Artificial Intelligence Algorithm for Early Detection of Pathogens in Clinical Samples

Algoritmo de Inteligência Artificial para Detecção Precoce de Patógenos Em Amostras Clínicas

Algoritmo de Inteligencia Artificial para la Detección Temprana de Patógenos en Muestras Clínicas

RESUMO

A inteligência artificial (IA) para detecção precoce de patógenos representa um avanço significativo em diagnósticos de saúde. Técnicas tradicionais, como microscopia de esfregaço e ensaios bioquímicos, frequentemente sofrem com tempos de processamento prolongados e sensibilidade limitada, necessitando de soluções de detecção mais rápidas e precisas [1]. Além de aprimorar as capacidades de diagnóstico, dá suporte a decisões de tratamento oportunas, num cenário cada vez mais desafiado por doenças infecciosas emergentes. Seu papel transformador, particularmente destacado durante a pandemia da COVID-19, facilitou processos de diagnóstico rápido e melhorou a tomada de decisão clínica por meio da análise de dados [2][3]. Permitiram o desenvolvimento de algoritmos sofisticados capazes de identificar patógenos com precisão notável, conforme demonstrado por estudos que mostram a eficácia de modelos como Gradient Boosting Machines (GBM) e K-Nearest Neighbors (KNN) em ambientes clínicos [4]. Auxiliam nos testes de suscetibilidade a antibióticos, otimizando as estratégias de tratamento. Apesar do potencial promissor, vários desafios e controvérsias notáveis persistem. A pesquisa envolveu revisão sistemática descritiva exploratória, feita de 2020 a 2024 na base de dados PubMed, mostrando problemas relacionados à qualidade e representatividade dos dados, que podem levar a vieses algorítmicos, o que pode prejudicar a eficácia das aplicações de IA em diversos grupos demográficos de pacientes [5][6]. As estruturas regulatórias também estão evoluindo para abordar as complexidades da IA na área da saúde, com foco na segurança, eficácia e considerações éticas em torno da privacidade dos dados do paciente e da transparência do algoritmo [7][8].
PALAVRAS CHAVE: Inteligência Artificial; Epidemiologia com IA; Análises Clínicas com IA; Diagnóstico com IA.

ABSTRACT

Artificial intelligence (AI) for the early detection of pathogens represents a significant advance in health diagnostics. Traditional techniques, such as smear microscopy and biochemical assays, often suffer from long processing times and limited sensitivity, requiring faster and more accurate detection solutions [1]. In addition to improving diagnostic capabilities, it supports timely treatment decisions in a scenario increasingly challenged by emerging infectious diseases. Its transformative role, particularly highlighted during the COVID-19 pandemic, has facilitated rapid diagnostic processes and improved clinical decision-making through data analysis [2][3]. They have enabled the development of sophisticated algorithms capable of identifying pathogens with remarkable accuracy, as demonstrated by studies showing the effectiveness of models such as Gradient Boosting Machines (GBM) and K-Nearest Neighbors (KNN) in clinical settings [4]. They help in antibiotic susceptibility testing, optimizing treatment strategies. Despite the promising potential, several notable challenges and controversies remain. Problems related to data quality and representativeness can lead to algorithmic biases, which can hinder the effectiveness of AI applications in various patient Bemographic groups [5][6]. Regulatory frameworks are also evolving to address the complexities of AI in healthcare, with a focus on safety, efficacy and ethical considerations around patient data privacy and algorithm transparency.
KEYWORDS: Artificial Intelligence; AI Epidemiology; AI Clinical Analysis; AI Diagnostics.

RESUMEN

La inteligencia artificial (IA) para la detección temprana de patógenos representa un avance significativo en los diagnósticos de salud. Las técnicas tradicionales, como la microscopía de extendido y los ensayos bioquímicos, a menudo enfrentan tiempos de procesamiento prolongados y una sensibilidad limitada,

DOI: https://doi.org/10.36489/saudecoletiva.2025v15i94p15283-15294

lo que requiere soluciones de detección más rápidas y precisas [1]. Además de mejorar las capacidades diagnósticas, respalda decisiones de tratamiento oportunas, en un escenario cada vez más desafiado por enfermedades infecciosas emergentes. Su papel transformador, particularmente destacado durante la pandemia de COVID-19, facilitó los procesos de diagnóstico rápido y mejoró la toma de decisiones clínicas a través del análisis de datos [2] [3]. Permitieron el desarrollo de algoritmos sofisticados capaces de identificar patógenos con una precisión notable, como lo demuestran estudios que muestran la eficacia de modelos como Gradient Boosting Machines (GBM) y K-Nearest Neighbors (KNN) en entornos clínicos [4]. Ayudan en las pruebas de susceptibilidad a antibióticos, optimizando las estrategias de tratamiento. A pesar del potencial prometedor, persisten varios desafíos y controversias notables. La investigación implicó una revisión sistemática descriptiva exploratoria, realizada entre 2020 y 2024 en la base de datos PubMed, que muestra problemas relacionados con la calidad y representatividad de los datos, lo que puede conducir a sesgos algorítmicos y perjudicar la eficacia de las aplicaciones de IA en diversos grupos demográficos de pacientes [5] [6]. Las estructuras regulatorias también están evolucionando para abordar las complejidades de la IA en el área de la salud, con enfoque en la seguridad, eficacia y consideraciones éticas en torno a la privacidad de los datos del paciente y la transparencia del algoritmo [7] [8].
PALABRAS CLAVE: Inteligencia Artificial; Epidemiología con IA; Análisis Clínicos con IA; Diagnóstico con IA.

RECEIVED: 02/26/2025 **APPROVED:** 03/12/2025

How to cite this article: Chaves ANS. Artificial Intelligence Algorithm For Early Detection Of Pathogens In Clinical Samples. Saúde Coletiva (Edição Brasileira) [Internet]. 2025 [acesso ano mês dia];15(94):15283-15294. Disponível em: DOI: 10.36489/saudecoletiva.2025v15i94p15283-15294

MSc. Alexandre Nascimento da Silva Chaves
ORCID: https://orcid.org/0009-0008-1286-0389

INTRODUCTION

Pathogen detection is critical for timely diagnosis and treatment in healthcare settings. Traditional methods for identifying pathogenic microorganisms, such as smear microscopy, isolation and cultivation, and biochemical assays, often face significant limitations, including prolonged processing times and suboptimal sensitivity. [1]

As a result, there is a growing demand for rapid and accurate detection techniques that can address these shortcomings. Recent advances in technology have led to the development of innovative pathogen detection methods, including nucleic acid and immunological approaches, that enhance the ability to identify pathogenic bacteria and assess potential health risks in a variety of contexts, including public health and environmental monitoring. [1] [9]

However, existing technologies still struggle to meet clinical demands due to cumbersome procedures and the need for large instruments, which can hinder efficient identification. [1]

Artificial Intelligence (AI) has emerged as a transformative tool in medical imaging, significantly improving the speed and accuracy of diagnostic processes. During the COVID-19 pandemic, AI has been instrumental in improving the diagnostic capabilities of chest CT scans and X-rays, facilitating rapid triage and identification of the disease. [2] [3]

AI's role extends beyond imaging; it also assists in analyzing data related to secondary infections in COVID-19 patients, providing crucial insights into disease severity and clinical outcomes. [2]

As AI technologies evolve, they are increasingly being applied in public health surveillance and epidemic modeling, enabling predictive analysis of disease outbreaks and other health risks. [3] [5]

Machine learning techniques have also been incorporated into microscopic imaging methods for pathogen identification, offering rapid results for pathogen detection and antibiotic susceptibility testing (AST) [1] [10].

This integration of AI into pathogen detection holds great promise for improving diagnostic accuracy, tailoring treatment strategies, and ultimately improving patient outcomes.

DEVELOPMENT

ALGORITHM DEVELOPMENT
Overview of AI in Healthcare

Artificial Intelligence (AI) has become increasingly essential in healthcare, particularly due to its ability to perform tasks that mimic human cognition, such as problem-solving and learning. This ability allows AI to automate tasks, identify patterns in data, and synthesize diverse sources of information. AI technologies are already used in a variety of healthcare applications, including radiology and the analysis of data from wearable sensors, enabling early detection of diseases and monitoring of health conditions. [6] [2]

Types of Algorithms

AI algorithms vary significantly, mainly falling into two categories: gated algorithms and adaptive algorithms. Gated algorithms produce consistent results for identical inputs, while adaptive algorithms can modify their responses based on new data, potentially generating different results over time. [6]

The FDA has so far approved AI devices that use gated algorithms, but has proposed a regulatory framework for those that use adaptive learning techniques. This presents both opportunities and challenges, as adaptive algorithms can evolve with incoming data, but can also introduce risks associated with real-time learning and potential biases in decision-making. [6]

Machine Learning Approaches

Most machine learning (ML) applications in healthcare rely on supervised learning, where labeled data trains the algorithm to recognize patterns and make predictions. [6]

For example, an algorithm can be trained on labeled medical image datasets to differentiate between healthy and diseased states. The accuracy of these models often depends on robust training datasets and extensive validation, which ensures that they perform well on new and previously unseen data. [6]

Data Collection and Validation

The effectiveness of AI algorithms to detect pathogens largely depends on data collection methods. Data can be obtained from large healthcare systems, collaborations between multiple data holders, or even from data brokers. Each method presents unique challenges, particularly regarding data representativeness and potential biases, which can distort the algorithm's performance. [7] The research involved an exploratory descriptive systematic review, carried out between 2020 and 2024 in the PubMed database, showing problems related to the quality and representativeness of the data, which can lead to algorithmic biases, which can harm the effectiveness of AI applications in different demographic groups of patients. [5] [6]

Analytical validation is crucial in this context, as it establishes that an algorithm's performance characteristics meet acceptable standards, ensuring safety and efficacy in real-world applications. [7]

Advances in AI techniques

Recent advances in scalable computing power have fostered the development of new AI techniques, particularly in healthcare. AI algorithms excel at processing large, high-dimensional datasets, making them well-suited to optimizing care pathways, standardizing diagnoses, and creating predictive models. [2]

For example, an ML model developed to distinguish COVID-19 patients based on blood indices demonstrated an impressive accuracy of nearly 97% in validation tests, showing the potential of AI in clinical diagnostics. [2]

Challenges and Future Directions

Despite the advantages offered by adaptive algorithms, they come with risks such as the potential for biased learning from flawed data. Furthermore, the dynamic nature of healthcare data—characterized by evolving treatment protocols and patient populations—necessitates ongoing validation of AI algorithms to maintain their accuracy over time. [6]

The path forward involves refining regulatory frameworks and validation processes, ensuring that AI systems can adapt while remaining trustworthy and ethical in their applications in healthcare settings. [6][7]

RESULTS

The study on the development of an artificial intelligence algorithm for early detection of pathogens in clinical samples yielded significant findings across several machine learning models employed. The Gradient Boosting Machine (GBM) model demonstrated exemplary performance, achieving an accuracy of 91.01% for the Enterobacteriaceae genus, with a corresponding F1 Score of 0.944 and a Brier Score of 0.214, indicating high accuracy in probabilistic predictions. [4]

The ability of this model to balance precision and recall was evident, particularly for other genera such as Streptococcus, Enterococci, and fungi, for which it achieved perfect F1 scores of 1.0000. [4]

The K-Nearest Neighbors (KNN) model showed consistent performance, notably with the Enterobacteriaceae genus, achieving an accuracy of 77.53% and an F1 Score of 0.779 [4].

Its reliability was further highlighted by a moderate Brier Score of 0.449, indicating reliable probabilistic predictions. Furthermore, the Boosted Logistic Regression model produced strong results, especially with the Streptococcus genus, where it achieved perfect scores across all evaluation metrics and maintained high predictive accuracy for Enterobacteriaceae and Fungi, with accuracy rates exceeding 83%. [4]

DOI: https://doi.org/10.36489/saudecoletiva.2025v15i94p15283-15294

Evaluation metrics including precision, accuracy, recall, and F1 score were used to assess the performance of the models. The consistent findings across all these metrics highlighted the superiority of the GBM model, which outperformed others by margins of 13.48%, 7.14%, and 4.49% in terms of accuracy. [4]

The study also employed 5-fold cross-validation to ensure reliability of accuracy rates, mitigating the impact of imbalanced data distributions. [11]

Additionally, the use of a confusion matrix for the CNN model provided a quick visual representation of misclassified genera, adding depth to the assessment of model performance. [11]

Applications

Improving clinical decision making

Artificial intelligence (AI) algorithms play a significant role in improving the effectiveness and accuracy of public health and clinical decision-making. These applications not only optimize healthcare outcomes but also highlight the need for a robust framework to responsibly manage these technologies. [3]

Integration with healthcare systems

Integrating AI algorithms into existing healthcare systems can be achieved through several technical approaches. For example, creating standardized Application Programming Interfaces (APIs) facilitates data exchange and access to functionality between Edge AI systems and healthcare infrastructures. [12]

Middleware and integration platforms designed specifically for healthcare can optimize data integration and workflow alignment, thereby increasing operational efficiency. [12]

Pilot projects serve as proof-of-concept studies, demonstrating the feasibility of integrating Edge AI technologies for early health prediction into established healthcare frameworks. [12]

Regulatory considerations

The Food and Drug Administration (FDA) plays a crucial role in regulating AI-based medical products. Many AI-based solutions are classified as Software as a Medical Device (SaMD), especially those intended for diagnostic purposes, such as software that analyzes MRI images to detect strokes or breast cancer. [6]

Regulation of these systems is based on their intended use and the associated risk levels, requiring careful assessment to ensure safety and effectiveness. [6]

AI and patient-centric approaches

AI applications also enhance patient engagement by leveraging diverse data sets to create personalized healthcare solutions. For example, the incorporation of AI IoT (Artificial Intelligence Internet of Things) improves the quality of care for chronic conditions and elderly patients through continuous monitoring and data capture. [5]

Technologies such as blockchain and Federated Learning ensure that patient data remains secure and private while enabling more personalized treatment plans. [5]

In addition, methods such as Homomorphic Encryption and Differential Privacy help protect patient identities during data analysis, thereby promoting a patient-centric approach to healthcare. [5]

Informing Clinical Management

Many clinical AI systems are designed to “inform” rather than “drive” clinical management, allowing experienced clinicians to corroborate and review AI-generated recommendations. [7]

These systems can improve the quality and consistency of diagnostic testing, ultimately improving clinical outcomes. [7] Regulators expect these AI systems to support safer and more effective clinical practices, aligning with the goals of personalized medicine. [7]

CHALLENGES AND LIMITATIONS

Data quality and availability

When developing AI algorithms for pathogen detection, data quality and availability pose significant challenges. Low- and middle-income countries (LMICs) often struggle to sustain daily data transmission due to resource constraints, making it difficult to collect comprehensive datasets needed for effective AI training and application. [9]

For example, the Federated States of Micronesia and Samoa faced connectivity issues and limited access to trained personnel when attempting to deploy a web-based surveillance tool during major events, highlighting the challenges in collecting and managing data in low-resource settings. [9]

Ethical and Privacy Concerns

The integration of AI technologies into healthcare raises substantial ethical issues, particularly with regard to patient privacy and data security. The use of large amounts of personal health data requires robust safeguards against unauthorized access and breaches. [3]

Anonymizing patient data, while essential for privacy, can lead to complications in ensuring the representativeness of datasets, which is crucial to mitigating bias in AI models. [6]

In addition, the debate surrounding patient consent for data sharing complicates the ethical landscape, as individuals may not fully understand how their data will be used. [6]

Bias and algorithmic fairness

DOI: https://doi.org/10.36489/saudecoletiva.2025v15i94p15283-15294

Bias in AI algorithms can arise from a variety of sources, including the quality of training data and the context in which an algorithm is developed and applied. Inconsistent labeling or insufficient experience during data collection can lead to biased models, while algorithms designed in well-resourced settings may not generalize effectively in less well-resourced settings. [6]

Addressing algorithmic fairness is critical to ensuring equitable treatment across diverse patient demographics, requiring the inclusion of diverse datasets in AI training processes. [5]

Technical limitations

Despite advances in pathogen detection technologies, many traditional methods remain limited by long processing times and complex procedures. These limitations hinder rapid pathogen identification, a critical factor for effective clinical diagnosis and public health responses. [1]

In addition, current detection techniques may not adequately meet clinical needs due to their reliance on large instruments, thus slowing the diagnostic process and limiting timely interventions. [1]

Implementation challenges

Successful deployment of AI-enabled tools in clinical settings requires not only technical integration with existing healthcare systems, but also comprehensive user training and awareness of potential risks. There is an urgent need for transparency and user trust in AI-driven healthcare solutions to mitigate fears around algorithmic decision-making and biases. [6]

Implementing AI without thorough validation in the local context can lead to inappropriate recommendations for less-resourced facilities, further complicating healthcare delivery. [6]

Regulatory Frameworks

The regulatory landscape for artificial intelligence (AI) in healthcare is rapidly evolving, necessitating frameworks that address the unique challenges posed by AI technologies, particularly in the context of health data management and patient privacy. Health data, often categorized as sensitive, is subject to stringent regulations under laws such as the General Data Protection Regulation (GDPR) in the European Union and various consumer protection laws in the United States, such as the California Consumer Protection Act. [7][8]

The GDPR mandates that personal data be collected and processed only for legitimate purposes with the explicit consent of individuals, thus influencing the privacy practices of entities involved in the development of medical AI, even outside the EU. [7]

Explainability and Transparency

Regulators are increasingly recognizing the importance of explainability and transparency in AI systems. Explainability may be necessary not only for safety and efficacy oversight, but also to ensure that clinicians, quality assurance officers, and developers can understand the decision-making processes of AI tools. [7]

This is particularly relevant in light of the 21st Century Cures Act, which leaves certain ambiguities regarding AI software used for clinical recommendations and requires healthcare professionals to independently evaluate such tools. [7]

The FDA's enforcement discretion further complicates the regulatory landscape by allowing some AI applications to circumvent stringent medical device regulations. [7]

CONCLUSION

Privacy and Data Protection

Privacy concerns are paramount in the development of AI systems, especially considering that AI training typically involves large datasets containing sensitive health information. [7] [8]

Effective safeguards are needed to protect patient privacy and ensure agency over personal data. Recent public-private partnerships in AI have raised alarms about inadequate privacy protections, highlighting the need for robust oversight mechanisms. [8]

In addition, the risk of data re-identification through advanced algorithms requires continued improvement in anonymization techniques and a focus on data stewardship by private custodians. [8]

International Perspectives

While the EU has established a strong regulatory framework with initiatives such as the proposed AI Act, other jurisdictions, such as Canada, are still developing tailored regulations. [8][13]

The current regulatory landscape is characterized by a patchwork of laws that may not fully address the implications of AI in healthcare. Therefore, there is an urgent need for comprehensive frameworks that align AI regulations with health, safety and human rights standards to promote ethical and effective implementation in clinical settings. [13][14]

Future Directions

The early stages of AI regulation indicate an urgent need for ongoing assessment and adaptation to keep pace with technological advances. [13]

As healthcare systems increasingly adopt AI technologies, regulatory frameworks must evolve to address specific challenges related to AI medical devices, data protection, and patient safety, thereby ensuring the responsible use of AI in pathogen detection and other clinical applications. [13][14]

CONCLUSION

Given the growing need for research on this topic, the search for proto-

DOI: https://doi.org/10.36489/saudecoletiva.2025v15i94p15283-15294

cols that optimize discoveries and can predict mass contagions, assist health professionals in diagnoses and treatments, and be part of the logistics of health management planning around the world, is a reality. However, privacy concerns are paramount in the development of AI systems, especially considering that AI training typically involves large data sets containing confidential health information.

Seeking to create databases that corroborate readings and understandings about pandemic contagions like those we have suffered in the past is of paramount importance. However, effective safeguards are necessary to protect patient privacy, guarantees over personal data and its security. Recent public-private partnerships in AI have raised alarms about inadequate privacy protections, highlighting the need for robust oversight mechanisms. In addition, the risk of data re-identification through advanced algorithms requires continuous improvement in anonymization techniques and a focus on data management by private custodians.

While the European Union has established a strong regulatory framework with initiatives such as the proposed AI Act, other jurisdictions, such as Canada, are still developing tailored regulations. Furthermore, the current regulatory landscape is characterized by a patchwork of laws that may not fully address the implications of AI in healthcare. Therefore, there is an urgent need for comprehensive frameworks that align AI regulations with health, safety, and human rights standards to promote ethical and effective implementation in clinical settings.

REFERENCES

YUNQIU, Gao; MIN, Liu. Application of machine learning based genome sequence analysis in pathogen identification. Front. Microbiol., 01 October 2024, Sec. Systems Microbiology. V15 – 2024. https://doi.org/10.3389/fmicb.2024.1474078.

MECKAWY, R., STUCKLER, D., MEHTA, A. et al. Eficácia dos sistemas de alerta precoce na detecção de surtos de doenças infecciosas: uma revisão sistemática. BMC Saúde Pública 22, 2216 (2022). https://doi.org/10.1186/s12889-022-14625-4.

ABDULKAREEM, M., AND PETERSEN, SE. (2021) The Promise of AI in Detection, Diagnosis, and Epidemiology for Combating COVID-19: Beyond the Hype. Front. Artif. Intell. 4:652669. doi: 10.3389/frai.2021.652669.

DANKWA-MULLAN, I. Equidade em saúde e considerações éticas no uso da inteligência artificial em saúde pública e medicina. Prev Chronic Dis 2024;21:240245 (em inglês). DOI: http://dx.doi.org/10.5888/pcd21.240245.

WILLIAMSON, S. M., AND PRYBUTOK, V. 2024. "Balancing Privacy and Progress: A Review of Privacy Challenges, Systemic Oversight, and Patient Perceptions in AI-Driven Healthcare" Applied Sciences 14, no. 2: 675. https://doi.org/10.3390/app14020675.

HARRIS, MOHAMMED. 2023. "Machine Learning and Artificial Intelligence for Pathogen Identification and Antibiotic Resistance Detection: Advancing Diagnostics for Urinary Tract Infections" BioMed 3, no. 2: 246-255. https://doi.org/10.3390/biomed3020022.

FDA. How FDA Regulates Artificial Intelligence in Medical Products. As technology evolves, oversight will need to keep pace. Health Care Products. August 5, 2021.

National Academies of Sciences, Engineering, and Medicine. 2022. Artificial Intelligence in Health Care: The Hope, the Hype, the Promise, the Peril. Washington, DC: The National Academies Press. https://doi.org/10.17226/27111.

LIU, Q., CHEN, Y., XIE, P. et al. Desenvolvimento de um modelo preditivo de aprendizado de máquina para perfis de patógenos em pacientes com imunodeficiência secundária. BMC Med Inform Decis Mak 24, 48 (2024). https:/doi.org/10.1186/s12911-024-02447-w.

Jia-Wei, Tang; Jia-Qi Li; Jia-Qi, Li; Xiao-Cong, Yin; Xiao-Cong, Yin; Wen-Wen, Xu; Wen-Wen, Xu; Ya-Cheng, Pan; Ya-Cheng, Pan; Qing-Hua, Liu; Qing-Hua, Liu; Bing, Gu; Bing, Gu; Xiao, Zhang; Xiao, Zhang; Liang, Wang; Liang, Wang. Rapid Discrimination of Clinically Important Pathogens Through Machine Learning Analysis of Surface Enhanced Raman Spectra. Front. Microbiol., 07 April 2022 Sec. Systems Microbiology. Volume 13 - 2022 | https://doi.org/10.3389/fmicb.2022.843417 .

BADIDI, ELARBI. 2023. "Edge AI for Early Detection of Chronic Diseases and the Spread of Infectious Diseases: Opportunities, Challenges, and Future Directions" Future Internet 15, no. 11: 370. https://doi.org/10.3390/fi15110370.

MURDOCH, EM B. Privacidade e inteligência artificial: desafios para proteger a informação de saúde em uma nova era. BMC Med Ética 22, 122 (2021). https://doi.org/10.1186/s12910-021-00687-3.

SCHMIDT J, SCHUTTE NM, BUTTIGIEG S, NOVILLO-ORTIZ D, SUTHERLAND E, ANDERSON M, DE WITTE B, PEOLSSON M, UNIM B, PAVLOVA M, STERN AD, MOSSIALOS E, VAN KESSEL R. Mapeamento do panorama regulamentar da inteligência artificial em saúde na União Europeia. Baixar o jogo NPJ Digit Med. 2024 Ago 27;7(1):229. doi: 10.1038/s41746-024-01221-6. PMID: 39191937; PMCID: PMC11350181.

SARANTOPOULOS, ANDREAS, CHRISTINA MASTORI KOURMPANI, ATSHAYA LILY YOKARASA, CHIEDZA MAKAMANZI, POLYNA ANTONIOU, NIKOLAOS SPERNOVASILIS, AND CONSTANTINOS TSIOUTIS. 2024. "Artificial Intelligence in Infectious Disease Clinical Practice: An Overview of Gaps, Opportunities, and Limitations" Tropical Medicine and Infectious Disease 9, no. 10: 228. https://doi.org/10.3390/tropicalmed9100228.

Huang T, Zhang R, Li J. CRISPR-Cas-based techniques for pathogen detection: Retrospect, recent advances, and future perspectives. J Adv Res. 2023 Aug;50:69-82. doi: 10.1016/j.jare.2022.10.011. Epub 2022 Oct 30. PMID: 36367481; PMCID: PMC10403697.

DOI: https://doi.org/10.36489/saudecoletiva.2025v15i94p15283-15294