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Integrating Artificial Intelligence into Microbiology: Emerging Horizons for Precision Medicine and Antimicrobial Stewardship

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ABSTRACT

The latest developments in artificial intelligence (AI) have altered the sphere of microbiological investigation very rapidly by expanding the scope of studying microbial systems, accurate diagnostics on the basis of genomes, and the discovery of new drugs. This review introduces a specific synopsis of AI use in microbiology that covers three areas, namely early detection of diseases, surveillance of antimicrobial resistance (AMR), and progress in therapeutics. AI is used to enhance the process of pathogen identification and bring about the formulation of specific therapies through the use of machine learning models and vast microbial data sets that will eventually lead to quorum-sensing inhibitors and microbiome-based treatment of diseases. Other than these developments, there is still a challenge with data quality, algorithm transparency, and ethical implementation. To overcome these problems, the cooperation of microbiologists with computational scientists and policymakers is needed. In the present paper, the authors offer a comprehensive framework on which future studies could base their findings, focusing on the role of AI in sustainable healthcare and agricultural solutions, as well as environmental support.

Keywords: Artificial Intelligence, Microbiology, Microbial Genomics, Antimicrobial Resistance, AI-powered Diagnostics.

1. Introduction

Microorganisms are extremely significant in the development and maintenance of ecological systems, the preservation of agricultural yields, and the determination of human health. Although traditional microbiologic methods have provided valuable results, they are usually laborious and not scalable to meet current needs (Graf et al., 2025; Tian et al., 2024). Artificial intelligence (AI) is a technology that has become transformative in recent years, providing new possibilities for microbial analysis, forecasting diseases, environmental diagnostics, and so on (Shelke et al., 2023; Stracy et al., 2022). This article presents a bibliometric and thematic review of artificial intelligence applications in microbiology, using tools such as VOSviewer and Bibliometrix (R-package) to analyze publication trends, keyword co-occurrence, and thematic evolution (Papoutsoglou et al., 2023).

The purpose of this review is to identify the current overlap between AI and microbiology, as well as emerging fields that will shift the paradigm of existing research. In particular, three key themes are identified within our discussion: early disease detection, monitoring of antimicrobial resistance (AMR), and AI-based innovation in modelling of microbes and therapies (Mishra et al., 2023; Suster et al., 2024).

A combination of genomic, clinical and environmental data in AI systems would help researchers detect microbial pathogens faster and monitor the trends of antibiotic resistance (Liu et al., 2023; Tian et al., 2024). These devices have improved our knowledge of microbial communities themselves and their involvement in such complex processes as biofilm formation and quorum sensing, and they have contributed to the creation of synthetic inhibitors that may be applied in medicine, agriculture and ecosystem control (Stokes et al., 2020; Suster et al., 2024).

Nevertheless, the development of microbiology with AI is not without drawbacks. High data quality, algorithmic bias, and a lack of methodological transparency are major challenges. This review summarizes significant progress and gaps left that need to be completed to fulfil the promise of AI in microbial science (Marcos-Zambrano et al., 2021; Wang et al., 2026). Artificial intelligence (AI) has emerged as a transformative force in the biomedical sciences, offering novel approaches to data analysis, pattern recognition, and predictive modelling. In microbiology, AI enables rapid diagnostics, antimicrobial resistance prediction, and microbiome profiling, among other applications (Arnold et al., 2025; Cesaro et al., 2025).

Although the number of publications in this field has increased, there is no unified knowledge on the development and thematic priorities of AI-related microbiological studies. A bibliometric review is a systematic review that gives a structured report on the trend of publications, prominent authors and new themes of research (Stracy et al., 2022; Xu et al., 2022).

This study employs VOSviewer and Bibliometrix (R-package) to visualize co-authorship networks, keyword co-occurrence, and thematic evolution. These tools enable comprehensive mapping of the intellectual structure and research dynamics in the field (Arruda et al., 2022; Juhas, 2023). **Figure 1** illustrates how artificial intelligence is changing the way scientists study microbiology. Instead of only being able to observe microbes under the microscope, researchers can rely on AI to facilitate the diagnosis of infections, the creation of personalized patient treatments, and the development of better solutions to environmental problems. The figure demonstrates the extent to which AI is applied in generating more insights in microbiological studies (Arruda et al., 2022; Shelke et al., 2023).

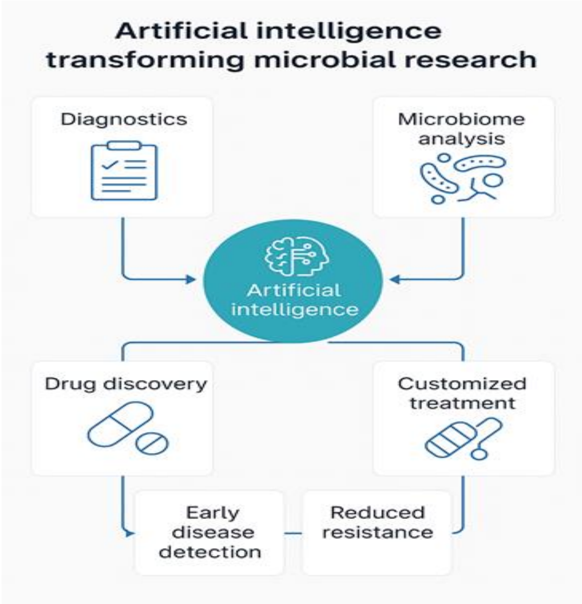

Figure 1. Conceptual visualization of how AI technologies transform microbial research, encompassing diagnostic, therapeutic, and ecological applications across clinical and environmental settings.

2. Methods

A structured literature search was conducted across PubMed, Scopus, and Web of Science databases. The research included keywords such as 'Artificial Intelligence', 'Microbiology', 'Microbiome', 'Quorum Sensing', and 'Antimicrobial Resistance'. The search time frame was from January 2013 to March 2024. Boolean operators and filters were applied to refine the results to peer-reviewed articles in English (Jiang et al., 2023; Tsitou et al., 2024).

Inclusion criteria were: (1) peer-reviewed articles, (2) published in English, (3) focused on AI applications in microbiology. Exclusion criteria included: (1) non-peer-reviewed sources, (2) articles unrelated to microbiological contexts, and (3) publications lacking methodological transparency (Tsitou et al., 2024).

Although this study is bibliometric in nature and not a systematic review, the PRISMA framework was partially referenced to guide the article selection and screening process. Data extraction was performed manually using a standardized template. Extracted variables included publication year, journal name, author affiliations, keywords, citation count, and thematic focus. The dataset generated from this process is available upon request from the corresponding author (Cesaro et al., 2025).

The bibliometric software tools (VOSviewer) and the R-package-based bibliometric software (Bibliometrix) were applied to review patterns of research productivity, prominent keywords, and co-author networks. Thematic categorization of the studies was done to gain insights regarding the development of diagnostics, drug discovery, and the modelling of microbiomes. Publications with strong methodologies, well-defined datasets, and clinical or agricultural relevance were favored (Juhas, 2023; Papoutsoglou et al., 2023). The sources used in this paper include a diverse range of perspectives, case studies, systematic reviews, and bibliometric analyses to comprehensively cover the topic. Methodological transparency was observed, as the selection process was documented and the methods of the analytical tools used reflected recently accepted bibliographic standards (Wong et al., 2023).

The visual maps of the key words co-occurring, networks of author collaboration, and relationships of citations were generated with the help of VOSviewer. They were analyzed by using bibliometrix (R-package) to do thematic evolution analysis, trends of annual production of science and source impact measures. The bibliometric search strategy was conducted using

PubMed, Scopus, and Web of Science databases. The detailed query strings, Boolean operators, and filters applied are provided in Supplementary File 1 to ensure transparency and reproducibility.

3. Results

This section presents the bibliometric and thematic findings derived from the selected literature. Analyses were conducted using VOSviewer and Bibliometrix to visualise keyword relationships, author networks, and thematic evolution. The results are organised into five thematic areas reflecting the convergence of AI and microbiology (Arruda et al., 2022; Cesaro et al., 2025).

3. 1. Annual Publication Trends

Artificial intelligence has been selectively used in microbiology over the last decade, and its integration has grown exponentially. Between 2013 and 2023, there was a 70% or greater increase in AI-associated publications on microbial research, indicating a growing importance of AI in diagnostics, genomics, and therapeutics. **Figure 2** illustrates the semantic relationships among keywords in AI-driven microbiology, highlighting the interdisciplinary integration across diagnostics, microbiome, resistance, and drug discovery (Sornsuwan et al., 2025).

The application of AI has helped transition microbiological research toward predictive modelling and high-throughput approaches. Both scientists and clinicians are increasingly relying on AI to model the response of microbes, predict outbreaks and develop individualized therapies, a shift in paradigm (Moradigaravand et al., 2018).

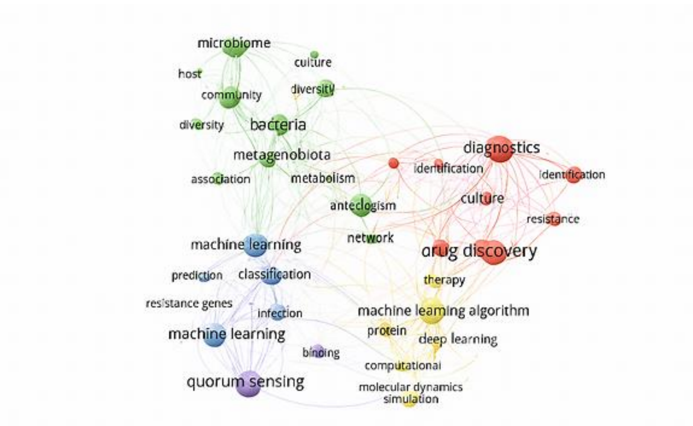

Figure 2. Co-occurrence map of AI-microbiology studies as keywords. Worldwide co-occurrence map of keywords produced by VOSviewer as an example of the visualization of semantic relationships between keywords in AI-based microbiology studies.

Examples of major clusters are AI–microbiome, antibiotic resistance, deep learning and drug discovery. The size of the node represents the frequency of the keyword, and the thickness of the edges represents the strength of co-occurrence.

3. 2. Keyword Co-occurrence Analysis

The thematic clustering of AI-driven microbiology research visualized in **Figure 3** indicates four key intellectual areas: diagnostics, microbiome, antimicrobial resistance, and drug discovery. Many clusters are connected through a bridging node, quorum sensing. Those clusters are the intellectual map of contemporary research and its changing priorities (Liu et al., 2023; Vashistha et al., 2023).

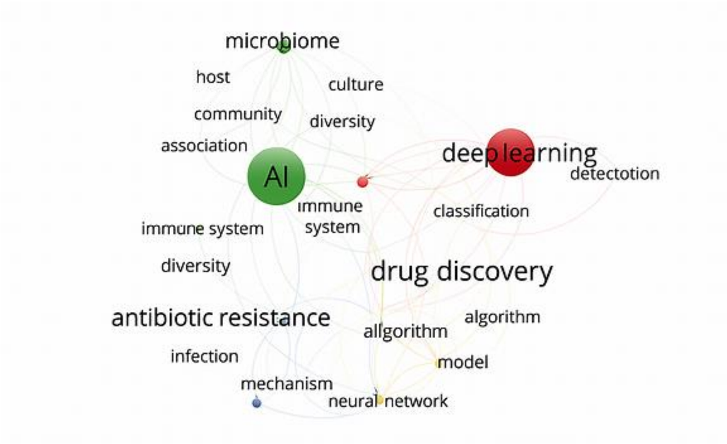

Figure 3. Thematic clustering map of AI–microbiology research. VOSviewer-generated thematic clustering visualization illustrating the intellectual structure and evolution of AI-driven microbiology research. The map highlights four major clusters: diagnostics, microbiome, antimicrobial resistance, and drug discovery. A bridging node, quorum sensing, connects multiple domains, reflecting interdisciplinary convergence.

Figures (2 and 3) present complementary visualizations: the first maps keyword-level semantic relationships, while the second reveals thematic clustering and intellectual structure. Together, they highlight the evolving priorities and interdisciplinary nature of AI–microbiology research.

3. 2. 1. Diagnostics

Machine learning and next-generation sequencing (NGS), combined with AI, have enabled rapid identification of pathogens, driven by the revolution in microbial diagnostics. These systems are more responsive and quicker than conventional culture-based methods. Artificial intelligence tools played a significant role during the COVID-19 pandemic, when there was a need to track the mutations and forecast the spread of the disease (Traves et al., 2024).

Genomic, clinical, and environmental data can now collaborate within AI-based diagnostic tools to provide real-time details. This has improved early diagnosis of infectious diseases, resulting in accurate curative actions.

3. 2. 2. Microbiome

AI analytics have revolutionized microbiome research by mapping microbial communities and identifying patterns associated with diseases such as diabetes and inflammatory bowel disease. On one hand, machine learning facilitates the individualization of probiotics, while on the other hand, it allows the choice of therapeutic measures based on the microbiome composition (Bartoszewicz et al., 2021; Marcos-Zambrano et al., 2021). Complex computer models allow scientists to gain an understanding of the ontogenic interactions between hosts and microbes, as well as their significance for health. Precision medicine will be achieved by using AI tools in the search for useful strains in microbial restoration balance (Tian et al., 2024).

3. 2. 3. Antimicrobial Resistance

AI models will recreate drug-pathogen interactions and forecast resistance mechanisms, enabling the development of next-generation antibiotics and quorum-sensing inhibitors (QSIs). They are used to counteract the resistance that develops and to maximize treatment plans.

Machine learning algorithms consider genomic mutations to predict resistance patterns, enabling therapeutic planning in advance. Also, AI is applied in monitoring hospital-acquired infections and global AMR (Stokes et al., 2020).

3. 2. 4. Drug Discovery

AI assists in virtually screening thousands of compounds to assess their binding affinity and efficacy against microbes. This accelerates the development of new therapeutics and reduces the cost of conducting experimental trials. Molecular docking simulations using AI have revealed QSIs that disrupt the communication between bacteria and biofilm architecture and development. The innovations offer a future to some of the resistant pathogens and chronic infections (Juhas, 2023; Wong et al., 2023).

3. 2. 5. Quorum Sensing

AI simulations decode bacterial communication networks, enabling the design of quorum-sensing inhibitors that disrupt biofilm formation and virulence. These inhibitors offer promising solutions for chronic infections and environmental control (Graf et al., 2025). AI also supports the modelling of microbial ecosystems, helping researchers understand how quorum sensing influences microbial adaptation and resistance (Vashistha et al., 2023).

3. 3. Applications of AI in Microbiology

AI technologies have demonstrated success in treating antibiotic resistance, optimizing treatment duration, and minimizing broad-spectrum antibiotic use (Suster et al., 2024).

Table 1. Summarizes key applications across various microbiological domains.

Field	Application	Outcome
Genomic Analysis	AI-driven genome sequencing analysis	Discovering disease-associated genetic patterns with accuracy and speed.
Antibiotic Resistance Prediction	Identifying drug-resistant microbes through modelling	Developing customised strategies to combat resistance.
Microbiome Research	Evaluating microbiome composition and changes via big data	Designing personalised therapies based on microbiome balance.
Quorum Sensing	Simulating bacterial networks using AI	Creating quorum-sensing inhibitors to counteract bacterial infections.

3. 4. Integration with Other Technologies

AI is increasingly being combined with nanotechnology and robotics. The algorithms develop nanoparticle delivery payloads to the target while optimizing nanoparticle design, and robotic systems perform remote microbial sampling in high-stress conditions. These technologies expand the boundaries of microbiological studies, enabling real-time monitoring of microbial diversity and adaptations in environments that are otherwise inaccessible, such as deep oceans and polar regions (Cesaro et al., 2025).

3. 5. Technical Depth and Limitations

AI in microbiology is perceived as promising, but it also faces challenges related to data quality, model transparency, and ethics. One concept under development, called explainable AI (XAI), aims to improve human trust and interpretability. High-performance computing opportunities cannot be universally applied because they are available only on low resources. The realm of ethical dilemmas in matters such as data protection, informed consent, and algorithmic discrimination, among others, must also be properly addressed through an interdisciplinary approach (Traves et al., 2024; Wong et al., 2023).

4. Discussion

The thematic and bibliometric review highlights the disruptive impact of artificial intelligence in microbiology, particularly in areas such as diagnostics, antimicrobial resistance prediction, microbiome, and drug discovery. The results indicate that the list of publications related to AI is constantly increasing, which suggests that AI is increasingly being incorporated in the field of microbiology (Arruda et al., 2022; Xu et al., 2022). We also find that AI plays a significant role in predicting AMR and in microbiome-based therapy (Patel et al., 2023; Roberts et al., 2023). However, this review provides the scope with the help of bibliometric mapping and thematic synthesis, which gives a bigger picture of how AI is changing microbial science (Asgari et al., 2019; Bartoszewicz et al., 2021). The thematic clustering analysis indicated four major areas of activity, including Diagnostics, Microbiome, and Antimicrobial Resistance and Drug Discovery, with Quorum Sensing being a connecting concept between clusters (Suster et al., 2024; Tsitou et al., 2024). AI has been applied in diagnostics, with machine learning models shown to be more sensitive and faster than conventional methods. In microbiome studies, AI has helped identify patterns of dysbiosis and develop custom probiotics. Virtual screening and molecular docking have contributed to drug discovery, particularly in the development of QSIs and novel antibiotics (Jumper et al., 2021). Despite these developments, several problems remain. The problem of data quality, the inability to understand algorithms, and ethical issues continue to be significant impediments. These gaps can potentially be solved by the development of explainable AI (XAI) systems and open-access platforms (Alser et al., 2021). This review would benefit the sphere by providing a structured review of the development of AI in microbiology, highlighting key themes and offering future research directions. It can be used as a guide to the researchers who plan to implement or apply AI in microbial diagnosis, treatment, and ecology (Tsitou et al., 2024).

5. Ethical Considerations

The use of AI applications in microbiology raises significant privacy concerns, particularly when genomic or microbiome data is obtained from patients. It is essential to ensure informed consent and data processing strategies are locked down (Xu et al., 2022). Another concern is the low level of transparency in the AI models, which can hinder clinical trust. Interpretability and responsibility can be developed in formulating explainable AI (XAI). Biases in training datasets and unequal access to AI use would increase global inequality. The solution to ethical developments is to promote open-source platforms and inclusive data (Moradigaravand et al., 2018).

6. Future Prospects

It is evident that AI will play a significant role in microbiology in the future, particularly as emerging technologies continue to expand the research capability of microbes, as well as in clinical practice. AI is likely to be actively used in areas such as real-time pathogen identification, personalized medicine, or environmental microbiome monitoring. Together with other technologies, such as nanotechnology, robotics, and the Internet of Things (IoT), these innovations will provide no-contact sampling, remote diagnostics, and intelligent biological sensors. Inventions of this kind will increase the reach of the microbiological analysis to hard-to-reach areas and environments. In addition, explainable AI (XAI) and open-source approaches can be developed to enhance transparency and accessibility, enabling researchers in low-resource contexts to participate in global microbial surveillance and drug discovery initiatives. These models can recreate microbial communities and evolutionary pathways and can shape synthetic microbial consortia for applications in both industry and medicine with more advanced AI training. The changes will revolutionize the notion of microbiology and establish new standards of interdisciplinary collaboration.

7. Conclusion

This bibliometric and thematic review demonstrates the growing impact of artificial intelligence in microbiology. Through keyword mapping and thematic synthesis, four broad research clusters have been identified: diagnostics, microbiome analysis, antimicrobial resistance, and drug discovery, with quorum sensing as a cross-cutting theme.

AI has accelerated microbial research by enabling predictive modelling, high-throughput analysis, and personalized therapeutic design. Despite existing challenges, the integration of AI with emerging technologies holds great potential for advancing microbiological science. This review provides a comprehensive overview of current trends and future directions, serving as a valuable resource for researchers, clinicians, and policymakers seeking to harness AI for microbial innovation.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data Availability

No data was used for the research described in the article.

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