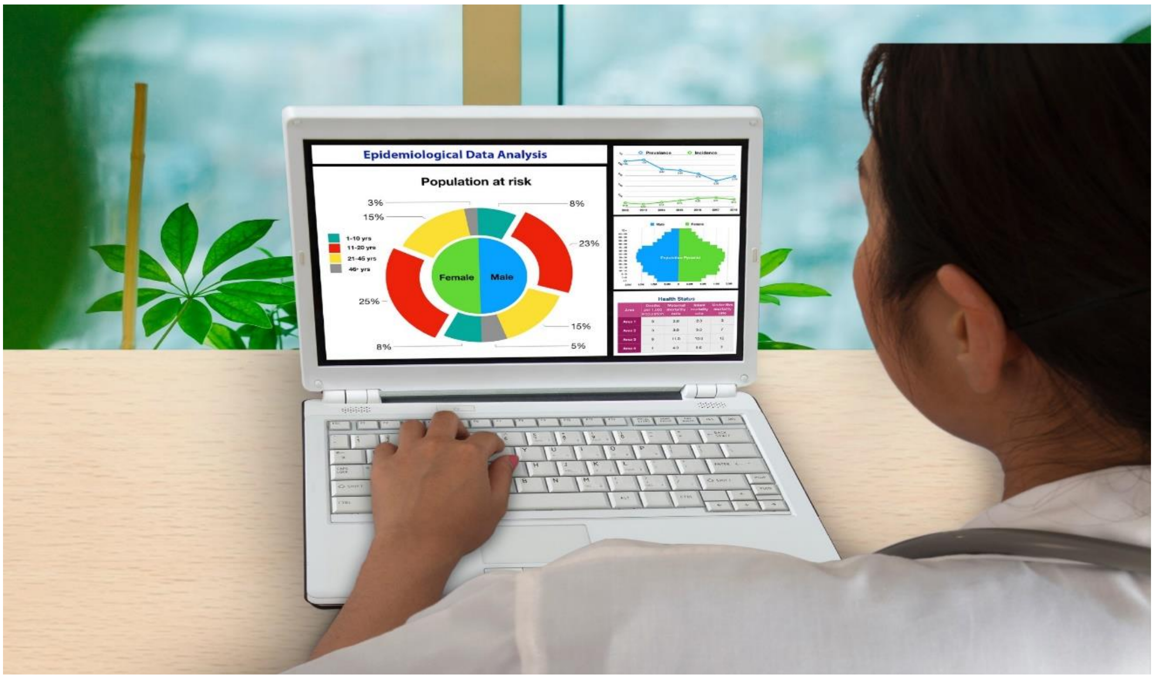

WHITE PAPER ON ARTIFICIAL INTELLIGENCE (AI) AND MACHINE LEARNING (ML) APPLIED TO TOXICOLOGY FOR HUMAN HEALTH PROTECTION WITH A FOCUS ON EPIDEMIOLOGY

INTRODUCTION

Artificial Intelligence (AI) and Machine Learning (ML) have revolutionized various fields, including toxicology and epidemiology. By leveraging large datasets across different modalities (e.g. images, audio, free text, genomic data, and others) and advanced algorithms, AI/ML technologies offer significant potential in terms of storage and computing power providing the necessary base to be integrated with fundamental sciences and diversified research aims.[1] In the public health field, AI has been instrumental in several applications, such as improving the coding of death records, optimizing case definitions for surveillance of both infectious disease outbreaks and chronic disease prevention, and enhancing vaccine safety monitoring.[2] AI/ML's for data analysis, modeling, and prediction can provide deeper insights into how environmental exposures, chemicals, and lifestyle factors affect human health. In chemical risk assessment, model building and data analysis play crucial roles.[3] AI/ML provides significant synergistic benefits in chemical risk assessment by enabling the analysis of large datasets, reducing the need for animal testing, and optimizing physiologically based kinetic models for better predictive accuracy. Additionally, it allows for the integration of diverse data sources, including epidemiological evidence, creating a more comprehensive understanding of potential chemical risks.[4] This comprehensive approach as presented in Figure 1 can be further improved by involving

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[1] Xu, Y., Liu, X., Cao, X., Huang, C., Liu, E., Qian, S., & Zhang, J. (2021). Artificial intelligence: A powerful paradigm for scientific research. The Innovation, 2(4).

[2] Centers for Disease Control and Prevention, Office of Public Health Data, Surveillance, and Technology. Accessed on 25.07.2024 at: https://www.cdc.gov/surveillance/data-modernization/technologies/ai-ml.html

[3] Di Guardo, A., Gouin, T., MacLeod, M., & Scheringer, M. (2018). Environmental fate and exposure models: advances and challenges in 21st century chemical risk assessment. Environmental Science: Processes & Impacts, 20(1), 58-71.

[4] OECD (2021), Guidance document on the characterisation, validation and reporting of Physiologically Based Kinetic (PBK) models for regulatory purposes, OECD Series on Testing and

a team of experts to provide insights, supported by a specialized modeling technique that uses data patterns to link observed effects to a scoring system, which measures potential harm. This method is considered reliable for connecting observed outcomes with potential risks.[5] Notably, the thorough and reliable combination of data from human, animal, and in vitro (lab-based) studies is essential for effective risk assessment. This integrated approach gathers insights on epidemiological research and interdisciplinary collaboration to make decisions that benefit public health.[6]

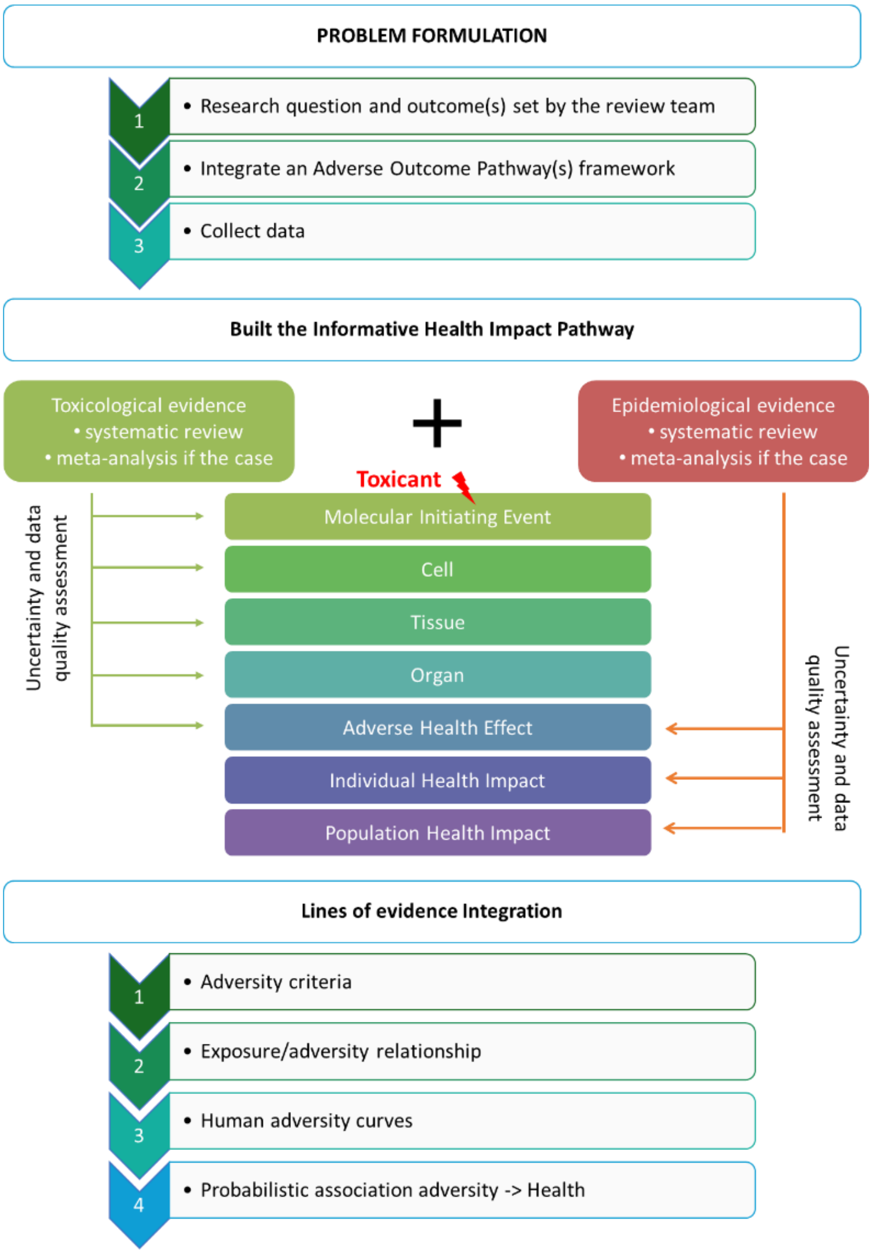

Figure 1. Overarching framework for toxicological and epidemiological integration for risk assessment (modified from [5]).

Assessment, No. 331, Environment,Health and Safety,Environment Directorate, OECD.
[5] Porcar, S. P., Sánchez-Íñigo, F. J., Nuñez-Corcuera, B., Suárez, J. L., Arca-Lafuente, S., Cárdaba, C. M., ... & Tarazona, J. V. (2024). Combination of toxicological and epidemiological approaches for estimating the health impact of atmospheric pollutants. A Proof of Concept for NO2. Chemosphere, 142883.
[6] LaKind, J. S., Burns, C. J., Johnson, G. T., & Lange, S. S. (2023). Epidemiology for risk assessment: the US Environmental Protection Agency quality considerations and the matrix. Hygiene and Environmental Health Advances, 6, 100059.

ARTIFICIAL INTELLIGENCE ADVANCEMENTS ADDRESSING GLOBAL HEALTH CHALLENGES

The increasing availability of large datasets and innovative analytical methods that utilize these datasets have propelled AI development.[7] The compilation of the extensive datasets has been driven by the urgency to achieve health-related Sustainable Development Goals (SDGs), especially considering their impact on morbidity and mortality.[8]

Most AI studies have concentrated on areas such as communicable diseases, non-infectious diseases, health policy, management performance, health facilities, and non-communicable diseases (NCDs).[9] Preventing and controlling non-communicable diseases (NCDs) is a critical development priority for the 21st century: According to the WHO's estimation, 23% of all global deaths are linked to the environment, and among these nearly two-thirds can be attributed to NCDs,[10] including the main NCDs cardiovascular disease, cancer, chronic respiratory disease, and diabetes. As showcased in Figure 2, these diseases are primarily driven by population growth and aging trends.[11]

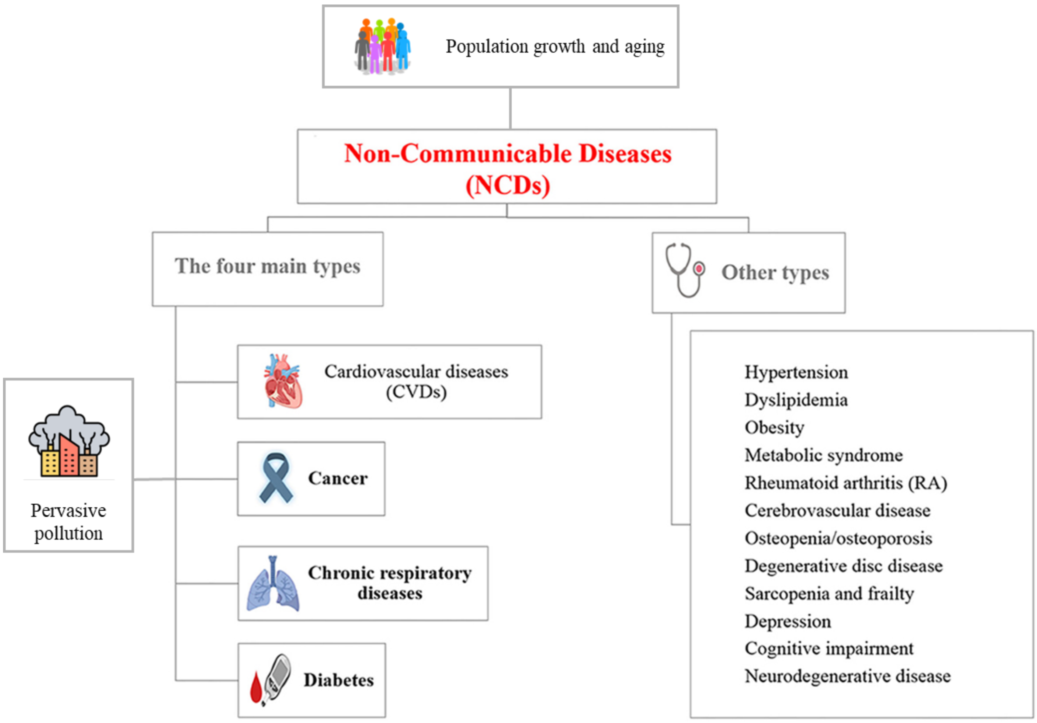

Figure 2. List of non-communicable diseases (NCDs) and links to society and environmental determinants (modified from [12]).

[7] Xu, Y., Liu, X., Cao, X., Huang, C., Liu, E., Qian, S., ... & Zhang, J. (2021). Artificial intelligence: A powerful paradigm for scientific research. The Innovation, 2(4).
[8] de la Santé, O. M. (2020). World health statistics 2020: monitoring health for the SDGs, sustainable development goals. Geneva: World Health Organization. Licence: CC BY-NC-SA.
[9] Schwalbe, N., & Wahl, B. (2020). Artificial intelligence and the future of global health. The Lancet, 395(10236), 1579-1586.
[10] Preventing noncommunicable diseases (NCDs) by reducing environmental risk factors. Geneva: World Health Organization; 2017 (WHO/FWC/EPE/17.1). Licence: CC BY-NC-SA 3.0 IGO.
[11] Padeiro, M., Santana, P., & Grant, M. (2023). Global aging and health determinants in a changing world. In Aging (pp. 3-30). Academic Press.
[12] Budreviciute, A., Damiati, S., Sabir, D. K., Onder, K., Schuller-Goetzburg, P., Plakys, G., ... & Kodzius, R. (2020). Management and prevention strategies for non-communicable diseases (NCDs) and their risk factors. Frontiers in public health, 8, 574111.

THE TRADITIONAL ROLE OF EPIDEMIOLOGY IN STUDYING DISEASE PATTERNS AND RISK FACTORS

Epidemiologists are tasked with identifying the factors that influence the occurrence of diseases. They can discern patterns, identify risk factors, and track disease outbreaks by analyzing data from various sources. This information is critical in developing strategies to prevent and control diseases, ultimately reducing the burden on healthcare systems and improving population health outcomes. Epidemiological investigation activities include:

- **Studying Disease Distribution and Frequency**: Epidemiology examines how diseases spread and how often they occur within different populations. This includes tracking new cases over a certain period (incidence), counting the total number of existing cases at a specific time (prevalence), and using morbidity and mortality rates to measure the severity and impact of diseases.
- **Analyzing Temporal Trends**: Epidemiologists analyze temporal trends to understand changes over time, including seasonal variations in diseases like influenza and long-term shifts that reflect the effects of public health measures or emerging health threats. Understanding geographic patterns allows for identifying areas with higher disease burden through techniques such as disease mapping, which visually represents prevalence across regions, and cluster analysis to detect localized outbreaks or environmental influences.
- **Assessing Various Exposures**: Epidemiology looks at different factors that might affect health, such as biological factors like pathogens and genetic influences, behavioural factors such as lifestyle choices (smoking, diet, physical activity), environmental elements like pollution and climate effects, and socioeconomic factors including income, education, and healthcare access—to determine their association with disease outcomes.
- **Employing Analytical Studies**: Epidemiologists use different studies to understand how exposure relates to diseases. They conduct cohort studies, following a group of people over time to see if certain exposures lead to diseases. They also use case-control studies, comparing people with those who have a disease to those who don't, to find out what might have caused the disease. Finally, they perform cross-sectional studies, which look at how common a disease is and what exposures people have at a single point in time.
- **Evaluating Intervention Effectiveness**: Epidemiologists use randomized controlled trials (RCTs) as the gold standard for assessing intervention effectiveness, where participants are randomly assigned to either the intervention or control group, and outcomes are compared. Observational studies, including natural experiments and before-and-after studies, offer insights when RCTs are impractical.
- **Conducting Epidemiologic Surveillance**: Epidemiologists keep a close watch on how diseases spread using two main methods: passive, where they gather data from existing reports and records, and active, where they actively seek out new information. During outbreaks, epidemiologists conduct field investigations and analyze epidemic curves to determine sources, transmission modes, and control strategies.
- **Informing Policy Development**: Epidemiologic evidence informs policy development by identifying health risks, evaluating intervention efficacy, and guiding resource allocation.

However, current study quality considerations, limitations, and elements of awareness should be addressed. This initiative fosters collaboration between researchers and regulatory bodies, promoting better communication to inform public health decisions. Whilst, a compendium of key study design and reporting elements provides a useful matrix tool to significantly improve the reliability and applicability of epidemiological findings in risk assessment.[13]

HOW AI/ML TECHNIQUES CAN ENHANCE DATA ANALYSIS, MODELING, AND PREDICTION IN EPIDEMIOLOGY

A wealth of data demonstrates how AI is being tested to tackle health challenges pertinent to achieving the SDGs.[14] These interventions encompass disease-specific applications and efforts to fortify health systems. AI/ML techniques include:

- **Complex algorithms** surpassing simple associations analysis, revealing hidden relationships and risk factors that deepen epidemiological understanding.
- **Machine learning** excelling in predicting disease outbreaks, recurrence, and progression through integration of real-time data streams such as social media trends, climate data, and healthcare records, facilitating timely interventions and resource allocation.
- **Natural language processing algorithms** extracting valuable insights from textual sources, aiding in epidemiological research and decision-making processes.

For example, studies have demonstrated the potential of AI/ML in predicting infectious disease outbreaks by analyzing various data sources and applying advanced algorithms like decision trees, random forests, and deep learning networks.[15,16] Additionally, explainable AI models are crucial for gaining trust and providing transparent and interpretable results to healthcare professionals.[17]

Whilst, AI/ML integration include ensuring data quality, addressing privacy concerns, maintaining algorithm transparency, and fostering interdisciplinary collaboration among computer scientists, epidemiologists, and healthcare professionals. The use of AI/ML in epidemiology raises several ethical concerns, including privacy, consent, and potential biases. Ensuring that data is used ethically and responsibly is paramount. Moreover, there must be safeguards to protect individual privacy and prevent discrimination based on AI/ML-generated predictions.

POTENTIAL BENEFITS OF AI/ML, SUCH AS IMPROVED ACCURACY, EFFICIENCY, AND SCALABILITY IN EPIDEMIOLOGY APPLICATIONS

The potential benefits of AI/ML in epidemiology applications include improved accuracy, efficiency, and scalability. These algorithms are powerful in analyzing large and complex datasets, allowing for the identification of subtle patterns and correlations across genetic, environmental, and behavioural factors with greater precision than traditional methods.[18] AI/ML automates data analysis tasks such as cleaning, feature

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[13] LaKind, J. S., Burns, C. J., Johnson, G. T., & Lange, S. S. (2023). Epidemiology for risk assessment: the US Environmental Protection Agency quality considerations and the matrix. Hygiene and Environmental Health Advances, 6, 100059.
[14] Schwalbe, N., & Wahl, B. (2020). Artificial intelligence and the future of global health. The Lancet, 395(10236), 1579-1586.
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[16] Yang, C. C. (2022). Explainable artificial intelligence for predictive modeling in healthcare. Journal of healthcare informatics research, 6(2), 228-239.
[17] Yang, C. C. (2022). Explainable artificial intelligence for predictive modeling in healthcare. Journal of healthcare informatics research, 6(2), 228-239.
[18] Feuerriegel, S., Frauen, D., Melnychuk, V., Schweisthal, J., Hess, K., Curth, A., ... & van das Schaar, M. (2024). Causal machine learning for predicting treatment outcomes. Nature Medicine, 30(4), 958-968.

selection, and model training, thereby reducing the time and resources required for epidemiological studies. Machine learning models are scalable, capable of adapting to different study sizes and complexities while maintaining performance and accuracy.[19] By integrating real-time data streams and healthcare records, AI/ML enables timely detection of disease outbreaks, monitoring of disease trends, and proactive intervention strategies.[20] Moreover, AI/ML techniques uncover complex relationships and interactions among variables, revealing hidden risk factors and disease pathways that traditional epidemiological approaches may overlook. This capability supports personalized approaches to healthcare and public health interventions, optimizing treatment strategies and preventive measures based on individual risk profiles. Overall, AI/ML holds promise in advancing epidemiology by enhancing predictive capabilities, guiding evidence-based policies, and improving health outcomes at both individual and population levels.

APPLICATIONS OF AI/ML IN EPIDEMIOLOGY

The use of AI and its methods can occur at different levels and in several areas of epidemiology, particularly in the domains of disease prediction, prevention and early symptom detection, and health diagnosis and treatment.[21] Figure 3 details how machine learning methods address the complexity of real-time data processing in health monitoring systems, enhancing health diagnosis, early symptom detection, and disease prediction across various health domains.

- **Disease surveillance and outbreak detection:** AI/ML technologies can significantly enhance disease surveillance and outbreak detection by analyzing large-scale data from diverse sources. AI/ML algorithms can identify patterns indicative of emerging health threats. For example, Health Monitoring Systems technologies enable real-time monitoring and rapid response which are crucial in containing outbreaks and preventing widespread transmission.[22,23] Moreover, AI/ML can analyze social media posts, hospital records, and other data to detect unusual increases in disease incidence, facilitating early intervention.
- **Risk Prediction and Disease Prevention:** AI/ML can also improve risk prediction by assessing individual´s susceptibility to diseases. By integrating data from genetic profiles, lifestyle factors, environmental exposures, and medical histories, AI/ML models can predict the likelihood of developing specific conditions. This predictive capability allows for targeted interventions and personalized prevention strategies, aiming to reduce disease incidence and improve health outcomes. In this way, AI/ML contributes to both prediction and prevention, helping to protect public health more effectively.
- **Treatment optimization/personalization:** In personalized medicine, AI/ML can optimize treatment plans based on individual patient characteristics. By analyzing vast amounts of clinical data, these technologies can identify the most effective treatments for specific patient subgroups, considering factors such as genetic makeup, disease severity, and response to previous treatments. This approach ensures that patients receive the most appropriate and effective care, improving treatment outcomes and reducing adverse effects.

[19] Zhou, L., Pan, S., Wang, J., & Vasilakos, A. V. (2017). Machine learning on big data: Opportunities and challenges. Neurocomputing, 237, 350-361.

[20] Paganelli, A. I., Mondéjar, A. G., da Silva, A. C., Silva-Calpa, G., Teixeira, M. F., Carvalho, F., ... & Endler, M. (2022). Real-time data analysis in health monitoring systems: A comprehensive systematic literature review. Journal of Biomedical Informatics, 127, 104009.

[21] Lefèvre, T., & Delpierre, C. (2022). Artificial Intelligence in Epidemiology. In Artificial Intelligence in Medicine (pp. 1341-1352). Cham: Springer International Publishing.

[22] Schwalbe, N., & Wahl, B. (2020). Artificial intelligence and the future of global health. The Lancet, 395(10236), 1579-1586.

[23] Paganelli, A. I., Mondéjar, A. G., da Silva, A. C., Silva-Calpa, G., Teixeira, M. F., Carvalho, F., ... & Endler, M. (2022). Real-time data analysis in health monitoring systems: A comprehensive systematic literature review. Journal of Biomedical Informatics, 127, 104009.

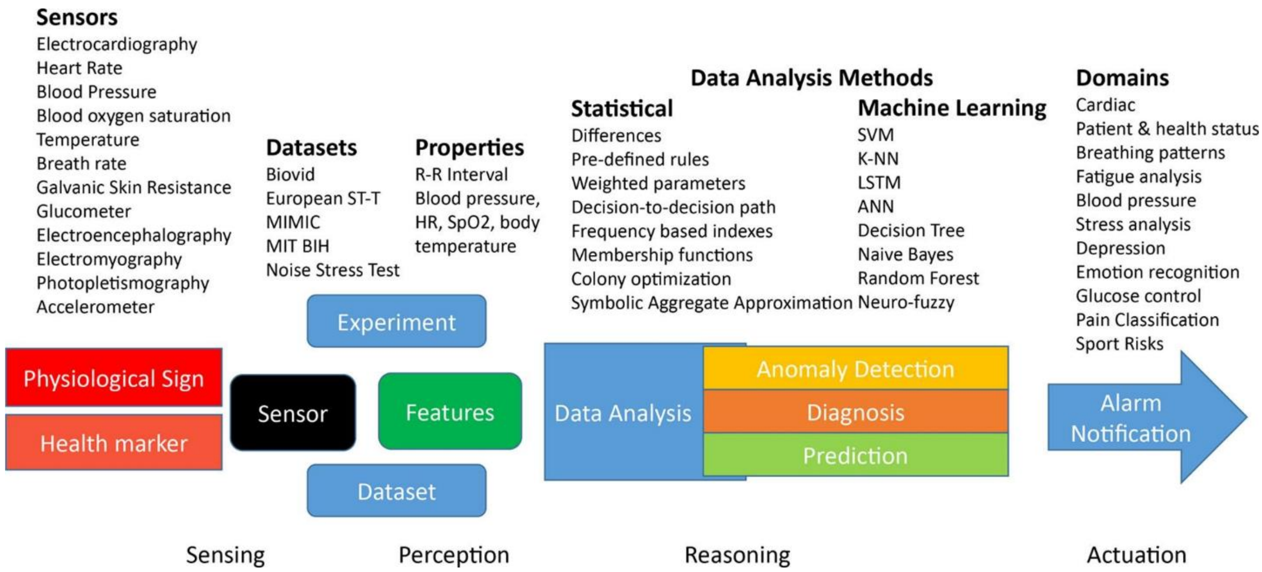

Figure 3. Comprehensive view on how machine learning methods address the complexity of real-time data processing in health monitoring systems, enhancing health diagnosis, early symptom detection, and disease prediction across various health domains. (Source: [24])

ROLE OF EPIDEMIOLOGISTS IN TECHNOLOGICAL TRANSFORMATION

Epidemiologists focus on leveraging new technologies, such as AI and ML, as tools to solve health problems. Expertise in study design, data interpretation, and exposure analysis is crucial for ensuring that the adoption of these technologies. Recent innovations in public health include the use of AI/ML models to integrate and analyze heterogeneous data sources such as electronic health records, genomic data, environmental sensors, and social media. Unlike traditional epidemiology which builds interpretable models based on explicit assumptions, AI focuses on predictive models derived from data without necessarily understanding the underlying reasons. This shift presents both challenges and opportunities in the field of public health.[25]

Epidemiologists must guide the implementation of these models, improving data interoperability and integration to achieve more robust and predictive analyses. Moreover, AI/ML technologies promise to enhance real-time epidemiological surveillance and early warning systems by processing streaming data to detect disease outbreaks early. Epidemiologists need to be involved in the development of these systems to ensure they are effective and that public health responses are timely and well-coordinated.

HARMONIZATION AND RISK REDUCTION

To harmonize technological developments with epidemiological practices and minimize risks of errors and misuse, a structured approach is needed:

- **Critical Assessment of Technologies**: Epidemiologists must critically evaluate statistical methods and AI/ML technologies, understanding that while these tools offer new opportunities, they also have limitations and potential errors. Technologies should address well-defined scientific questions.

[24] Paganelli, A. I., Mondéjar, A. G., da Silva, A. C., Silva-Calpa, G., Teixeira, M. F., Carvalho, F., ... & Endler, M. (2022). Real-time data analysis in health monitoring systems: A comprehensive systematic literature review. Journal of Biomedical Informatics, 127, 104009.

[25] Sung, J., & Hopper, J. L. (2023). Co-evolution of epidemiology and artificial intelligence: challenges and opportunities. International Journal of Epidemiology, 52(4), 969-973.

- **Training and Updates:** Upskilling for epidemiologists is essential to keep them updated on the latest methodologies and technologies. This includes understanding how new techniques can impact study design, data collection, and result interpretation.[26]
- **Robust Study Design**: Solid study design remains crucial. Epidemiologists must ensure that even with new technologies, the fundamentals of study design, such as questionnaire development and participant selection, are strategized and FAIR processes rigorously followed to avoid bias and ensure reliable results.[27]
- **Multidisciplinary Integration**: Collaboration with experts in bioinformatics, data science, toxicology and other fields is critical for effectively integrating AI/ML technologies. Epidemiologists should act as a hub in multidisciplinary teams to address challenges related to study design and data analysis, ensuring that emerging technologies are applied correctly.[28]
- **Monitoring and Evaluation:** Implementing continuous monitoring and evaluation of the effectiveness of the technologies used is important. Epidemiologists should be involved in assessing the results produced by AI/ML to ensure they are reliable and useful for public health decisions.

CHALLENGES AND LIMITATIONS OF APPLYING AI/ML IN EPIDEMIOLOGY

Epidemiologists play a pivotal role in guiding the integration of artificial intelligence (AI) and machine learning (ML) into public health. Given that the field of epidemiology has historically lagged 5–8 years behind the latest advancements in data science, it is essential that epidemiologists not only adopt these emerging techniques but also lead their effective and safe application. This leadership is crucial for ensuring that new technologies are used to address relevant public health questions, improve health outcomes, and minimize associated risks.[29] Applying AI/ML in epidemiology presents several challenges and considerations that need to be addressed. First, ensuring the quality and completeness of data is crucial as AI/ML algorithms heavily rely on accurate and representative datasets for reliable analysis and predictive modeling.

DATA QUALITY & ETHICS

The effectiveness of AI/ML applications in epidemiology heavily depends on the quality of the data. Inaccurate, incomplete, or biased data can lead to erroneous conclusions and undermine the reliability of AI/ML models. Ensuring data quality requires robust data collection, validation, and management processes.

Data fragmentation, inconsistencies, biases, and missing data can all undermine the validity and generalizability of machine learning outcomes in epidemiological studies.[30] Second, the interpretability of AI/ML models poses a significant challenge. Complex algorithms like deep neural networks often operate as "black boxes," making it difficult to understand the underlying reasons for their predictions. This lack of

[26] Lau, B., Duggal, P., Ehrhardt, S., Armenian, H., Branas, C. C., Colditz, G. A., ... & Celentano, D. D. (2020). Perspectives on the future of epidemiology: a framework for training. American journal of epidemiology, 189(7), 634-639.
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transparency can hinder validation efforts, limit trust from healthcare professionals, and impede the translation of findings into actionable insights for public health interventions.

Ethical considerations are also paramount in AI/ML applications in epidemiology. Protecting patient confidentiality, ensuring data privacy, and addressing algorithmic bias are critical aspects. Compliance with regulatory standards such as GDPR and HIPAA is essential to safeguard sensitive health information while leveraging large-scale datasets for analysis. Moreover, efforts to mitigate biases in algorithmic decision-making are crucial to ensure fairness and equity, particularly in healthcare delivery where vulnerable populations may be disproportionately affected.

INTERPRETABILITY

Technical expertise and resource availability present additional challenges. Successful implementation of AI/ML in epidemiology requires specialized skills in data science, machine learning, and computational biology. Access to robust computing infrastructure, advanced software tools, and interdisciplinary collaboration between epidemiologists, computer scientists, and healthcare professionals is essential to overcome technical barriers and maximize the impact of AI/ML applications. Finally, validating the reliability and integrating AI/ML-driven insights into epidemiological practices and healthcare workflows is critical. Rigorous validation processes, pilot testing, and continuous evaluation are necessary to ensure the clinical relevance, correctness, usability, and positive impact of AI/ML models on public health outcomes. Addressing these challenges comprehensively is essential to harnessing the full potential of AI/ML in epidemiology for enhancing disease surveillance, improving risk prediction, and advancing personalized healthcare delivery while upholding ethical standards and promoting data-driven decision-making.

EMERGING TRENDS AND FUTURE DIRECTIONS IN AI/ML APPLIED TO EPIDEMIOLOGY

Emerging trends and future directions in AI/ML applied to epidemiology indicate a transformative impact on public health practices. These advancements are poised to enhance epidemiological research and healthcare delivery through several key avenues.

Firstly, there is a growing emphasis on developing AI/ML models that can handle heterogeneous data sources more effectively. Integrating data from diverse sources such as electronic health records, genomics, environmental sensors, and social media can provide a comprehensive understanding of disease dynamics and risk factors. Future AI/ML systems will likely focus on improving data interoperability, standardization, and integration across these disparate datasets to enable more robust analyses and predictive capabilities. Secondly, the evolution towards real-time epidemiological surveillance and early warning systems is accelerating. AI/ML algorithms capable of processing streaming data in real-time, including diverse channels, environmental monitoring data, and healthcare utilization patterns, hold promise for detecting disease outbreaks promptly. These advancements can facilitate proactive public health interventions, resource allocation, and mitigation strategies to contain infectious diseases and mitigate health risks. Moreover, the future of AI/ML in epidemiology entails enhancing precision medicine and personalized healthcare approaches. Machine learning algorithms can analyse large-scale genomic and clinical datasets to identify biomarkers, predict individual disease risks, and tailor treatment strategies based on patient-specific characteristics. This personalized approach has the potential to improve therapeutic outcomes, reduce adverse events, and optimize healthcare resource utilization. Additionally, the integration of AI/ML with other emerging technologies such as wearable devices, telemedicine platforms, and Internet of Things (IoT) devices is expected to expand. These synergies can enable continuous health monitoring, remote patient management, and real-time data collection, thereby revolutionizing epidemiological studies and enhancing population health management.

REGULATORY CONSIDERATIONS

The European Union emphasizes strict regulations for high-risk AI applications, which include AI used in healthcare and epidemiology. The criteria for determining high-risk AI depends on the sector of use (e.g., healthcare) and the specific purpose (e.g., disease diagnosis or risk prediction). High-risk AI applications must comply with rigorous standards to ensure safety, consumer rights, and fundamental rights are protected.

- **EU Commission White Paper on Artificial Intelligence (2020):** This document outlines the EU's strategy for fostering AI development while ensuring safety, ethical standards, and fundamental rights. It emphasizes the need for a framework that supports innovation while addressing risks associated with AI technologies.

  European Commission. (2020). White Paper on Artificial Intelligence - A European approach to excellence and trust. Retrieved from EU Commission website.

- **First Regulatory Act on AI (2024):** The AI Act, adopted in 2024, introduces stringent regulations for high-risk AI systems, including those in healthcare and epidemiology. It sets out clear criteria for high-risk AI, focusing on sectors such as healthcare and specific applications like disease diagnosis and risk prediction.

  European Parliament and Council. (2024). Regulation (EU) 2024/XX on Artificial Intelligence. Retrieved from EU Law Portal.

CONCLUSION

Looking ahead, the potential impact of AI/ML in epidemiology is vast. Epidemiology is the cornerstone of public health, playing a vital role in understanding and mitigating the spread of diseases.[31] It studies the distribution and determinants of health-related states or events in specific populations. Through rigorous data analysis on disease patterns and risk factors, epidemiology brings insights on preventive measures, and health interventions that protect human health on a large scale.[32] AI/ML offers a distinct approach to epidemiology that differs from traditional methods by not prioritizing causal inference[33]. While traditionalists may view this as a flaw leading to poor predictions of intervention outcomes, there is potential for ML to make accurate predictions and drive conceptual innovation in epidemiology. Efforts are underway to merge ML with graphical causal models, allowing ML to discover high-level causal relationships without extensive prior domain knowledge. This approach promises benefits like improved model validity and better identification of public health interventions, despite differing from the hypothesis-driven traditional methods. Thus, continued advancements in computational power and algorithmic sophistication will enable even more precise and actionable insights. Collaborative efforts across disciplines, such as bioinformatics, data science, and public health, will be crucial in harnessing the full potential of AI/ML technologies.

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