potential, these tools require careful integration with counseling systems and appropriate follow-up infrastructure (Eisenstein, 2025). DNA methylation profiling has shown strong diagnostic value in tumor classification and recurrence prediction, as confirmed in recent epigenetic studies (Sahoo *et al.*, 2025). However, these studies also highlighted technical challenges, such as variability in biomarker panels and the high cost of sequencing, which align with the limitations discussed in this review. VOC shifts in perioperative breathomics have been used to distinguish lung cancer patients from healthy individuals. The study also acknowledged challenges such as sample heterogeneity and handling inconsistencies, which are common issues in breath-based diagnostic approaches (Wang *et al.*, 2022).

In radiomics, AI-enhanced imaging workflows can uncover tumor features beyond visual interpretation, supporting diagnostic and prognostic tasks, yet reproducibility and clinical validation remain key challenges (Shur *et al.*, 2021). Biosensors have also demonstrated strong potential in detecting biochemical changes through sweat and saliva, though issues such as environmental variability and signal instability continue to pose significant challenges (Iqbal *et al.*, 2022). The future potential of advanced tools like CRISPR-Cas9 and organoids remains substantial and cannot be overlooked. CRISPR has progressed from a genome-editing tool to a platform for functional cancer screening, as recent work has demonstrated (Rabaan *et al.*, 2023). While this analysis supports the broader application of CRISPR, concerns such as off-target effects and delivery challenges need to be resolved prior to clinical implementation. Organoids have been recognized for preserving tumor heterogeneity and serving as a personalized platform for drug response testing, making them valuable tools in precision medicine (Ma *et al.*, 2023). At the same time, their lengthy growth periods and inconsistent results raise concerns about feasibility, particularly in resource-

limited healthcare settings. In parallel, the potential of AI to accelerate clinical decision-making has been acknowledged, though ethical concerns surrounding black-box algorithms and biased datasets remain significant challenges (Huhulea *et al*., 2023).

These concerns are consistently reflected in the broader discussion presented here. These findings underscore the growing shift from traditional diagnostics to more personalized, minimally invasive, and scalable platforms. In particular, integration of AI with molecular tools, such as CRISPR data or VOC profiles, may offer hybrid systems that enhance both diagnostic precision and interpretability. For Low- and Middle-Income Countries (LMICs), the key will be not just to adopt these technologies, but to adapt them; creating decentralized systems that can handle biosensors, wearable diagnostics, and blood-based MCED without over-relying on hospital infrastructure. Further research should focus on four areas: real-world validation in diverse populations, standardization of protocols, cost-reduction strategies, and development of ethical frameworks for AI use. Tools like MCED, biosensors, and organoids need regulatory pathways and integration plans to ensure responsible deployment. Without such frameworks, even high-performing technologies may stay confined to research labs.

In sum, while each tool has its strengths and gaps, their convergence offers hope for earlier, more equitable cancer detection. The collective evidence presented in this review makes it clear that biotechnology is no longer just a future promise; it is already transforming the way diagnostics are approached today. This shift is also reflected in global market trends. According to Grand View Research (2024), the biotechnology market was valued at USD 1.55 trillion in 2023 and is expected to grow to USD 3.88 trillion by 2030, with a compound annual growth rate of 13.96%. This rapid growth highlights the increasing relevance of biotech solutions and reinforces the need to ensure that these advancements are effectively translated into policy and practice. When implemented thoughtfully, they can help bridge the gap between innovation and access, especially in the communities that need them the most.

Like most narrative reviews, this study has a few limitations. It does not aim to cover every single article on the topic but focuses on those that are recent, relevant, and freely accessible; most included sources are peer-reviewed articles published between 2021 and 2025. Unpublished studies, emerging tool prototypes, and data in other languages may have been excluded due to access and selection criteria. Additionally, some technologies examined, such as multi-cancer early detection (MCED) platforms and wearable biosensors, still lack robust clinical validation in diverse patient populations, and many reported diagnostic metrics come from small or highly controlled research settings. No formal quality scoring or statistical meta-analysis was used, so the findings offer a broad synthesis rather than strong, evidence-based conclusions. Even with these boundaries, care was taken to select articles ethically and present the information clearly. By bringing together open-access research in a structured and meaningful way, this review supports learning, academic inquiry, and sets the stage for future studies that can address these gaps through more inclusive data sharing, standardization, and real-world validation.

5. Future Perspectives

What would it take to ensure early cancer detection reaches everyone and not just those with access to top hospitals or cutting-edge labs? As biotechnology continues to evolve, the goal must move beyond discovery to delivery. Tools such as breathomics, wearable biosensors, and paper-based microfluidics are promising not only for their innovation, but also for their potential to be affordable, portable, and widely accessible. Still, how well these tools work in the real world depends on solving some key issues, such as unstable signals, sensitivity to different environments, and the need for consistent standards across labs and clinics. Artificial intelligence will play a central role in interpreting large datasets and refining diagnostics, but it must become more human-aligned: transparent, interpretable, and culturally adaptable, especially when deployed in diverse clinical environments (Sebastian & Peter, 2022). The future of diagnostics lies not only in technological advancement but also in creating meaningful impact that considers the specific needs of different communities and contexts.

Beyond early detection, biotechnology must now move toward prevention. Using individual genetic profiles to guide treatment decisions and recommend preventive lifestyle changes is becoming increasingly practical. To ensure cancer preventive efforts, future developments should include exploring new chemoprevention targets and preventive compounds/drugs, identifying intermediate biomarkers to evaluate the effectiveness of prevention, and utilizing individual genetic profiles (Benetou *et al*., 2015, as cited in Seong *et al*., 2025). Organoids and CRISPR-based diagnostics could evolve into preventive modeling tools capable of simulating patient-specific cancer risk and testing preventive therapies before clinical onset. Imagine a future where a person doesn't just get diagnosed early but is also offered a personalized prevention plan years before disease develops.

Yet, scientific breakthroughs are not enough. The real leap will come from how equitably we scale these innovations (Patil, 2022). For low- and middle-income countries, decentralized

diagnostic models are not optional, they are essential. Microfluidics kits that work with just a finger-prick of blood, breath-based diagnostics that require no lab, and biosensors integrated into wearable patches could redefine what screening looks like in resource-constrained environments. However, this will require more than engineering; it demands policy reform, funding models that support accessibility, and global collaboration on regulatory standards. Ethical frameworks for AI, patient data protection, and standardized clinical validation must all move in parallel with innovation.

If done right, biotechnology won't just catch cancer early, it will also change what "early" even means, shifting care from reactive to proactive, from fear-driven to informed. And in doing so, it may bring us closer to a future where early detection is not a privilege but a global norm.

Abbreviations

CRISPR: Clustered Regularly Interspaced Short Palindromic Repeats; **AI**: Artificial Intelligence; **WHO**: World Health Organization; **NIC**: National Cancer Institute; **CAR-T**: Chimeric Antigen Receptor-T cells; **POC**: Point-of-care; **MCED**: Multi-cancer early detection; **PMC**: PubMed Central; **ctDNA**: Circulating tumor DNA; **ddPCR**: Droplet digital Polymerase Chain Reaction; **NGS**: Next Generation Sequencing; **VOC**: Volatile Organic Compounds; **PET/CT**: Positron Emission Tomography/Computed Tomography; **CEA**: Carcinoembryonic antigen; **cfDNA**: Circulating free DNA; **scRNA-seq**: Single-cell RNA sequencing; **CNN**: Convolutional Neural Networks; **LFA**: Lateral Flow Assays; **LMIC**: Low- and Middle-Income Countries.

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Ethical Approvals

No ethical approvals were required for this study.

Declarations

The authors declare that they have followed all ethical standards in conducting this research. All data supporting the findings are available within the manuscript

Conflict of Interest

The authors declare no conflict of interest related to this study.

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