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Review article

Perspective in the biomedical sciences field: Education and career

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Abstract

The biomedical sciences are a dynamic, multidisciplinary field that is pivotal to advancing human health through research, education, and innovation. This review explores the evolving landscape of biomedical education and its related career pathways, driven by technological advancements, interdisciplinary integration, and global health demands. A literature search was performed using the PubMed, Scopus, and Web of Science databases for articles published between 2009 and 2024. Search terms included “biomedical science education,” “biomedical laboratory scientist,” “BLS career,” “biomedical engineering,” and “biomedicine.” The inclusion criteria were peer-reviewed articles in English addressing biomedical education, career pathways, or workforce development. whereas the exclusion criteria included non-English publications, editorials, and conference abstracts without the full text being available. We examine the distinctions between biomedical science, biomedicine, and biomedical engineering, and present their historical origins and contemporary roles. The education and career trajectories of biomedical laboratory scientists (BLS) are analyzed, emphasizing the diverse competencies, core curricula, and the impact of regional policies on professional qualifications. Furthermore, emerging trends and ethical/regulatory challenges are discussed. The identified key trends include the emergence of artificial intelligence, nanotechnology, synthetic biology, and digital health, which are shaping research. BLS require core scientific competencies, as well as skills such as bioinformatics and entrepreneurship. In addition, there are differences in BLS qualifications and education worldwide, and collaboration between BLS and physicians is essential in clinical research. By synthesizing recent literature, this review identifies key opportunities and challenges in preparing BLS for impactful careers and offers recommendations to optimize education and workforce development in this rapidly changing field. Collaboration and responsible innovation are critical for promoting scientific discovery and improving global health.

Keywords: Biomedical laboratory scientists, biomedical science, biomedicine, career pathways, education.

The biomedical sciences are a vast and dynamic field that includes biology, medicine, engineering, data science, and numerous other disciplines.[1, 2] As our understanding of biological systems and disease mechanisms becomes increasingly sophisticated, biomedical scientists’ educational pathways and their career opportunities continue to rapidly evolve. The traditional career trajectory from undergraduate studies through doctoral training to academic positions has expanded into a complex network of educational options as well as professional pathways.[3, 4]

This transformation in biomedical education and careers has been driven by several key factors, including exponential advances in technology, emerging interdisciplinary fields, shifting funding landscapes,

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global health challenges, and evolving societal needs.[3,5] The Coronavirus Disease 2019 (COVID-19) pandemic further accelerated changes in educational delivery models and research priorities, which created challenges and opportunities for biomedical scientists.[6, 7]

In this rapidly changing ecosystem, stakeholders across education, research, healthcare, and industry face the difficulty of preparing and supporting biomedical scientists for a diverse range of evolving careers. This review aims to comprehensively analyze the contemporary landscapes of biomedical sciences education and careers, identifying key trends, along with their challenges, opportunities, and future directions.

This review addresses four principal areas, namely, understanding biomedical sciences; education and careers of biomedical laboratory scientists (BLS); diverse career pathways and workforce needs; and future directions and recommendations for optimizing biomedical education and career development. Through the synthesis of insights from recent literature, this review aims to contribute to the ongoing discourse on how best to prepare BLS for impactful careers in a complex field and changing world.

To provide a comprehensive understanding, this review first clarifies the conceptual distinctions among biomedical science, biomedicine, and biomedical engineering, which are often used interchangeably despite their distinct scopes. This foundational understanding is essential before the educational pathways and career trajectories of BLS can be examined, which is the focus of this review. Subsequently, this study explores the boundaries and directions of biomedical research, followed by an analysis of the current and emerging trends that are reshaping the field. This structured approach provides a clear roadmap for stakeholders seeking to optimize biomedical education and workforce development.

Differences between biomedical science, biomedicine, and biomedical engineering

The terms "biomedical science" and "biomedicine" are often used interchangeably; however, they emerged from distinct historical contexts. Biomedical science first appeared in 1920, with biomedicine following approximately a decade later.[1] The field gained considerable momentum during the Second World War, when biologists, physicians, and industry were compelled to collaborate for the production of penicillin. This effort formalized the term "biomedical science" to describe the work of scientists operating at the intersection of biology and medicine.[8]

As defined by the American Medical Dictionary, biomedical science includes clinical medicine as it relates to physiology and biochemistry, and it is a laboratory-based discipline rather than a clinical healing practice.[3, 9] Furthermore, it studies the structure and function of the human body, pathology, diagnostic methods, and treatment.[9] This field is defined by three core characteristics: 1) disease and its causes are understood through biology, chemistry, and physics; 2) it emphasizes laboratory-based research and technology within the health domain; and 3) it adheres to rigorous philosophical and methodological principles.[4]

Biomedical science encompasses three main subfields, namely biological science, physiological science, and biotechnology.[10] Its advancement accelerated with the discovery of molecular biology in the 1960s, which shaped it as a laboratory science.[3] Today, mathematics and informatics serve as essential foundations for modern biomedical research, thereby reflecting the increasingly complex and interdisciplinary nature of the field.[9, 11]

Biomedical engineering, by contrast, applies engineering principles and design concepts to improve human health. It combines engineering with the biological and medical sciences, with a specific focus on developing new knowledge about living systems through engineering-based experimental and analytical techniques, as well as on creating new devices, algorithms, processes, and systems that advance clinical practice.[2] For example, the use of infrared lasers for reducing oxidative stress and inflammation represents a practical application within the biomedical engineering scope.[12]

Education and career of BLS

After completing their university education, biomedical researchers often work in clinical and biomedical research laboratories, as well as in biotech and pharmaceutical companies. Researchers who work in the biomedical field are referred to as BLSs, and BLS qualifications vary by country. In some countries, a laboratory staff member has a (bio)medical laboratory degree; however, in others, medical laboratories are only staffed by medical specialists. Furthermore, the degree requirements are more or less stringent depending on the country's legislation.[13]

Policy factors influence the differences in qualifications across countries. In addition, the career development of a BLS is influenced by professional bodies, employment needs, legal regulations, and basic education.[14]

The direction of a BLS's basic education depends on the core curriculum established by the institution where they study. The core curriculum is essential for students to achieve the expected competencies. These competencies are used as supporting requirements for professional work. The curriculum developed by an educational institution characterizes its biomedical research direction. Moreover, some biomedical higher education institutions are part of the faculty of medicine, while others are not. This difference makes biomedical research characteristics vary across institutions and even occurs in developed countries such as the USA.[18] Furthermore, these differences reflect the institution's decisions regarding research direction and the characteristics of its biomedical programs. The International Federation of Biomedical Laboratory Science (IFBLS) has released a core curriculum that can be used as a benchmark for basic biomedical education at educational institutions, which is summarized in **Table 1.**

In general, there are several careers for BLSs in the workforce, including 1) careers in pure research; 2) careers in a laboratory to understand biological functions and diseases; 3) careers in the medical field to diagnose diseases and treatment methods; 4) careers in a hospital to perform tests and assist physicians; and 5) careers in education and public health. However, it should be noted that the career of a BLS depends on a country's policies.[15] In America, BLSs have a broader scope, whereas in the UK, a BLS only works in specialized research in human health (i.e., a medical scientist).

The future career of a BLS has enormous potential and an increasingly broad domain. In addition, since the COVID-19 pandemic began in 2020, health research, especially related to COVID-19, has rapidly increased by 6.5 times. [6] Moreover, educational development, especially in the biomedical field, has increased the number of biomedical graduates. This trend will increase the competitiveness of biomedical graduates in the job market. Therefore, qualified skills are needed by a BLS to compete in a tight job market.

Mason JL, *et al*.[15, 16] summarized 15 additional skills that a BLS most needs from job advertisements, namely, Microsoft PowerPoint, building effective relationships, Microsoft Office, quality assurance and

Table 1. Core curriculum developed by the International Federation of Biomedical Laboratory Science (IFBLS).[16, 17]

Science topics (~75 ECTS)	**Specific topics** (~90 ECTS)	**Other topics** (~15 ECTS)	**Practical training**
Chemistry	Molecular Biology	Research Methodology	Hospital Laboratories
Physics	Hematology Genetic/ Medical Genetics	Epidemiology	Laboratories at a university/university college
Mathematics	Immunology	Bio Safety	Industry
Statistics	Immunohaematology/ Transfusion Medicine	Quality Control/ Assurance	Primary healthcare units
Biochemistry/Biomedical Science	Histology/ Embryology	Ethics	
Anatomy and Physiology	General Pathology and Pathophysiology	Human and Social Science	
	General microbiology/ Clinical Microbiology	Health Information Systems	
	Virology	Economy and Management	
	Parasitology	Public Health	
	Pharmacology/Toxicology		
	Forensic		
	Haematology		
	Clinical Biochemistry		
	Clinical Pathology		
	Clinical Cytology		
	Analytical Methods (e.g., Immunohistochemistry)		

control, presentation skills, troubleshooting, project management, Microsoft Excel, detail orientation, planning, problem-solving, organization skills, writing, communication skills, and research. In addition to these skills, a BLS must also have core skills, such as bioinformatics, statistics, omics, nanotechnology, regenerative biology, economics, social and behavioral sciences, and communication. Moreover, laboratory-based skills are essential because laboratory research results from 70.0% of human disease diagnoses.

Currently, the demand for BLSs is lower than the supply of workers. This trend makes it challenging for BLSs to find employment.[17] Entrepreneurship is an alternative career field for BLSs. Entrepreneurship and biomedical skills can effectively collaborate by leveraging technology to improve human health. This provides an open niche for a BLS supported by the latest technology to utilize in business.

Special skills are required for a BLS who wants to enter the entrepreneurial world; these skills will help BLSs translate biomedical capabilities to produce health products and services that are attractive and needed by society. Entrepreneurial skills are divided into those related to entrepreneurship, leadership, and management. All three must be built together to develop a BLS's potential to become an entrepreneur in the biomedical field.[18]

Directions and boundaries in biomedical science

Since its inception, biomedical science has been a field of laboratory-based research rather than a clinical setting.[1, 20] Biomedical research addresses medical problems using technical molecular biology methods and human or pathological cells. Biomedical science is a multidisciplinary field that includes laboratory research on human biology and health. Although it may not be as well-known as other medical fields, almost everything related to the treatment and care of patients is a product of biomedical research.

Based on the purpose of the research, medical research is categorized into three categories, namely basic medical research, clinical research, and epidemiological research.[20, 21] Basic medical research is related to proving fundamental theories through experiments, such as animal experiments, cell studies, and biochemical, genetic, and physiological investigations, as well as studies on the properties of drugs and materials. Clinical research involves the development of basic theories their application in human trials, such as assessing the effects of pharmacology, surgical procedures, physical therapy, or psychotherapy. Epidemiologic research examines the distribution and history of a disease and its causes within a community. Biomedical research is basic medical research. This is related to the primary purpose of biomedical research, which is to provide an understanding of the mechanisms underlying normal human development and function, thereby providing insight into the pathological and pathophysiological mechanisms that cause human disease.

Furthermore, basic medical research comprises two domains, namely basic and preclinical research. Basic research examines general and fundamental problems via laboratory experiments, such as analytical calculations, physiological and biochemical investigations, process descriptions, and the effects of different methods. Furthermore, preclinical research, such as animal experiments, genetic engineering, and cell biology, builds on basic research and can be applied in real-world settings. Clinical research requires humans as its subjects and can be divided into interventional and noninterventional methods. Noninterventional research is observational, while interventional research is experimental. In addition, epidemiological research can be divided into experimental and observational domains **(Figure 1)**.[21]

Research involving human subjects requires strict rules, more stringent procedures, and careful consideration, and thus necessitates the assistance of a physician to carry it out. A BLS can conduct clinical research but requires the assistance of a physician to perform research involving human subjects, such as collecting blood samples or performing interventions on the human body. A BLS and a doctor have different levels of expertise.

A BLS focuses on laboratory analysis, experimental design, and understanding diseases at the molecular level, rather than providing direct patient care or clinical intervention. In contrast, physicians are trained to treat patients, collect clinical samples, or directly observe and manage patient conditions.[23] Therefore, collaboration between BLSs and physicians is essential in clinical research.

In epidemiological research, the BLS does not require collaboration with a physician, provided the research does not involve human research subjects. Epidemiological research examines the distribution and history of disease, how it changes, and its causes within a community. Epidemiology encompasses

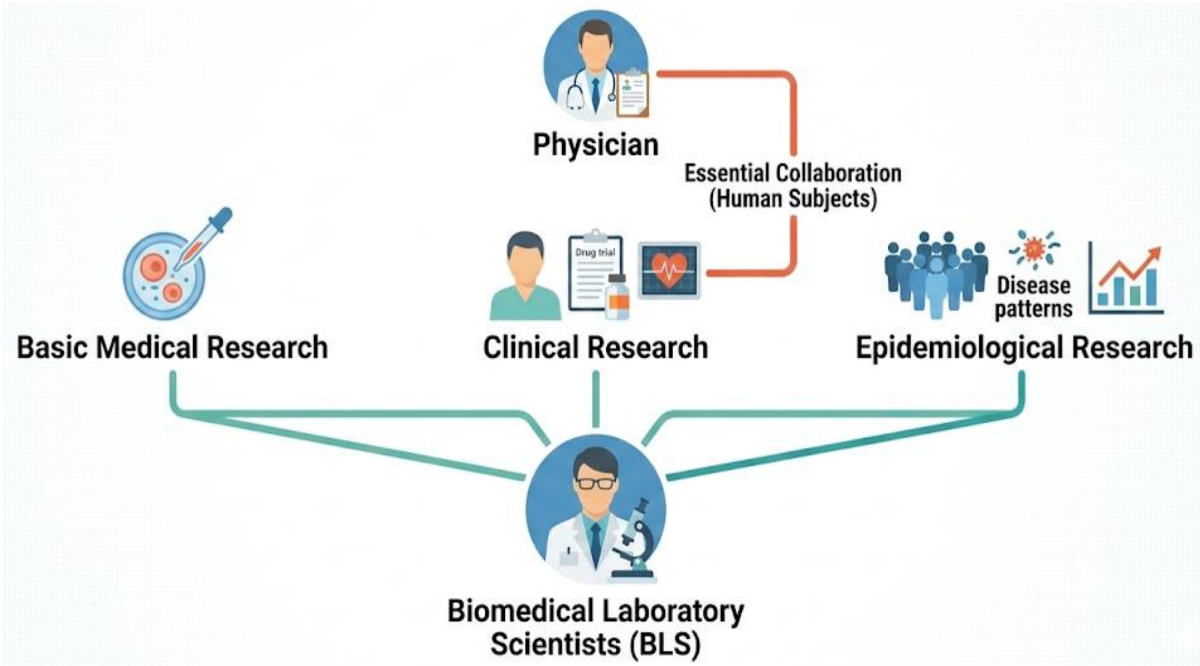

Figure 1. Classification of medical research and the role of BLS in medical research. BLS, biomedical laboratory scientists.

biology, clinical medicine, social science, and ecology. Furthermore, epidemiological research can be conducted by researchers in the fields of biology or public health. This is because of the broad scope of biology within epidemiology, which includes genetics, ecology, microbiology, and related sciences.

Communication and collaboration between basic medical research and clinical research are necessary. However, the boundaries of basic medical and clinical research sometimes require clarification, which may even occur in some educational institutions. There are academic institutions whose biomedical curriculum includes clinical research outcomes and educational institutions whose biomedical curriculum includes basic medical research outcomes. Usually, biomedical educational institutions with a more clinical-based curriculum are academic institutions with hospitals or medical faculties, and vice versa. In addition, factors related to research funding affect the institution's curriculum when choosing its biomedical domain. Clinical-based research requires expensive equipment and considerable funding.[(24)]

Current and future developments in biomedical research

Biomedical research, propelled by innovative technologies and a deeper understanding of biological systems, is at a pivotal juncture. This section explores the latest trends shaping the field and anticipated future directions that promise to revolutionize healthcare and scientific discovery. As the scope of biomedical research expands, BLS professionals are increasingly required to engage with emerging technological disciplines. The integration of computational tools, nanotechnology, synthetic biology, and digital platforms is transforming what is possible in research and reshaping the competencies required of biomedical scientists. The following subsections examine how each domain intersects with biomedical research and the evolving role of BLS in these contexts.

Artificial intelligence (AI) and computational biology

AI and computational biology are transforming biomedical research by enabling the analysis of complex datasets with exceptional speed and accuracy. AI-driven tools are now integral to drug discovery, where they can predict molecular interactions and identify novel therapeutic targets. For instance, AI models have accelerated the identification of potential treatments for diseases such as Alzheimer's by simulating protein folding.[(25)]

In diagnostics, AI-powered image analysis enhances the detection of conditions such as diabetic retinopathy and lung cancer, often surpassing human accuracy during early-stage identification. Furthermore, computational biology complements these efforts by modeling biological processes at the cellular level, thereby offering insights into disease mechanisms and potential interventions.[26]

Nanotechnology for precision medicine

Nanotechnology is redefining precision medicine through innovations in drug delivery and diagnostics. Nanoparticles can be engineered to target specific tissues and deliver drugs with minimal off-target effects. Recent studies have demonstrated the efficacy of lipid-based nanoparticles for delivering mRNA vaccines, a breakthrough that is exemplified by the development of COVID-19 vaccines.[27]

In diagnostics, nanosensors enable the real-time monitoring of biomarkers, thereby facilitating the early detection of diseases such as cancer and cardiovascular disorders. These sensors, embedded in wearable devices or implantable systems, provide a continuous stream of data that informs clinical decisions.[28] Integrating nanotechnology with other fields, such as bioinformatics, will enhance its impact further.

Synthetic biology and gene editing

Synthetic biology and gene editing technologies, particularly CRISPR/Cas9, are opening new frontiers in biomedical research. These tools enable the precise modification of genetic sequences, which offer potential cures for genetic disorders such as sickle cell anemia and cystic fibrosis. Recent trials have demonstrated promising results in using CRISPR to correct mutations in vivo, thus marking a substantial step toward clinical applications.

Synthetic biology extends beyond gene editing, as it also enables the design of synthetic organisms for therapeutic purposes. For example, engineered bacteria are being developed to deliver drugs directly to tumor sites, which enhances treatment efficacy while reducing systemic toxicity. These advancements highlight the potential of synthetic biology to address previously complex medical challenges.

Digital health and big data analytics

The rise of digital health technologies, including telemedicine and wearable health-monitoring devices, generates vast datasets that are reshaping biomedical research. These technologies facilitate longitudinal studies by providing real-time data on patient health metrics, such as their heart rate and glucose levels. Big data analytics, powered by machine learning, can identify patterns in these datasets, thereby informing population health strategies and personalized treatment plans.[29]

Integrating digital health with electronic health records also streamlines clinical research, enabling researchers to easily access comprehensive patient histories. This convergence fosters a data-driven approach to healthcare, with implications for research and clinical practice.[30]

Ethical and regulatory challenges

As biomedical research advances, ethical and regulatory challenges develop that must be carefully navigated. AI raises concerns about algorithmic bias and data privacy, which necessitate robust frameworks to ensure equitable and secure applications. Similarly, gene editing technologies pose ethical dilemmas regarding germline modifications and their long-term impact on society.[31]

Regulatory bodies are adapting to these challenges by establishing guidelines for emerging technologies. For example, frameworks for approving AI-based diagnostics and gene therapies are being refined to balance innovation with patient safety. Addressing these challenges is critical to maintaining public trust and maximizing the benefits of biomedical advancements **(Figure 2)**.

Conclusion

Biomedical sciences are undergoing a transformative era, which is propelled by technological breakthroughs and a deeper understanding of biological systems. This review highlights the multifaceted nature of biomedical education and career pathways, emphasizing the need for adaptable curricula and diverse skill sets to meet the evolving workforce demands. Integrating AI, nanotechnology, synthetic biology, and digital health is revolutionizing research and healthcare, offering valuable opportunities for innovation. However, these advancements come with ethical and regulatory challenges that require careful navigation to ensure their application in their equitable and safe application. For biomedical laboratory scientists, acquiring core scientific competencies and supplementary skills, such as bioinformatics and entrepreneurship, is essential to thriving in the competitive job market. Furthermore, educational institutions, policymakers, and industry stakeholders must collaborate to align training

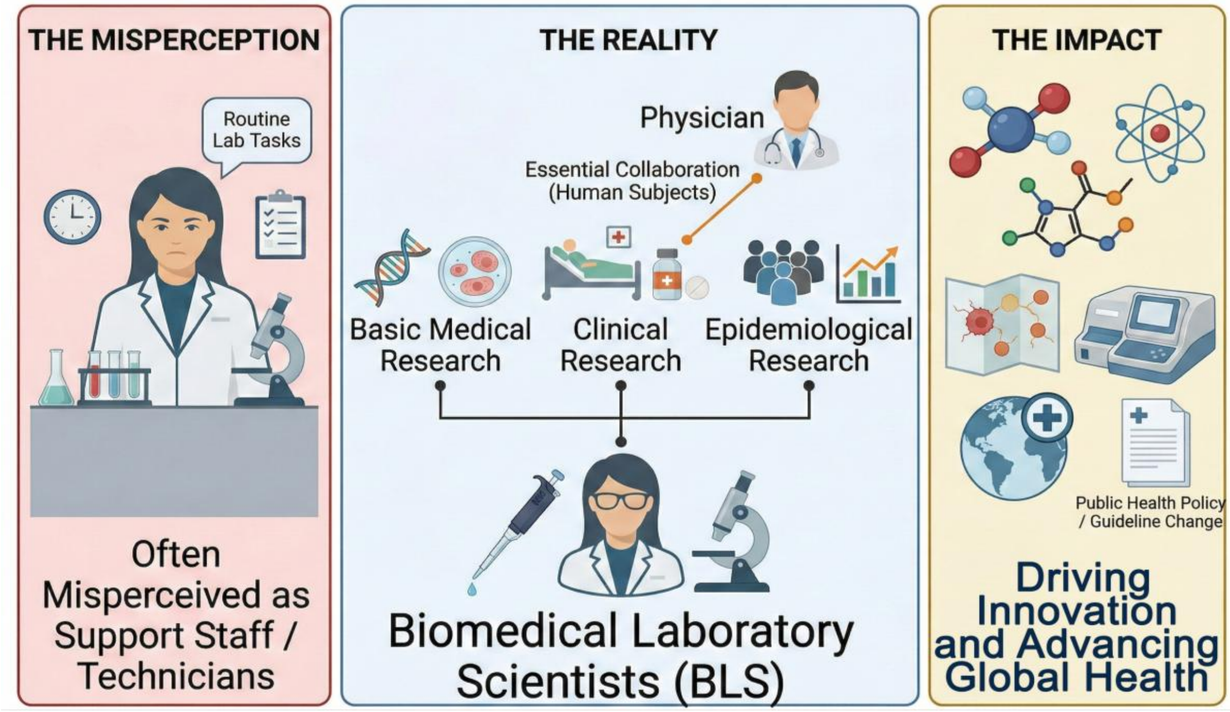

Figure 2. BLS as professional medical researchers. The figure illustrates the misperception (i.e., BLS seen as support staff/ technicians), the reality (i.e., BLS conducting basic medical research, clinical research, and epidemiological research, with essential physician collaboration for human subjects), and the impact (i.e., driving innovation and advancing global health). BLS, biomedical laboratory scientists.

programs with emerging trends and societal needs. By fostering interdisciplinary collaboration and embracing responsible innovation, biomedical sciences can continue to drive scientific discovery and improve global health outcomes in the decades ahead.

Author contributions

FAP contributed substantially to the concept and design of this study; reviewed the literature, its analysis, and interpretation; drafted the manuscript; and edited it critically for important intellectual content. MOSKS contributed substantially to data acquisition and literature review. IR substantially contributed to data acquisition and to drafting the manuscript. PFA contributed substantially to data acquisition and to drafting the manuscript. HW contributed substantially to data acquisition and to drafting the manuscript. DW edited the manuscript critically for important intellectual content and contributed to data analysis and interpretation. AB critically edited the manuscript for important intellectual content and contributed to the study's concept and design. All authors approved the final version of the article submitted for publication and take responsibility for statements made in the published article.

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Conflict of interest statement

All authors have completed and submitted the International Committee of Medical Journal Editors Uniform Disclosure Form for Potential Conflicts of Interest. All authors declare that they have no conflicts of interest.

Data sharing statement

The present review is based on the references cited. All data generated or analyzed during the present study are included in this published article and the citations herein. Further details, opinions, and interpretation are available from the corresponding author on reasonable request.

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References

1. Scheffler RW, Strasser BJ. Biomedical sciences, history and sociology of. In: Wright JD, editor. International encyclopedia of the social & behavioral sciences. 2nd ed. Amsterdam: Elsevier; 2015. p. 663–9
2. Weerarathna IN, Kumar P, Luharia A, Mishra G. Engineering with biomedical sciences changing the horizon of healthcare: a review. Bioengineered 2024;15:2401269.
3. Fuhrmann CN. Enhancing graduate and postdoctoral education to create a sustainable biomedical workforce. Hum Gene Ther 2016;27:871–9.
4. Gunn JS, Ledford CH, Mousetes SJ, Grever MR. Biomedical science undergraduate major: a new pathway to advance research and the health professions. Teach Learn Med 2018;30:184–92.
5. Sohrabi C, Mathew G, Franchi T, Kerwan A, Griffin M, Del Mundo JSD, Ali SA, Agha M, Agha R. Impact of the coronavirus (COVID-19) pandemic on scientific research and implications for clinical academic training - A review. Int J Surg 2021;86:57–63.
6. Raynaud M, Goutaudier V, Louis K, Al-Awadhi S, Dubourg Q, Truchot A, et al. Impact of the COVID-19 pandemic on publication dynamics and non-COVID-19 research production. BMC Med Res Methodol 2021;21:255.
7. Ibrahim K, Ahmad-Annuar A. COVID-19 pandemic: Lessons learned for undergraduate research training. Biochem Mol Biol Educ 2022;50:476–8.
8. Lowy I. Historiography of Biomedicine: “Bio,” “Medicine,” and In Between. Isis 2011;102:116–22.
9. Keating P, Cambrosio A. Biomedical Platforms: Realigning the Normal and the Pathological in Late-Twentieth-Century Medicine. Cambridge, MA: MIT Press; 2003.
10. Hales AP. Biomedicine relies heavily on biological macro-molecules. EJBI 2021;17:76–7.
11. Froshauer S. Careers at biotech start-ups and in entrepreneurship. Cold Spring Harb Perspect Biol 2017;9:a032938.
12. Ribeiro IM, de Souza Barroso ME, Kampke EH, Braga LTF, Campagnaro BP, Meyrelles SDS. Infrared laser therapy decreases systemic oxidative stress and inflammation in hypercholesterolemic mice with periodontitis. Lipids Health Dis 2023;22:171.
13. Stollenwerk MM, Gustafsson A, Edgren G, Gudmundsson P, Lindqvist M, Eriksson T. Core competencies for a biomedical laboratory scientist - a Delphi study. BMC Med Educ 2022;22:476.
14. Plebani M, Laposata M, Lippi G. A manifesto for the future of laboratory medicine professionals. Clin Chim Acta 2019;489:49–52.
15. Mason JL, Johnston E, Berndt S, Segal K, Lei M, Wiest JS. Labor and skills gap analysis of the biomedical research workforce. FASEB J 2016;30:2673–83.
16. IFBLS. Guidelines regarding Core Competence and Core Curriculum. International Federation of Biomedical Laboratory Science (IFBLS); Adopted 2012, Updated 2016.
17. Meyers FJ, Pomeroy C. Creating the future biomedical research workforce. Sci Transl Med 2011;3:102fs5.
18. Zimmerman AM. Navigating the path to a biomedical science career. PLoS One 2018;13:e0203783.
19. Sousa MJ. Entrepreneurship skills development in higher education courses for teams leaders. Adm Sci 2018;8:18.
20. Bustin SA, Jellinger KA. Advances in molecular medicine: unravelling disease complexity and pioneering precision healthcare. Int J Mol Sci 2023; 24:14168.
21. Rohrig B, Du Prel JB, Wachtlin D, Blettner M. Types of study in medical research: part 3 of a series on evaluation of scientific publications. Dtsch Arztebl Int 2009;106:262–8.
22. Fontanarosa PB, DeAngelis CD. Basic science and translational research in JAMA. JAMA 2002;287:1728.
23. Bonetta L. Biomedical science: putting research into practice. Nature 2010;467:995–6.
24. Flier JS. The diversity of institutions conducting biomedical research. Perspect Biol Med 2023;66: 58–88.
25. Topol EJ. High-performance medicine: the convergence of human and artificial intelligence. Nat Med. 2019;25:44–56.
26. Wu Z, Guo M, Jin X, Chen J, Liu B. CFAGO: cross-fusion of network and attributes based on attention mechanism for protein function prediction. Bioinformatics 2023;39:btad123.
27. Hald Albertsen C, Kulkarni JA, Witzigmann D, Lind M, Petersson K, Simonsen JB. The role of lipid components in lipid nanoparticles for vaccines and gene therapy. Adv Drug Deliv Rev 2022;188:114416.
28. Lin J, Ma K, Chen H, Chen Z, Xing B. Influence of different types of nanomaterials on soil enzyme activity: A global meta-analysis. Nano Today 2022; 42:101345.
29. Claggett J, Petter S, Joshi A, Ponzio T, Kirkendall E. An infrastructure framework for remote patient monitoring interventions and research. J Med Internet Res 2024;26:e51234.
30. Honeyford K, Expert P, Mendelsohn EE, et al. Challenges and recommendations for high quality research using electronic health records. Front Digit Health 2022;4:940330.
31. Mulvihill JJ, Capps B, Joly Y, Lysaght T, Zwart HA, Chadwick R. Ethical issues of CRISPR technology and gene editing through the lens of solidarity. Br Med Bull 2017;122:17–29.