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Mapping the landscape of AI and ML in vaccine innovation: A bibliometric study

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ABSTRACT

With the rapid advancement of artificial intelligence (AI) and machine learning (ML) technologies, their applications in the medical field have expanded significantly. Particularly in vaccine innovation, AI and ML have shown considerable potential. This article employs bibliometric analysis to examine the progress of AI and ML in vaccine innovation over recent years. By conducting literature retrieval, data extraction, and intelligent analysis through Web of Science, it provides more accurate and comprehensive insights into vaccine development and dosimetry. The rapid growth in research publications since 2012, particularly the geometric growth observed since 2017, underscores the increasing recognition of the potential of AI and ML to revolutionize vaccine development. However, despite the substantial benefits of AI and ML in vaccine innovation, challenges remain regarding data quality, algorithm reliability, and ethical considerations. As technology continues to advance and research deepens, AI and machine learning are anticipated to play an even more pivotal role in vaccine innovation. Notably, AI has the potential to accelerate vaccine development timelines, particularly in the context of emerging infectious diseases. By leveraging data-driven insights and predictive modeling, AI can streamline processes such as antigen discovery, clinical trial design, and risk assessment, thereby enabling faster responses to public health emergencies. This capability is especially critical for addressing sudden outbreaks of infectious diseases, where rapid deployment of effective vaccines can significantly mitigate global health risks.

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Artificial intelligence; machine learning; vaccines; bibliometrics

Introduction

In recent years, the rapid advancement of artificial intelligence (AI) and machine learning (ML) technologies has significantly impacted various sectors, including the medical field.[1,2] Despite the significant strides made in leveraging AI and ML for various healthcare applications, traditional vaccine development methods remain time-consuming, costly, and inefficient.[3,4] This inefficiency poses a significant challenge, especially in the face of emerging infectious diseases and the need for rapid vaccine responses. The current literature highlights the substantial potential of AI and ML in vaccine innovation, but there is a gap in addressing how these technologies can practically enhance the process from antigen selection to clinical trials.[5,6] This study aims to bridge this gap by exploring the practical value of AI and ML in vaccine innovation and discussing the challenges and future prospects.

Vaccines are a cornerstone of public health efforts, crucial for controlling infectious diseases and reducing global morbidity and mortality.[7,8] However, traditional vaccine development often relies on trial-and-error methods, which can take years to yield successful candidates. AI and ML, on the other hand, offer unprecedented opportunities to expedite this process by leveraging vast amounts of data and advanced algorithms. Particularly in vaccine innovation, AI and ML have demonstrated substantial practical value. For instance, these technologies can efficiently streamline antigen selection and immunogen design by leveraging genomic data, protein structures, and immune system interactions.[9,10] Machine learning algorithms predict antigenic epitopes and assess immunogenicity, enabling researchers to identify promising vaccine candidates more rapidly.[11] Furthermore, AI-driven approaches facilitate the rational design of immunogens and the identification of novel adjuvant candidates, which can significantly enhance the efficacy and safety of vaccines.[12,13]

The practical value of AI and ML in vaccine innovation extends beyond the design phase. These technologies can also enhance vaccine trial efficiency through predictive analytics, allowing researchers to anticipate potential issues and optimize trial design.[14] This can lead to faster and more cost-effective clinical development processes, ultimately accelerating the delivery of safe and effective vaccines to the public.

Therefore, they accelerate antigen design by swiftly analyzing genetic data to identify promising candidates, reducing the time from concept to preclinical testing. In clinical trials, predictive models enhance efficiency by identifying suitable patient cohorts and forecasting outcomes, thus minimizing

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failures and cutting costs.[15,16] Vaccines are a cornerstone of public health efforts, crucial for controlling infectious diseases and reducing global morbidity and mortality.[17,18] However, traditional vaccine development often relies on trial-and-error methods, which can take years to yield successful candidates. AI and ML, on the other hand, offer unprecedented opportunities to expedite this process by leveraging vast amounts of data and advanced algorithms. The integration of AI and ML technologies has ushered in a new era in vaccine design, offering unprecedented opportunities to expedite the process.

AI and ML can efficiently streamline antigen selection and immunogen design by leveraging genomic data, protein structures, and immune system interactions.[19,20] Machine learning algorithms predict antigenic epitopes and assess immunogenicity, while AI-driven approaches facilitate the rational design of immunogens and the identification of novel adjuvant candidates.[21–23] These technologies enhance vaccine trial efficiency through predictive analytics and improve the overall development process. Despite the significant advantages of AI and ML in vaccine innovation, several challenges remain. Data heterogeneity and model interpretability are critical issues that need to be addressed to fully realize the potential of these technologies. Additionally, ethical concerns regarding data privacy and algorithm transparency are paramount, especially in sensitive areas such as healthcare. Regulatory considerations also play a crucial role in ensuring the safe and effective deployment of AI-driven vaccine innovations.

As technology continues to advance, AI and ML are expected to play an even more pivotal role in vaccine innovation. Future developments will likely focus on integrating emerging technologies such as single-cell omics and synthetic biology to enhance vaccine design precision and scalability. Interdisciplinary collaborations and regulatory harmonization will be essential to accelerate the delivery of safe and effective vaccines against infectious diseases.

Materials and methods

Search strategy

We conducted a literature search on the Web of Science Core Collection (WoSCC) database (https://www.webofscience.com/wos/woscc/basic-search) on 31st December 2024. The search formula was (TS = artificial intelligence AND TS=vaccines) OR (TS = machine learning AND TS = vaccines) OR (TS = Generative AI AND TS = vaccines) OR (TS = deep learning AND TS = vaccines), and the type of documents is set to "articles" and "review." The language of the literature was restricted to English. 1752 articles were selected and saved in plain text format for further bibliometric analysis. The search tactics are shown in Figure 1.

Data analysis

In the context of mapping the landscape of AI and ML in vaccine innovation, several bibliometric tools and methods were employed to analyze and visualize the research trends and collaborations in this field.[24,25] VOSviewer (version 1.6.20) was utilized for bibliometric analysis, extracting key information from a multitude of vaccine-related publications.[26,27] This software facilitated analyses such as country and institution analysis, journal and co-cited journal analysis, author and co-cited author analysis, and keyword co-occurrence analysis. The maps generated by VOSviewer used nodes to represent entities like countries, institutions, journals, and authors; the size of these nodes indicated the number of vaccine publications associated with each item, and the color signified the classification. The thickness of the lines connecting nodes reflected the degree of collaboration or co-citation among these items.

CiteSpace (version 6.3.1), developed by Professor Chen, was another tool leveraged for bibliometric analysis and visualization in vaccine research. Specifically, it was used to analyze references with Citation Bursts, thereby identifying significant and influential publications in the field.[27,28]

The R package "bibliometrix" (version 4.3.0) was employed for thematic evolution analysis and constructing a global distribution network of vaccine publications.[29,30] This package aided in understanding the evolution of research themes and identifying key players in the field. The quartile and impact factor of journals were obtained from the Journal Citation Reports 2024, which were used to assess the quality and influence of vaccine-related publications.

Additionally, Microsoft Office Excel 2021 was used to conduct quantitative analysis of vaccine publications, enabling researchers to organize, process, and analyze data efficiently. Through the application of AI and ML techniques, researchers were able to gain deeper insights into vaccine research trends, collaborations, and the evolution of knowledge in the field. This comprehensive approach allowed for a thorough understanding of the current state and future directions of AI and ML in vaccine innovation.

Results

Quantitative analysis of publications

In Figure 2, the exploration of the application of machine learning and artificial intelligence technology in the field of vaccine development can be traced back to 2012, marking the initial foray of these technologies into the medical domain of vaccine research. Since then, with the continuous advancement of technology and the vigorous development of data science, research in this field has gradually emerged. Particularly, since 2017, this research trend has shown remarkable geometric growth, indicating exponential expansion in the field. This significant growth not only reflects the strong interest of the scientific research community in using advanced algorithms to improve the efficiency and accuracy of vaccine development but also highlights the great potential of interdisciplinary collaboration in promoting medical progress.

By 2024, as shown in Figure 2, the number of academic papers on the application of machine learning and artificial intelligence in vaccine innovation has surged to more than 150. This surge is not only a direct reflection of the research boom in the past few years but also a strong indication of the continued prosperity and innovation in this field in the future. These studies cover a wide range of topics, from streamlining antigen selection and immunogen design to predicting antigenic epitopes and assessing immunogenicity using machine learning algorithms. They also include

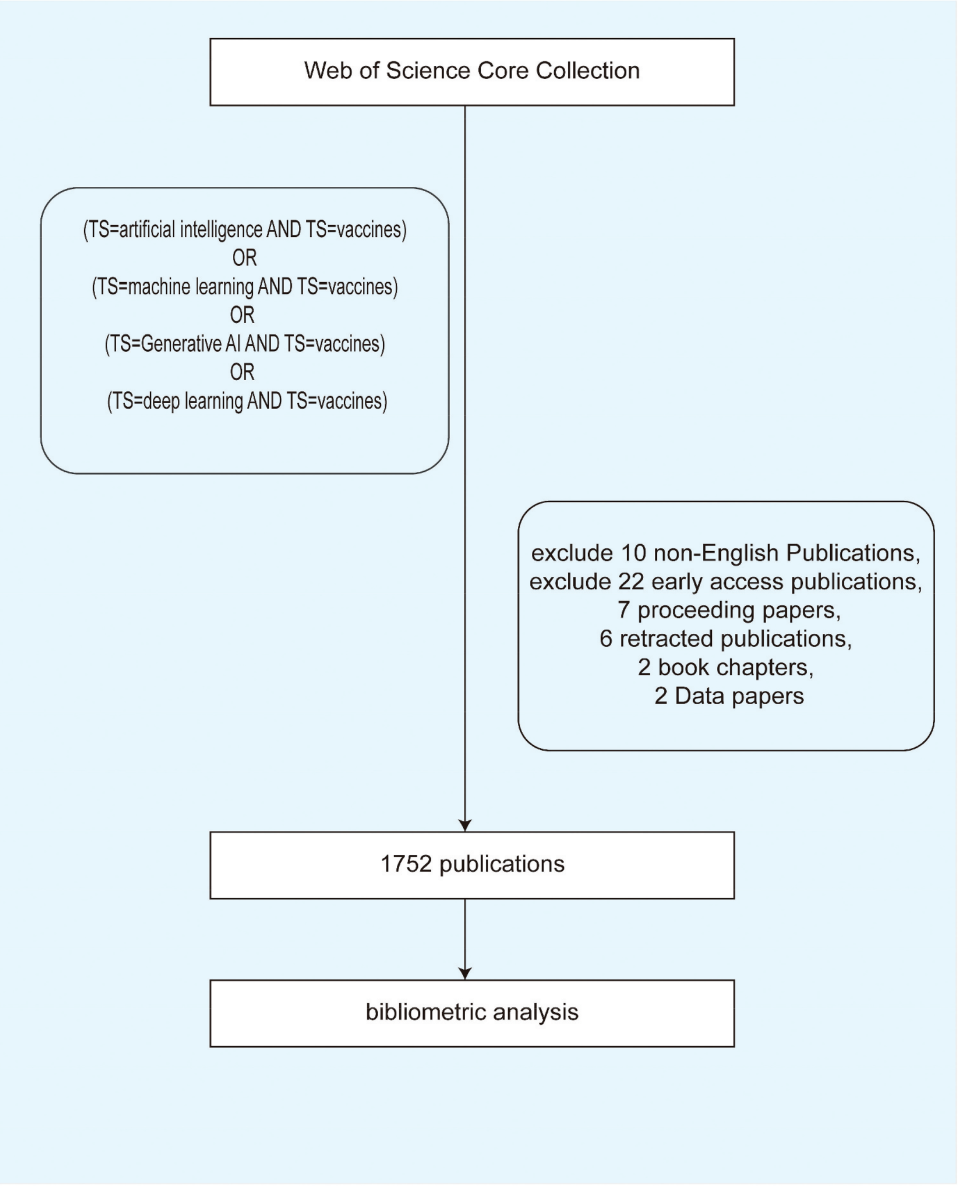

Figure 1. Detailed flowchart steps of the search strategy in screening publications. Legend: The figure showed the publications were selected.

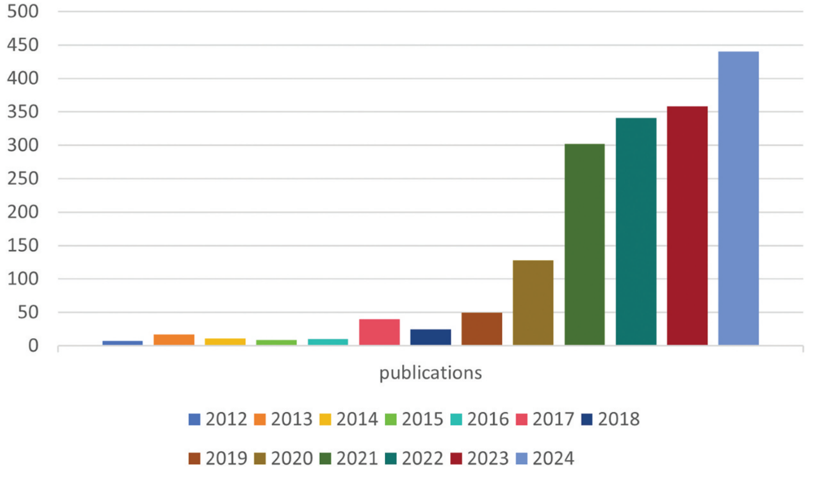

Figure 2. Annual output of research of AI and ML in vaccines. Legend: This figure illustrates the annual output of research articles on AI and ML in the field of vaccines.

the use of deep learning models for analyzing genomic data and immune system interactions, as well as identifying novel adjuvants through AI-driven molecular interactions analysis. These advancements greatly enrich our understanding of the complex mechanisms involved in vaccine development and provide a more scientific and personalized basis for vaccine design and optimization.

Country and institutional analysis

Figure 3 presented an in-depth analysis of the national distribution of artificial intelligence and machine learning in the field of vaccine innovation, utilizing VOSviewer software. In the figure, each country was represented as a node, with the size of the node indicating the volume of research papers in that field within that country. The lines connecting the nodes revealed the cooperation and communication between nations. The variation in color intensity reflected differences in research popularity, with darker shades signifying higher research activity.

In Figure 3a, it was evident that the United States led in the field of artificial intelligence and machine learning research in vaccine innovation, followed by England and China. In Figure 3b, the citation weight of countries is

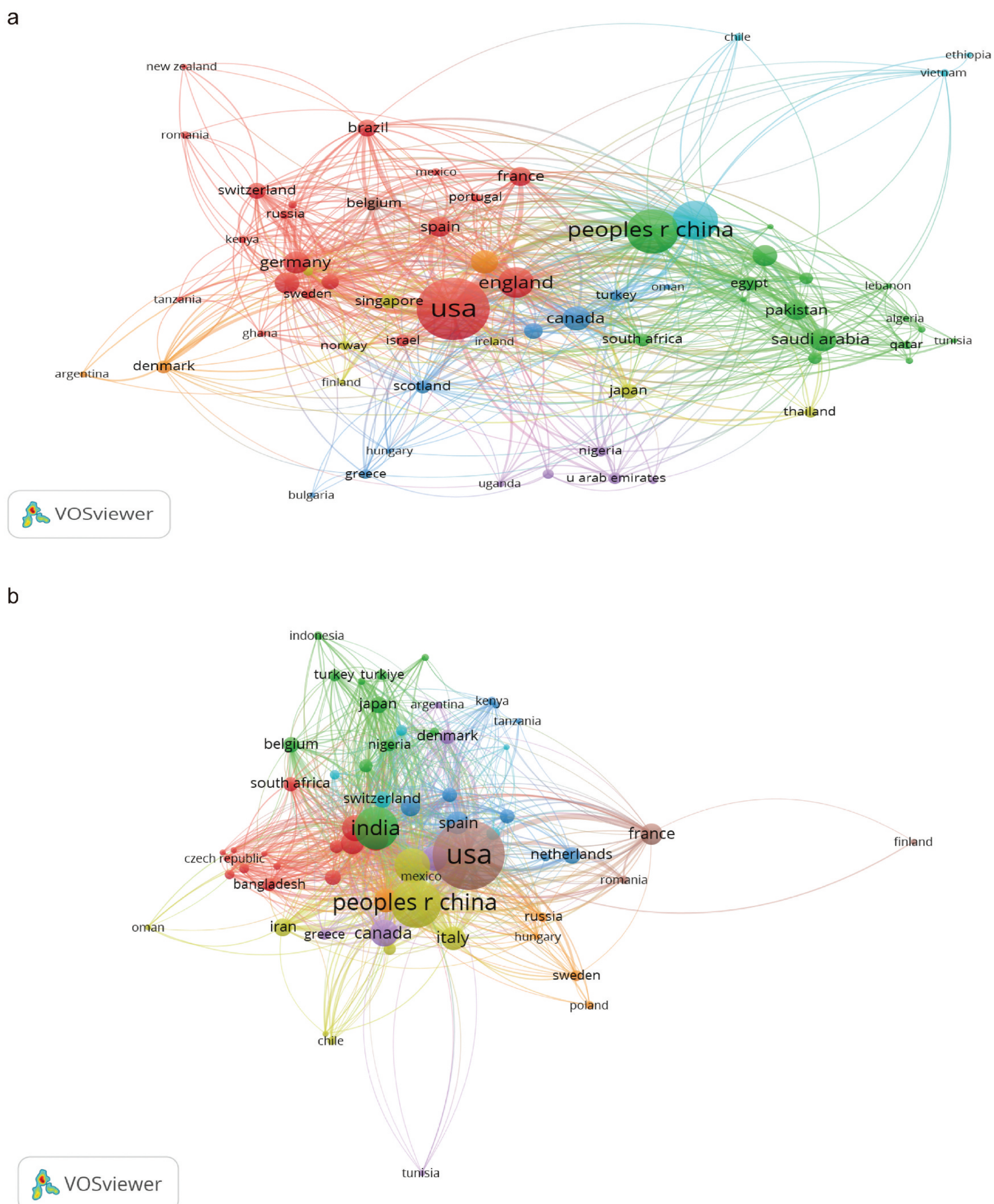

Figure 3. Visualization of countries (a) visualization of co-cite (b) countries on research of AI and ML in vaccines. Legend: The figure is composed of two key elements. Part (a) provides a comprehensive country-by-country analysis, meticulously detailing the research output of specific nations. Part (b) features a co-citation network, which vividly visualizes the intricate interconnections among countries as derived from their research endeavors.

dominated by the USA, followed by India and then China. These countries not only had a significant number of research papers but also engaged in frequent cooperation with other countries, forming a dense research network. Concurrently, emerging economies and developing countries were also gradually making their presence felt in this field, demonstrating robust research potential and developmental momentum.

Figure 4 provided a detailed analysis of the institutional distribution and citation impact of artificial intelligence and machine learning in the field of vaccine innovation. Through the precise calculations provided by VOSviewer software, an accurate understanding of the academic influence and contributions of each research institution in this field was achieved. From Figure 4, it was observed that several renowned universities, research institutions, and enterprises had taken the lead

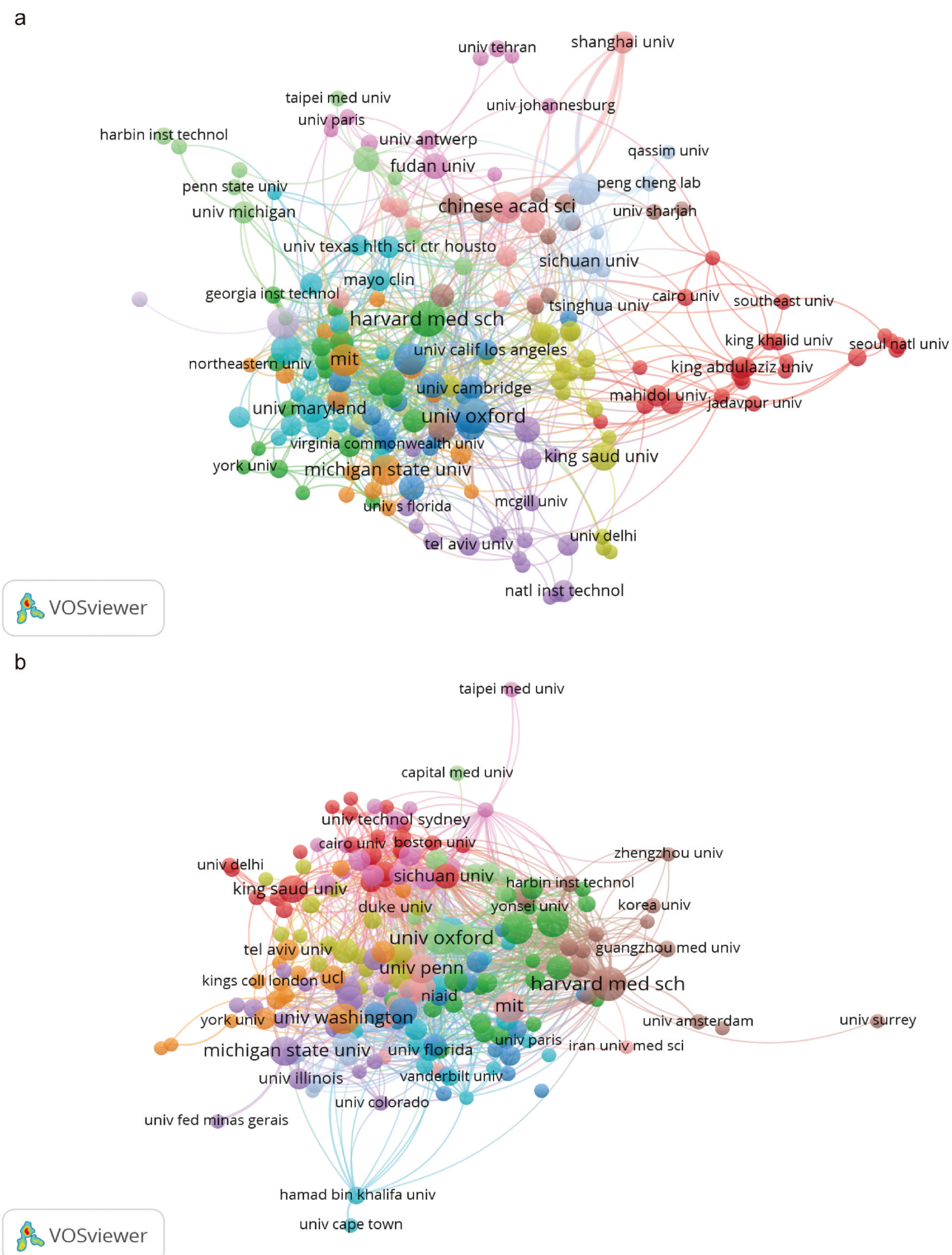

Figure 4. Visualization of institutions (a) visualization of co-cite (b) institutions on research of AI and ML in vaccines. Legend: The figure is composed of two key elements. Part (a) provides a comprehensive institution-by-institution analysis, meticulously detailing the research output of specific institutions. Part (b) features a co-citation network, which vividly visualizes the intricate interconnections among institutions as derived from their research endeavors.

in this domain. Among them, Harvard University stands out as one of the most authoritative institutions in the field of AI and ML applications for vaccine innovation. These institutions not only possessed strong research capabilities and abundant resources but also had research outcomes that were widely recognized, playing a pivotal role in advancing artificial intelligence and machine learning research in vaccine innovation.

Sources and co-cited sources

Figure 5 revealed the extensive scope and significant impact of literature on the application of artificial intelligence and machine learning in vaccines research published across various journals. A comprehensive analysis utilizing bibliometrix was conducted, which highlighted their contributions and citation frequencies in this domain, offering valuable insights for researchers. Notably, the most relevant sources in terms of publication count were found to be Frontiers in Immunology with 61 articles, Scientific Reports with 45 articles, and Vaccines with 39 articles. In terms of local citation frequency, the most cited sources were identified as Nature, New England Journal of Medicine, and Science Report. These findings underscored the pivotal role of these journals in advancing the field of vaccines research through the lens of artificial intelligence and machine learning.

Authors and co-authors

In Figure 6, VOSviewer was used to vividly display the clustering relationships among authors who focused on the application of artificial intelligence and machine learning in vaccines research. The software visualized their collaborations, effectively highlighting the research communities and their intricate interconnections

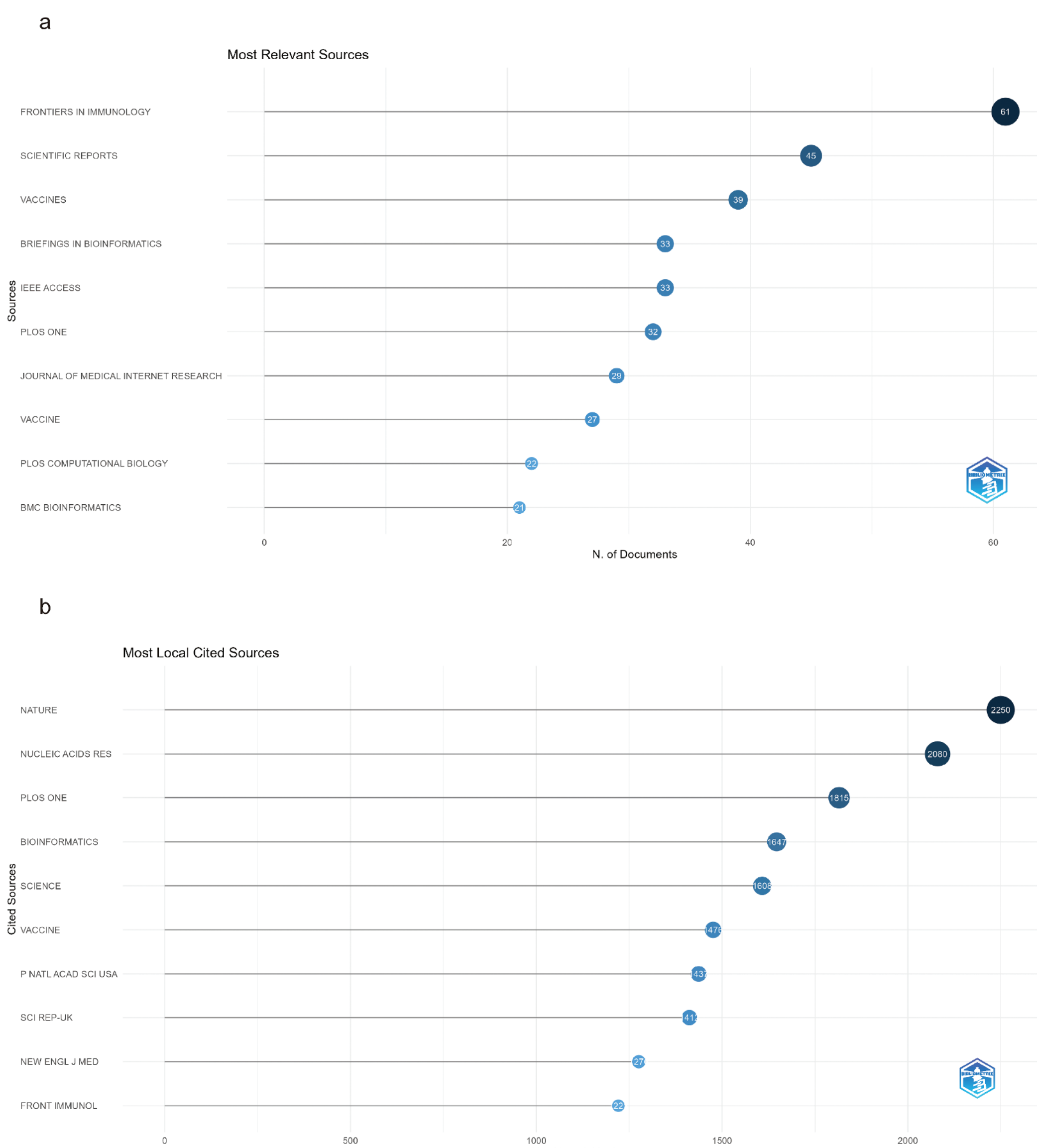

Figure 5. Visualization of institutions (a) most relevant sources (b) most locally cited sources in AI and ML research on vaccines. Legend: The figure comprises two essential components. Panel (a) presents an in-depth analysis of the most relevant sources, highlighting the research output of prominent institutions in the field of AI and ML applied to vaccines. Panel (b) showcases a network of the most locally cited sources, illustrating the interconnections among institutions based on the frequency of citations within their research communities. This visualization provides insights into both the globally significant contributions and the localized scholarly exchanges in this research domain.

within the field. Notably, Raghava, a distinguished scholar has made significant contributions to this field. His work has been influential in advancing the application of artificial intelligence and machine learning in vaccines research.

Reference with citation bursts

Figure 7a presented a keyword visualization generated by VOSviewer, centered around the themes of artificial intelligence, machine learning, prediction, diagnosis, and deep learning. This figure illustrated the interconnectedness and prominence of these concepts within the research landscape. Figure 7b, on the other hand, displayed a keyword clustering from Citespace, highlighting key areas such as artificial intelligence and COVID-19 patients. This clustering provided insights into the specific applications and focus areas within the broader context of artificial intelligence research, particularly in relation to the management and understanding of COVID-19 patients. Together, these figures offered a comprehensive view of the key topics and their interrelations in the field of artificial intelligence and its applications in medical contexts.

Discussion

The integration of AI and ML in vaccine innovation has emerged as a transformative force in the medical field, as evidenced by the bibliometric analysis presented in this

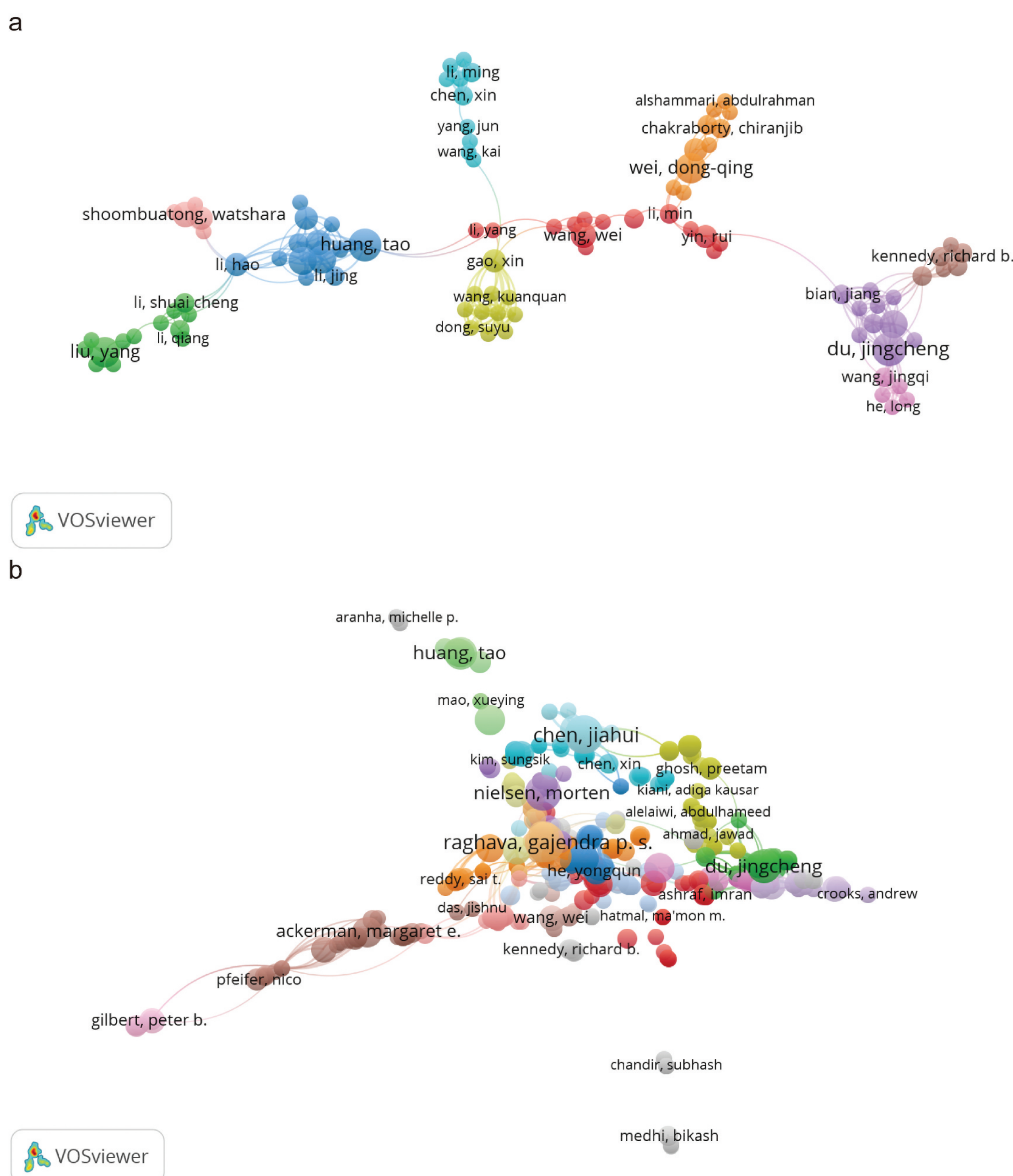

Figure 6. Author relationships and citation networks. Legend: Figure 6 includes (a) author relationship visuals showing collaborations via networks and (b) citation network visuals highlighting authors' influence through citations.

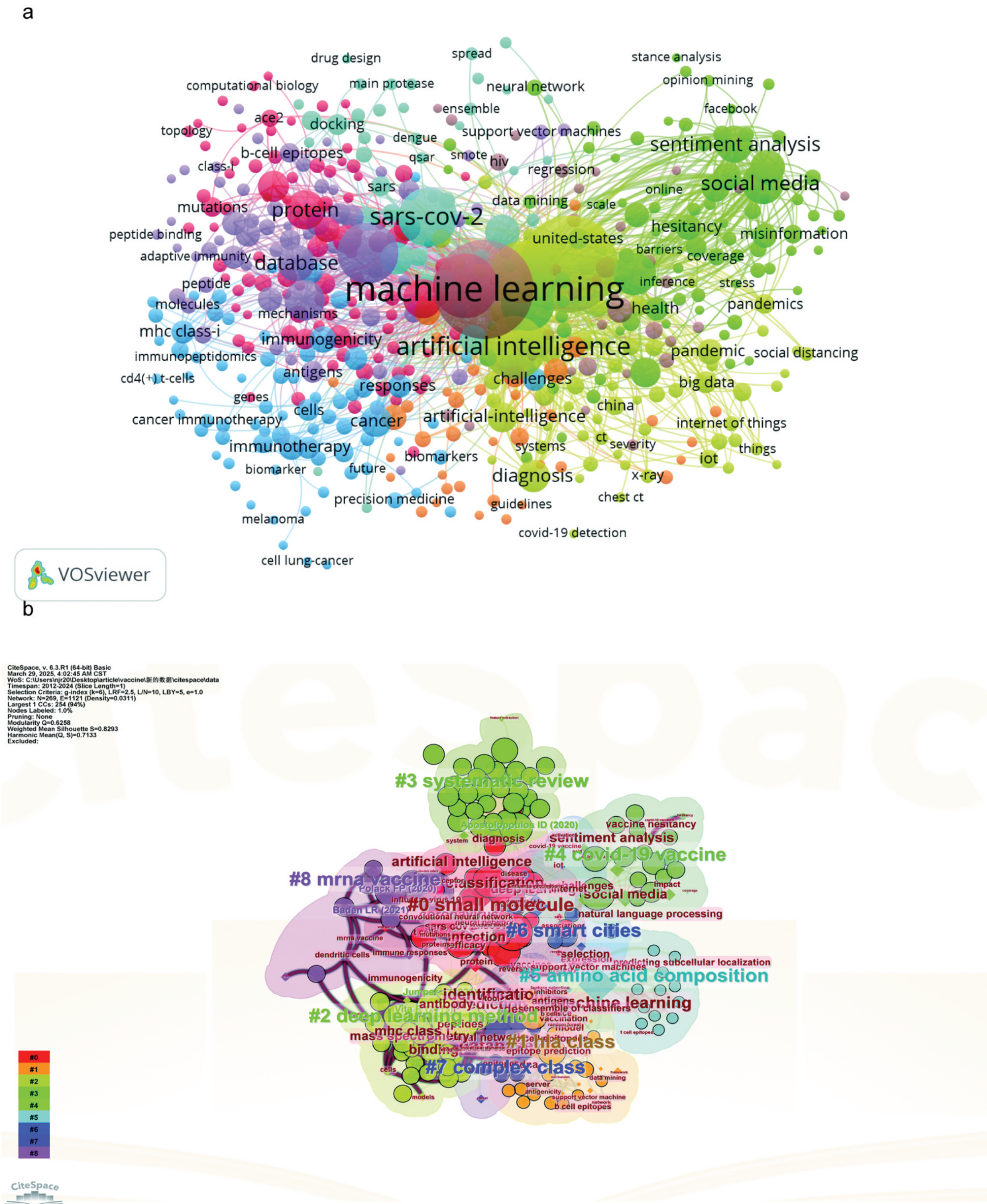

Figure 7. Focus of AI and ML keywords in vaccines. Legend: This figure presents a visualization of the focus of artificial intelligence (AI) keywords in the context of bibliometric analysis using tools such as VOSviewer(a), and CiteSpace(b).

study. The rapid growth in research publications since 2012, particularly the geometric growth observed since 2017, underscores the increasing recognition of the potential of AI and ML to revolutionize vaccine development. This trend is not only a testament to the scientific community's interest but also a reflection of the significant strides made in data science and computational technologies.

The integration of hybrid models, such as those combining AI with mechanistic models, represents a promising frontier in systems biology and bioengineering. These hybrid approaches leverage the strengths of both data-driven and knowledge-based methodologies to address complex biological problems that neither approach could tackle alone. For instance, Russo et al.[31] demonstrated how a multi-step, multi-scale bioinformatic protocol could identify potential SARS-CoV-2 vaccine targets by integrating sequence analysis, structural biology, and immunoinformatics. Similarly, Pinto et al.[32]proposed a hybrid modeling framework that merges mechanistic knowledge with deep neural networks under the Systems Biology Markup Language (SBML) standard, enabling the redesign of existing SBML models into hybrid systems capable of enhanced predictive power. These studies highlight the

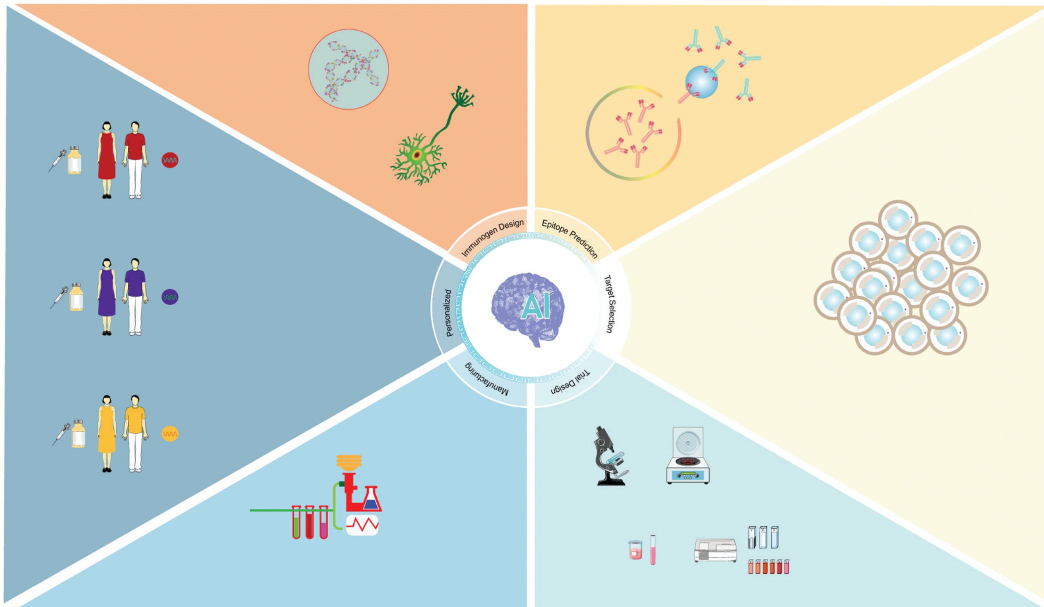

Figure 8. Six future directions in AI and ML-Integrated vaccines. Legend: This proposed direction outlines six key areas of focus for future research in integrating artificial intelligence (AI) and machine learning (ML) with vaccines research.

versatility of hybrid models in applications ranging from vaccine design to metabolic pathway optimization.

The integration of artificial intelligence (AI) and machine learning (ML) in vaccine research has revolutionized the field, offering new tools and techniques to accelerate and enhance the development of vaccines.

Here are some key applications in Figure 8:

Antigen selection and immunogen design

AI and ML algorithms can efficiently streamline the process of antigen selection and immunogen design. By leveraging genomic data, protein structures, and immune system interactions, these technologies can predict antigenic epitopes and assess immunogenicity. For example, reverse vaccinology (RV) techniques, assisted by AI, have been used to identify potential vaccine candidates from pathogen genomes.[33,34]

Epitope prediction

ML algorithms are crucial for predicting B-cell and T-cell epitopes, which are essential for triggering immune responses.[35,36] These predictions help in the development of refined AI- and ML-based prediction servers, which can identify immunogenic epitopes with high accuracy. For instance, AI-driven methods have been used to identify and characterize T-cell epitopes in SARS-CoV-2 variants, aiding in the development of candidate vaccines.[35]

Vaccine target selection

AI and ML can assist in the selection of vaccine targets by analyzing large datasets to identify pathogen regions targeted by the immune system.[37–39] This is particularly useful in the design of protein subunit vaccines, where the selection of specific antigens is crucial for inducing protective immunity. ML-based reverse vaccinology pipelines have been developed to predict bacterial protective antigens and SARS-CoV-2 antigens, significantly reducing the number of candidate targets for in vitro and in vivo testing.[39]

Clinical trial design and optimization

AI and ML algorithms can optimize clinical trial designs by identifying suitable patient cohorts and selecting participants based on specific characteristics, such as HLA haplotypes.[40,41] This can streamline product evaluations and reduce trial durations. Additionally, real-time data analysis during trials can facilitate more accurate decision-making and improve safety profiles.

Manufacturing and supply chain optimization

AI algorithms can support the development of adaptive manufacturing processes, capable of responding to demand variability and population behavior changes.[42,43] They can also facilitate real-time monitoring of vaccine safety and efficacy, enabling rapid responses to adverse events or changing epidemiological dynamics. Furthermore, AI can optimize supply chain logistics to ensure efficient distribution of vaccines.

Personalized medicine

AI and ML have the potential to revolutionize personalized medicine, particularly in the context of cancer vaccines.[44–46] The rising incidence of cancer each year has spurred the advancement of personalized treatment approaches. AI can help in the design of vaccines tailored to individual patient needs, improving treatment outcomes.[44]

Challenges and Future Directions

Despite the significant progress, several challenges remain. Data heterogeneity and model interpretability are critical issues that need to be addressed to fully realize the potential of AI and ML in vaccine innovation. Ensuring the quality and reliability of data is essential for the accuracy of predictions and the validity of research findings.

Ethical considerations, particularly regarding data privacy and algorithm transparency, remain paramount in vaccine innovation. The sensitive nature of health data demands robust ethical frameworks and stringent regulatory oversight to safeguard individual rights, prevent misuse, and maintain public trust. However, the current regulatory landscape struggles to keep pace with the rapid integration of emerging technologies, creating critical gaps that must be addressed to ensure responsible innovation. For instance, while health data regulations provide baseline protections, their enforcement across international collaborative projects remains inconsistent, complicating data-sharing initiatives vital for global pandemic responses. Moreover, the application of AI/ML in vaccine design introduces novel regulatory challenges, such as validating "black box" algorithms used in predictive immunology or ensuring transparency in automated clinical trial design.

As the field evolves, future regulatory frameworks must adapt to accommodate transformative technologies like single-cell omics and synthetic biology. For example, synthetic biology-engineered vaccine platforms may require novel risk-assessment paradigms to evaluate genetically modified organisms or cell-based therapies, while single-cell omics data – often generated through invasive sampling methods – could necessitate revisiting informed consent protocols. Regulatory harmonization across jurisdictions will be essential to avoid fragmented standards impeding cross-border research and deployment. Initiatives like the WHO's Global Pandemic Vaccine R&D Framework offer a model for aligning regulatory priorities, yet persistent disparities in resource allocation and governance structures threaten equity in access and oversight.

Furthermore, the interplay between ethics and regulation must be continuously recalibrated. Preemptive governance models, such as "regulatory sandboxes" for AI-driven vaccine design, could enable controlled testing of innovative tools while upholding ethical standards. Equally critical is the integration of public and stakeholder engagement into regulatory decision-making, ensuring transparency and accountability. Without such adaptive, inclusive frameworks, technological advancements risk exacerbating existing health disparities or eroding public confidence. Ultimately, realizing the transformative potential of vaccine innovation demands not only technical progress but also a cohesive, forward-looking regulatory ecosystem that balances innovation, ethics, and global equity.As technology continues to advance, future developments will likely focus on integrating emerging technologies such as single-cell omics and synthetic biology to enhance vaccine design precision and scalability. Interdisciplinary collaborations and regulatory harmonization will be essential to accelerate the delivery of safe and effective vaccines against infectious diseases. The continued evolution of AI and ML technologies, coupled with a collaborative and ethical approach, will be crucial in addressing these challenges and realizing the full potential of these technologies in vaccine innovation.

Limitations

This study acknowledges the limitation of relying solely on the Web of Science database, which may introduce bias due to its selective coverage of literature. While Web of Science is a high-quality resource, it does not encompass all relevant publications, particularly those indexed in other databases such as Scopus or PubMed. This limitation could affect the comprehensiveness of the analysis, potentially excluding important regional or specialized studies. Future research could address this limitation by adopting hybrid models that integrate multiple databases, ensuring a more robust and inclusive evaluation of AI and ML applications in vaccine innovation.

Conclusions

In conclusion, the applications of AI and ML in vaccine research are diverse and transformative, offering significant opportunities to accelerate and enhance vaccine development. Addressing the remaining challenges will be key to ensuring that these technologies continue to play a pivotal role in advancing vaccine research and development, ultimately contributing to global health and well-being.

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Author contributions

JN, RD, ZD, XY drafted the manuscript. JK drew the pictures. JN analyzed the data. RD, ZD, XY and JK reviewed and revised the manuscript. All the authors have read and approved the final version of the manuscript. All the authors contributed to the manuscript and approved the submitted version.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Notes on contributor

Jian Kang is a distinguished researcher renowned for his substantial contributions to the field of artificial intelligence in medicine and worked in Heilongjiang Provincial Hospital, Heilongjiang Provincial Hospital, Harbin Institute of Technology, Harbin. He has published numerous articles in SCI journals, with several individual articles achieving an impact factor of over 10.

Data availability statement

The original contributions of this study are included in the article and supplementary material at http://www.webofscience.com/wos/woscc/basic-search. Further inquiries can be directed to the corresponding authors.

Institutional review board statement

Not applicable for studies not involving humans or animals.

Abbreviations

The following abbreviations are used in this manuscript:

AI Artificial intelligence
ML Machine Learning

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