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Transforming Biomedicine for Future Health: Roles, Technological Convergence, Translational Prospects, and Governance Challenges

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A B S T R A C T

Biomedical science is undergoing rapid transformation through the convergence of cell and molecular biology, genomics and multi-omics, immunology, gene editing, organoids, mRNA technology, bioinformatics, and artificial intelligence. This article aims to analyze the strategic role of biomedical science in modern health, review the prospects for biomedical technology development in future healthcare services, and identify challenges in translation, ethics, governance, infrastructure, and access equity. The study uses a qualitative literature review approach with a narrative-integrative synthesis of reputable journal articles mainly published from 2020 to 2026. The results show that biomedical science is increasingly shifting healthcare from a reactive and one-size-fits-all approach toward earlier diagnosis, risk stratification, precision therapy, accelerated drug development, continuous monitoring, and public health preparedness. The greatest value comes from the convergence between technologies, such as integrating multi-omics data with AI, validating biomarkers through advanced biological models, and translating genomic findings into gene and cell therapies. However, these benefits are limited by infrastructure gaps, bias and representation in data, technology costs, the need for clinical validation, privacy protection, and uneven access. In the context of Indonesia, strengthening genomic capacity, laboratories, biomedical data, multidisciplinary human resources, and translational governance is a priority. The article concludes that the future of biomedicine depends on the ability to connect basic discoveries, technology platforms, clinical evaluation, and health system implementation in a safe, effective, inclusive, and sustainable way

INTRODUCTION

Biomedical science has evolved from a discipline that mainly explains basic biological mechanisms into a translational field that connects cell and molecular biology, genetics, immunology, biochemistry, bioinformatics, biomedical engineering, and data science to understand diseases and create more precise health interventions. This shift is driven by the ability to measure biological systems at increasingly high resolution using multi-omics, single-cell and spatial transcriptomics approaches, as well as human cell atlases. At the same time, the development of the human pangenome expands the representation of human genetic variation and reduces the limitations that arise if analysis relies solely on a single linear reference genome. As a result, modern biomedical science is increasingly focused on understanding complex, heterogeneous, dynamic, and contextual biological systems, rather than just looking at a single gene, protein, or disease pathway on its own (Subramanian et al., 2020; Longo et al., 2021; The Tabula Sapiens Consortium, 2022; Liao et al., 2023).

The urgency of biomedical science is also seen in its ability to turn mechanistic knowledge into health technology faster and faster. The development of mRNA vaccine platforms during the COVID-19 pandemic showed that understanding RNA biology, immunology, lipid nanoparticle delivery systems, and molecular design can come together to create global health interventions. On the other hand, CRISPR-based genome editing has moved from an experimental concept to clinical evidence, for instance through editing hematopoietic cells in sickle cell disease and beta-thalassemia, as well as in vivo genome editing for transthyretin amyloidosis. These developments mark an important shift from treatments that mainly control symptoms to interventions that can more directly target the biological causes of diseases, even though long-term safety, target accuracy, delivery, and ethics still need serious attention (Doudna, 2020; Chaudhary, Weissman and Whitehead, 2021; Frangoul et al., 2021; Gillmore et al., 2021).

In the field of diagnosis and therapy development, biomedical advances have expanded our ability to detect diseases earlier, map biological heterogeneity, and test therapy responses in ways that are more relevant to human conditions. Liquid biopsy, for example, allows us to analyze tumor components circulating in the blood and opens up opportunities for more dynamic molecular monitoring. Meanwhile, organoids and organ-on-chip provide three-dimensional and microphysiological experimental models that can recapitulate some characteristics of human tissues, thus potentially enhancing research on disease mechanisms, drug screening, toxicology, and therapy personalization. These advances are important because one of the classic challenges in health research is the translational gap between laboratory findings, animal models, and clinical effectiveness in humans (Kim, Koo and Knoblich, 2020; Ignatiadis, Sledge and Jeffrey, 2021; Ingber, 2022).

Digital transformation is further expanding the scope of biomedical science by integrating artificial intelligence (AI) with medical imaging, electronic health records, lab data, genomics, and various multimodal data sources. AI has the potential to help with pattern recognition, risk prediction, therapy candidate

selection, drug discovery, and clinical decision-making; the new generation of foundation models is even designed to handle multiple types of medical data and tasks at once. However, high technical performance on research data doesn't automatically mean clinical benefit, so external validation, evaluation in real-world settings, human factors, transparency, and proper reporting are important prerequisites before AI systems can be widely integrated into healthcare (Rajpurkar et al., 2022; Vasey et al., 2022; Moor et al., 2023).

Behind these opportunities, there are significant challenges that determine whether biomedical innovations will truly lead to safe and equitable health improvements. Unequal representation of populations in genomic studies can limit the generalization of findings and widen the gap in the benefits of precision medicine, while bias in data and AI algorithms can maintain or even worsen health disparities if models are developed from populations that don't reflect user diversity. In addition, the use of large-scale genomic and clinical data brings about the need for data governance, privacy protection, interoperability, quality standards, decision traceability, and stronger accountability mechanisms. Therefore, the success of future biomedical science should be assessed not only based on the novelty of technology but also on scientific validity, safety, clinical usefulness, affordability, and fairness of access (Celi et al., 2022; Fatumo et al., 2022; Vasey et al., 2022).

The context in Indonesia strengthens the urgency of this discussion. Experiences with SARS-CoV-2 genomic surveillance show the importance of sequencing and genome analysis capacity to understand pathogen dynamics and support public health responses. At the same time, recent studies on medical genetics in Indonesia show the development of national genome initiatives and precision medicine infrastructure, but also highlight gaps in expertise, infrastructure, funding, and access that still need to be addressed so that the benefits of genomics and biomedical technologies can be applied more broadly and fairly. With Indonesia's characteristic as an archipelagic country with a large and genetically diverse population, strengthening biomedical capacity is not only relevant for clinical innovation, but also for health resilience, disease surveillance, developing therapies that are more suitable for the population, and reducing dependence on knowledge or technology mainly developed from populations outside Indonesia (Cahyani et al., 2022; Ciabini et al., 2026).

Based on these developments, this article sees biomedical science as an ecosystem of knowledge and technology that links basic knowledge, translational innovation, clinical validation, and health implementation. The analysis isn't just focused on technological optimism, but rather on balancing the potential of innovation with scientific, ethical, regulatory, and institutional capacity requirements, as well as equitable access that shapes its impact on future health. This framework is needed so that discussions about biomedicine don't stop at simply listing technologies, but can explain how innovations can be turned into real, safe, accountable, and sustainable health benefits (Doudna, 2020; Rajpurkar et al., 2022; Fatumo et al., 2022; Ingber, 2022).

On that basis, this article raises two research questions: (RQ1) how is the development of contemporary biomedical science—especially genomics and

multi-omics, gene editing, advanced biological models, molecular diagnostic technologies, and artificial intelligence—shaping the role and prospects of diagnosis, prevention, therapy development, and healthcare in the future? (RQ2) what scientific, translational, ethical, regulatory, infrastructure, financing, and access equity challenges need to be managed so that advances in biomedical science lead to safe, effective, and inclusive health benefits? In line with these questions, the aim of this article is to critically analyze the role of biomedical science in health transformation, identify the key prospects that could shape future healthcare services, and synthesize the challenges and priorities that need to be addressed to ensure that biomedical innovations translate into sustainable and equitable health outcomes.

LITERATURE REVIEW

Biomedical Science as an Integrative and Translational Science

Conceptually, biomedical science is no longer accurately understood as a collection of standalone basic disciplines, but rather as an integrative field that explains how biological processes at the molecular, cellular, tissue, organ, and organism levels relate to health and disease. Cell and molecular biology, biochemistry, genetics, immunology, physiology, bioinformatics, pharmacology, and biomedical engineering provide complementary layers of knowledge. Within this framework, disease is seen as a disturbance of dynamic biological systems, influenced by interactions between genetic variations, gene expression regulation, metabolism, immune responses, the environment, and exposures throughout life. This perspective forms the basis for systems medicine and precision medicine because mechanistic explanations don't stop at identifying a single cause, but are aimed at mapping the biological networks that shape disease phenotypes (Subramanian et al., 2020; GTEx Consortium, 2020; Castelli et al., 2022).The second dimension is translation. Biomedical science gains health value when mechanistic knowledge can move from basic discoveries to experimental validation, biomarker or intervention development, clinical evaluation, service implementation, and ultimately health impact on the population. Therefore, the bench-to-bedside concept should not be understood as a one-way linear flow. Modern translation is an iterative process because clinical observations can lead to new biological questions that are then tested back in the lab. Surveys of biomedical researchers show that translational science is understood as a cross-disciplinary practice that requires integration between basic research, preclinical models, clinical evidence, regulations, data, and the needs of end users. This translation framework is important for articles because the prospects of a biomedical technology can't be judged just by its scientific novelty, but also by its validity, safety, clinical utility, scalability, and social acceptability (Walker et al., 2022; Vasey et al., 2022).

Cellular, Molecular, and Biochemical Foundations of Disease

Cells are the main functional units where genetic information, molecular signals, metabolism, stress responses, and cell-to-cell interactions come together. Modern ideas about disease, therefore, see cellular heterogeneity as a key aspect. Tissues that look uniform anatomically can actually be made up of cell subpopulations with different transcription programs, differentiation states, immune responses, and therapy sensitivities. Cross-organ single-cell transcriptome atlases have shown that mapping cell identities at high resolution can improve our understanding of normal functions as well as pathological changes. Combining single-cell RNA sequencing with spatial transcriptomics adds information about cell positions and local communication, so the relationship between molecular states and tissue architecture can be studied in a more complete way (The Tabula Sapiens Consortium, 2022; Longo et al., 2021). At the biochemical level, disease phenotypes show up through changes in metabolic flow, protein modifications, lipid composition, metabolites, and enzyme activity, which can't always be explained just by DNA sequences. Metabolomics and proteomics, therefore, act as a bridge between genomic information and the actual physiological state. Metabolites mainly reflect the end result of interactions between genes, microbiota, diet, drugs, environment, and clinical conditions, making them potentially useful for patient stratification and monitoring therapy response. However, putting this into clinical practice requires standardizing pre-analytical and analytical steps, external validation, and turning complex signatures into tests that are reproducible and usable in healthcare (Castelli et al., 2022; Subramanian et al., 2020).

Genomics, Gene Regulation, Multi-Omics, and Precision Medicine

Modern genomics has changed our understanding of human variation from a model based on a single reference genome to a broader representation of population diversity. Large-scale genomic variation databases show that interpreting mutations requires considering population frequency and gene constraint, while the human pangenome aims to reduce the bias that comes from mapping human variation only to a single linear reference. At the same time, GTEx data shows that the impact of genetic variation on expression and splicing differs across tissues. Theoretically, this confirms that genotype-phenotype relationships are contextual: the same variant can have different consequences depending on the tissue, gene regulation, and molecular environment where it's expressed (Karczewski et al., 2020; GTEx Consortium, 2020; Liao et al., 2023). Multi-omics expands analysis by combining genomics, epigenomics, transcriptomics, proteomics, metabolomics, and phenotypic data. The basic idea is that a single layer of data is rarely enough to capture the complexity of multifactorial diseases. Cross-omics integration allows for the identification of biological pathways, composite biomarkers, disease subtypes, and therapy targets that are more informative than single-modality analysis. That said, the challenges include differences in data scale, batch effects, missing data, temporal integration, and the need for interpretable computational models. So, precision medicine isn't just about genome sequencing; it's about combining biological and

clinical information to choose prevention, diagnosis, or treatment strategies that are more suited to a specific patient's characteristics (Subramanian et al., 2020; Castelli et al., 2022).

The aspect of population diversity is a theoretical part that cannot be separated from precision medicine. If genomic databases are dominated by certain populations, the accuracy of variant interpretation and the transferability of risk models can decrease for underrepresented populations. Therefore, genomic representation is both a matter of scientific validity and health equity. Recent literature emphasizes the need to expand ancestry diversity, build local research capacity, and establish data governance that allows genomic benefits to be more evenly distributed. For Indonesia, which has huge genetic, geographic, and ethnic diversity, the need for a local population database and genomic infrastructure is very important so that precision medicine does not rely solely on evidence from other populations (Fatumo et al., 2022; Ciabini et al., 2026).

Immunology as the Basis for Vaccines, Immunotherapy, and Understanding Diseases

The immune system is made up of networks of cells, lymphoid tissues, soluble mediators, and memory mechanisms that work to protect the body from pathogens while also maintaining tolerance to its own structures. The conceptual separation between innate immunity and adaptive immunity is still important, but modern research shows a close interaction between the two. Knowledge about antigen presentation, lymphocyte activation, antibodies, memory cells, interferons, cytokines, and immune regulatory mechanisms forms the foundation of vaccinology. The development of modern vaccines shows that antigen design, delivery platforms, adjuvants, and understanding the correlates of protection need to be combined to produce effective and long-lasting immunity (Pollard and Bijker, 2021; Chaudhary et al., 2021).

The same principle also forms the basis of cancer immunotherapy. Immune checkpoint inhibitors work by releasing the biological brakes that hold back T cell activation, while CAR-T therapy engineers T cells to recognize target antigens more specifically. The success of these approaches also highlights the complexity of cancer biology, because responses are influenced by tumor heterogeneity, the microenvironment, systemic immune status, antigen escape, and resistance mechanisms. For this reason, immunotherapy is an important example of how mechanistic knowledge in biomedical science is translated into therapy, but it still requires biomarkers and predictive models to identify patients most likely to benefit and to reduce toxicity (Bagchi et al., 2021; Larson and Maus, 2021; Morad et al., 2021).

Advanced Biological Models: Organoids, Organ-on-Chip, and Cell Atlas

Experimental models act as a bridge between molecular hypotheses and human applications. Two-dimensional cultures and animal models still play important roles, but both have limitations in replicating human heterogeneity, architecture, and responses. Organoids derived from stem cells or patient tissues can preserve some three-dimensional organization, cell types, and genetic traits of the original tissue. Because of this, organoids are used to study organ

development, infections, cancer, genetic disorders, and drug responses, including in patient-derived model approaches that bring research closer to precision medicine (Kim et al., 2020).

Organ-on-chip complements organoids by using microfluidic systems that allow human cells to experience flow, mechanical pressure, chemical gradients, and interactions between cell types that more closely resemble in vivo physiology. Conceptually, this technology shifts preclinical models from merely representing structure to reconstructing controlled physiological functions. The combination of organoids, organ-on-chip, single-cell analysis, and spatial profiling has the potential to create more human-like disease models, improve drug response predictions, and reduce some translational failures caused by differences between preclinical models and patients. Challenges still include standardization, reproducibility, cell maturity, vascularization, production scale, and validation criteria for regulatory use (Ingber, 2022; Kim et al., 2020; Longo et al., 2021).

Gene Editing, Gene Therapy, and mRNA PlatformsGene Editing, Gene Therapy, and mRNA Platforms

Genome editing is an example of a paradigm shift from therapies that only modulate symptoms or proteins to interventions that can actually change the genetic information causing disease. CRISPR-Cas allows specific DNA targets to be cut or modified using RNA guides. In theory, the success of the therapy depends on three components: target accuracy, delivery efficiency to relevant cells, and control of biological consequences including off-target effects and immune responses. Since gene changes can be permanent, safety standards and long-term monitoring are stricter compared to many conventional pharmacological interventions (Doudna, 2020). The development of prime editing expands this toolkit by allowing various substitutions, small insertions, and deletions without needing to break the double-stranded DNA at the specific target (Chen and Liu, 2023).

Clinical developments show two main strategies, namely ex vivo editing and in vivo editing. In ex vivo editing, cells are taken out from the patient, edited, tested, and then returned; this approach has been used for hemoglobinopathies. In in vivo editing, the editing components are delivered directly to the target tissue, as shown in transthyretin amyloidosis. This evidence supports the idea that the future of biomedicine will increasingly combine genetics, delivery materials, cell engineering, and molecular monitoring. However, the generalization of the technology is still limited by tissue accessibility, payload size, long-term safety, production costs, and ethical issues, especially when editing touches the germline (Frangoul et al., 2021; Gillmore et al., 2021; Doudna, 2020).

The mRNA platform adds another approach because the therapeutic information is delivered in the form of RNA molecules that are temporary and translated into proteins inside the cell. The success of mRNA vaccines heavily relies on lipid nanoparticles that protect the RNA, help it get into cells, and allow the cargo to be released into the cytoplasm. The platform concept means that the

basic technology components can be reused by changing the mRNA sequence according to the target antigen or protein. Besides infectious disease vaccines, the same principle is being developed for cancer vaccines, therapeutic proteins, and gene editing. The main challenges include targeted delivery, stability, cold-chain or storage, reactogenicity, manufacturing, and dose optimization (Chaudhary et al., 2021; Hou et al., 2021). The clinical success of RNA therapeutics also heavily depends on delivery systems that can carry RNA cargo to target cell types while limiting unwanted immune responses (Paunovska, Loughrey and Dahlman, 2022).

Molecular Diagnostics, Biomarkers, and Early Detection

Modern biomedical diagnosis is moving from identifying anatomical changes or symptoms to detecting molecular signals that appear before clinical signs. Biomarkers can be diagnostic, prognostic, predictive, pharmacodynamic, or used for monitoring. Conceptually, a good biomarker not only has a biological connection to the disease but also needs to meet analytical validity, clinical validity, and clinical utility. This distinction is important because many biomarker candidates show strong associations during the discovery phase but fail to provide benefits when applied to a more diverse population or in real-world healthcare settings (Castelli et al., 2022; Ignatiadis et al., 2021). Liquid biopsy reflects this shift by using circulating tumor DNA, circulating tumor cells, or other components in body fluids to get disease information in a minimally invasive way. In oncology, this approach can help identify targetable alterations, monitor residual disease, track clonal evolution, and therapy resistance. However, performance really depends on tumor fraction, disease stage, pre-analytic methods, assay sensitivity, and clinical context. That's why diagnostic technology should be evaluated not just based on sensitivity and specificity, but on whether the test results actually change clinical decisions and improve patient outcomes (Ignatiadis et al., 2021).

Bioinformatics, Artificial Intelligence, and Multimodal Biomedical Data

The explosion of genomic, transcriptomic, imaging data, electronic health records, wearable devices, and scientific literature has made bioinformatics and artificial intelligence an integral part of contemporary biomedicine. AI can help with classification, segmentation, prediction, representation learning, and multimodal integration, which are hard to do manually. In medical imaging and some diagnostic fields, algorithm performance can be very high on research datasets; however, comparisons with clinicians are often influenced by study design, dataset selection, reference standards, and inconsistent reporting. So, just because a model is mathematically capable doesn't automatically mean it has clinical benefits (Nagendran et al., 2020; Rajpurkar et al., 2022).

The development of foundation models and generalist medical AI is expanding the possibilities of integrating text, images, lab data, genomics, and clinical records into a single architecture. In theory, models like this could reduce the need for task-specific labeling and support cross-modality reasoning. However, the broader a model's scope, the greater the need to evaluate its reliability, calibration, interpretability, privacy, security, and how its

performance changes when applied to different hospitals or populations. The DECIDE-AI guidelines emphasize that AI system evaluation should include human factors and implementation context, not just computational metrics (Moor et al., 2023; Vasey et al., 2022). A multimodal perspective highlights that AI's clinical value increases when images, text, lab data, omics, and sensors can be analyzed together, even though privacy and data harmonization challenges remain significant (Acosta et al., 2022). Data bias is a particular challenge because models will learn the inequalities present in the dataset. If the training data mainly comes from certain countries, hospitals, devices, or demographic groups, the model might make uneven errors when applied to other groups. So, AI fairness is closely related to data representation, sampling design, outcome definition, infrastructure access, and post-deployment monitoring. This principle is similar to diversity issues in genomics: scientific quality and equity can't be separated because poor representation can lead to less valid inferences while also increasing health disparities (Celi et al., 2022; Fatumo et al., 2022).

Conceptual Framework of Biomedical Translation: From Mechanisms to Health Impact

Based on the literature, the development of biomedical science can be synthesized into a layered translational framework. The first layer is discovery, which involves identifying mechanisms, targets, and biological heterogeneity through experiments and omics. The second layer is measurement and modeling, which includes the development of biomarkers, assays, organoids, organ-on-chip systems, computational models, and prediction tools. The third layer is intervention, covering molecular drugs, biologics, cell and gene therapies, vaccines, and biomedical devices. The fourth layer is clinical validation, which involves proving safety, efficacy, diagnostic performance, and clinical utility. The fifth layer is implementation and population impact, meaning integration into clinical workflows, financing, regulation, surveillance, and evaluating benefits at the population level. This process is cyclical because clinical evidence and implementation generate new data that can refine the underlying hypotheses and biological models (Walker et al., 2022; Vasey et al., 2022)

The framework also highlights four cross-layer requirements: quality of evidence, reproducibility, data interoperability, and governance. Highly innovative technology can fail to translate if assays aren't standardized, cohorts aren't representative, models aren't reproducible, data isn't interoperable, or regulations don't match the level of innovation risk. Because of this, biomedical prospects should be analyzed through a balance between scientific possibility and translational readiness. This perspective helps avoid technological determinism, which is the assumption that more advanced technology will automatically lead to better health (Castelli et al., 2022; Ingber, 2022; Vasey et al., 2022).

Ethics, Governance, Fair Access, and Relevance for Indonesia

Contemporary biomedical ethics covers more than just informed consent in research. Genomics and AI raise questions about the secondary use of data, re-identification, family rights to genetic information, data ownership, benefit sharing, as well as discrimination based on risk prediction. Genome editing adds issues regarding irreversibility and the limits of acceptable intervention, while AI models introduce challenges in transparency and accountability when clinical decisions are influenced by computational systems. Therefore, responsible biomedical innovation requires governance that follows the technology's lifecycle, from the collection of samples or data to monitoring after implementation (Doudna, 2020; Celi et al., 2022; Vasey et al., 2022). Access fairness is also a measure of translation success. Precision medicine, gene therapy, advanced diagnostics, and high-performance computing can improve service quality, but costs, concentration of facilities in big cities, limited experts, and fragmented data can create two tiers of service. In Indonesia, the development of clinical genomics and various national initiatives open up big opportunities, but integrating into the healthcare system requires strengthening laboratories, bioinformatics, genetic counseling, standardization, funding, and population representation. The experience of SARS-CoV-2 genomic surveillance shows that sequencing capacity and data sharing have direct value for public health while also highlighting the importance of laboratory networks and quality metadata (Cahyani et al., 2022; Ciabini et al., 2026). Thus, this literature review places biomedical science within three interconnected dimensions. First, the mechanistic dimension explains diseases through molecular, cellular, genetic, immunological, and metabolic processes. Second, the technological dimension turns that knowledge into measurement tools, disease models, diagnostics, therapies, and predictive systems. Third, the translational and governance dimension determines whether innovations can be validated, applied, funded, regulated, and accessed fairly. This three-dimensional framework serves as the basis for the following discussion on the roles, prospects, and challenges of biomedical science for future health, as well as providing a conceptual foundation to answer the two research questions formulated in the Introduction section (Fatumo et al., 2022; Rajpurkar et al., 2022; Walker et al., 2022; Ciabini et al., 2026).

METHODOLOGY

Artikel ini menggunakan pendekatan Qualitative Literature Review (QLR) dengan sintesis naratif-integratif, bukan Systematic Literature Review (SLR). Pendekatan ini dipilih karena tujuan kajian bukan menghitung ukuran efek, melakukan meta-analisis, atau menginventarisasi seluruh bukti secara exhaustif, melainkan menafsirkan perkembangan ilmu biomedik, menghubungkan konsep dan teknologi yang berasal dari beragam subbidang, serta menyusun sintesis konseptual mengenai prospek dan tantangannya bagi kesehatan masa depan. Dalam review naratif, rigor dapat diperkuat melalui kejelasan rasional, batas kajian, logika pemilihan literatur, serta transparansi proses interpretasi; sementara review integratif menekankan analisis kritis dan sintesis untuk menghasilkan wawasan yang melampaui rangkuman deskriptif semata (Elsbach

and van Knippenberg, 2020; Sukhera, 2022). Literatur diidentifikasi secara purposif dan iteratif dengan fokus utama pada artikel jurnal peer-reviewed yang terbit pada periode 2020-2026. Penelusuran dilakukan terutama melalui PubMed dan Google Scholar, kemudian dilengkapi dengan penelusuran silang daftar referensi dan verifikasi melalui laman penerbit atau DOI. Kata dan kombinasi kata kunci mencakup biomedical science, translational medicine, genomics, multi-omics, precision medicine, CRISPR, gene therapy, mRNA, immunotherapy, organoid, organ-on-chip, molecular diagnostics, biomarkers, artificial intelligence in medicine, bioethics, health equity, serta padanan istilah yang relevan. Artikel diprioritaskan apabila secara langsung mendukung research questions, berasal dari jurnal bereputasi, memiliki keterlacakan bibliografis yang jelas, serta memberi perspektif ilmiah yang saling melengkapi. Karena kajian ini bukan SLR, tidak digunakan diagram PRISMA, registrasi protokol, sensus database yang exhaustif, penilaian risiko bias formal, maupun meta-analisis; pemilihan bukti dilakukan secara terarah untuk mendukung sintesis konseptual dan interpretatif (Lubbe, ten Ham-Baloyi and Smit, 2020; Sukhera, 2022). Analisis literatur dilakukan melalui pembacaan berulang, pengodean tematik, dan perbandingan naratif untuk mengidentifikasi konsep, mekanisme biologis, platform teknologi, aplikasi klinis, hambatan translasi, serta isu etika, tata kelola, dan keadilan akses. Temuan kemudian dikelompokkan ke dalam tema-tema yang konsisten dengan kerangka artikel, yaitu fondasi seluler-molekuler, genomik dan multi-omics, imunologi, model biologis lanjut, terapi gen dan mRNA, diagnostik dan biomarker, kecerdasan buatan serta data biomedik, dan dimensi translasi-governance. Sintesis lintas tema menilai pola kesamaan dan perbedaan, tingkat kematangan bukti, area konvergensi atau ketidakpastian, serta kesenjangan penelitian untuk membangun alur mekanisme -> pengukuran/pemodelan -> intervensi -> implementasi dan dampak kesehatan. Prosedur ini sejalan dengan prinsip review integratif dan state-of-the-art yang menekankan kategorisasi transparan, interpretasi, dan pengembangan agenda riset dari suatu badan pengetahuan yang berkembang cepat (Dwertmann and van Knippenberg, 2021; Barry, Merkebu and Varpio, 2022).

RESULTS AND DISCUSSION

The Application of Biomedical Science in Life

Biomedical science contributes to human health through the integration of biological mechanisms, diagnostic technology, molecular therapy, cell and gene engineering, and data analytics. This convergence allows for a more mechanistic understanding of diseases while supporting the translation of basic knowledge into more precise clinical interventions. With the development of genomics, multi-omics, biological modeling, and artificial intelligence, the scope of biomedicine is expanding from diagnosis and treatment toward risk prediction, prevention, and continuous health monitoring (Rajpurkar et al., 2022; Acosta et al., 2022; Walker et al., 2022).

Biomedical Technology in Disease Diagnosis

Biomedical technology is changing the way diseases are detected and characterized through a combination of imaging, molecular diagnostics, biomarkers, and AI-based analytics. MRI, CT scans, ultrasounds, and other imaging methods remain important for visualizing organ structures and functions, while AI helps extract complex patterns from images and clinical data. Recent literature shows that the potential of diagnostic AI is quite large, but its performance needs to be evaluated through external validation, transparent study designs, and prospective assessments before being widely used in clinical practice (Nagendran et al., 2020; Rajpurkar et al., 2022; Acosta et al., 2022). Molecular technologies like polymerase chain reaction (PCR) are a key foundation for detecting nucleic acids in infectious diseases and various genetic conditions. The development of point-of-care diagnostics expands on this principle through devices that combine microfluidics, biosensors, molecular amplification, and digital readouts so tests can be done closer to the patient. The COVID-19 pandemic experience has shown that the quality of point-of-care ecosystems isn't just about analytic sensitivity, but also ease of use, speed, interoperability, supply chains, and how well they can be implemented across different healthcare settings (Harpaldas et al., 2021; Qin et al., 2022).

Innovation in portable and wearable devices is expanding health monitoring beyond healthcare facilities. Sensors worn on the body can record vital signs, activity, and physiological parameters over time, while the integration of machine learning opens up opportunities to link continuous data with clinical changes. This technology has the potential to support early detection, remote patient monitoring, and service decentralization, but it still requires clinical validation, privacy protection, interoperability standards, and design that fits user needs (Dunn et al., 2021; Iqbal et al., 2021; Harpaldas et al., 2021).

Drug Development and Genetic Therapy

Drug development based on biomedical science is increasingly combining high-throughput screening, structural biology, multi-omics data, pharmacogenomics, and artificial intelligence. These approaches help prioritize drug targets and candidates, while pharmacogenetics and model-informed precision dosing allow patient characteristics to be used to optimize both therapy selection and dosage. In the field of genome editing, CRISPR and newer, more precise technologies expand the possibilities for direct intervention in the molecular causes of diseases, although safety, delivery, off-target effects, and clinical relevance remain major focuses of translation (Doudna, 2020; Mizuno et al., 2022; Chen and Liu, 2023; Bender et al., 2026).

Gene therapy and cell-based therapy have expanded options for diseases that were previously hard to treat. Clinical evidence in hemoglobinopathies and transthyretin amyloidosis shows that genome editing has moved from an experimental idea to therapeutic applications in humans, while engineering stem and progenitor cells opens the way for correcting single-gene disorders and tissue regeneration. That said, the clinical benefits need to be weighed alongside how long the effects last, the potential long-term side effects, manufacturing

capacity, and access to these expensive therapies (Frangoul et al., 2021; Gillmore et al., 2021; Ferrari, Thrasher and Aiuti, 2021; Kimbrel and Lanza, 2020).

The progress of mRNA platforms shows how biomedical science can speed up the design and production of vaccines based on genetic information. The success of mRNA vaccines against COVID-19 has been supported by advances in immunology, RNA engineering, nucleoside modifications, and lipid nanoparticles as delivery systems. The same platform is now becoming the foundation for research into other infectious disease vaccines and various therapeutic applications, but stability, tissue-specific delivery, reactogenicity, scalability, and cost still remain important aspects for future development (Chaudhary, Weissman and Whitehead, 2021; Hou et al., 2021; Paunovska, Loughrey and Dahlman, 2022).

The Role of Biomedics in Clinical Research

Clinical research is an important stage to determine the safety, effectiveness, generalizability, and real benefits of biomedical innovations. Using AI and decision-support systems can help with patient stratification, multimodal data processing, and study design, but these technologies require transparent protocols and reporting so that algorithm performance can be evaluated clinically. The SPIRIT-AI and DECIDE-AI guidelines emphasize the importance of documenting the usage context, human-AI interactions, data quality, and potential system failures during clinical evaluation (Cruz Rivera et al., 2020; Vasey et al., 2022).

The use of AI in drug discovery has evolved from virtual screening and predicting molecular properties to target modeling, candidate design, integrating biological data, and supporting decision-making. However, the success of computational models doesn't always translate to clinical impact; the translational value depends on data quality, problem formulation, experimental validation, and the technology's ability to enhance drug development decisions. Biobanks and population databases also enrich the analysis of gene-environment relationships, but population representation needs to be maintained so findings can be generalized fairly (Karczewski et al., 2020; Acosta et al., 2022; Bender et al., 2026).

Global collaboration is becoming increasingly important because developing vaccines, medicines, biomarkers, and diagnostic technologies requires sharing knowledge, data, samples, as well as manufacturing and evaluation capacities. The COVID-19 pandemic showed that rapid progress can be achieved when basic immunology knowledge, technology platforms, clinical trial networks, and adaptive regulations work together effectively. That experience also highlights the need to maintain safety standards, evidence transparency, and equitable access when innovation is developed at high speed (Pollard and Bijker, 2021; Chaudhary, Weissman and Whitehead, 2021).

The Use of Biomedicine in Rehabilitation and Prosthetics

The use of biomedical science in rehabilitation and prosthetics is developing through the integration of neurophysiology, sensors, robotics, smart materials, and human-machine interfaces. Modern bionic prosthetics aim not only to restore movement but also to bring back sensory information so that users can gain more natural control. Advances in neuroprosthetics show that function quality is greatly influenced by the system's ability to capture motor signals, provide sensory feedback, and adapt to the user's needs in daily life (Bensmaia, Tyler and Micera, 2023).

The role of biomedicine in rehabilitation also shows up in the development of robotic exoskeletons and orthoses to help with neuromotor exercises and daily activities. These devices combine mechanics, sensors, adaptive control, and sometimes brain-computer interfaces to predict the user's movement intentions. While they have the potential to boost exercise intensity and independence, their effectiveness depends on personalized support, safety, comfort, cost, and clinical evidence in the target population (Kirchner and Bütefür, 2022).

The Role of Biomedical Science in Health

Biomedical science plays an important role in advancing health because it expands our ability to identify biological changes before diseases develop into severe clinical manifestations. Molecular biomarkers, circulating tumor DNA, metabolomics, and synthetic biomarkers illustrate the shift from symptom-based diagnosis to earlier and more measurable detection of biological signals. Its implementation still requires assay standardization, clinical validation, proof of clinical utility, and integration into care workflows (Cescon et al., 2020; Ignatiadis, Sledge and Jeffrey, 2021; Kwong et al., 2021).

In therapy, biomedical science becomes the foundation for increasingly specific interventions targeting molecules, cells, and genes. Immunotherapy, CAR-T cells, gene therapy, stem cell engineering, and RNA platforms show that modern treatments can be designed based on disease mechanisms, not just symptoms or affected organs. These developments increase the chances of more targeted responses, but they also require monitoring toxicity, durability, manufacturing quality, and patient access (Bagchi, Yuan, and Engleman, 2021; Larson and Maus, 2021; Ferrari, Thrasher, and Aiuti, 2021; Kimbrel and Lanza, 2020).

The impact of biomedical science is also seen in public health through vaccinology, genomic surveillance, molecular diagnostics, and pathogen monitoring. The COVID-19 experience shows that sequencing capabilities and genome data sharing can help understand virus evolution, variant spread, and public health response needs. So, biomedical capacity strengthens not just individual care, but also outbreak preparedness and cross-border health threat readiness (Pollard and Bijker, 2021; Cahyani et al., 2022).

The Relationship Between Biomedical Science and Medical Science

Biomedical science and medical science are closely linked because discoveries about biological mechanisms gain clinical value when they can be translated into diagnostic tools, interventions, or healthcare decisions. Translational science frames this relationship as a two-way process: clinical needs shape basic research agendas, while lab findings require validation and implementation before they benefit patients. Models like organ-on-chip show how experimental human systems can strengthen the bridge between disease mechanisms and therapy development (Walker et al., 2022; Ingber, 2022). In clinical practice, medicine uses biomedical findings to tailor diagnoses and treatments to patients' biological characteristics. Examples include immunotherapy for cancer, gene therapy for monogenic diseases, as well as pharmacogenetics and model-informed precision dosing to reduce variations in drug responses. This kind of integration shows that precision medicine is the result of interactions between biological evidence, clinical data, analytical technology, and professional judgment, not just the use of genetic tests on their own (Bagchi, Yuan and Engleman, 2021; Mizuno et al., 2022; Ferrari, Thrasher and Aiuti, 2021). Collaboration between biomedical science and medicine is also evident in the development of imaging, wearable devices, robotics, genomic diagnostics, and decision support systems. These technologies expand clinicians' ability to monitor patients, interpret complex data, and carry out more precise interventions. However, their clinical value still depends on human factors, interoperability, validation, and integration into service workflows so that the technology supports, rather than uncritically replaces, professional judgment (Rajpurkar et al., 2022; Dunn et al., 2021; Iqbal et al., 2021).

Challenges and Opportunities in Biomedical Science

Even though biomedical science has made a lot of progress, the complexity and volume of biological data are major challenges. Advanced sequencing, imaging, electronic health records, wearables, and multi-omics data require increasingly powerful computing and analysis capabilities. AI and foundation models can help integrate multimodal information, but data quality, bias, explainability, generalizability, and security need to be managed systematically so that increased analytical capacity doesn’t lead to misleading decisions (Acosta et al., 2022; Celi et al., 2022; Moor et al., 2023). Ethical issues are a major concern in the development of biomedical science, especially in genome engineering, the use of genomic data, AI, and the use of secondary data. Questions about informed consent, privacy, re-identification, algorithmic bias, population representation, and benefit distribution are becoming increasingly relevant when biological datasets are used across institutions and purposes. Transparent and representative governance is needed so that innovation doesn't worsen existing health gaps (Celi et al., 2022; Fatumo et al., 2022). Biomedical science offers huge opportunities for more personalized treatment through the integration of genomics, proteomics, metabolomics, pharmacogenetics, and clinical data. This approach can help with patient stratification, therapy selection, dosing decisions, and monitoring responses more individually. However,

precision medicine will only provide broad benefits if biomarkers are validated, algorithms can be generalized, population data is diverse enough, and the technology is accessible beyond high-tech service centers (Castelli et al., 2022; Mizuno et al., 2022; Fatumo et al., 2022).

The Strategic Role of Biomedicine in the Future

The strategic role of biomedicine in the future lies in its ability to bridge basic discoveries with the transformation of healthcare services that are increasingly predictive, precise, preventive, and participatory. Developments in genomics, multi-omics, and single-cell mapping have expanded our understanding of human biological heterogeneity, so diseases are no longer seen as uniform entities, but rather as a spectrum of biological states that require more targeted interventions. In this context, biomedical science not only produces new knowledge but also lays the scientific foundation for designing biomarkers, risk prediction algorithms, and treatments tailored to a patient's biological profile (Subramanian et al., 2020; Longo et al., 2021; The Tabula Sapiens Consortium, 2022; Liao et al., 2023). The strategic role becomes even clearer when modern biomedical platforms—like organoids, organs-on-chips, artificial intelligence, and gene editing—are used to speed up translation from the lab to the clinic. Organoids and organs-on-chips allow for more realistic modeling of human diseases compared to conventional models, while CRISPR opens up possibilities for genetic corrections that were previously hard to imagine. On the other hand, mRNA platforms and biomedical computing accelerate the development of vaccines, therapies, and drug candidate screening more efficiently. In this way, the future of biomedicine will increasingly be defined by the ability to integrate biological experiments, computation, and clinical validation in a coherent translational ecosystem (Doudna, 2020; Frangoul et al., 2021; Gillmore et al., 2021; Chaudhary et al., 2021; Ingber, 2022; Rajpurkar et al., 2022). To clarify that flow of strategic value, Figure 1 summarizes the continuity of biomedical translation from basic discoveries to their impact on health systems and population health.

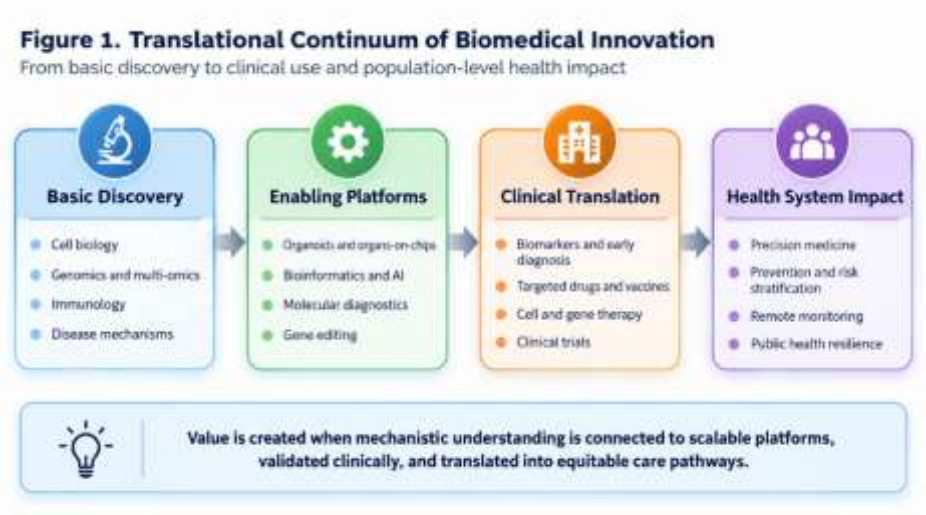


Figure 1. Translational Continuum of Biomedical Innovation.

Figure 1 shows that the benefits of biomedical science don't automatically come from basic knowledge, but rather through a gradual process that involves supporting platforms, clinical validation, and implementation mechanisms within the health system. This means that the success of biomedicine is greatly influenced by the capacity of translational science, the quality of research infrastructure, and the ability of health institutions to safely and effectively absorb innovations. This framework also emphasizes that the ultimate impact of biomedicine isn't just new technology, but improved diagnosis, therapy, prevention, and public health resilience (Walker et al., 2022; Rajpurkar et al., 2022; Moor et al., 2023).

The Future Outlook of Biomedicine

The future of biomedical science is closely tied to the convergence of various technology platforms that previously developed separately. Combining genomics, liquid biopsy, metabolomics, spatial transcriptomics, and AI-based computational models will enable earlier disease detection, more accurate patient stratification, and more targeted therapies. Advances in computational structural biology, including large-scale protein structure prediction, also speed up drug target identification and shorten the therapeutic innovation cycle. Therefore, the prospects of biomedicine are not just about expanding knowledge, but also about shifting the way healthcare systems produce evidence and make clinical decisions (Ignatiadis et al., 2021; Castelli et al., 2022; Longo et al., 2021; Jumper et al., 2021; Varadi et al., 2022; Marx, 2021). This convergence can be visualized through Figure 2, which shows how various biomedical platforms reinforce each other in shaping the future of healthcare.

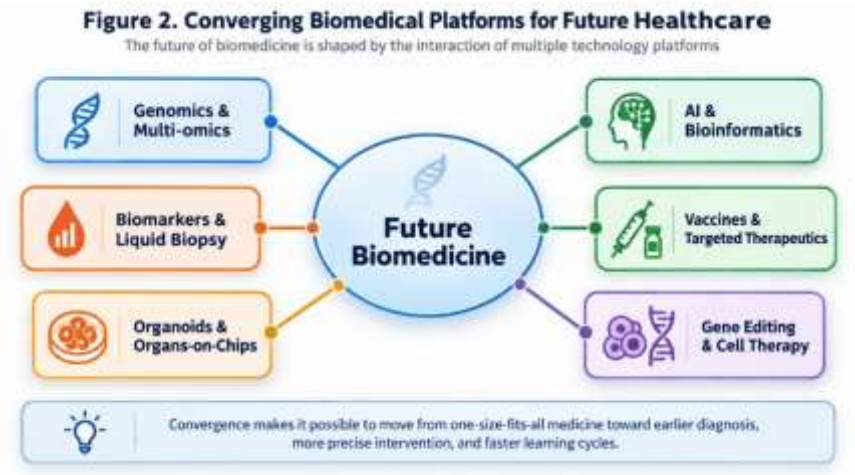


Figure 2. Converging Biomedical Platforms for Future Healthcare

As shown in Figure 2, there isn't a single technology that will dominate the entire biomedical landscape. Instead, the biggest value comes from the interaction between technologies, for example when genomic data is analyzed with AI and then validated through biomarkers, organoids, or cell therapy systems. This combination supports the formation of a learning health system that continuously learns from biological and clinical data. However, for this

potential to be realized, reporting standards, data interoperability, and strict clinical evaluation still need to be maintained so that innovation doesn't stop at just the proof-of-concept level (Nagendran et al., 2020; Rajpurkar et al., 2022; Vasey et al., 2022; Moor et al., 2023).

From a broader perspective, the prospects of biomedical science also depend on governance and fair access. Developing countries, including Indonesia, have a big opportunity to use biomedicine to strengthen genomic surveillance, precise diagnosis, and data-driven health policy development. However, these opportunities will only be fully realized if paired with strengthening multidisciplinary human resources, laboratories, data infrastructure, as well as adaptive ethical and regulatory mechanisms. Population representation is also important, because the benefits of precision medicine will be uneven if the data base isn't diverse enough or doesn't reflect the local context (Cahyani et al., 2022; Fatumo et al., 2022; Ciabini et al., 2026). To underline the balance between expectations and constraints, Figure 3 presents a summary of opportunities, obstacles, and policy priorities that need to be considered in the future development of biomedicine.



Figure 3. Opportunities, Barriers, and Policy Priorities in Future Biomedicine

Figure 3 emphasizes that the future of biomedicine must be built on two pillars that go hand in hand: scientific innovation and inclusive governance. Opportunities like early diagnosis, personalized therapy, faster drug discovery, and better outbreak preparedness will be hard to achieve if blocked by high costs, infrastructure gaps, data privacy issues, and unequal access. That's why policy focus shouldn't just be on research and technology alone, but also on funding, regulation, data literacy, and ensuring that the benefits of biomedicine reach different communities (Celi et al., 2022; Moor et al., 2023; Ciabini et al., 2026).

Synthesis and Analysis to Answer Research Questions

Based on the overall synthesis, the first research question about how biomedical science plays a role in human life and health can be answered clearly: biomedical science acts as a central engine connecting biological understanding with clinical interventions and health policies. Its role is evident in earlier disease detection, more accurate identification of pathological mechanisms, faster development of drugs and vaccines, and expanded possibilities for personalized

therapies. In other words, biomedical science contributes not only to treating diseases but also to prevention, risk prediction, and strengthening the resilience of health systems (Chaudhary et al., 2021; Doudna, 2020; Rajpurkar et al., 2022; Ingber, 2022). The second research question about the prospects and direction of biomedical science development can be answered through the finding that the future of biomedicine will increasingly be marked by the convergence of multi-omics, smart computing, advanced biological models, and more precise therapy technologies. This development leads to a more adaptive and individualized healthcare model, but its success depends on clinical validation, transparent reporting, and integration into real-world health practices. So, the future of biomedicine is not just about technological discoveries, but also about the ability to build a strong bridge between innovation, evaluation, and implementation (Longo et al., 2021; Moor et al., 2023; Vasey et al., 2022; Walker et al., 2022).

This analysis also shows that the most important challenges lie in three layers of issues. The first layer is scientific complexity and translation, which is about how to turn laboratory findings into innovations that are safe, effective, and scalable. The second layer is governance, covering ethics, regulation, data privacy, and mitigating algorithmic bias. The third layer is access equity, because without investment in infrastructure, human resource skills, and diverse data, biomedical advances could widen health gaps across regions and social groups. Therefore, the relevant strategy for future biomedical development is one that is scientific, collaborative, and inclusive all at once (Fatumo et al., 2022; Celi et al., 2022; Ciabini et al., 2026).

Overall, the results and discussion of this article emphasize that the importance of biomedical science is not just about its ability to produce new technologies, but also because it serves as a knowledge infrastructure for the future of health. When developed responsibly, biomedical science can be the backbone of health transformation towards more responsive, effective, and equitable services. On the other hand, if aspects of translation and governance are neglected, that potential will be hard to realize widely. This synthesis also highlights the urgency of sustained investment in biomedical research, interdisciplinary collaboration, and health innovation systems that can continuously learn (Rajpurkar et al., 2022; Moor et al., 2023; Walker et al., 2022).

CONCLUSIONS AND RECOMMENDATIONS

Biomedical science is a strategic foundation for the advancement of modern health science because it can connect the understanding of biological processes with diagnosis, therapy, prevention, and improving people's quality of life. From the discussion in this article, it’s clear that the role of biomedical science isn't limited to lab work but also extends to clinical practice, health policy, and strengthening the resilience of the health system. Its value lies in the ability to produce knowledge that can be turned into real benefits for patients and the community.

The synthesis results show that biomedical science has driven major changes in how diseases are understood and managed. Developments in genomics, multi-omics, organoids, AI, liquid biopsy, mRNA platforms, and gene

editing create opportunities for earlier diagnosis, more personalized therapies, and faster drug and vaccine discovery. In this way, biomedical science acts as a key enabler for shifting from a reactive health approach to a more predictive, precise, and preventive one.

Even though the prospects are huge, this article also points out that the future of biomedicine faces some serious challenges. High technology costs, the need for clinical validation, issues with data bias and interoperability, ethical complexities, and unequal access are major hurdles that can slow down or even distort the benefits of innovation. So, succeeding in biomedical development isn't just about having advanced technology, but also about good governance, institutional readiness, and the ability to collaborate across disciplines.

For Indonesia and other developing countries, the importance of biomedical science is becoming increasingly clear because it can serve as a tool to strengthen disease surveillance, precision diagnosis, research capacity development, and evidence-based health policies. However, realizing these benefits requires ongoing investment in laboratories, data, education, research ethics, and a translation ecosystem that can connect universities, hospitals, industry, and government. With such a foundation, biomedical science can contribute to a more self-reliant, innovative, and inclusive healthcare system

Looking ahead, research in biomedical science needs to be more focused on strengthening translational science, evaluating the real-world implementation of biomedical technologies, reducing bias and access gaps, and developing safe and fair data governance models. Further studies also need to explore how various biomedical platforms can be effectively integrated into local contexts, especially in resource-limited countries. With such a research agenda, biomedical science will not only grow as a field of science but also serve as a driver for sustainable and equitable health transformation.

FURTHER STUDY

This research still has limitations, so further studies on the topic Transforming Biomedicine for Future Health: Roles, Technological Convergence, Translational Prospects, and Governance Challenges are needed to improve this research and expand knowledge for both the writer and the readers.

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