

Digital Transformation of Antimicrobial Stewardship: Mobile Applications, Clinical Decision Support Systems, Artificial Intelligence, and the Future of Antimicrobial Governance

Nagma Firdose^{1*}, Prathima C², Saddique Choudhury³, Rashmi P Mahale⁴

^{1*} Assistant Professor, Department of Pharmacology, JSS Medical College, Mysuru, Karnataka, India

² Associate Professor, Department of Pharmacology, JSS Medical College, Mysuru, Karnataka, India

³ PhD Scholar, Department of Pharmacology, JSS Medical College, Mysuru, Karnataka, India

⁴ Professor & HOD, Department of Microbiology, JSS Medical College, Mysuru, Karnataka, India

*Corresponding Author

DOI: <https://doi.org/10.51244/IJRSI.2026.1308000330>

Received: 07 September 2026; Accepted: 14 September 2026; Published: 25 September 2026

ABSTRACT

Background: Antimicrobial resistance (AMR) is a critical public health problem worldwide, affecting the effectiveness of available antimicrobial therapies. Antimicrobial stewardship programs (ASPs) have been successful in reducing the use of antimicrobials; however, classic stewardship strategies can be constrained by resources, time delays, and the complexity of clinical decision making. New digital health technologies have emerged over the last few years that offer the potential for improving stewardship by providing real-time decision support, monitoring and forecasting capabilities. **Objective:** To review the impact of digital technologies on antimicrobial stewardship, particularly mobile health apps, clinical decision support systems (CDSSs), artificial intelligence (AI), rapid diagnostics and digital antimicrobial governance. **Methods:** A narrative review was performed on the current literature to assess the applications, benefits, challenges and future directions of digital innovations for antimicrobial stewardship and AMR containment. **Results:** Digital technologies are revolutionizing antimicrobial stewardship by enhancing the timeliness, accuracy, and scale of interventions. AI and machine learning aid in resistance prediction, optimizing empirical therapy, sepsis detection, surveillance, and antimicrobial management. Rapid diagnostics (RDT) can be integrated to achieve earlier identification of the pathogen, targeted treatment, and antimicrobial de-escalation. Data-driven decision-making and real-time monitoring are enhanced with digital surveillance platforms, supporting antimicrobial governance. However, implementation is still hindered by user adoption, cybersecurity, cost, data quality, interoperability, and infrastructure issues. **Conclusion:** An era of closed-loop stewardship models is giving way to a new era of predictive, proactive, and precision antimicrobial governance as digital health technologies, advanced diagnostics, and AI combine. These technologies can be strategically integrated to enhance antimicrobial optimization and contribute to the global fight against AMR.

Keywords: Antimicrobial stewardship; Antimicrobial resistance; Digital health; Mobile health; Clinical decision support systems; Artificial intelligence; Antimicrobial governance

INTRODUCTION

Background

Antimicrobial resistance (AMR) is one of the most significant threats to global health, undermining decades of progress achieved through the development and use of antimicrobial agents. The burden of AMR is particularly important in low- and middle-income countries (LMICs), where limited access to diagnostic services, weaknesses in surveillance systems, and inappropriate antimicrobial use can contribute to the emergence and

spread of resistant pathogens. [2]

Antimicrobial stewardship programs (ASPs) are an essential component of strategies aimed at preserving the effectiveness of antimicrobial agents and promoting their appropriate use. Stewardship interventions have been associated with improvements in antimicrobial prescribing, reductions in unnecessary antimicrobial use, and improvements in selected patient and healthcare outcomes. Consequently, antimicrobial stewardship has become an important component of antimicrobial governance and has been supported by organizations including the World Health Organization (WHO), the Infectious Diseases Society of America (IDSA), and the Society for Healthcare Epidemiology of America (SHEA). [3–5]

Conventional stewardship approaches commonly involve prospective audit and feedback, formulary restriction, educational interventions, manual prescription review, and specialist consultation. Although these approaches remain important, their implementation can be constrained by workforce requirements, increasing prescribing complexity, delays in obtaining microbiological information, and the need for continuous surveillance. These limitations have stimulated interest in the application of digital technologies to antimicrobial stewardship. [6,16–18]

The increasing availability of electronic health records, computerized prescribing systems, clinical decision support systems (CDSSs), mobile health applications, advanced diagnostic technologies, artificial intelligence (AI), and machine learning has created new opportunities for antimicrobial stewardship. These technologies can facilitate access to treatment guidelines, support antimicrobial prescribing decisions, improve antimicrobial-use surveillance, assist antimicrobial de-escalation, and enable more timely stewardship interventions. [5,7–12]

Mobile health applications can provide point-of-care access to antimicrobial guidelines and prescribing information, whereas CDSSs can integrate clinical, microbiological and patient-specific information to support prescribing decisions. AI and machine learning have additionally been investigated for antimicrobial resistance prediction, optimization of empirical therapy, early identification of clinical deterioration, and antimicrobial surveillance. Rapid diagnostic technologies, including molecular diagnostic platforms, MALDI-TOF mass spectrometry, and automated antimicrobial susceptibility testing, may further enhance stewardship by providing clinically actionable microbiological information earlier in the course of treatment. [7–13]

The integration of these technologies represents a broader transition from predominantly retrospective stewardship interventions toward more proactive and data-driven antimicrobial management. However, digital transformation does not eliminate the need for multidisciplinary stewardship expertise. Infrastructure limitations, interoperability, data quality, implementation costs, cybersecurity, clinician acceptance, digital literacy, and regulatory considerations remain important determinants of successful implementation, particularly in resource-constrained healthcare settings. [5,10]

Justification of the Review

The increasing availability of digital health technologies has created new opportunities to strengthen antimicrobial stewardship, but their applications, benefits and implementation challenges are distributed across a heterogeneous body of literature. Evidence differs according to the technology used, healthcare setting, availability of digital infrastructure, clinical workflow, antimicrobial prescribing practices, and local epidemiology of antimicrobial resistance. These differences are particularly relevant in LMICs, where the burden of AMR may be substantial while access to specialist stewardship personnel, diagnostic facilities, interoperable health information systems and technical infrastructure remains variable.

A focused synthesis of the current evidence is therefore needed to understand how mobile applications, CDSSs, AI and machine learning, rapid diagnostics, and digital surveillance systems can contribute to antimicrobial stewardship and antimicrobial governance. In addition to technological capabilities, consideration of implementation barriers, equity, sustainability, data governance and the applicability of these approaches in LMICs is necessary for understanding their potential contribution to AMR containment.

Objectives

The primary objective of this narrative review was to examine the role of digital health technologies in antimicrobial stewardship and antimicrobial governance.

The specific objectives were:

1. To examine the applications of mobile health applications in antimicrobial stewardship.
2. To describe the role of clinical decision support systems in antimicrobial prescribing and optimization.
3. To examine the applications of artificial intelligence and machine learning in antimicrobial resistance prediction, antimicrobial prescribing, clinical deterioration detection and surveillance.
4. To evaluate the contribution of rapid diagnostic technologies to antimicrobial optimization, targeted therapy and de-escalation.
5. To examine the role of digital surveillance and integrated information systems in antimicrobial governance.
6. To identify technological, organizational, financial, ethical and regulatory barriers to implementing digital antimicrobial stewardship.
7. To consider the applicability of digital stewardship approaches in LMICs, including issues of infrastructure, equity, digital literacy and sustainability.
8. To discuss emerging directions in digital antimicrobial governance, including predictive analytics, precision antimicrobial stewardship, genomics and One Health approaches.

Research Questions

The review was guided by the following research questions:

1. How are digital health technologies being applied to antimicrobial stewardship?
2. How do mobile applications and CDSSs support appropriate antimicrobial prescribing and optimization?
3. What roles do AI and machine learning play in antimicrobial resistance prediction, empirical therapy and antimicrobial surveillance?
4. How can rapid diagnostic technologies, integrated with digital stewardship systems facilitate targeted antimicrobial therapy and de-escalation?
5. What technological, organizational, financial, ethical and regulatory barriers influence the implementation of digital antimicrobial stewardship?
6. What factors influence the applicability and sustainability of digital stewardship approaches in LMICs?
7. How might emerging technologies contribute to future antimicrobial governance and One Health approaches to AMR containment?

Hypothesis

The review hypothesized that appropriately integrated digital health technologies can strengthen antimicrobial stewardship by improving the timeliness and accessibility of prescribing information, supporting evidence-based antimicrobial decisions, facilitating antimicrobial-use and resistance surveillance, and enabling earlier optimization and de-escalation of antimicrobial therapy. However, the effectiveness, scalability and

sustainability of these technologies are expected to depend on healthcare infrastructure, data quality, interoperability, clinician acceptance, digital literacy, affordability, equity, cybersecurity and appropriate governance.

Definitions of Key Terms

Antimicrobial stewardship: A coordinated set of interventions designed to promote the appropriate use of antimicrobial agents, improve patient outcomes, and minimize adverse consequences associated with antimicrobial use, including antimicrobial resistance.

Digital antimicrobial stewardship: The application of digital health technologies to support antimicrobial prescribing, optimization, monitoring, surveillance, education and stewardship interventions.

Mobile health application: A software application used on a mobile device to provide health-related information, clinical guidance, educational resources or decision support.

Clinical decision support system: A computerized system that provides clinicians with patient-specific information, recommendations or alerts to support clinical decision-making within the healthcare workflow.

Artificial intelligence: Computational methods that enable systems to perform tasks involving the analysis of complex data, pattern recognition, prediction or decision support.

Machine learning: A subset of artificial intelligence in which computational models learn patterns from data to generate predictions or classifications without relying exclusively on explicitly programmed rules.

Rapid diagnostic technology: A diagnostic method capable of providing clinically relevant information regarding pathogens or antimicrobial resistance more rapidly than conventional diagnostic approaches.

Digital antimicrobial governance: The use of digital technologies and information systems to support antimicrobial-use monitoring, antimicrobial resistance surveillance, stewardship performance assessment, accountability and coordinated decision-making at institutional, regional, national or global levels.

One Health: An integrated approach that recognizes the interconnections among human, animal and environmental health in addressing health threats, including antimicrobial resistance.

METHODOLOGY

Study Design

This study was conducted as a narrative literature review to synthesize published evidence on the application of digital health technologies in antimicrobial stewardship (AMS) and antimicrobial resistance (AMR) containment. The review focused on mobile health applications, clinical decision support systems (CDSSs), artificial intelligence (AI), machine learning (ML), rapid diagnostic technologies, digital surveillance, and antimicrobial governance.

Study Area / Literature Sources

As a literature-based review, no specific geographical study area or primary study population was involved. Literature was searched using PubMed/MEDLINE and Google Scholar from May 2026 to July 2026. Reference lists of relevant publications were also manually screened to identify additional literature. Evidence from diverse healthcare settings was considered, with particular attention to low- and middle-income countries (LMICs) and their infrastructural, technological, and resource-related considerations.

Method of Data Collection

Literature searches were conducted using combinations of keywords related to antimicrobial stewardship,

antimicrobial resistance, digital health, mobile health applications, clinical decision support systems, artificial intelligence, machine learning, rapid diagnostics, antimicrobial surveillance, digital governance, and precision antimicrobial stewardship. Boolean operators were used where appropriate to combine search concepts.

Table 1. Summary of the Literature Search and Review Methodology

Concept	Representative search terms
Antimicrobial stewardship	"antimicrobial stewardship" OR "antibiotic stewardship"
AMR	"antimicrobial resistance" OR "antibiotic resistance"
Digital health	"digital health" OR "digital technology"
Mobile technology	"mobile health" OR mHealth OR "mobile application"
CDSS	"clinical decision support system" OR CDSS
AI	"artificial intelligence" OR "machine learning"
Diagnostics	"rapid diagnostics" OR "rapid diagnostic testing"
Governance	"antimicrobial governance" OR "digital governance"
One Health	"One Health" AND antimicrobial resistance

Data Collection Procedure

The literature search and selection process was conducted between May 2026 and July 2026. A total of 71 potentially relevant publications were initially identified through PubMed/MEDLINE and Google Scholar. Publications were manually screened for relevance to the objectives and research questions, and reference lists of relevant articles were examined to identify additional sources.

Relevant literature was organized according to the major domains of digital antimicrobial stewardship, including mobile applications, CDSSs, AI/ML, rapid diagnostics, digital surveillance, antimicrobial governance, implementation barriers, and future directions.

Study Instrument / Data Extraction Framework

As this was a literature review, no primary field-data collection instrument or questionnaire was used. A structured literature extraction framework was used to record publication characteristics, healthcare and geographical setting, digital technology, antimicrobial stewardship application, reported outcomes, implementation requirements, limitations, and governance considerations

Sampling Technique / Literature Selection

Participant sampling was not applicable to this literature-based review. Publications were purposively selected based on their relevance to the objectives and research questions. Original research, systematic and scoping reviews, clinical guidance, consensus documents, and relevant reports from recognized organizations were considered where directly relevant to the scope of the review. Particular attention was given to evidence addressing LMIC settings, implementation, equity, and sustainability.

Data Analysis and Synthesis

The identified literature was analyzed using a qualitative thematic synthesis approach. Evidence was organized according to the major domains of digital antimicrobial stewardship and examined in relation to clinical

applications, reported benefits, implementation requirements, limitations, and governance considerations.

Particular attention was given to infrastructure, interoperability, data quality, workforce capacity, digital literacy, cost, cybersecurity, privacy, equity, sustainability, and LMIC applicability. Owing to the heterogeneity of the available literature, quantitative meta-analysis was not undertaken.

Limitations

This narrative review has certain methodological limitations. The heterogeneity of the available literature with respect to study designs, interventions, healthcare settings, and outcome measures limited direct comparison of findings and precluded quantitative meta-analysis. Furthermore, evidence from low- and middle-income countries (LMICs) remains limited for certain digital technologies, which may constrain the generalizability of findings to resource-limited settings. Further systematic reviews and implementation studies are warranted to strengthen the evidence base.

Evolution of Antimicrobial Stewardship Programs: From Traditional Stewardship to Digital Governance

Initial stewardship initiatives were focused mainly on limiting use of antimicrobial agents and on rational prescribing by means of education, formulary controls and proactive audit-and-feedback interventions, with manual intervention by infectious disease specialists or stewardship teams playing a dominant role. While they were effective in limiting unnecessary antimicrobial use and enhancing antimicrobial prescribing practices, they were often limited by the requirements of the healthcare workforce, resource constraints, and delays in clinical interventions. [16]

One of the key milestones in the evolution of stewardship was the publication of stewardship guidelines by the Infectious Diseases Society of America (IDSA) and the Society for Healthcare Epidemiology of America (SHEA), which recognized stewardship as a fundamental educational piece of healthcare. Later guidelines highlighted the need for institutional stewardship governance and need to embed stewardship into the standard clinical practice. [17]

However, traditional stewardship models still are challenged in their operation, despite their widespread adoption. Indeed, labour is needed to ensure effective stewardship, by personnel who are knowledgeable in infectious diseases and clinical microbiology as well as antimicrobial pharmacotherapy. Furthermore, manual stewardship is time-consuming and is becoming harder to maintain in complex healthcare settings with increasing antimicrobial choices and patient numbers in many health institutions, especially in LMICs. [18]

With electronic healthcare data becoming more and more available, the stewardship landscape has changed. With the transition to electronic infrastructure, stewardship programs were increasingly integrated into the routine of healthcare organizations with electronic surveillance tools, automated alerts, prescribing dashboards, and clinical decision-support mechanisms. [5,12]

This transition has given rise to the concept of digital antimicrobial stewardship. Digital stewardship tools provide real-time decision support, continuous surveillance of antimicrobial use, and proactive antimicrobial optimization, which can help reduce inappropriate prescribing patterns, monitor antimicrobial use, follow and track resistance trends, and intervene sooner in the prescribing process to enhance efficiency and scalability. [21]

CDSSs are a clinical stewardship initiative that is often the first to integrate the principles of stewardship into a clinical workflow, thus changing stewardship from a corrective model to a prospective decision-support model. This has been further speeded up by developments in diagnostic microbiology. With digital stewardship systems integrated with these technologies, it is possible to rapidly move from empirical to targeted therapy, facilitate antimicrobial de-escalation, and encourage culture guided prescribing, which can significantly reduce the time needed to identify a pathogen and determine its susceptibility. [21]

In more recent years, stewardship has become a more dynamic and data-driven field, including the use of mobile

health apps, cloud-based surveillance systems, predictive analytics, and artificial intelligence (AI). [7,11,13] The evolution of antimicrobial stewardship from audit-based interventions to digitally enabled governance frameworks are summarized in Figure 1.

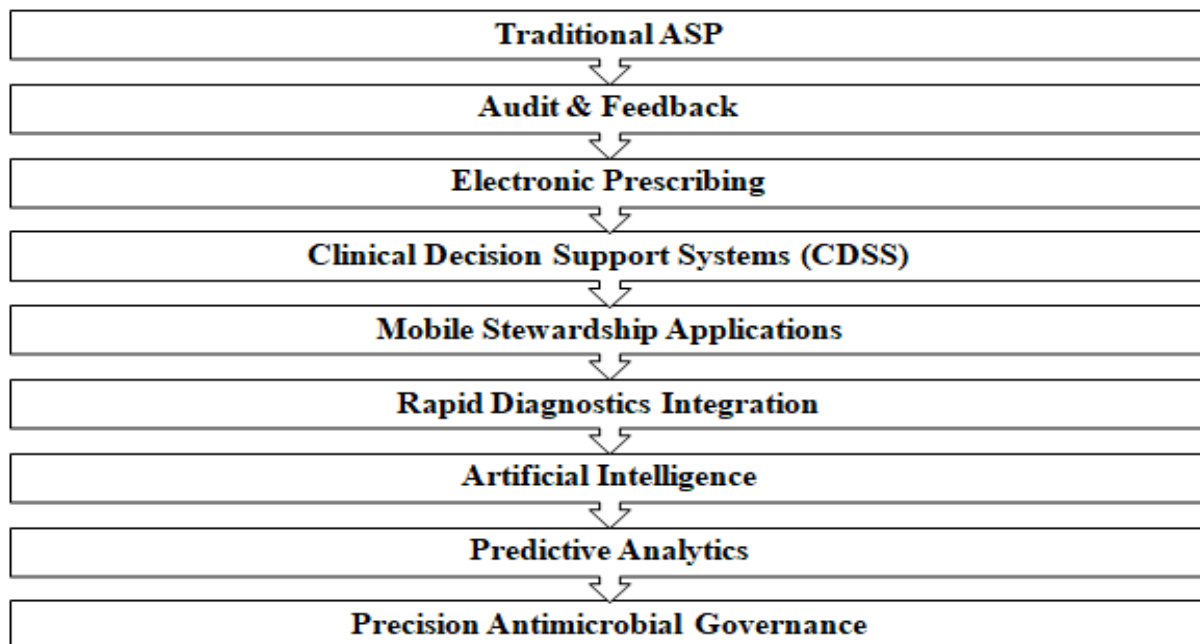


Figure 1: Evolution of Antimicrobial Stewardship: From Traditional Stewardship to Digital Antimicrobial Governance

This evolution also reflects a broader shift toward digital antimicrobial governance. Today, antimicrobial optimization is becoming an important part of infection prevention and control programs, microbiological surveillance systems, resistance monitoring networks and quality-improvement efforts. Digital dashboards, automated reporting systems and real-time stewardship utilisation monitoring allow for ongoing measurement of stewardship performance and quicker response to new resistance risks. [10]

However, the digital technologies cannot substitute for stewardship expertise. They require a multidisciplinary approach to clinical management, strong microbiological support and the will of the institution. Interoperability and data quality issues, as well as implementation costs, cybersecurity concerns, clinician acceptance and regulatory challenges, remain to impact adoption within healthcare systems.

Digital Health and Antimicrobial Stewardship: Foundations of A Connected Stewardship Ecosystem

The advent of digitalization in healthcare has revolutionized the generation, storage and use of clinical data, which has opened up additional opportunities to enhance antimicrobial stewardship. Digital health encompasses a wide spectrum of technologies such as electronic health records (EHRs), clinical decision support systems (CDSSs), mobile health applications, artificial intelligence (AI), cloud computing, and advanced data analytics, and in the context of infectious diseases, has been increasingly important in tackling the growing complexity of antimicrobial prescribing and antimicrobial resistance (AMR). [26,27]

Many traditional stewardship programs are based on manual review and a retrospective intervention approach, which can hinder the ability to provide timely support for antimicrobial decision making. Digital health tools, in contrast, can facilitate the integration of clinical, microbiological, pharmaceutical, and epidemiological data, enabling the transition from reactive stewardship to proactive, data-driven antimicrobial stewardship. [28] By bringing relevant information together within clinical workflows, these technologies can support more timely assessment of antimicrobial therapy and facilitate informed prescribing decisions.

A computerized physician order entry (CPOE) system that integrates antimicrobial prescribing into the electronic

workflow also enables real-time monitoring of antimicrobial use and provides easier access to clinically relevant information, helping to ensure adherence to institutional stewardship guidelines. [21] Integration of antimicrobial prescribing within electronic workflows can therefore strengthen the ability of stewardship teams to monitor prescribing practices and identify opportunities for timely intervention.

One of the critical success factors of digital stewardship is interoperability between health care information systems. Connectivity with EHRs, pharmacology databases, microbiology laboratories, infection prevention programs, and surveillance platforms provides clinicians and stewardship teams with access to comprehensive information to support antimicrobial prescribing decisions. [29] This connectivity also provides access to real-time information regarding antimicrobial utilization, resistance trends and stewardship performance indicators, which can help identify inappropriate prescribing practices earlier and provide opportunities for timely intervention. [22,30]

Healthcare institutions can now share, view, and analyze stewardship information across health care networks and institutions through cloud-based technologies. Concurrently, embedding microbiological diagnosis into a digital ecosystem enables earlier communication of laboratory results, facilitating earlier optimization of antimicrobial therapy and supporting the transition from "empirical" to "directed" therapy. [23,31] Such integration can improve the availability and timeliness of microbiological information at the point of antimicrobial decision making.

While interoperability, infrastructure, cybersecurity and user adoption issues remain, these integrated systems are increasingly serving as the backbone of today's antimicrobial stewardship programs. [11,26] The interconnected components of a contemporary digital antimicrobial stewardship ecosystem are illustrated in Figure 2.

With the ongoing evolution of healthcare systems, connected digital ecosystems will be key to enable evidence-based antimicrobial prescribing, real-time surveillance and continuous stewardship improvement. They are the technological infrastructure on which current and future digital stewardship innovations are built.

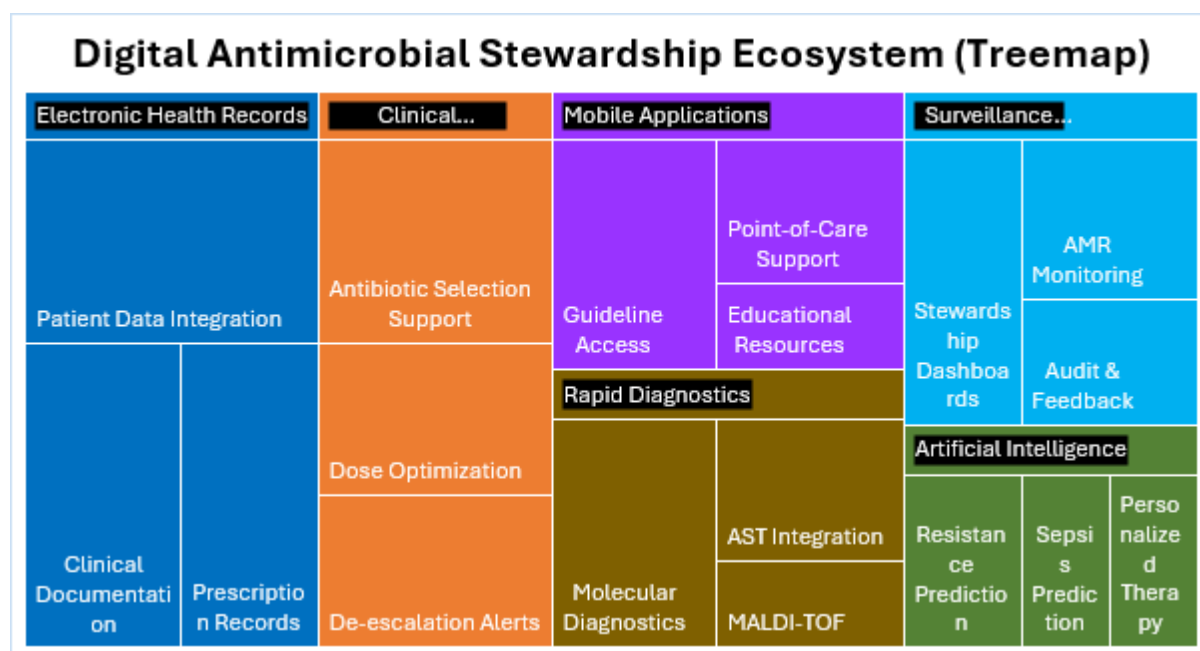


Figure 2: Digital Antimicrobial Stewardship Ecosystem

Mobile Applications in Antimicrobial Stewardship

The rise of the smartphone and mobile technologies has opened new possibilities for antimicrobial stewardship implementation. [10] Mobile health (mHealth) apps have become practical tools to provide evidence-based prescribing guidance, provide access to antimicrobial resources, and support clinical decision-making at the

point of care. Their increasing relevance is due to the need for prompt antimicrobial data in increasingly complex and time-limited health care settings.

The traditional stewardship interventions are mostly based on print guidelines, educational programs, manual audits and specialist consultation. These strategies are effective, but can be constrained by access and availability of stewardship staff. Mobile stewardship applications help mitigate these issues, as they enable the rapid access of recommendations on antimicrobial use, dosing and institutional policies, treatment algorithms and local antibiograms directly via a clinician's smartphone or tablet. [18]

Early stewardship applications to a large degree were online versions of institutional antimicrobial guidelines. Modern platforms, however, have become more all-encompassing decision support programmes that include syndrome-specific treatment pathways, dosage calculators, microbiological data, antimicrobial restriction criteria and stewardship alerts. A large number of applications also contain content that can be searched to efficiently find evidence-based recommendations during daily clinical practice. [25]

One of the greatest benefits of mobile stewardship apps is access to antimicrobial information that is more accessible. These platforms could eliminate prescription variation and enhance prescription adherence to institutional policies, while offering centralized and continually updated stewardship resources, several studies have shown improvements in prescription adherence to guidelines, in prescribing confidence, and in satisfaction of the prescribers after these mobile applications have been implemented. Hoff and colleagues showed that a mobile clinical decision support application facilitated access to antimicrobial recommendations and met the objectives of local stewardship. [7,23]

In low- and middle-income countries (LMICs), where few people have access to infectious disease specialists and disease-specific stewardship teams, mobile applications can be especially useful. In these environments, mobile technologies can be used to bring stewardship support to the frontline clinician by delivering easy-to-access, evidence-based recommendations, which can improve stewardship implementation and ensure more appropriate use of antimicrobials. [34]

Many stewardship applications also have educational roles, such as education about appropriate antimicrobial use through algorithms for clinical selection of antimicrobials, stewardship updates and learning materials. [16] Integration with local microbiological surveillance data adds value, supporting empirical antimicrobial selection, and enabling earlier transition to culture guided therapy. [18]

There are a number of difficulties to be overcome with mobile stewardship applications. There are also multiple other obstacles that arise like differences in digital literacy, technological infrastructure, data security needs, and user engagement, which require regular content updates to ensure the information remains relevant. [24] In addition, further mobile stewardship platforms will likely include artificial intelligence, integration of microbiological data in real time, cloud-based analytics, and personalised decision support. [26] The integration of EHRs and hospital information system (HIS) could augment their capabilities even more and drive seamless stewardship workflows. [35]

Clinical Decision Support Systems in Antimicrobial Stewardship

CDSSs are one of the most powerful digital interventions in antimicrobial stewardship, and they provide evidence-based recommendations tailored to the individual patient within the clinical workflow, rather than mobile applications for accessing antimicrobial guidelines and education. [36,37] CDSSs integrate clinical information, laboratory data, microbiological data, medication records, and institutional policies into the clinical care environment for the purpose of informing real-time antimicrobial prescribing decisions.

The use of antimicrobials has become increasingly complex thus the need for technology that aids in making decisions. There are many factors to be taken into consideration such as infection source, susceptibility of pathogen, local resistance pattern, organ function, allergy status, drug interaction and pharmacokinetic-pharmacodynamic principles. One way to address this challenge is for CDSSs to aggregate large quantities of information and generate actionable recommendations at the point of care. [5]

Initially, CDSSs were used to detect antimicrobial allergies, contraindications and dosages. With the development of more complex systems in the field of healthcare informatics, antimicrobial selection, optimization of dosing, duration of antimicrobial therapy, conversion of intravenous-to-oral, and antimicrobial de-escalation are now supported. Existing platforms can also be integrated to provide institution-specific policies and microbiological data to provide tailored recommendations for prescription. [23]

Stewardship CDSSs are one of the most critical applications to support empirical antimicrobial therapy. Such systems can optimize the initial selection of antimicrobials by integrating local antibiograms and patient-specific risk factors and automatically adapting recommendations to patient's body weight, hepatic function, renal function, severity of illness and age to improve antimicrobial efficacy/safety. [18]

Increasingly the effectiveness of CDSSs is being proven. Others found that the use of CDSS was correlated with decrease in antimicrobial use, antimicrobial prescribing variability, and antimicrobial documentation errors. [22-24]

There are however some barriers. This can contribute to fatigue, and reduce clinician responsiveness to stewardship recommendations. Quality and complete clinical and microbiological data are also correlated with the effectiveness of the system. Limited clinical impact can be achieved due to poor integration with existing workflows, poor interoperability and outdated stewardship protocols. [36]

The implementation of a high-end CDSS system requires investments in information technology, in training of people and in integrating systems. Adoption may be affected due to resource constraints, especially in the low- and middle-income countries. There are numerous other things to take into account, including cybersecurity, legal liability and ethical management of patient data. [18]

The future of stewardship CDSSs increasingly is linked to Artificial Intelligence and predictive analytics. AI-driven systems could further improve resistance prediction, identification of high-risk patients and the more tailored recommendations for antimicrobial treatment. All of these are part of the overall goal of precision antimicrobial stewardship (PAMS): selecting the right antimicrobial therapy for the right patient at the right time for the right reason. [11]

Artificial Intelligence and Machine Learning in Antimicrobial Stewardship

The integration of artificial intelligence (AI) and machine learning (ML) into antimicrobial stewardship presents novel opportunities to tackle the most pressing stewardship challenges, ranging from diagnostic uncertainty, to delayed microbiological results and inappropriate empirical therapy, to a rising tide of antimicrobial resistance (AMR). [10,11,37]

AI models can analyze vast amounts of data to detect patterns that aid in more accurate and personalized treatment decisions for antimicrobial use, unlike traditional rule-based decision-support systems. Their potential to consider several patient-specific and microbiological variables makes them especially useful in antimicrobial stewardship, as many clinical factors impact on antibiotic prescribing decisions. [23]

Antimicrobial resistance prediction is one of the most widely researched applications of AI. Traditional antibiograms offer population susceptibility information while machine learning can model individual patient susceptibility risk by using demographic, clinical, microbiological and healthcare utilization data. Several studies have shown that such models can aid in the selection of more appropriate antimicrobials and minimise the need for unnecessary exposure to broad spectrum agents whilst still providing adequate therapeutic coverage. [38,39]

AI has also demonstrated significant potential for optimising empirical antimicrobial therapy. While empirical treatment is still recommended in many clinical scenarios including the critically ill, inappropriate empirical treatment is a driver of treatment failure, extended hospitalisation and resistance selection pressure. AI systems can be used to make better recommendations for antimicrobial prescribing that improve the chances of both effectiveness and stewardship compliance by taking into account patient-related factors, local resistance epidemiology and historical prescribing practices. [40]

One of the other major uses is the early identification of sepsis and clinical deterioration. Physiological parameters, laboratory data, medication history, and clinical records can be constantly analyzed by machine learning models, providing the ability to identify patients at risk of sepsis ahead of time, aiding timely antimicrobial initiation, and potentially improving patient outcomes. [42]

AI is not only used for empirical therapy and sepsis management, but it is also being used for personalized antimicrobial therapy. AI-driven platforms offer a template for how all these factors can be combined and how they can be used in more individual treatment decisions. [27]

AI, combined with state-of-the-art diagnostics, further increases stewardship capabilities. Combining machine learning with rapid diagnostics, whole genome sequencing, MALDI-TOF mass spectrometry and automated susceptibility testing could help identify pathogens earlier, predict a pathogen's susceptibility, and help select appropriate antimicrobials more quickly, reducing the time required to move from empirical to definitive therapy. [2,44]

Population-level use of AI can assist with antimicrobial surveillance and antimicrobial governance by analysing antimicrobial usage patterns, antimicrobial resistance trends, and HAIN data, as well as epidemiological data. Predictive analytics can potentially be used to detect new threats to resistance and anticipate future resistance trends and to inform better, more proactive stewardship planning. [23,45]

The potential of these technologies remains unexploited, however, due to several limitations. The effectiveness of AI systems largely relies on the quality and representativeness of the data used for training, and AI models created in one healthcare context may not be as effective in another. Some caveats are warranted before widespread implementation: limited transparency of “black box” algorithms, trust by the clinician of the algorithms, algorithmic bias, data privacy, and regulatory oversight. [43-45]

Integration Of Rapid Diagnostics and Digital Stewardship

Timely and accurate microbiological information is essential for effective antimicrobial stewardship. Several days are often required for culture-based methods to identify the pathogen and determine their antimicrobial sensitivity, leading to broad spectrum empirical antibiotic therapy being continued in many cases. [13] Therefore, the adoption of rapid diagnostic technologies alongside digital stewardship systems are critical to antimicrobial optimization and precision antimicrobial management. [47]

Diagnostic stewardship is the complementary approach to antimicrobial stewardship that focuses on the thoughtful selection, interpretation and utilization of microbiologic investigations to inform evidence-based antimicrobial therapy. Rapid diagnostics and digital health technologies mean earlier access to clinically actionable information and easier stewardship intervention. [22]

There have been a number of innovations which have revolutionized diagnostic microbiology. Rapid molecular diagnostic platforms, such as the polymerase chain reaction (PCR) based assays, multiplex molecular panels and nucleic acid amplification technologies, can identify pathogens and select resistance determinants in hours instead of days. [18,29] Automated antimicrobial susceptibility testing (AST) can assess resistance patterns quickly and more routinely. Together, these technologies facilitate earlier antimicrobial optimization and more targeted treatment. [3,4,48,49]

Rapid diagnostics have the greatest clinical impact when embedded in digital stewardship ecosystems. Microbiological results, clinical decision support systems (CDSSs), stewardship platforms can all automatically alert clinicians to microbiological data, can generate stewardship alerts, and can suggest antimicrobial modifications for all this data and institutional guidelines for susceptibility. This integration minimizes the lag time between laboratory reporting and clinical action, thereby aiding in quicker and evidence-based antimicrobial management. [27]

Results have been shown in a few studies that rapid diagnostics and stewardship interventions are more effective than diagnostics alone. In other infectious disease contexts, the combination of rapid molecular diagnostics and antimicrobial stewardship activities has been shown to be associated with improvements in survival, time to

effective therapy, and antimicrobial optimization. [11,16]

The use of rapid detection tests is especially useful in aid of antimicrobial de-escalation. Early detection and understanding of pathogen mechanisms and resistance allows for faster selection of specific treatment approaches, thereby minimizing exposure to agents that include carbapenems, anti-MRSA agents and combination products. This helps to reduce antimicrobial use, lower health care costs and the selection pressure for antimicrobial resistance. [5]

Evidence of the usefulness of rapid diagnostics in conjunction with stewardship systems has been particularly promising in the management of blood stream infections and sepsis where effective antimicrobial therapy is essential and needs to be administered promptly. Digital stewardship platforms that are integrated with rapid diagnostic technologies enable rapid initiation of appropriate therapy and timely optimization as soon as microbiologic data is available. [12]

There are key challenges to implementation. However, adoption can be hindered by high acquisition costs, infrastructure needs, staff training requirements, and interoperability challenges, especially in resource-poor environments. Moreover, RTDs require good stewardship engagement and receptivity to changing therapies based on new microbiological data. [20]

These developments will further improve diagnostic stewardship – integration of these approaches into digital stewardship platforms will enable more personalized antimicrobial management and the faster approach to precision antimicrobial governance. [50] Major applications of artificial intelligence within antimicrobial stewardship are summarized in Figure 3.



Figure 3: Artificial Intelligence Applications in Antimicrobial Stewardship

Digital Antimicrobial Governance

Digital health technologies have expanded the scope of antimicrobial stewardship beyond the patient and prescriber and are introducing antimicrobial governance. The modern antimicrobial governance framework is

moving beyond optimizing antimicrobial use at the patient level to also incorporate institutional, regional, national and global antimicrobial stewardship efforts to enhance antimicrobial use, monitor antimicrobial resistance trends and reduce antimicrobial resistance (AMR). [32] Digital technologies have played an increasingly important role in this evolution, providing real-time monitoring, automated reporting, advanced analytics, and continuous performance monitoring. [33]

To achieve good antimicrobial governance there is a need for accurate measurement of antimicrobial use, monitoring for resistance trends, evaluation of antimicrobial stewardship performance and implementation of evidence-based interventions. Traditionally, these tasks were very dependent on manual data gathering and retrospective reporting. This process has been digitalized with access to real-time clinical, microbiological and pharmaceutical data, which help to enable more responsive stewardship strategies. [28]

Digital antimicrobial governance is built on electronic monitoring. Modern platforms are used to provide constant surveillance of antimicrobial prescribing, utilization, antibiotic resistance trends and monitoring of healthcare-associated infections as well as stewardship performance indicators. These systems allow for earlier detection of troubling trends and more prompt stewardship actions. [3]

The introduction of electronic prescribing systems, pharmacy databases, microbiology laboratories and stewardship platforms have greatly enhanced the monitoring of antimicrobial use. Standardised reporting tools such as defined daily doses (DDD) and days of therapy (DOT) can be employed to monitor antimicrobial use and facilitate benchmarking, assessment of antimicrobial stewardship interventions and identification of high use of antimicrobials and opportunities for targeted interventions. [11]

Stewardship dashboards also support governance by bringing together information on antimicrobial use, microbiological results, antimicrobial resistance, and performance indicators in easy-to-grab visual displays. These tools facilitate informed decision making for the clinician, pharmacist, microbiologist, administrator and policymaker, and enhance stewardship oversight and resource allocation. [14]

Prospective audit and feedback activities have also been enhanced by the use of digital platforms. Complementary to this, the integration of microbiology laboratories with electronic reporting systems has extended stewardship reach and improved surveillance of antimicrobial resistance, leading to the creation of institutional antibiograms, regional antimicrobial resistance maps and national antimicrobial resistance surveillance datasets for the guidance of antimicrobial stewardship policies and empirical treatment guidance. [51]

The digital technologies at national and international level enables coordination of antimicrobial stewardship and AMR surveillance programmes. Standardized digital reporting frameworks for surveillance and reporting changes in antimicrobial resistance and the use of antimicrobials, such as the Global Antimicrobial Resistance and Use Surveillance System (GLASS) by the World Health Organization, also underscore the value of standardized digital reporting systems. [1]

The addition of predictive analytics and AI further enhances digital governance. Machine learning models can detect new resistance patterns, predict antimicrobial use and trends, pinpoint outbreaks and guide proactive stewardship planning. These technologies allow for a shift from reactive surveillance to more proactive and predictive strategies for managing AMR. [26]

Table 2. Comparison of Major Digital Technologies in Antimicrobial Stewardship

Technology	Primary Function	Key Clinical Applications	Major Advantages	Key Limitations	Reference (s)
Mobile Health	Point-of-care	Guidelines, dosing tools, antibiograms, prescribing advice	Available, easy to scale, supports education	Requires updates,	5, 7, 10, 32–34

(mHealth) Applications	stewardship support			variable adoption	
Clinical Decision Support Systems (CDSSs)	Patient-specific prescribing support	Drug selection, dose optimization, de-escalation, IV-to-oral conversion	Improves prescribing quality and guideline adherence	Alert fatigue, interoperability issues	8, 20-23, 30
Artificial Intelligence and Machine Learning	Predictive and precision stewardship	Resistance prediction, empirical therapy, sepsis detection, personalized treatment	Advanced analytics, individualized recommendations	Bias, limited explainability, validation concerns	10, 11, 23, 38
Rapid Diagnostic Technologies	Rapid pathogen and resistance detection	PCR, MALDI-TOF MS, susceptibility testing	Earlier targeted therapy, supports de-escalation	High cost, infrastructure requirements	10, 12, 13, 18, 27, 29, 35, 47–50
Digital Surveillance and Governance Platforms	Stewardship monitoring and oversight	Dashboards, utilization tracking, resistance surveillance, benchmarking	Real-time monitoring, supports governance	Data integration and privacy challenges	1, 3, 5, 11, 13, 14, 26, 29–31, 51

The possible future antimicrobial governance models are proposed to be part of a single digital ecosystem that will incorporate stewardship platforms, surveillance systems, electronic health records, AI applications, and databases of public health. These can contribute to more adaptive, transparent and data-driven strategies in AMS and to global efforts to control AMR. [30,47]

At the heart of digital antimicrobial governance is a vision of how to improve surveillance, add complied stewardship oversight, boost evidence-based policy making, and foster proactive approaches to AMR. Digital technologies are transforming antimicrobial governance and are playing a role in promoting more sustainable implementation of antimicrobial stewardship by integrating real-time monitoring, advanced analytics and coordinated surveillance networks.

Challenges And Barriers to Implementing Digital Antimicrobial Stewardship

Digital technologies have significant potential to support antimicrobial stewardship, but there are significant barriers to implementation in many healthcare settings. The use of mobile apps, clinical decision support systems (CDSSs), and artificial intelligence (AI), as well as digital surveillance platforms has the potential to significantly enhance antimicrobial use and the fight against antimicrobial resistance (AMR) but requires technological infrastructure, data quality, organizational preparedness, user engagement, and regulatory support.

One of the primary obstacles is the inconsistencies in the healthcare infrastructures. Robust electronic health records (EHRs), laboratory information systems, secure data storage solutions, and reliable internet connectivity are essential for effective digital stewardship. But there are significant differences among healthcare institutions and regions in terms of digital maturity. Despite rising AMR burdens in many low- and middle-income countries (LMICs), the implementation of these systems is still limited due to challenges related to fragmented information systems, limited technical support, and inadequate digital infrastructure. [49]

Another big challenge is interoperability. The key to digital stewardship is the ability to connect EHRs, a pharmacy database, the microbiology lab, surveillance systems, and decision support. While interoperability is

crucial to maximise the value of digital stewardship interventions, the current level of integration can lead to various issues, such as incomplete data exchange, duplication of effort, delayed information transfer, and reduced system effectiveness. [3]

Data quality and data standardization are also key to digital stewardship success. The clinical, microbiological and prescribing information needs to be accurate to enable effective surveillance, decision support and AI applications. Good data governance and quality assurance processes are essential to the successful implementation of stewardship recommendations and for creating reliable digital tools. [27]

The acceptance of the user is also essential. The introduction of digital tools may be resisted by clinicians if they feel they are disruptive, time consuming or do not fit well with clinical workflows. Stiff resistance to change, low digital literacy and fears of automated recommendations could also be barriers to uptake. User-centered design, stakeholder engagement, and continued education are thus critical to ensuring sustained implementation, as "alert fatigue" has become a related challenge with too many alerts being produced from electronic prescribing and decision support systems decreasing the ability of the clinician to respond to the most critical alerts.

The use of AI poses further transparency, explainability, and bias challenges. Many machine learning models are "black boxes" that are hard for clinicians to understand, as to the logic behind recommendations. Additionally, any algorithm trained on a small or unrepresentative data set might not work well in various healthcare environments and patient populations, so it is important that they are thoroughly validated and monitored before they are broadly implemented. [1,18]

There are also implementation considerations related to financial factors. Digital stewardship infrastructure investments in software, hardware, cybersecurity, personnel training, and technical support, are significant for

development, deployment, maintenance and updating. [5] Further, cyber security, privacy and regulatory issues need to be considered. Digital stewardship platforms tend to be quite large, and can contain sensitive clinical and microbiological data, which can raise concerns about access to this information, data breaches and regulatory adherence. Stewardship systems need to be working under a suitable legal, ethical and data protection framework. [26]

However, they are especially strong in LMICs, where infrastructure constraints or the limited availability of health workers and of laboratories could make adoption difficult. However, scalable solutions, like mobile health apps and cloud-based platforms, could potentially help to increase stewardship support in resource-poor settings. [11]

While there are many factors supporting successful digital antimicrobial stewardship, there is one main factor that will support the successful sustainable implementation: The establishment and use of a framework that includes adequate infrastructure, access to quality data, collaboration and communication among all stakeholders, clinician involvement; and an appropriate and supportive governance structure. These factors will be crucial to overcoming the common barriers to fully utilizing digital technology to improve the use of antimicrobials and reduce AMR.

Future Of Antimicrobial Stewardship: Toward Precision Antimicrobial Governance

Advancements in precision medicine, data science, digital health and artificial intelligence (AI) are ushering in a new era for antimicrobial stewardship. Future stewardship models are likely to become more proactive, predictive, and personalized, and the current expansion of digital technologies, sophisticated diagnostics, and clinical informatics will help usher in a new era of antimicrobial governance, beyond the traditional stewardship programs, that is characterized by precision. [53]

Precision antimicrobial therapy is a key aspect of this shift. Much of the current stewardship advice is founded on evidence from the population level and standardised treatment guidelines. There is however a significant variability in immune status, comorbidities, pharmacokinetic parameters, pathogen characteristics, resistance mechanisms, and treatment response between the patients. Precision stewardship aims to synergize these factors to provide personalized antimicrobial recommendations that are optimally therapeutic and with the lowest risk

of toxicity and antimicrobial resistance. [51]

AI is thought to have significant impact in helping to attain this objective. More sophisticated AI stewardship systems are likely to adapt to changing resistance trends and clinical outcomes, driving even better stewardship performance. [47]

Pathogen genomics will also change stewardship practice as a result of advances in pathogen genetics. The pace with which resistance determinants, virulence factors and transmission routes are identified is increasing and the results are becoming more accurate and precise using whole genome sequencing and metagenomic technologies. Using genomic data to support digital stewardship can help identify resistant organisms earlier, assist with targeted antimicrobial treatment and enhance outbreak investigations and surveillance efforts. [7]

Predictive analytics and integrated surveillance systems are likely to play an increasing role at the population level. New stewardship platforms could integrate antimicrobial usage information, microbiological results, genomic data, health services utilization data and public health data to determine new resistance risk and be able to prioritize interventions. This can help healthcare organizations predict the resistance instead of reacting to it once it has occurred. [10]

The One Health approach will also shape the future of stewardship, bringing together human, animal and environmental health. Digital surveillance systems that are capable of inter-sectoral data integration could potentially be used to reinforce antimicrobial resistance monitoring and enable more robust containment efforts. [50] The anticipated evolution from current stewardship models toward precision antimicrobial governance is presented in Figure 4.

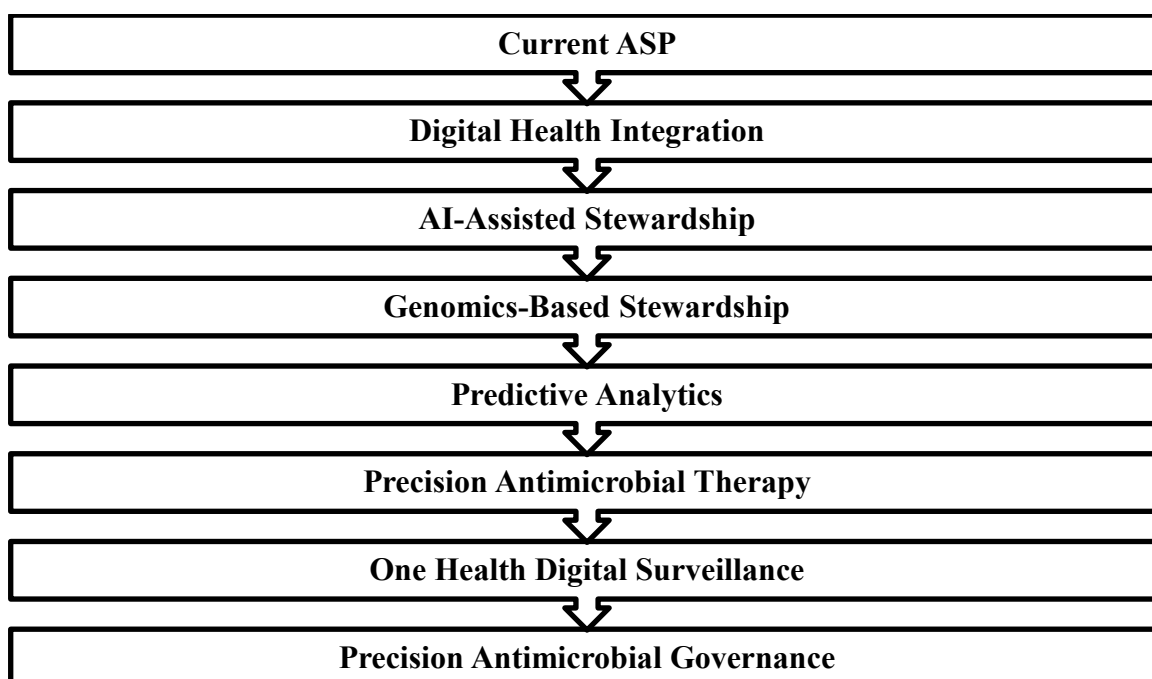


Figure 4: Future Roadmap for Precision Antimicrobial Governance

Future stewardship models should be based on clinical skill, multiple disciplines, and ethical oversight. Digital technologies should be used in addition to professional judgment to maintain the patient-centred nature of antimicrobial choices and to ensure that they are consistent with stewardship principles.

The future of antimicrobial stewardship will likely see advancements in precision-based approaches through the use of artificial intelligence (AI), genomics, new technologies for advanced diagnostics, predictive analytics, and integrated surveillance systems. These developments may lead to a shift from reactive to predictive, personalised and data-driven designs of antimicrobial usage, thereby enhancing global efforts to maintain effective use of antimicrobics against antimicrobial resistance (AMR).

Implications For Clinical Practice and Public Health

With growing antimicrobial resistance (AMR) challenge in healthcare systems, digital technology can help to make antimicrobial stewardship more effective, better prescribe and expand the reach of evidence-based antimicrobial management. [55]

On the clinical side, digital stewardship tools can help to inform and facilitate timely and informed prescribing decisions. These tools can help improve antimicrobial appropriateness, minimize unnecessary broad-spectrum antimicrobial exposure, and maximize outcomes for your patients. [56] Taken together; these tools can help you optimize patient care and make more effective use of antimicrobials. [8]

The public health level is also enhanced by digital technologies that enable more effective monitoring, real-time surveillance, and data-driven policy decisions. [26,27] The ability to monitor antimicrobial usage and trends in antimicrobial resistance at the national level can be enhanced by the integration of electronic prescribing systems, microbiological laboratories and surveillance systems, allowing for more timely identification of emerging antimicrobial resistance threats, more rapid detection of outbreaks and targeted antimicrobial stewardship interventions. [25, 27-29] In addition, large-scale digital surveillance networks can play a role in national action plans on antimicrobial resistance and in global initiatives to maintain the effectiveness of antimicrobials.

Investment in supporting digital infrastructure, workforce, interoperability, cybersecurity, and regulatory frameworks are critical to successful implementation, with a focus on engaging clinicians and designing a user-centric approach. [34] Investing in these areas and supporting scalable and sustainable stewardship strategies, especially in low- and middle-income countries, is critical to successful implementation.

Digital technologies can be seen as tools that complement and do not replace clinical knowledge and stewardship leadership of multidisciplinary teams, with well-planned implementation in healthcare systems that can enhance antimicrobial stewardship, patient care and global public health to manage the spread of antimicrobial resistance.

CONCLUSION

Antimicrobial resistance (AMR) continues to pose a major global health challenge, requiring innovative approaches to optimize antimicrobial use and preserve the effectiveness of existing therapies. Digital transformation is reshaping antimicrobial stewardship by enabling a shift from reactive, manual approaches toward proactive, data-driven practice through mobile applications, clinical decision support systems, artificial intelligence, rapid diagnostics, and advanced surveillance platforms.

These technologies can support timely, personalized antimicrobial decision-making, improve surveillance and governance, and facilitate early optimization and de-escalation of therapy. However, their successful adoption remains dependent on adequate infrastructure, interoperability, data quality, cybersecurity, clinician acceptance, affordability, and appropriate regulatory oversight, particularly in resource-constrained settings.

The future of antimicrobial stewardship lies in the careful integration of digital technologies with clinical expertise and multidisciplinary stewardship leadership. Sustained investment in digital infrastructure, interdisciplinary collaboration, and evidence-based implementation strategies will be essential to realize the potential of digital health and strengthen antimicrobial governance in the continuing fight against AMR.

REFERENCES

1. Murray CJ, Ikuta KS, Sharara F, Swetschinski L, Aguilar GR, Gray A, Han C, Bisignano C, Rao P, Wool E, Johnson SC. Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. *The lancet*. 2022 Feb 12;399(10325):629-55. [doi:10.1016/S0140-6736\(21\)02724-0](https://doi.org/10.1016/S0140-6736(21)02724-0)
2. Lewnard JA, Charani E, Gleason A, Hsu LY, Khan WA, Karkey A, Chandler CI, Mashe T, Khan EA, Bulabula AN, Donado-Godoy P. Burden of bacterial antimicrobial resistance in low-income and middle-income countries avertible by existing interventions: an evidence review and modelling analysis. *The Lancet*. 2024 Jun 1;403(10442):2439-54. [doi:10.1016/S0140-6736\(24\)00862-6](https://doi.org/10.1016/S0140-6736(24)00862-6)

3. Barlam TF, Cosgrove SE, Abbo LM, MacDougall C, Schuetz AN, Septimus EJ, Srinivasan A, Dellit TH, Falck-Ytter YT, Fishman NO, Hamilton CW. Implementing an antibiotic stewardship program: guidelines by the Infectious Diseases Society of America and the Society for Healthcare Epidemiology of America. *Clinical infectious diseases*. 2016 May 15;62(10):e51-77. [doi:10.1093/cid/ciw118](https://doi.org/10.1093/cid/ciw118)
4. Fishman N. Antimicrobial stewardship. *American journal of infection control*. 2006 Jun 1;34(5):S55-63. [doi:10.1016/j.ajic.2006.05.237](https://doi.org/10.1016/j.ajic.2006.05.237)
5. Rawson TM, Zhu N, Galiwango R, Cocker D, Islam MS, Myall A, Vasikasin V, Wilson R, Shafiq N, Das S, Holmes AH. Using digital health technologies to optimise antimicrobial use globally. *The Lancet Digital Health*. 2024 Dec 1;6(12):e914-25. [doi:10.1016/S2589-7500\(24\)00198-5](https://doi.org/10.1016/S2589-7500(24)00198-5)
6. Charani E, Holmes AH. Antimicrobial stewardship programmes: the need for wider engagement. *BMJ quality & safety*. 2013 Nov 1;22(11):885-7. [doi:10.1136/bmjqs-2013-002444](https://doi.org/10.1136/bmjqs-2013-002444)
7. Hoff BM, Ford DC, Ince D, Ernst EJ, Livorsi DJ, Heinitz BH, Masse V, Brownlee MJ, Ford BA. Implementation of a mobile clinical decision support application to augment local antimicrobial stewardship. *Journal of pathology informatics*. 2018 Jan 1;9(1):10. [doi:10.4103/jpi.jpi_77_17](https://doi.org/10.4103/jpi.jpi_77_17)
8. Rittmann B, Stevens MP. Clinical decision support systems and their role in antibiotic stewardship: a systematic review. *Current infectious disease reports*. 2019 Aug;21(8):29. [doi:10.1007/s11908-019-0683-8](https://doi.org/10.1007/s11908-019-0683-8)
9. Catho G, Sauser J, Coray V, Da Silva S, Elzi L, Harbarth S, Kaiser L, Marti C, Meyer R, Pagnamenta F, Portela J. Impact of interactive computerised decision support for hospital antibiotic use (COMPASS): an open-label, cluster-randomised trial in three Swiss hospitals. *The Lancet Infectious Diseases*. 2022 Oct 1;22(10):1493-502. [doi:10.1016/S1473-3099\(22\)00308-5](https://doi.org/10.1016/S1473-3099(22)00308-5)
10. Howard A, Reza N, Green PL, Yin M, Duffy E, Mwandumba HC, Gerada A, Hope W. Artificial intelligence and infectious diseases: tackling antimicrobial resistance, from personalised care to antibiotic discovery. *The Lancet Infectious Diseases*. 2026 Mar 1;26(3):e181-92. [doi:10.1016/S1473-3099\(25\)00313-5](https://doi.org/10.1016/S1473-3099(25)00313-5)
11. Pennisi F, Pinto A, Ricciardi GE, Signorelli C, Gianfredi V. The role of artificial intelligence and machine learning models in antimicrobial stewardship in public health: a narrative review. *Antibiotics*. 2025 Jan 30;14(2):134. [doi:10.3390/antibiotics14020134](https://doi.org/10.3390/antibiotics14020134)
12. Al Mazrouei N, Ahmed Elnour A, Badi S, Alsulami FT, Awadallah Mohamed Saeed A, Awad Al-Kubaisi K, Menon V, Yousif Khidir I, Ismail M, Osman Mahagoub MM, Ramiseti AK. The impact of artificial intelligence on the prescribing, selection, resistance, and stewardship of antimicrobials: a scoping review. *BMC Infectious Diseases*. 2025 Dec 30. [doi:10.1186/s12879-025-12320-4](https://doi.org/10.1186/s12879-025-12320-4)
13. Donà D, Barbieri E, Brigadoi G, Liberati C, Bosis S, Castagnola E, Colomba C, Galli L, Lancella L, Lo Vecchio A, Meschiari M. State of the art of antimicrobial and diagnostic stewardship in pediatric setting. *Antibiotics*. 2025 Jan 27;14(2):132. [doi:10.3390/antibiotics14020132](https://doi.org/10.3390/antibiotics14020132)
14. Fishman N. Antimicrobial stewardship. *American journal of infection control*. 2006 Jun 1;34(5):S55-63. [doi:10.1016/j.ajic.2006.05.237](https://doi.org/10.1016/j.ajic.2006.05.237)
15. Dellit TH, Owens RC, McGowan JE, Gerding DN, Weinstein RA, Burke JP, Huskins WC, Paterson DL, Fishman NO, Carpenter CF, Brennan PJ. Infectious Diseases Society of America and the Society for Healthcare Epidemiology of America guidelines for developing an institutional program to enhance antimicrobial stewardship. *Clinical infectious diseases*. 2007 Jan 15;44(2):159-77. [doi:10.1086/510393](https://doi.org/10.1086/510393)
16. Dyar OJ, Huttner B, Schouten J, Pulcini C. What is antimicrobial stewardship?. *Clinical microbiology and infection*. 2017 Nov 1;23(11):793-8. [doi:10.1016/j.cmi.2017.08.026](https://doi.org/10.1016/j.cmi.2017.08.026)
17. Tamma PD, Miller MA, Cosgrove SE. Rethinking how antibiotics are prescribed: incorporating the 4 moments of antibiotic decision making into clinical practice. *Jama*. 2019 Jan 15;321(2):139-40. [doi:10.1001/jama.2018.19509](https://doi.org/10.1001/jama.2018.19509)
18. Cox JA, Vlieghe E, Mendelson M, Wertheim H, Ndegwa L, Villegas MV, Gould I, Hara GL. Antibiotic stewardship in low-and middle-income countries: the same but different?. *Clinical microbiology and infection*. 2017 Nov 1;23(11):812-8. [doi:10.1016/j.cmi.2017.07.010](https://doi.org/10.1016/j.cmi.2017.07.010)
19. Charani E, Holmes A. Antibiotic stewardship—twenty years in the making. *Antibiotics*. 2019 Jan 24;8(1):7. [doi:10.3390/antibiotics8010007](https://doi.org/10.3390/antibiotics8010007)
20. Baysari MT, Lehnbohm EC, Li L, Hargreaves A, Day RO, Westbrook JI. The effectiveness of information technology to improve antimicrobial prescribing in hospitals: a systematic review and meta-analysis. *International journal of medical informatics*. 2016 Aug 1;92:15-34.

[doi:10.1016/j.ijmedinf.2016.04.008](https://doi.org/10.1016/j.ijmedinf.2016.04.008)

21. Catho G, Sauser J, Coray V, Da Silva S, Elzi L, Harbarth S, Kaiser L, Marti C, Meyer R, Pagnamenta F, Portela J. Impact of interactive computerised decision support for hospital antibiotic use (COMPASS): an open-label, cluster-randomised trial in three Swiss hospitals. *The Lancet Infectious Diseases*. 2022 Oct 1;22(10):1493-502. [doi:10.1016/S1473-3099\(22\)00308-5](https://doi.org/10.1016/S1473-3099(22)00308-5)
22. Timbrook TT, Morton JB, McConeghy KW, Caffrey AR, Mylonakis E, LaPlante KL. The effect of molecular rapid diagnostic testing on clinical outcomes in bloodstream infections: a systematic review and meta-analysis. *Clinical Infectious Diseases*. 2016 Sep 27;ciw649. [doi:10.1093/cid/ciw649](https://doi.org/10.1093/cid/ciw649)
23. Rawson TM, Castro-Sánchez E, Charani E, et al. Socio-cultural and behavioural factors affecting hospital-based antibiotic prescribing: a systematic review and meta-analysis. *Clin Microbiol Infect*. 2019 Apr;25(4):471-482. [doi:10.1016/j.cmi.2018.12.014](https://doi.org/10.1016/j.cmi.2018.12.014).
24. Topol EJ. High-performance medicine: the convergence of human and artificial intelligence. *Nature medicine*. 2019 Jan;25(1):44-56. [doi:10.1038/s41591-018-0300-7](https://doi.org/10.1038/s41591-018-0300-7)
25. World Health Organization. Global strategy on digital health 2020-2027. World Health Organization; 2025 Dec 1. Available from: <https://www.who.int/publications/i/item/9789240116870>
26. Cresswell K, Mozaffar H, Shah S, Sheikh A. Approaches to promoting the appropriate use of antibiotics through hospital electronic prescribing systems: a scoping review. *International Journal of Pharmacy Practice*. 2017 Feb;25(1):5-17. [doi:10.1111/ijpp.12274](https://doi.org/10.1111/ijpp.12274)
27. Pulcini C, Binda F, Lamkang AS, Trett A, Charani E, Goff DA, Harbarth S, Hinrichsen SL, Levy-Hara G, Mendelson M, Nathwani D. Developing core elements and checklist items for global hospital antimicrobial stewardship programmes: a consensus approach. *Clinical Microbiology and Infection*. 2019 Jan 1;25(1):20-5. [doi:10.1016/j.cmi.2018.03.033](https://doi.org/10.1016/j.cmi.2018.03.033)
28. Antimicrobial Resistance Collaborators. Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. *Lancet (London, England)*. 2022 Jan 19;399(10325):629. [doi:10.1016/S0140-6736\(21\)02724-0](https://doi.org/10.1016/S0140-6736(21)02724-0)
29. Cox JA, Vlieghe E, Mendelson M, Wertheim H, Ndegwa L, Villegas MV, Gould I, Hara GL. Antibiotic stewardship in low-and middle-income countries: the same but different?. *Clinical microbiology and infection*. 2017 Nov 1;23(11):812-8. [doi:10.1016/j.cmi.2017.07.010](https://doi.org/10.1016/j.cmi.2017.07.010)
30. Free C, Phillips G, Watson L, Galli L, Felix L, Edwards P, Patel V, Haines A. The effectiveness of mobile-health technologies to improve health care service delivery processes: a systematic review and meta-analysis. *PLoS medicine*. 2013 Jan 15;10(1):e1001363. [doi:10.1371/journal.pmed.1001363](https://doi.org/10.1371/journal.pmed.1001363)
31. Charani E, Castro-Sánchez E, Sevdalis N, Kyriatsis Y, Drumright L, Shah N, Holmes A. Understanding the determinants of antimicrobial prescribing within hospitals: the role of “prescribing etiquette”. *Clinical Infectious Diseases*. 2013 Jul 15;57(2):188-96. [doi:10.1093/cid/cit212](https://doi.org/10.1093/cid/cit212)
32. Helou RI, Foudraïne DE, Catho G, Peyravi Latif A, Verkaik NJ, Verbon A. Use of stewardship smartphone applications by physicians and prescribing of antimicrobials in hospitals: a systematic review. *PLoS One*. 2020;15(9):e0239751. [doi: 10.1371/journal.pone.0239751](https://doi.org/10.1371/journal.pone.0239751).
33. Pennisi F, Pinto A, Ricciardi GE, Signorelli C, Gianfredi V. The role of artificial intelligence and machine learning models in antimicrobial stewardship in public health: a narrative review. *Antibiotics*. 2025 Jan 30;14(2):134. [doi:10.3390/antibiotics14020134](https://doi.org/10.3390/antibiotics14020134)
34. Tamma PD, Cosgrove SE. Antimicrobial stewardship. *Infectious Disease Clinics*. 2011 Mar 1;25(1):245-60. [doi:10.1016/j.idc.2010.11.011](https://doi.org/10.1016/j.idc.2010.11.011)
35. Yu KH, Beam AL, Kohane IS. Artificial intelligence in healthcare. *Nature biomedical engineering*. 2018 Oct;2(10):719-31. [doi:10.1038/s41551-018-0305-z](https://doi.org/10.1038/s41551-018-0305-z)
36. Feretzakis G, Loupelis E, Sakagianni A, Gialeraki A, Kalles D, Martsoukou M, et al. Machine learning prediction of antimicrobial resistance. *J Clin Med*. 2020 Oct 14;9(10):3293. [doi:10.3390/jcm9103293](https://doi.org/10.3390/jcm9103293)
37. Yelin I, Snitser O, Novich G, Katz R, Tal O, Parizade M, Chodick G, Koren G, Shalev V, Kishony R. Personal clinical history predicts antibiotic resistance of urinary tract infections. *Nature medicine*. 2019 Jul;25(7):1143-52. [doi:10.1038/s41591-019-0503-6](https://doi.org/10.1038/s41591-019-0503-6)
38. Komorowski M, Celi LA, Badawi O, Gordon AC, Faisal AA. Artificial intelligence in intensive care medicine. *Intensive Care Med*. 2020 Jul;46(7):1407-1420. [doi:10.1007/s00134-020-06096-3](https://doi.org/10.1007/s00134-020-06096-3)
39. Sendak MP, Ratliff W, Sarro D, Alderton E, Futoma J, Gao M, Nichols M, Revoir M, Yashar F, Miller C, Kester K. Real-world integration of a sepsis deep learning technology into routine clinical care: implementation study. *JMIR medical informatics*. 2020 Jul 15;8(7):e15182. [doi:10.2196/15182](https://doi.org/10.2196/15182)

40. Ghassemi M, Oakden-Rayner L, Beam AL. The false hope of current approaches to explainable artificial intelligence in health care. *The lancet digital health*. 2021 Nov 1;3(11):e745-50. [doi:10.1016/S2589-7500\(21\)00208-9](https://doi.org/10.1016/S2589-7500(21)00208-9)
41. Wiens J, Saria S, Sendak M, Ghassemi M, Liu VX, Doshi-Velez F, Jung K, Heller K, Kale D, Saeed M, Ossorio PN. Do no harm: a roadmap for responsible machine learning for health care. *Nature medicine*. 2019 Sep;25(9):1337-40. [doi:10.1038/s41591-019-0548-6](https://doi.org/10.1038/s41591-019-0548-6)
42. Holzinger A, Biemann C, Pattichis CS, Kell DB. What do we need to build explainable AI systems for the medical domain?. *arXiv preprint arXiv:1712.09923*. 2017 Dec 28. Available from: <https://arxiv.org/abs/1712.09923>.
43. Morgan DJ, Malani P, Diekema DJ. Diagnostic stewardship—leveraging the laboratory to improve antimicrobial use. *Jama*. 2017 Aug 15;318(7):607-8. [doi:10.1001/jama.2017.8531](https://doi.org/10.1001/jama.2017.8531)
44. Banerjee R, Humphries R. Clinical and laboratory considerations for rapid molecular diagnostics. *Clin Infect Dis*. 2017 Jan 15;64(2):223-228. [doi:10.1093/cid/ciw720](https://doi.org/10.1093/cid/ciw720)
45. Messacar K, Parker SK, Todd JK, Dominguez SR. Implementation of rapid molecular infectious disease diagnostics: the role of diagnostic and antimicrobial stewardship. *Journal of clinical microbiology*. 2017 Mar;55(3):715-23. [doi:10.1128/JCM.02264-16](https://doi.org/10.1128/JCM.02264-16)
46. Patel R. MALDI-TOF MS for the diagnosis of infectious diseases. *Clinical chemistry*. 2015 Jan 1;61(1):100-11. [doi:10.1373/clinchem.2014.221770](https://doi.org/10.1373/clinchem.2014.221770)
47. Clerc O, Prod'homme G, Vogne C, Meylan G, Albertini A, Greub G, et al. Impact of MALDI-TOF and stewardship interventions. *Clin Infect Dis*. 2013 Apr;56(8):1101-1107. [doi:10.1093/cid/cit067](https://doi.org/10.1093/cid/cit067)
48. Kumar A, Roberts D, Wood KE, Light B, Parrillo JE, Sharma S, Suppes R, Feinstein D, Zanotti S, Taiberg L, Gurka D. Duration of hypotension before initiation of effective antimicrobial therapy is the critical determinant of survival in human septic shock. *Critical care medicine*. 2006 Jun 1;34(6):1589-96. [doi:10.1097/01.CCM.0000217961.75225.E9](https://doi.org/10.1097/01.CCM.0000217961.75225.E9)
49. Chiu CY, Miller SA. Clinical metagenomics. *Nature Reviews Genetics*. 2019 Jun;20(6):341-55. [doi:10.1038/s41576-019-0113-7](https://doi.org/10.1038/s41576-019-0113-7)
50. Polk RE, Hohmann SF, Medvedev S, Ibrahim O. Benchmarking risk-adjusted adult antibacterial drug use in 70 US academic medical center hospitals. *Clinical infectious diseases*. 2011 Dec 1;53(11):1100-10. [doi:10.1093/cid/cir672](https://doi.org/10.1093/cid/cir672)
51. World Health Organization. Global antimicrobial resistance and use surveillance system (GLASS) report 2022. World Health Organization; 2022 Dec 8. Available from: <https://www.who.int/publications/i/item/9789240062702>.
52. WHO W. Global action plan on antimicrobial resistance. World Health Organization. 2015 Apr 2. Available from: <https://iris.who.int/items/b6a20419-f956-4c94-84ba-e0bf5f21e074>.
53. World Health Organization. WHO consultation towards the development of guidance on ethics and governance of artificial intelligence for health: meeting report, Geneva, Switzerland, 2–4 October 2019. World Health Organization; 2021. Available from: <https://www.who.int/publications/i/item/9789240012752>.
54. Corral-Acero J, Margara F, Marciniak M, Roderio C, Loncaric F, Feng Y, Gilbert A, Fernandes JF, Bukhari HA, Wajdan A, Martinez MV. The ‘Digital Twin’ to enable the vision of precision cardiology. *European heart journal*. 2020 Dec 21;41(48):4556-64. [doi:10.1093/eurheartj/ehaa159](https://doi.org/10.1093/eurheartj/ehaa159)
55. Schuetz P, Wirz Y, Sager R, Christ-Crain M, Stolz D, Tamm M, Bouadma L, Luyt CE, Wolff M, Chastre J, Tubach F. Effect of procalcitonin-guided antibiotic treatment on mortality in acute respiratory infections: a patient level meta-analysis. *The Lancet infectious diseases*. 2018 Jan 1;18(1):95-107. [doi:10.1016/S1473-3099\(17\)30592-3](https://doi.org/10.1016/S1473-3099(17)30592-3)
56. Rieke N, Hancox J, Li W, Milletari F, Roth HR, Albarqouni S, Bakas S, Galtier MN, Landman BA, Maier-Hein K, Ourselin S. The future of digital health with federated learning. *NPJ digital medicine*. 2020 Sep 14;3(1):119. [doi:10.1038/s41746-020-00323-1](https://doi.org/10.1038/s41746-020-00323-1)
57. Murray CJ, Ikuta KS, Sharara F, Swetschinski L, Aguilar GR, Gray A, Han C, Bisignano C, Rao P, Wool E, Johnson SC. Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. *The lancet*. 2022 Feb 12;399(10325):629-55. [doi:10.1016/S0140-6736\(21\)02724-0](https://doi.org/10.1016/S0140-6736(21)02724-0)