ARTIFICIAL INTELLIGENCE IN EPIDEMIOLOGY: TRANSFORMING DISEASE SURVEILLANCE AND PUBLIC HEALTH

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ABSTRACT

Introduction: Epidemiology studies the distribution and determinants of health events in populations to control and prevent diseases. The integration of artificial intelligence (AI) has recently transformed epidemiology by enabling analysis of complex, large-scale data to improve disease surveillance, prediction, and decision-making.

Aim: To summarize recent advances in AI applications within epidemiology.

Materials and Methods: A structured search of major databases identified English-language studies from 2018 to 2025. Relevant articles on AI techniques for modeling, prediction, outbreak detection, and integration with traditional methods were included.

Results and Discussion: AI's role in epidemiology has evolved from early machine learning to advanced deep learning and natural language processing, enhancing outbreak tracking, disease modeling, geospatial visualization, diagnosis, and public sentiment analysis. Integration of AI with mechanistic models has improved forecasting and intervention assessments by capturing complex transmission dynamics and adapting to real-time data. AI-driven tools outperform traditional methods in predictive accuracy, enabling earlier detection of diseases. AI also processes large, heterogeneous datasets, uncovering non-linear relationships and supporting causal inference. Challenges remain, including data bias, privacy concerns, and the opacity of "black box" models. Addressing these requires ethical frameworks, transparency, and interdisciplinary collaboration. The expanding AI epidemiology market, driven by globalization, climate change, and big data, offers opportunities for improved public health responsiveness. Future research should focus on standardizing validation, integrating biological and social factors, and ensuring transparency.

Conclusion: AI has transformative potential for epidemiology, but responsible use depends on overcoming ethical, technical, and structural challenges through collaborative governance to promote health equity and public trust.

Key words: Artificial Intelligence, Machine Learning, Disease Modeling, Outbreak Detection, Public Health Surveillance

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INTRODUCTION

Epidemiology is a medical discipline dedicated to studying the distribution and determinants of health-related states or events in specified populations, in order to achieve the goal of controlling and preventing them. Rooted in the Greek words epi (upon), demos (people), and logos (study), epidemiology primarily investigates how often diseases occur, who they affect, and why, using systematic data collection, analysis, and interpretation methods [1,2]. It is fundamentally a quantitative science that combines knowledge from biology, statistics, social sciences, and informatics to understand patterns of disease occurrence and the factors influencing them. Epidemiology acts as a function of public health by informing evidence-based interventions, guiding policy decisions, and improving population health outcomes through causal reasoning and hypothesis testing grounded in multidisciplinary research [3].

Recently, artificial intelligence (AI), encompassing machine learning (ML) and related computational methods, has emerged as an innovative tool in epidemiology, enhancing the ability to analyze complex, large-scale data and improving disease surveillance, prediction, and decision-making processes [4,5,6]. The increasing complexity of disease dynamics, combined with the exponential growth of big data sources such as electronic health records, social media, and environmental sensors, has created an urgent need for such advanced analytical technologies [4,5].

By uncovering complex, non-linear patterns and generating predictive models, AI enables early outbreak detection, disease forecasting, risk assessment, and real-time decision support, thereby improving the timeliness and accuracy of public health responses [7,8,9,10,11]. AI-driven platforms have the ability to detect emerging infectious disease outbreaks even earlier than conventional surveillance systems [12,13]. For instance, AI can significantly help malaria control by forecasting outbreaks through the analysis of climate patterns, environmental conditions, and health data, and also by boosting diagnostic precision and reliability through refining rapid test accuracy and automating blood smear evaluations [11]. Other examples include AI-driven platforms like BlueDot and HealthMap, which have successfully provided early alerts during pandemics such as COVID-19, illustrating AI's potential to enhance public health responsiveness and preparedness [5,14]. Moreover, AI supports the integration of mechanistic epidemiological models with data-driven approaches, enriching the knowledge of disease transmission and intervention impacts [13]. Understanding the current landscape of AI applications in epidemiology is essential for guiding future research and policy development in this rapidly evolving field.

Aim

This literature review aims to synthesize recent research on the application of AI in epidemiology. It will also examine the methodological innovations, benefits, and challenges associated with AI integration in epidemiological research, seeking to highlight how AI contributes to advancing epidemiological science and public health practice in the context of evolving global health challenges.

Materials and methods

A narrative review was conducted to identify relevant studies on the use of artificial intelligence (AI) in the field of epidemiology. Articles were identified through structured searches of major scientific databases such as Scopus, Web of Science, PubMed and Google Scholar, as well as official websites. Original research studies, as well as reviews, meta-analyses, and systematic reviews, were considered. Inclusion criteria included studies published in English between 2018 and June 2025 that described the application of AI techniques, such as ML or DL, to epidemiological modeling, disease prediction, or outbreak detection, including integration with traditional models, benefits, challenges, and future directions. Exclusion criteria consisted of non-peer-reviewed literature, publications outside the specified date range, and studies not directly related to AI applications in epidemiology. Only publications that met the criteria were reviewed and key information was extracted for qualitative synthesis.

Results and Discussion

Evolution of AI in Epidemiology

The application of artificial intelligence (AI) in epidemiology has evolved significantly, alongside advances in computational power and data availability. Although AI as a concept dates back to the 1950s, its integration into epidemiology began in the 1990s, when ML techniques started to be applied to healthcare data for diagnostic support and disease surveillance. Early AI efforts in epidemiology primarily involved rule-based systems and basic ML algorithms aimed at improving diagnostic accuracy and identifying outbreak patterns from limited datasets [15].

The 2000s marked a new period associated with more advanced ML models and the increasing digitization of health records [15]. This era saw the emergence of AI applications in predictive analytics, risk stratification, and clinical decision support systems, enabling epidemiologists to process larger datasets with improved precision and speed [13] The integration of electronic health records (EHRs) and the growth of genomic and environmental data further expanded the scope of AI in epidemiological research, allowing for more complex understanding and modeling of disease dynamics.

Since the 2010s, the evolution of deep learning (DL) and natural language processing (NLP) has revolutionized AI capabilities in epidemiology. DL models, capable of handling high-dimensional and multimodal data, have enhanced outbreak detection, disease forecasting, and causal inference by uncovering intricate, non-linear relationships within large datasets [9, 13]. NLP techniques have enabled the extraction of relevant information from unstructured data sources such as clinical notes and social media, improving real-time surveillance and public sentiment analysis [16].

In recent years (2023-2025) the use of AI in epidemiology has grown significantly, driven by the urgent need to manage disease outbreaks amid globalization and climate change. Advances in this technology now enable seamless integration with mechanistic epidemiological models, combining data-driven insights with biological and socio-behavioral understanding to improve forecasting and intervention strategies [13]. The increased use of wearable devices and health apps has additionally generated valuable real-time data streams, further enhancing AI's role in dynamic disease monitoring and response [16].

This evolution reflects technological advancements and the expanding complexity of epidemiological data, positioning AI as a critical tool for modern public health research and practice.

Key applications

The main applications of artificial intelligence (AI) in epidemiology include several key areas:

Epidemic Outbreak Tracking and Surveillance

AI facilitates real-time monitoring and early detection of outbreaks by integrating multiple data sources such as electronic health records (EHRs), social media, as well as wearable devices and apps. These data streams enable AI models to capture dynamic patterns in disease spread and human behavior, enhancing situational awareness and response speed. For example, AI-driven platforms have successfully analyzed mobility data and public health policy information to predict hotspots and hospitalization trends during the COVID-19 pandemic, outperforming traditional forecasting methods [17,18,19].

Disease Modeling and Prediction

AI is increasingly integrated with mechanistic epidemiological models to improve forecasting accuracy and intervention assessments. ML and DL techniques complement traditional models by processing heterogeneous data and capturing complex transmission dynamics. Integrated AI-mechanistic frameworks have demonstrated enhanced predictive performance and adaptability to rapidly changing epidemiological conditions, addressing limitations of static parameter assumptions in conventional models [13,19] For example, AI models forecasted COVID-19 spread by integrating mobility, social, and health data, improving prediction accuracy beyond traditional methods [17].

Geolocation and Visualization

Geographic information systems (GIS) combined with AI enable spatial mapping and visualization of disease data, facilitating identification of geographic clusters and transmission pathways. This spatial analysis supports targeted interventions and resource allocation by public health authorities [17]. For example, GIS+AI tools identified COVID-19 hotspots by analyzing spatial and environmental data to aid targeted interventions [18].

Diagnosis and Patient Monitoring

AI improves diagnostic accuracy and symptom analysis through predictive models trained on clinical data, aiding early detection and monitoring of disease progression and recovery. AI tools also contribute to bio-surveillance by identifying emerging health threats from EHRs and other clinical data sources [17,18,20]. Examples include analysis of chest imaging by AI to accelerate COVID-19 diagnosis, increasing speed and accuracy [14] and AI models analyzing EHR data predicted sepsis onset earlier than clinical diagnosis, improving early intervention [21].

Sentiment Analysis and Vaccine Hesitancy

AI techniques such as NLP analyze public sentiment and misinformation on social media and other platforms, providing insights into vaccine hesitancy and informing communication strategies to improve vaccine uptake [17]. For instance, NLP analyzed social media for COVID-19 vaccine hesitancy trends, informing public health messaging [22].

Decision Support Systems

AI-powered decision support tools assist public health officials in policy formulation and outbreak management by synthesizing complex data inputs and simulating intervention scenarios. These systems enhance evidence-based decision-making and optimize resource deployment during epidemics [17, 19]. An exemplary real-world application is the European Centre for Disease Prevention and Control (ECDC), which utilizes AI-powered platforms to enhance epidemiological surveillance, outbreak prediction, and resource allocation. By integrating varied data streams, including mobility, clinical, and environmental inputs, ECDC's AI tools improve the timeliness and accuracy of public health responses. These platforms exemplify the practical benefits of AI deployment in public health decision support [13, 23].

AI Methodologies and Integration Approaches

Recent advances in AI have significantly enhanced disease modeling capabilities. Table 1 provides a comprehensive overview of the predominant AI techniques, integration frameworks, and multimodal data handling approaches utilized in this field.

Benefits and Advancements

AI in epidemiology offers many benefits and advancements, all of which contribute to more effective disease prevention and control strategies.

Improved predictive accuracy and early detection

AI models outperform traditional methods by achieving higher sensitivity and specificity in predicting diseases such as sepsis, preeclampsia, and infectious outbreaks. For example, AI algorithms predicted sepsis onset with an AUC of 0.94 up to 12 hours earlier than clinical diagnosis, increasing early detection by up to 32% [21]. Similarly, AI models for preeclampsia prediction reached detection rates of about 70%, surpassing traditional models that detect only 30-50% [28]. AI also enables early detection of infectious diseases like avian influenza and monkeypox by integrating diverse data sources [29,30].

Ability to process large, complex datasets and uncover non-linear patterns

AI and ML techniques handle vast, high-dimensional data, including electronic health records, genomic data, imaging, and environmental exposures. This capability allows identification of intricate, non-linear relationships between risk factors and health outcomes that traditional statistical methods may miss [9,22].

Enhanced causal inference and risk prediction models

Advanced AI methods improve causal inference by adjusting for confounding factors and identifying potential causal pathways in observational epidemiological stud-

Table 1. Summary of AI Methods and Data Integration Approaches in Epidemiology

Category	AI Technique / Framework	Explanation	Sources
Predominant AI Techniques	*Machine Learning (ML)*	Supervised learning (e.g., regression, random forests) predicts outcomes like outbreak trajectories, while unsupervised learning (e.g., clustering) identifies hidden patterns in disease clusters.	[13,24]
	Deep Learning (DL)	Neural networks (CNNs, RNNs) process high-dimensional data (e.g., genomic sequences, medical images) to detect complex disease patterns and predict outcomes like patient deterioration.	[22,25,26]
	Natural Language Processing (NLP)	Extracts insights from unstructured data (clinical notes, social media) for real-time surveillance and sentiment analysis.	[13,22]
	Reinforcement Learning (RL)	Optimizes intervention strategies (e.g., testing allocation during pandemics) through adaptive decision-making.	[24,26]
	Bayesian Networks	Model probabilistic relationships among risk factors to support causal inference and outbreak forecasting.	[24,27].
	Ensemble Learning	Combines multiple models (e.g., boosting, stacking) to improve prediction robustness, such as in mortality risk assessment.	[9,27].
Integration Frameworks with Traditional Models	*Surrogate Modeling*	AI emulates computationally intensive simulations (e.g., pandemic scenarios), accelerating analysis while preserving biological fidelity.	[13,26]
	AI-Augmented Models	ML dynamically calibrates mechanistic model parameters (e.g., transmission rates) using real-time data streams (EHRs, mobility data), enhancing forecast accuracy.	[13,26].
	Synthetic Data Generation	Generative adversarial networks (GANs) create realistic synthetic datasets to address data scarcity, enabling robust model training without compromising privacy.	[9,22]
Handling Multimodal Data	*Genomic Data*	DL identifies mutations and transmission pathways from viral sequences during outbreaks (e.g., COVID-19 variant tracking).	[22,26]
	Clinical Data	ML fuses EHRs, imaging, and wearables to predict disease progression and comorbidities (e.g., hypertension, diabetes).	[9,22]
	Environmental/ Social Data	NLP and geospatial AI link pollution, climate, and socioeconomic factors to disease risk, revealing disparities in vulnerability.	[9,22,24]

ies. This leads to more accurate risk prediction and understanding of disease determinants [9, 22].

Real-time data analysis enabling timely public health responses

AI enables real-time monitoring and forecasting of disease outbreaks by integrating genetic, environmental, and epidemiological data. This supports rapid public health decision-making and resource allocation during emerging health threats [29,30,31].

Additional advancements

AI enhances diagnostic accuracy through image analysis and biosensors, improving pathogen detection and antimicrobial resistance prediction in microbial epidemiology [29,32]. It also supports personalized medicine by tailoring interventions based on individual risk profiles derived from multimodal data [31].

Ethical, Privacy, and Equity Challenges

AI models often suffer from bias due to underrepresentation of marginalized populations and uneven data infrastructure globally. This leads to inequitable health outcomes and perpetuates existing disparities in epidemiological research and public health interventions [33,34].

The use of surveillance data from personal devices, social media, and other digital sources raises significant privacy issues. Protecting individual confidentiality while leveraging such data for epidemiological insights remains a critical challenge [33,35].

Many AI-driven decision-making systems operate as "black box" models, lacking transparency in how decisions are made. This opacity complicates accountability and undermines trust among public health professionals and the public [33,36].

There is a pressing requirement for ethical frameworks to guide the equitable and trustworthy deployment of AI in epidemiology. Such frameworks should address fairness, consent, data privacy, and regulatory oversight to ensure responsible AI use [33,37]. Additional reviews emphasize the importance of continuous ethical scrutiny, interdisciplinary collaboration, and regulatory measures to mitigate bias, protect privacy, and promote justice and fairness in AI applications in public health [38,39,40]. Addressing these challenges is essential for AI to fulfill its potential in epidemiology without exacerbating health inequities or compromising individual rights. Ethical frameworks must guide AI deployment to ensure fairness, data privacy, informed consent, and regulatory oversight, preventing exacerbation of health disparities and maintaining public trust [24]. Practical challenges include data heterogeneity, quality, and infrastructure gaps, especially in low-resource settings, which must be addressed to maximize AI's public health impact globally [24,41]. Transparency and explainability of AI models are critical to overcoming the "black box" problem and enabling accountability in public health decision-making.

Trends and Future Directions

The AI epidemiology market is expanding rapidly. Globalization and climate change are intensifying the complexity and spread of infectious diseases, necessitating advanced tools for surveillance and response. AI's ability to analyze large-scale, heterogeneous data helps address these challenges effectively [41,42]. The availability of big data, from sources like electronic health records, mobile devices, social media, and environmental sensors, fuels AI's capacity to detect outbreaks early, model disease spread, and optimize interventions [43,44]. In addition, The COVID-19 pandemic has further accelerated investment and interest in AI-powered epidemiological tools, highlighting their potential to improve early warning, diagnosis, and resource allocation during health crises [24,44].

Potential future research areas include enhanced integration of AI with mechanistic models to better incorporate biological, social, and behavioral factors influencing disease spread, enabling more realistic and actionable epidemiological insights [9,13]. Expansion of AI use in diverse epidemiological contexts, including life-course epidemiology, antimicrobial resistance, chronic disease modeling, and global health surveillance beyond infectious diseases is another topic gaining notoriety [9,41]. Development of standardized protocols and validation frameworks to ensure AI model reliability, reproducibility, and generalizability across populations and settings is crucial for the future use of these technologies [44]. In addition, exploration of ethical, legal, and social implications to address privacy, fairness, transparency, and accountability challenges in AI epidemiology should also be investigated further [24].

ECDC further promotes adoption of standardized validation protocols and ethical frameworks for AI in epidemiology, setting a leading example for governance and trustworthiness. Their guidelines emphasize transparency, reproducibility, and equity, addressing key challenges in practical AI implementation and serving as best practices for broader adoption [13,23].

CONCLUSION

AI has the potential to reshape epidemiology and infectious disease control fundamentally, but its responsible implementation depends on coordinated efforts to overcome structural, ethical, and technical barriers while fostering interdisciplinary collaboration and inclusive governance. Key gaps remain in integrating AI with mechanistic epidemiological models to combine data-driven insights with biological understanding, expanding AI applications across diverse epidemiological contexts, and developing standardized validation and governance frameworks. Future research should also focus on ethical frameworks ensuring fairness, consent, and accountability to maintain public trust and maximize health equity.

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