ESJ Natural/Life/Medical Sciences Peer-reviewed

Impact of Metaverse Technologies Integration on Biotechnological Innovation: A Literature Review

Amra Abazi Feta
Hiqmet Kamberaj
International Balkan University, Faculty of Engineering,
Department of Computer Engineering, Skopje, R.N. Macedonia

Doi:10.19044/esj.2025.v21n21p1

Submitted: 09 May 2025
Accepted: 25 July 2025
Published: 31 July 2025

Cite As:
Feta, A.A. & Kamberaj, H. (2025). *Impact of Metaverse Technologies Integration on Biotechnological Innovation: A Literature Review.* European Scientific Journal, ESJ, 21 (21), 1. https://doi.org/10.19044/esj.2025.v21n21p1

Abstract

The convergence of metaverse technologies (such as virtual reality, augmented reality, artificial intelligence, and digital twins) into biotechnology is ushering in a new age for the creation of pharmaceuticals, medical science research, and teaching. The interactive and immersive environments enable collaboration without geographical limitations through virtual labs, improve the articulation of complex biological processes, and accelerate experiments using enhanced models powered by artificial intelligence. High-visibility use cases comprise virtual clinical trials founded on digital twin models that simulate individual patient profiles. The application of AI in drug discovery medicine, with its expedited time-to-market and 3D learning environments, enhances the knowledge and procedural precision of biotech professionals. This systematic review focuses on the transformative role of the metaverse in biotechnology, analysing its capacity to enable global collaboration, advanced simulations, and immersive education. By synthesising peer-reviewed literature (2019-2025), we highlight key advancements, such as AI-driven drug discovery and virtual laboratories, while addressing critical challenges, including data privacy, ethical concerns, and computational requirements. In this review, we aim to highlight the metaverse's potential to transform biotechnological research and emphasise the need for interdisciplinary solutions to harness its benefits. This study employs a qualitative methodological approach, comprising an extensive literature review coupled with a case study analysis, to reflect on the participation of metaverse technologies within the biotechnology sector. Drawing on an analysis of trends in cloud collaboration, digital simulation, immersive learning, and ethical issues, the research provides a critical analysis of the challenges and problems posed by the digital revolution. Key areas discussed in immense detail include data privacy, algorithm bias, computational infrastructure, and regulatory uncertainty. Our findings emphasise the need for interdisciplinary research and the provision of comprehensive ethical and technical guidelines to enable the secure and equitable use of metaverse technologies in biotechnology. This study will primarily contribute to the growing corpus of scholarly literature by providing a concise and logical synthesis of existing knowledge, identifying key areas for future research and development.

Keywords: Metaverse, Biotechnological Innovation, Virtual Collaboration, Immersive Environments, Digital Twins, Simulation, Data Security

Introduction

The metaverse is a virtual networking space that incorporates various technologies, like Virtual Reality (VR), Augmented Reality (AR), Blockchain, and Artificial Intelligence (AI). It presents a transformative potential for biotechnological developments (Mystakidis, 2022; Lee, 2021). The review synthesises the current research to explore how metaverse technologies drive innovation in biotechnology, from virtual labs to AI-powered clinical trials. The capabilities of this emerging digital ecosystem enable a new era of virtual interaction, overcoming traditional research obstacles. The metaverse adopts an environment that enables academic researchers, scientists, and industrial professionals to optimise their time, facilitating efficient collaborative work and advanced research, achieving the desired speed and effectiveness.

With continuous advancement in the network infrastructure and computational power, the evolution of the metaverse is growing rapidly and becoming a robust platform that supports real-time developments, immersive experiences across medicine, scientific research, and educational training (Shen, 2025; Uddin, 2024).

Biotechnology is an advanced discipline that encompasses complex biological processes, such as genetic modification, computational analysis, and drug discovery. They require high-level interdisciplinary collaborative work, the use of advanced simulation techniques, and big data analysis to support high-probability decision-making (Bordukova, 2023; Mercado, 2023).

In conventional settings, research is often hindered by natural restraints, partly due to limited access to the laboratory's equipment and the high costs of the experiments. In contrast, in the metaverse, the transformative

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

solution through virtual labs enables scientists to engage in virtual experimentation (Mercado, 2023).

The latest research suggests that the integration of virtual reality into biotechnological advancements has paved the way for discoveries. Innovation includes AI-based drug discovery, virtual clinical trials, and cross-border global collaboration. By studying virtual clinical trials, we create patient representations, called *digital twins*. Virtual constructs that enable the testing of molecular drugs in their preliminary stages prior to traditional clinical trials are made possible through digital twins (Venkatesh, 2022).

Digital twins are utilised for various purposes, such as testing, simulation, and adapting models from the physical to the virtual world, allowing failures to be predicted. In contrast to traditional clinical trials, digital twins facilitate the initial stages of virtual constructs testing for molecular drugs in medicine. Simulation, based on Artificial Intelligence, enables research on real-time virtual models. Additionally, the metaverse gives the possibility for researchers to connect without any geographical constraints (Venkatesh, 2022).

The potential of the metaverse in biotechnology also raises several challenges. Securing data in the metaverse remains the main critical issue. Data (such as genetic and medical information) about patients must be protected from misuse, vulnerabilities and cyber threats. Another challenge of the metaverse includes the demand for computational resources, such as cloud storage, powerful Graphical Processing Units (GPUs), and high-speed internet connections, which may not be available to all researchers worldwide (Mosharraf, 2025).

Policies surrounding ethics will be significantly important for scientific accuracy when dealing with virtual constructions and simulations. The privacy of participants, informed consent in virtual trials, and the right to equitable access to resources within the metaverse require attention to avoid discrimination and inequality gaps in biotechnological advancements (Mosharraf, 2025; Kaddoura, 2023).

The integration of the metaverse into biotechnology is a specific problem, which, however, has already captured the interest of numerous businesses and academic research institutions willing to invest in focused research and development. In practice, the merging of different technologies is not limited to research and development; it also revolutionises teaching and training in the industrial biotechnological sector.

Students and professionals can externally visualise complicated biological concepts in a 3-dimensional (3D) environment using the metaverse, which makes it easier for them to grasp and apply the information provided. The acquisition of practical skills, combined with enhanced retention of knowledge, proves beneficial. Advanced virtual laboratories have the potential

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

to be invaluable in the education of future biotechnologists and medical professionals (Kaddoura, 2023; Venkatesh, 2022; Petrigna, 2022).

This review paper is structured as follows. Section 2 reviews the relevant work-related publications, focused on the most important milestones in understanding metaverse use in biotechnology. In Section 3, we discuss the methodology of how the virtual metaverse simulation influences our understanding of major concepts in a biological system. Section 4 discusses the main findings. In Section 5, we discuss the most significant practices of integrating the metaverse in biotechnology.

Finally, we draw the main conclusions of this study in Section 6.

Literature Review

The integration of metaverse technologies into biotechnology has taken significant attention in recent years, with exploration of their potential use in promoting collaborative work, accelerating drug discovery, and revolutionising medical training (Mystakidis, 2022; OOi et al., 2024). This literature review categorises the existing body of knowledge into four key areas: (i) the convergence of metaverse technologies with biotechnology, (ii) the role of AI, digital twins, and simulation in biotech research, (iii) immersive training and education platforms within the metaverse, and (iv) data privacy, security and integrity, and ethical issues related with virtual environments of biotechnological resources.

Metaverse and Biotechnological Convergence

The metaverse serves as an interconnected virtual space that enables individuals to interact with each other utilising digital avatars. This is an ongoing, rapidly evolving experience. Additionally, other fields have found it helpful, including healthcare and biotechnology (Mystakidis, 2022). Bioinformatics research is undergoing a transformation with the integration of virtual environments (Taylor, 2022). It has been found that interactive 3D models significantly aid in the understanding of large and complex biological systems. By utilising these models in the field of bioinformatics, researchers can gain a deeper understanding of the types of structures and processes that take place at the molecular level.

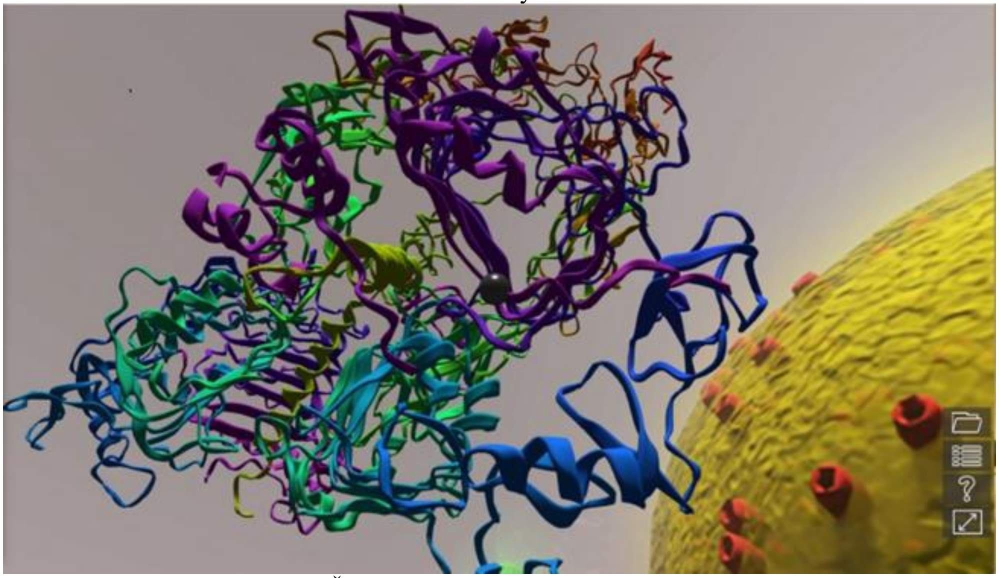
Biotechnology researchers are increasingly employing metaverse technologies to mimic complex biological systems. Molecular dynamics simulations in virtual reality enable an interactive and intuitive experience with proteins and their interactions in cells (Deeks, 2020). This highly interactive approach may enable us in the future to examine a simulated organism at a molecular level - an engineering achievement that could someday transform medicine. Drug delivery systems (DDS) that release their payload in the appropriate quantity at the proper time and location will propel

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

the discipline toward more efficient, targeted, and personalised therapy. Increasing insight in these areas, owing to VR, can only serve to advance biomedicine.

Figure 1 illustrates, as an example, the virtual reality of an insulin protein (T. Gutmann, 2019), prepared using the ProteinVR software (Cassidy, Šefčík, Raghav, Chang, & Durrant, 2020).

Figure 1: Human insulin receptor ectodomain bound by four insulins in an intercellular virtual environment created by the ProteinVR software



(Cassidy, Šefčík, Raghav, Chang, & Durrant, 2020)

Furthermore, remote collaboration platforms powered by the metaverse are breaking down geographical boundaries, allowing international research consortia to conduct joint experiments in virtual labs. According to Lee et al., these platforms are found to be especially useful during the COVID-19 pandemic era, when travel was heavily restricted and organisations had to turn to substitutes for maintaining the kind of collaborative biomedical research that typically takes place at numerous locations (Williams, 2023).

Ultimately, the use of virtual environments in bioinformatics enhances research and enables unprecedented global collaboration, leading to entirely new, groundbreaking solutions that are quite possible in this space. Despite these advantages, some challenges arise regarding the standardisation of metaverse applications in biotechnology. Notably, the lack of universal regulatory frameworks and the high cost of metaverse hardware have limited its widespread adoption (Chengoden, 2023).

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

AI, Digital Twins, and Simulation in Biotechnology

Artificial intelligence and digital twin technologies are at the heart of the metaverse-based biotechnology revolution. AI algorithms improve predictive modelling in drug discovery, and digital twins (virtual replicas of the same biological systems) allow for personalised simulation of disease progression and response to their treatment (Patel, 2022; Wang, 2023).

Digital twins have also proven to be of great significance in clinical trial planning, enabling scientists to run virtual trials on AI-modelled patient simulations prior to proceeding to human trials. Patel indicates that digital twins can reduce the duration and expenses of traditional clinical trials by approximately 40% and thereby enhance the effectiveness of experimental treatments (Patel, 2022). Similarly, Wang et al. highlight the role of AI in streamlining medical drug development, employing metaverse-based digital twins to optimise molecule production processes (Wang, 2023).

Virtual reality-based surgery simulations, coupled with an AI-powered feedback system, have also significantly improved the precision in the field of medicine (Gani, 2022). Such immersive technologies enable biomedical engineering researchers and clinicians to refine and implement their technical skills in an adaptable and risk-free setting. Simulation of obscure stages with real-time feedback, these systems, known as in-silico, enhance surgical precision, reduce errors, and streamline overall medical training before it occurs either in vitro or in vivo.

Immersive Training and Education in Biotechnology

The metaverse has introduced new methods of learning and professional development in biotechnology. Traditional models of learning are textbook-based and utilise static 2-dimensional (2D) diagrams, which are insufficient to explain the complexity of some systems, such as cells and biological molecular structures. Interactive VR-based learning systems, on the other hand, provide interactive 3D learning modules that significantly enhance knowledge retention (Mystakidis, 2022).

For example, Tsai et al. contrasted conventional medical instruction with metaverse instruction. The study revealed that students subjected to VR learning systems demonstrated a 25% improvement in comprehension and a 30% increase in procedural accuracy for laboratory simulations (Tsai, 2022). Wiederhold reported similar findings, revealing that medical professionals trained in VR environments were more competent and self-assured when performing real surgeries (Wiederhold, 2022).

Another application of the metaverse in education is the establishment of virtual laboratories, which allow researchers and students to conduct experiments in controlled, secure virtual environments (Taylor, 2022). The laboratories provide access to high-end equipment that may be prohibitively

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

expensive due to budget constraints, facilitating inclusive high-level biotechnological research.

However, viability for metaverse learning depends on accessibility and infrastructure. Prohibitive expenses on VR hardware and software development may eliminate large-scale use in low-income regions (Kim, Lee, & Choi, 2023). In addition, inclusivity in virtual learning environments encompasses consideration of factors, such as the compatibility of haptic devices for individuals with disabilities (Kostick-Quenet, 2023).

Data privacy, security and integrity, and ethical issues related to virtual environments of biotechnological resources

The handling of personal biological and patient data in the metaverse raises important questions about privacy invasions, cybersecurity threats, and ethical controls. While blockchain and encryption technologies offer some answers (Shah, 2024), the decentralized nature of virtual worlds makes it challenging to oblige region-specific laws like GDPR or HIPAA, resulting in loopholes in data protection. For instance, genomic-based digital twins of anonymized individuals are at risk of re-identification, exacerbating consent challenges in virtual clinical trials (Kostick-Quenet, 2023). Additionally, AI-based diagnostic biases such as the underrepresentation of non-Western populations in training data can perpetuate healthcare inequalities if unaddressed. They need technological protection as well as interdisciplinary frameworks to safeguard innovation from patient rights and fair access.

Methodology

This qualitative research study aims to examine the effect of metaverse applications on biotechnological innovation with a focus on artificial intelligence, digital twins, virtual reality, and augmented reality applications. A methodological framework is designed to provide an integrative synthesis of existing research, utilising a systematic literature review followed by chosen case studies. These enable a comprehensive understanding of metaverse technologies in the biotechnology sector.

Research Design

The study is exploratory and attempts to investigate and explain the prevailing knowledge on biotechnology applications in the metaverse. Here, the systematic literature review aimed to define key technological leaps, strengths, and weaknesses of the emerging technology. A comparative evaluation of metaverse-driven educational training models and digital twins infused with AI in clinical research was conducted to validate findings.

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

Data Collection

Data for this study were collected from peer-reviewed journal articles, conference proceedings, government reports, and industry white papers published between 2019 and 2025. Principal databases used were:

- PubMed (for biomedical and clinical applications) (PubMed, 2025)
- IEEE Xplore (for AI and digital twin technologies) (IEEE Xplore Digital Library, 2025)
- SpringerLink & ScienceDirect (for interdisciplinary biotechnology applications) (SpringerLink, 2025) (ScienceDirect, 2025)
- Google Scholar (for supplementary academic literature) (Google Scholar, 2025)

The search criteria included terms, such as (PubMed, 2025; SpringerLink, 2025):

- "Metaverse in biotechnology,"
- "AI-driven molecule drug discovery in medicine,"
- "Digital twins in healthcare,"
- "VR-based medical training,"
- "Metaverse and sustainability in biotech."

The so-called "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) model (Nikulina, Simon, Ny, & Baumann, 2019) and its guidelines were utilised in this study to select the information, which is known for its accuracy and suitability.

Data Analysis

The collected literature was examined utilising thematic content analysis to identify emerging trends and recurring themes. Our analysis focused on four primary themes derived from the literature review, as outlined below.

1. The Convergence of the Metaverse and Biotechnology: The focus was on examining the impact of VR, AR, and AI-powered digital twins in pharmaceutical development and biological research.
2. AI and Digital Twin Technologies in Clinical Applications: Here, we aim to evaluate their role in molecular medicine drug development, precision in medicine, and virtual clinical trials.
3. Immersive Education and Training in Biotechnology: We evaluated the effectiveness of VR-based learning models compared to conventional methods.
4. Ethical, Regulatory, and Sustainability Challenges: We aimed to analyse the ethical concerns regarding bias in AI, data privacy and

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

security, and the environmental impact of applications demanding high computational power.

Case Study Approach

We conducted a case study analysis to examine the implementation of virtual clinical trials as a complement to the literature review. For that, we utilised digital twin models. The case study employed real-world applications of AI-powered simulations in molecular drug testing in medicine and patient modelling, thereby evaluating their efficiency, accuracy, and limitations.

Reliability and Validity

- Reliability: Our study included only peer-reviewed studies and high-impact sources to ensure consistency and validity. Gathered studies were cross-verified across multiple databases.
- Validity: We compared the findings with real-world case studies and expert opinions from white papers published by the World Health Organisation (WHO), MIT Technology Review, and Harvard Medical School.

Limitations

- Technological Scope: The study is limited to AI, VR, AR, and digital twin applications in biotechnology. Other emerging technologies (e.g., quantum computing and blockchain in biotech) were not extensively covered.
- Timeframe: Due to rapid technological advancements, some findings may become outdated as newer research emerges.
- Data Availability: Some proprietary industry reports were inaccessible, restricting insights into specific commercial applications of the metaverse in biotechnology.

Findings

From the analysis of published research and case studies, we found various crucial findings concerning the impact of metaverse technologies (including AI, digital twins, VR, and AR) on biotechnological innovation. The outcomes indicate how these technologies are transforming research practice, clinical trials, medical education, and sustainability activities in the field of biotechnology.

The findings are organised into four major areas, which are described in the following discussion.

1. Metaverse-Enabled Virtual Collaboration in Biotechnology.

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

2. AI-Driven Simulation and Digital Twins in Drug Discovery and Clinical Trials.
3. Immersive Learning and Training through VR-Based Education.
4. Metaverse challenges in Data Security, Ethical AI, and Privacy.

Metaverse-Enabled Virtual Collaboration in Biotechnology

The most significant impact of the metaverse includes its ability to facilitate global collaboration between biotechnology researchers, pharmaceutical companies, and healthcare institutions. Virtual laboratories and digital research environments eliminate geographical constraints, enabling real-time experimentation, data sharing, and AI-driven modelling.

Case Study: Virtual Research Laboratories

A study by Lee et al. (2022) found that metaverse-based research environments increased collaboration efficiency by 35% compared to traditional lab-based work. Researchers in different locations could simulate protein-folding experiments in shared virtual spaces, analyse molecular interactions in 3D, and conduct remote-controlled lab experiments without requiring physical access to laboratory infrastructure (Lee, 2021).

Key Findings:

- Virtual collaboration allows interdisciplinary teams to access high-resolution simulations, real-time data, and AI-assisted molecular modelling.
- Global teams can replicate laboratory conditions in the metaverse without expensive physical resources.
- Real-time VR-based interactions in virtual biotechnological hubs provide faster peer reviewing and knowledge transfer.

AI-Driven Simulation and Digital Twins in Drug Discovery and Clinical Trials

AI-powered digital twins, precise virtual replicas of human patients, cells, and molecular-level interactions of medical drugs, are revolutionising drug development in medicine and clinical trials. These data-driven models simulate disease progression, predict patient-specific treatment responses, and reduce reliance on traditional animal and human testing.

Findings from AI-Powered Drug Discovery Models

- Patel (2022) reports that AI-driven drug simulations reduce the average drug development timeline from 12 years to 5 years by predicting molecular interactions more efficiently than traditional testing (Patel, 2022).

- Wang et al. (2023) highlight that digital twins improve personalised medicine accuracy by 40%, allowing for targeted drug design based on real-time biological data (Wang, 2023).
- AI-powered models can test millions of drug compounds in silico, identifying the most promising candidates in weeks instead of years.

Case Study: AI-Powered Simulations and Digital Twin Models in Drug Testing

Ren et al. (2025) demonstrated a groundbreaking application of AI-driven digital twin technology in Alzheimer's disease (AD) research, as seen in their work on virtual clinical trials and precision drug discovery. The study leveraged multi-omics data (genomics, transcriptomics, and proteomics) and longitudinal clinical records from leading Alzheimer's disease databases (e.g., ADNI, ROS-MAP, and electronic health record systems) to construct patient-specific digital twins. These AI-powered virtual models simulated disease progression under various drug interventions, enabling in silico clinical trials that reduced reliance on large control groups and accelerated therapeutic validation (Yunxiao Ren, 2025).

A key innovation was the integration of network-based AI frameworks (e.g., GPSnet) with data-driven generated perturbation responses. By combining GWAS data and single-cell RNA sequencing, researchers identified medical drugs, such as anti-inflammatory agents, with potential efficacy against Alzheimer's disease (Yunxiao Ren, 2025). Additionally, DTs were continuously updated with real-time biomarker data (such as MRI/PET imaging, CSF, and blood biomarkers), which provided higher predictions of early disease detection and significantly improved personalised treatment procedures.

While maintaining high predictive accuracy, this approach reduces the development timelines and costs compared with traditional clinical trials. The success of these AI-powered simulations highlights the transformative potential of digital twin technology in precision medicine, providing a faster and more efficient pathway to drug discovery for complex neurodegenerative diseases (Yunxiao Ren, 2025).

Immersive Learning and Training through VR-Based Education

While the cited studies (Tsai, 2022)(Wiederhold, 2022) show measurable benefits of VR/AR training for medicine, the assessment overlooks significant weaknesses that temper their transformative potential. For instance, those same-improved comprehension (25%) and process effectiveness (30%) may not account for selection bias - studies select very small numbers of technologically savvy volunteers or controlled environments that lack the diversity of real-world classrooms. Furthermore, the prohibitively

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

high costs of VR hardware, software development, and maintenance (Kim et al., 2023) render it unavailable, unfairly affecting low-resource institution representation disproportionately. Attention to the effectiveness of haptic feedback circumvents accusations of fidelity; in complex surgeries, VR haptic nuances during training might be responsible for cadaveric training persisting (Gani et al., 2022), which raises doubts about long-term skill transfer.

Moreover, pedagogical reasoning - i.e., better retention of knowledge - is generally founded on short-term assessment, and few studies demonstrate the long-term learning outcomes. Interactive 3D modelling, while engaging, also has the potential to prioritize visual appeal over complexity of conception; students may retain molecular shapes better but can't place them in wider biological contexts (Taylor, 2022). The UC Medical Centre VR integration case study, as uplifting as it is, does not raise discussion of challenges to implementation, such as resistance from teachers or the time required to redesign curricula. A more balanced synthesis would acknowledge such trade-offs, weighing enthusiasm for innovation against careful consideration of scalability, equity, and pedagogical strength (Tsai, 2022), (Wiederhold, 2022).

Challenges in Data Security, Ethical AI, and Privacy in the Metaverse

With the adoption of metaverse technologies in biotechnology, security, privacy, and ethical concerns remain significant challenges. AI-driven decision-making models, digital twins, and VR-based patient data management raise concerns over data protection, patient confidentiality, and algorithmic biases.

Findings on AI Bias and Ethical Challenges

- Shah et al. (2024) highlighted concerns that 80% of AI-powered clinical trial datasets still rely on Western-centric medical data, potentially misrepresenting global patient populations (Shah, 2024).
- Rahimzadeh found that AI models in digital twin healthcare applications showed biases in diagnostic accuracy, with up to 15% higher error rates for underrepresented demographic groups (Rahimzadeh).

Discussion

The combination of AI, digital twins, AR, and VR in biotechnology is revolutionising drug discovery, medical education, and clinical trials through greater efficiency, cost-effectiveness, and global collaboration. AI-powered digital twins enhance drug development by reducing reliance on physical testing and improving accuracy in precision medicine, while virtual clinical trials reduce cost and risk for pharmaceutical companies (Patel, 2022). Second, VR-based training in medicine enhances procedural accuracy and knowledge retention, enabling students and medical professionals to hone complex techniques in simulated environments (Tsai, 2022). However, AI bias, regulatory gaps, and data security attacks remain pressing concerns, as AI-assisted healthcare models must be rigorously tested to prevent diagnosis errors and ensure effective treatment protocols (Kostick-Quenet, 2023).

Moreover, metaverse apps require enormous amounts of computational capabilities, which have implications for sustainability, with AI model energy consumption having no signs of decline (Shah, 2024). Improved AI regulation, ethical standards, and environmentally friendly computing solutions are required to realise the full potential of the metaverse in biotechnology.

In the classroom environment, the teaching methodology should incorporate a variety of supportive learning techniques, including scientific reading materials, data structures, tables and graphs, videos, interactive discussion, animations, and software. They should be combined with problem and project-based learning methodologies, including AR, VR, and AI technologies (Goldstein, 2016; W. Muliawan, 2016) (S. T. Kanyesigye, 2022) (J. R. C., 2024) (J. A. V., 2024) (J. P. W., 2024) (Vaughan, 2016). More importantly, the students should be prepared to identify the most important quantities and to measure and identify trends in the user data, utilising data processing tools and graphics (Vaughan, 2016).

Conclusion

The integration of metaverse technologies into biotechnology constitutes a paradigm shift with real potential to transform drug discovery, medical education, and the practice of medicine, according to recent research showing improved efficiency in trials involving digital twins (Patel, 2022) and improved learning outcomes with VR training (Tsai, 2022). Such promising uses, though, must be offset against substantial limitations and problems, such as the preponderance of initial study (frequently at modest sample sizes and short test durations), substantial infrastructural demands potentially exacerbating existing healthcare inequities, and issues regarding long-term maintenance of learning and transfer of skill. The rapid development of these technologies has been outpacing the development of effective regulatory measures, leaving governing gaps in AI testing, security of patient data in virtual environments, and digital twin standardization of healthcare applications. Secondly, despite having potential sustainability benefits through reduced physical use of resources, the high energy intensity of metaverse solutions and their environmental impact cannot be overlooked. Unleashing the promise of this tech convergence will require concerted effort on multiple fronts: large-scale, rigorous clinical testing of metaverse technology; development of holistic, globally harmonized regulation standards; access policies to ensure fairness and avoid widening the digital divide; and environmentally sustainable computing infrastructure investment. The biotechnology community must contemplate treating this new discipline in an even-handed sense of optimism, understanding that metaverse technologies possess transformative potential but their successful application depends on solutions of these early challenges by interdisciplinary action, evidence-based policy formation, and ongoing critical evaluation of the benefits and the limitations. (V. K. LaBoskey, 2004) (Vygotsky, 1978) (Vaughan, 2016).

Conflict of Interest: The authors reported no conflict of interest.

Data Availability: All data are included in the content of the paper.

Funding Statement: The authors did not obtain any funding for this research.

References:

1. Mystakidis, S. (2022). Metaverse. Encyclopedia, 2(1), 486-497. https://doi.org/10.3390/encyclopedia2010031
2. Lee, L. H., Braud, T., Zhou, P., Wang, L., Xu, D., Lin, Z., Kumar, A., Bermejo, C., & Hui, P. (2021). All One Needs to Know about Metaverse: A Complete Survey on Technological Singularity, Virtual Ecosystem, and Research Agenda. *arXiv preprint arXiv:2110.05352*. URL: https://arxiv.org/abs/2110.05352
3. Shen, S., Qi, W., Liu, X. et al. From virtual to reality: Innovative practices of digital twins in tumor therapy. J Transl Med 23, 348 (2025). https://doi.org/10.1186/s12967-025-06371-z
4. Uddin, Mueen & Obaidat, Muath & Manickam, Selvakumar & Laghari, Shams Ul Arfeen & Dandoush, Abdulhalim & Ullah, Hidayat & Ullah, Syed Sajid. (2024). Exploring the convergence of Metaverse, Blockchain, and AI: A comprehensive survey of enabling technologies, applications, challenges, and future directions. Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery. 14. 10.1002/widm.1556.
5. Bordukova, M., Makarov, N., Rodriguez-Esteban, R., Schmich, F., & Menden, M. P. (2023). Generative artificial intelligence empowers digital twins in drug discovery and clinical trials. *Expert Opinion on Drug Discovery*, *19*(1), 33–42. https://doi.org/10.1080/17460441.2023.2273839
6. Mercado, Justine & Picardal, Jay. (2023). Virtual Laboratory Simulations in Biotechnology: A Systematic Review. Science Education International. 34. 52-57. 10.33828/sei.v34.i1.6.

7. Maedeh Mosharraf, Data governance in metaverse: Addressing security threats and countermeasures across the data lifecycle, Technology in Society, Volume 82, 2025, 102910, ISSN 0160-791X, https://doi.org/10.1016/j.techsoc.2025.102910.
8. Kaddoura S, Al Husseiny F. The rising trend of Metaverse in education: challenges, opportunities, and ethical considerations. *PeerJ Computer Science*, 2023 Feb 13;9:e1252. doi: 10.7717/peerj-cs.1252. PMID: 37346578; PMCID: PMC10280453.
9. Venkatesh, K.P., Raza, M.M. & Kvedar, J.C. Health digital twins as tools for precision medicine: Considerations for computation, implementation, and regulation. *npj Digit. Med.* **5**, 150 (2022). https://doi.org/10.1038/s41746-022-00694-7
10. Petrigna, L., & Musumeci, G. (2022). *The Metaverse: A New Challenge for the Healthcare System: A Scoping Review*. *Journal of Functional Morphology and Kinesiology,* *7*(3), 63, 10.3390/jfmk7030063
11. K. -B. Ooi et al., "The Metaverse in Engineering Management: Overview, Opportunities, Challenges, and Future Research Agenda" in IEEE Transactions on Engineering Management, vol. 71, pp. 13882-13889, 2024, doi: 10.1109/TEM.2023.3307562.
12. Taylor, S., & Soneji, S. (2022). Bioinformatics and the Metaverse: Are We Ready? *Frontiers in Bioinformatics, 2*, 863676. DOI: 10.3389/fbinf.2022.863676
13. Deeks, H. M., Walters, R. K., Hare, S. R., O'Connor, M. B., Mulholland, A. J., & Glowacki, D. R. (2020). Interactive Molecular Dynamics in Virtual Reality for Accurate Flexible Protein-Ligand Docking. *PLOS ONE, 15*(3), e0228461. DOI: 10.1371/journal.pone.0228461
14. T. Gutmann, I. B. Schaefer, C. S. Poojai, I. Vattulainen, M. Strauss, U. Coskun, Cryo-EM structure of the complete and ligand-saturated insulin receptor ectodomain
15. J. Cell Biol., 219, 1540-8140, 2020 in an intercellular virtual environment created using the ProteinVR software.
16. Williams, A., Lee, J., Kadakia, K., et al. (Eds.). (2023, February 10). Emerging stronger from COVID-19: Priorities for health system transformation**.** *The Learning Health System Series*. National Academy of Medicine. National Academies Press. https://www.ncbi.nlm.nih.gov/books/NBK589824/
17. Chengoden, R., Victor, N., Huynh-The, T., Yenduri, G., Jhaveri, R. H., Alazab, M., & Gadekallu, T. R. (2023). Metaverse for healthcare: a survey on potential applications, challenges and future directions. *IEEE Access*, *11*, 12765-12795.

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

18. Patel, S. K. (2022). R&D Using the Metaverse and Digital Twins. *Applied Clinical Trials, 31*(7/8). URL: https://www.appliedclinicaltrialsonline.com/view/r-d-using-the-metaverse-and-digital-twins
19. Wang, X., Zhang, Y., & Zhang, Y. (2023). AI-Driven Virtual Environments for Predictive Medicine. *arXiv preprint arXiv:2301.00001*. URL: https://arxiv.org/abs/2301.00001
20. Gani, Abrara; Pickering, Oliver; Ellis, Caroline; Sabri, Omar; Pucher, Philip. Impact of haptic feedback on surgical training outcomes: A Randomised Controlled Trial of haptic versus non-haptic immersive virtual reality training. *Annals of Medicine & Surgery* 83(), November 2022. | DOI: 10.1016/j.amsu.2022.104734
21. Kostick-Quenet, K., Rahimzadeh, V. Ethical hazards of health data governance in the metaverse. *Nature Machine Intelligence,* 5, 480–482 (2023). https://doi.org/10.1038/s42256-023-00658-w
22. Tsai, M. C., Liang, J. C., & Tsai, C. C. (2022). Virtual Reality Enhancing Medical Education and Practice: Brief Communication. *Journal of Medical Education, 26*(4), 599–601. DOI: 10.3946/kjme.2022.234
23. Wiederhold, B. K. (2022). The Metaverse in Healthcare: Accelerating Research and Innovation. *Cyberpsychology, Behavior, and Social Networking, 25*(6), 345–346. DOI: 10.1089/cyber.2022.29210.editorial
24. Wiederhold BK. Metaverse Games: Game Changer for Healthcare? *Cyberpsychology, Behavior, and Social Networking*, 2022 May; 25(5):267-269. doi: 10.1089/cyber.2022.29246.editorial. PMID: 35549346.
25. Minji Kim, Seungzoon Lee, Jeongil Choi. (2023). A Study on Factors Affecting Intention to Continuous Use Metaverse Platform Service. *Journal of Korean Society for Quality Management*, 51(1), 97–117. https://doi.org/10.7469/JKSQM.2023.51.1.97
26. Shah, C., Pathak, J., & Kumar, S. (2024). Utilizing Blockchain Technology for Healthcare and Biomedical Research: A Review. *Cureus, 16*(10), e72040. DOI: 10.7759/cureus.72040
27. Rahimzadeh, V., Kostick-Quenet, K., Blumenthal Barby, J., & McGuire, A. L. (2023). Ethics Education for Healthcare Professionals in the Era of ChatGPT and Other Large Language Models: Do We Still Need It? *The American Journal of Bioethics*, *23*(10), 17–27. https://doi.org/10.1080/15265161.2023.2233358
28. PubMed. (n.d.). https://pubmed.ncbi.nlm.nih.gov/
29. IEEE Xplore Digital Library*. (n.d.). Retrieved from [https://ieeexplore.ieee.org/Xplore/home.jsp]

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

30. *SpringerLink*. (n.d.). Retrieved from https://link.springer.com/
31. *ScienceDirect*. (n.d.). Retrieved from https://www.sciencedirect.com/
32. *Google Scholar*. (n.d.). Retrieved from https://scholar.google.com/
33. Sakala IG, Eichinger KM, Petrovsky N. Neonatal vaccine effectiveness and the role of adjuvants. *Expert Review of Clinical Immunology,* 2019 Aug;15(8):869-878. doi: 10.1080/1744666X.2019.1642748. Epub 2019 Jul 25. PMID: 31293189; PMCID: PMC6678067.
34. Yunxiao Ren, Andrew A. Pieper, Feixiong Cheng, Utilization of precision medicine digital twins for drug discovery in Alzheimer's disease, *Neurotherapeutics*, Volume 22, Issue 3, 2025, e00553, ISSN 1878-7479, https://doi.org/10.1016/j.neurot.2025.e00553.
35. O. Goldstein. *Cogent Education* 3, 1200833 (2016).
36. W. Muliawan, W. S. Nahar, C. E. Sebastian, E. Yuliza, and Khairurrijal. Journal of Physics: Conference Series 739, 012139 (2016).
37. S. T. Kanyesigye, J. Uwamahoro, and I. Kemeza. *Physical Review Physics Education Research* 18, 010140 (2022).
38. R. Cross. *European Journal of Physics*, 45, 035003 (2024).
39. A. Vidak et al. *European Journal of Physics*, 45, 023002 (2024).
40. P. Wul. *European Journal of Physics*, 45, 023001 (2024).
41. L. Moran and H. Vaughan. New Directions in the Teaching of the Physical Sciences 8, 17–21 (2016).
42. V. K. LaBoskey, J. Loughran, and M. L. Hamilton. International Handbook of Self-study of Teaching and Teacher Education Practices 2, 817–869 (2004).
43. L. S. Vygotsky. Mind in Society: The Development of Higher Psychological Processes. Cambridge, MA, Harvard, (1978).