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Systems-level modeling of antimicrobial utilization patterns to optimize stewardship interventions and suppress emerging resistance pathways

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Abstract

Rising antimicrobial resistance (AMR) presents a profound threat to global health, driven in part by complex and often poorly understood patterns of antimicrobial utilization across healthcare systems. Traditional stewardship approaches focused on guideline adherence, formulary controls, or individual prescribing behaviors are insufficient when viewed against the scale and dynamism of resistance evolution. Systems-level modeling offers a broader analytical lens, enabling researchers and stewardship teams to examine antimicrobial use not as isolated prescribing events but as interconnected patterns shaped by clinical workflows, patient demographics, institutional pressures, and microbial ecology. From a macro perspective, systems models integrate multi-source data including electronic health records, pharmacy distributions, resistance phenotypes, and patient-flow dynamics to map utilization trends across wards, hospitals, and regional care networks. These models reveal latent drivers of inappropriate use, identify clusters of high-risk prescribing, and detect feedback loops that accelerate resistance emergence. Agent-based simulations and compartmental models can further characterize how antimicrobial pressure influences microbial population shifts, revealing pathways through which resistant strains develop, propagate, and persist within healthcare environments. Narrowing the focus, this study emphasizes how advanced modeling techniques, such as machine learning–enhanced forecasting, causal inference frameworks, and network-based transmission analysis, can guide precision stewardship interventions. By simulating the outcomes of alternative policies such as formulary restrictions, diagnostic stewardship, or targeted provider education systems-level models enable proactive selection of strategies most likely to reduce selective pressure while preserving clinical effectiveness. Ultimately, integrating systems-level modeling into antimicrobial stewardship transforms reactive management into anticipatory control. Such an approach not only optimizes utilization patterns but also helps suppress emerging resistance pathways, contributing to a more sustainable, resilient antimicrobial ecosystem across healthcare settings.

Keywords: Antimicrobial stewardship; Resistance modeling; Systems-level analysis; Utilization patterns; Predictive simulation; Healthcare optimization

1. Introduction

1.1. The escalating threat of antimicrobial resistance (AMR) in clinical ecosystems

Antimicrobial resistance (AMR) has become one of the most urgent threats to global health systems, undermining the effectiveness of antibiotics, prolonging hospital stays, and increasing morbidity and mortality across patient populations [1]. Hospitals face disproportionate risk because they serve as concentrated hubs of antimicrobial use, invasive procedures, and high-acuity care, all of which accelerate selective pressure for resistant organisms [2]. Rising prevalence of multidrug-resistant pathogens such as carbapenem-resistant Enterobacterales and methicillin-resistant

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Staphylococcus aureus has created unprecedented challenges for infection prevention and therapeutic decision-making [3].

Compounding this threat is the expanding reservoir of resistance genes circulating through hospital wastewater, equipment surfaces, and patient microbiomes [4]. As treatment options narrow, stewardship failures have escalating consequences, raising the likelihood of untreatable infections and cascading outbreaks. AMR is therefore not merely a microbiological issue but a systemic risk affecting every layer of hospital operations and patient safety [5].

1.2. Limitations of conventional stewardship approaches lacking systems-level insight

Traditional antimicrobial stewardship (AMS) programs focus on clinician prescribing behavior, formulary restrictions, and periodic audits of utilization patterns. While essential, these approaches often overlook the complex organizational, behavioral, and environmental factors that shape antimicrobial exposure within hospitals [6]. Conventional stewardship frameworks rarely account for interdependencies between patient flow, diagnostic delays, staffing patterns, and supply-chain pressures, all of which influence prescribing pathways more powerfully than isolated clinician decisions [7].

Furthermore, most stewardship interventions are reactive, triggered only after utilization spikes or resistance trends become apparent. This lag impedes the capacity to intervene early, allowing inappropriate use to persist undetected across departments [8]. Without systems-level insight, AMS programs struggle to anticipate downstream effects such as increased isolation needs, device-associated infections, or operational congestion that arise from shifts in antimicrobial use [9]. As a result, stewardship initiatives often achieve incremental gains rather than transformative reductions in resistance pressure.

1.3. Why systems modeling is essential for capturing complex antimicrobial utilization dynamics

Systems modeling provides the analytical depth needed to illuminate the full complexity of antimicrobial utilization in hospitals. Because antimicrobial use emerges from interactions among clinicians, diagnostic pathways, workflows, and patient trajectories, linear or single-variable analyses cannot capture its true dynamics [8]. Systems modelling encompassing agent-based simulations, compartmental models, and systems-dynamics frameworks allows researchers to trace how prescribing decisions propagate through patient care processes, microbial ecology, and institutional resource flows.

These models can identify hidden feedback loops, such as how diagnostic turnaround times influence empirical therapy decisions or how bed-capacity strain drives broader-spectrum antimicrobial use. They also quantify unintended consequences of stewardship interventions, revealing trade-offs that traditional audits cannot detect [6]. By operationalizing AMR as a property of interconnected systems rather than isolated prescribing events, systems modeling provides a powerful lens for designing proactive, adaptive, and institution-wide stewardship strategies [1].

1.4. Purpose, scope, and contributions of this article

This article presents an integrated systems-modeling framework for analyzing antimicrobial utilization across hospital ecosystems, linking prescribing behavior, diagnostic uncertainty, workflow dynamics, and resistance evolution [7]. It outlines conceptual foundations, modeling techniques, and applied use cases to guide the development of next-generation, systems-aware stewardship interventions [3].

2. Conceptual foundations of systems-level antimicrobial utilization modeling

2.1. Clinical uncertainty and diagnostic delays

Clinical uncertainty plays a central role in antimicrobial utilization because clinicians must often make high-stakes decisions before diagnostic clarity is available. When laboratory results, imaging interpretations, or microbiologic confirmations are delayed, empiric broad-spectrum therapies become the default approach to mitigate clinical risk [10]. This precautionary prescribing is further amplified in critically ill patients, where even minor delays in initiating therapy may worsen outcomes.

However, uncertainty-driven prescribing creates cascading effects: prolonged therapy durations, combination regimens, and early escalation to reserve agents, all of which increase resistance pressure [6]. Diagnostic ambiguity also prompts repeated antimicrobial adjustments as clinicians react to evolving but incomplete information. These patterns illustrate how antimicrobial decisions emerge not solely from clinical knowledge but from constraints, risk perceptions, and information gaps embedded within hospital systems [14].

2.2. Organizational, workflow, and cultural contributors

Antimicrobial use is also shaped by organizational structures, workflow limitations, and cultural norms. High patient turnover, staffing shortages, and time-pressured decision-making environments often reduce opportunities for nuanced prescribing deliberation [9]. In such settings, clinicians may rely on habitual prescribing patterns or inherited norms within specialty teams, allowing unwarranted antimicrobial use to persist unchallenged.

Workflow bottlenecks—such as delayed consult responses, limited oversight from stewardship teams during nights or weekends, and inconsistent access to decision support—further distort prescribing behavior [12]. Cultural expectations, including fear of adverse outcomes or perceived pressure to "do something," reinforce broad-spectrum prescribing even when clinical indicators are weak [7]. These organizational dynamics demonstrate that antimicrobial use is tightly coupled to institutional context rather than strictly clinical rationale.

2.3. Transmission dynamics and ecological effects of antimicrobial exposure

2.3.1. Selection pressure, microbial community shifts, and resistance evolution

Antimicrobial exposure exerts a strong selective pressure on microbial populations, reshaping hospital ecological landscapes. When broad-spectrum agents suppress susceptible organisms, resistant strains proliferate, establishing dominance within patient microbiomes, environmental reservoirs, and device-associated biofilms [15]. Such microbial community shifts increase the probability of colonization and infection with resistant pathogens, expanding the pool of transmissible organisms across the hospital ecosystem.

At the molecular level, antimicrobial pressure accelerates mechanisms such as gene amplification, horizontal gene transfer, and plasmid mobilization, enabling rapid adaptation among bacterial populations [6]. These processes are further amplified by repeated or prolonged antibiotic courses, which create sustained ecological disturbances. Even short-term antimicrobial exposure can produce long-lasting resistance phenotypes, especially in environments where patient density and contact frequency facilitate organism exchange [13].

Because ecological responses occur simultaneously at patient, unit, and facility scales, resistance evolution becomes a systems phenomenon rather than a linear consequence of individual prescribing decisions. This interdependence underscores the necessity of modeling antimicrobial exposure within broader ecological and operational contexts.

2.3.2. Interdependence between prescribing patterns and hospital transmission pathways

Prescribing patterns strongly interact with hospital transmission networks. When antimicrobials alter patient microbiota, colonization with resistant organisms becomes more likely, increasing the probability of onward transmission through staff contact, shared equipment, and environmental contamination [11]. High antimicrobial use within certain units such as ICUs or surgical wards creates micro-ecological hotspots where resistant pathogens flourish and spread.

Conversely, transmission networks shape prescribing behavior: outbreaks or suspected clusters often prompt escalated therapy, generating further resistance pressure [16]. Patient flow dynamics admissions, transfers, discharges link prescribing decisions across departments, enabling resistant organisms to propagate along movement corridors. This reciprocal relationship highlights antimicrobial exposure as both a driver and consequence of transmission dynamics.

2.4. Systems thinking as a blueprint for modeling antimicrobial utilization

2.4.1. Feedback loops, bottlenecks, and nonlinear outcomes

Systems thinking provides a framework for understanding how antimicrobial utilization emerges from interacting clinical, operational, and ecological influences. Feedback loops such as increased resistance prompting broader-spectrum prescribing, which further accelerates resistance create reinforcing cycles that traditional stewardship analysis fails to capture [8].

Bottlenecks, including delayed diagnostics or constrained staffing, generate nonlinear effects: small disruptions can trigger disproportionately large antimicrobial shifts as clinicians compensate for perceived vulnerability. These nonlinearities produce outcomes that are highly sensitive to initial conditions, making systems modeling essential for predicting how small interventions may yield large-scale changes in resistance patterns [12].

2.4.2. How system structures amplify or suppress resistance emergence

Structural features of hospital systems play a decisive role in amplifying or moderating resistance pressures. For example, high patient turnover combined with centralized equipment pools can accelerate cross-unit dissemination of resistant organisms [14]. Conversely, robust isolation capacity, rapid diagnostics, and effective antimicrobial decision-support systems can suppress resistance emergence by reducing unnecessary exposure.

Systems models reveal how structural interventions revised rounding protocols, modified staffing assignments, or streamlined diagnostic workflows alter antimicrobial use indirectly by reshaping clinician decision landscapes [9]. Understanding these structural effects enables hospitals to design interventions that shift system behavior toward reduced resistance pressure rather than relying solely on individual prescribing changes [15].

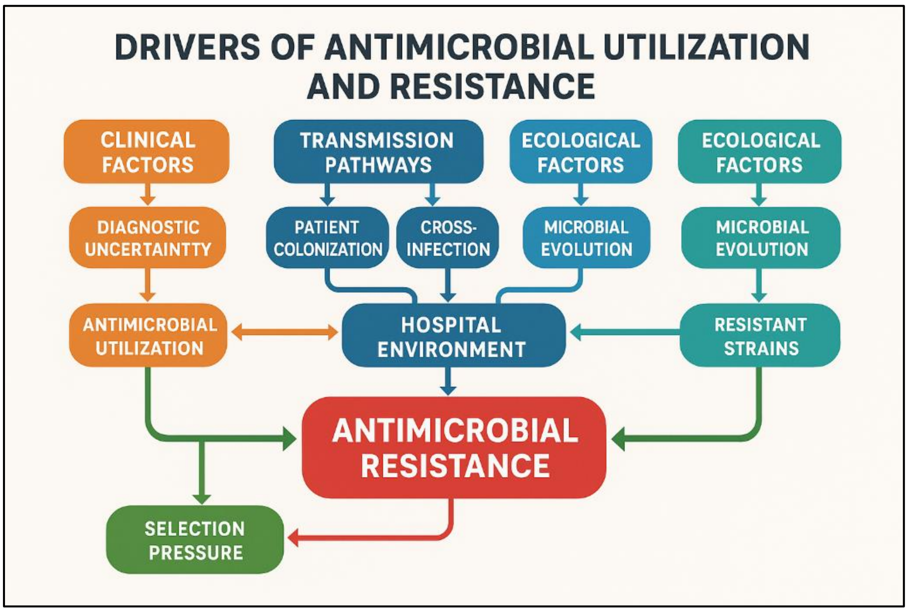

Figure 1 Systems map illustrating the interacting drivers of antimicrobial utilization and resistance pathways

3. Analytical and computational methods for modeling utilization patterns

3.1. Data sources and integration challenges in antimicrobial utilization modeling

3.1.1. EHR prescriptions, microbiology results, and clinical pathways

Electronic health records (EHRs) offer essential data streams for modeling antimicrobial utilization, including timestamps of prescriptions, dose modifications, and escalation or de-escalation decisions [15]. These prescribing patterns gain interpretive value when integrated with microbiology results, which reveal organism identity, resistance profiles, and time-to-positivity trends. Yet linking these datasets is challenging due to asynchronous recording practices, incomplete metadata, and variation in documentation quality across departments [13].

Clinical pathways admission routes, diagnostic sequences, care transitions, and surgical episodes introduce additional complexity, as antimicrobial decisions often depend on time-sensitive trajectory shifts rather than isolated clinical events [19]. Modeling these pathways requires accurate mapping of how diagnostic ordering, symptom evolution, and consult responses unfold over time. Data fragmentation, variable coding standards, and inconsistent integration between microbiology and prescribing modules can obscure these relationships. Therefore, robust data harmonization frameworks are essential to achieve reliable modeling inputs capable of capturing real-world antimicrobial dynamics [20].

3.1.2. Pharmacy dispensing data, stewardship logs, and operational workflows

Pharmacy dispensing systems provide real-time insight into drug availability, dispensing frequency, and unit-level utilization trends, complementing EHR prescribing data with operational context [18]. Variations between what is prescribed and what is dispensed often reveal discrepancies driven by supply constraints, medication substitution, or delayed administration factors that influence resistance pressure but rarely surface in traditional stewardship analysis.

Stewardship logs, including audit results, intervention notes, and guideline-adherence assessments, provide qualitative and quantitative signals illustrating how human oversight interacts with prescribing behavior [21]. Meanwhile, operational workflows such as staffing variability, diagnostic turnaround times, and bed-flow dynamics shape antimicrobial exposure trajectories by influencing the timing and accuracy of clinical decisions [14].

Integrating these three domains dispensing, stewardship oversight, and workflow operations requires interoperability strategies capable of aligning disparate temporal resolutions and data taxonomies. When harmonized effectively, these sources create a multidimensional dataset that reflects antimicrobial use as a complex socio-technical process rather than a series of isolated prescriptions [22].

3.2. Time-series and machine learning models for utilization forecasting

3.2.1. Identification of prescribing deviations, spikes, or drift patterns

Time-series models detect deviations in antimicrobial use by analyzing historical prescribing patterns and identifying anomalies that deviate from expected temporal behavior. These deviations may include short-term spikes associated with suspected outbreaks, gradual upward drift in broad-spectrum therapy, or abrupt changes triggered by staffing shifts, guideline updates, or supply shortages [17].

Classical models such as ARIMA and exponential smoothing capture seasonality and trend behavior, while machine learning approaches including random forests, gradient boosting, and LSTM networks reveal nonlinear dependencies between utilization and contributing factors such as diagnostic delays, patient acuity surges, or workflow congestion [13]. Drift detection models help identify when prescribing norms shift gradually but meaningfully, enabling early stewardship intervention before patterns become entrenched. By linking deviations to contextual events, forecasting models provide real-time situational awareness of emerging prescribing risks [20].

3.2.2. Predicting inappropriate use linked to diagnostic and workflow delays

Machine learning models can also forecast inappropriate antimicrobial use by analyzing indicators of diagnostic uncertainty and workflow disruptions. Delays in culture processing, imaging interpretation, or consult completion often prompt empiric broad-spectrum therapy, creating high-risk windows for inappropriate prescribing [19]. Predictive models trained on workflow timestamps, diagnostic lag patterns, and acuity indicators can identify scenarios where clinicians are most likely to choose unnecessary or overly aggressive antimicrobial regimens [14].

Incorporating patient-level features comorbidities, prior colonization, symptom progression further enhances predictive accuracy. By learning when inappropriate use is most probable, models enable proactive stewardship actions such as real-time alerts, automated recommendations, or targeted consults. These forecasting capabilities shift stewardship from retrospective correction to anticipatory intervention, improving both timeliness and clinical relevance [21].

3.3. Agent-based and systems-dynamics models of antimicrobial utilization

3.3.1. Modeling clinician decision-making and patient-level transitions

Agent-based models (ABMs) simulate antimicrobial utilization as the emergent outcome of interactions among clinicians, patients, diagnostic systems, and environmental conditions [22]. Each clinician-agent makes prescribing decisions based on risk perception, workload, and diagnostic feedback, while patient-agents transition through states such as suspected infection, confirmed diagnosis, and de-escalation eligibility [16]. These micro-level interactions reveal how workflow pressures and uncertainty shape prescribing norms.

3.3.2. Simulating resistance evolution under variable antimicrobial pressure

Systems-dynamics models complement ABMs by simulating resistance evolution at population scale. These models capture how antimicrobial pressure alters microbial ecology, enabling researchers to test how different prescribing strategies influence long-term resistance trends [18]. By adjusting parameters such as therapy duration, agent spectrum, and patient movement across units, systems-dynamics frameworks reveal nonlinear resistance patterns that would be difficult to observe empirically.

3.4. Network-based models of resistance emergence and transmission

3.4.1. Identifying structural vulnerabilities in prescribing networks

Network-based models examine prescribing ecosystems as interconnected structures linking clinicians, specialties, and patient cohorts. Centrality metrics reveal influential prescribers whose behaviors disproportionately shape antimicrobial culture across units [17]. Detecting hubs, bottlenecks, and bridging nodes allows stewardship teams to identify structural vulnerabilities where small behavior changes may create large-scale resistance impact [15].

3.4.2. Linking colonization, infection, and resistance propagation

Resistance emergence is closely intertwined with patient movement and contact patterns. Network models integrate colonization states, infection episodes, and movement pathways to predict how resistant organisms propagate between individuals and departments [13]. These models identify high-risk transmission corridors and quantify how antimicrobial exposure facilitates spread, enabling more strategic containment and stewardship interventions [20].

4. Using systems models to optimize stewardship interventions

4.1. Identifying high-impact leverage points for intervention

4.1.1. Detecting inappropriate prescribing clusters or feedback loops

Systems-level modeling uncovers prescribing clusters, temporal spikes, and reinforcing feedback loops that conventional audits fail to detect. For example, simulation outputs may reveal that a subset of clinicians consistently escalates therapy following diagnostic delays, creating a feedback loop in which operational bottlenecks generate persistent broad-spectrum use [22]. Cluster detection algorithms applied to prescribing networks identify local hot spots of inappropriate therapy, allowing stewardship teams to target influential prescribers whose behaviors propagate across departments [19].

Time-series analyses also highlight drift patterns gradual increases in antimicrobial intensity or duration that emerge subtly across units. These drifts often correlate with seasonal acuity surges, workflow congestion, or misinterpreted guideline updates. Identifying these systemic signatures transforms stewardship from retrospective correction to proactive structural intervention targeting foundational drivers of misuse rather than isolated prescribing events [24].

4.1.2. Recognizing workflow-embedded contributors to antimicrobial misuse

Workflow modeling clarifies how organizational constraints shape antimicrobial decisions. Delayed imaging, slow culture processing, bottlenecked consult pathways, and staffing shortages all create uncertainty conditions that encourage precautionary broad-spectrum prescribing [20]. Systems models demonstrate how even minor disruptions in patient flow can trigger major shifts in clinician behavior, especially during peak operational strain [27].

Additionally, pressure to discharge patients rapidly or maintain throughput may incentivize prematurely broad therapy to avoid delays, embedding misuse into workflow norms. By mapping these operational drivers, models reveal leverage points such as diagnostic acceleration, consult prioritization, or resource redistribution that can indirectly reduce inappropriate prescribing. This perspective positions stewardship as a systems-redesign activity rather than solely a prescriber-oriented intervention [18].

4.2. Simulation-driven stewardship optimization

4.2.1. Testing prospective interventions: formulary changes, diagnostic acceleration, audit-and-feedback

Simulation environments provide a safe testbed for examining the effects of stewardship interventions before real-world implementation. Formulary changes such as restricting specific broad-spectrum agents can be modeled to assess downstream impacts on resistance trends and clinical outcomes [25]. Simulation also evaluates diagnostic acceleration strategies (e.g., rapid PCR panels), quantifying how earlier organism identification reduces empiric therapy intensity and duration [21].

Audit-and-feedback systems can be tested virtually to estimate their capacity to modify clinician behavior across diverse workflows. By comparing hypothetical intervention packages, simulation identifies combinations likely to yield the greatest impact under varying operational constraints, allowing stewardship teams to deploy evidence-informed policies tailored to local conditions.

4.2.2. Modeling intervention interactions with real-world constraints

Simulation also exposes how interventions interact with operational constraints such as staffing shortages, diagnostic capacity, and bed-flow pressures [23]. For instance, restricting antimicrobials without parallel improvements in diagnostic turnaround times may inadvertently increase uncertainty-driven empiric escalation. Models illuminate these trade-offs by showing how interventions shift bottlenecks from one part of the system to another.

They also evaluate implementation feasibility: some interventions may be effective under ideal conditions but fail when resource constraints impede recommended prescribing pathways. Systems modeling therefore supports realistic, context-sensitive stewardship design that anticipates both intended outcomes and unintended consequences [28].

4.3. Behavioral and operational interventions guided by modeling outputs

4.3.1. Provider education, alerts, nudges, and decision-support logic

Model outputs can inform targeted behavioral interventions such as context-aware alerts, nudges, and decision-support prompts that activate when patterns of misuse are detected [19]. For example, if forecasting models identify circumstances where inappropriate empiric therapy is highly probable, real-time prompts can guide clinicians toward narrower or delayed initiation strategies.

Educational interventions can be tailored to specific prescribing clusters, focusing on decision drivers revealed by modelling such as misinterpreted risk thresholds or habitual escalation patterns. These tailored strategies address root causes rather than generic prescribing errors [24].

4.3.2. Department-level coordination and resource alignment

Operational interventions informed by modeling may include redistributing diagnostic resources, adjusting staffing patterns, or reorganizing patient flow to reduce uncertainty-driven prescribing [20]. Department-level coordination ensures that stewardship actions align with local operational pressures: emergency departments may require workflow streamlining, whereas ICUs may benefit more from enhanced rapid diagnostics [27].

By aligning interventions with structural drivers of antimicrobial misuse, hospitals can achieve more durable reductions in resistance pressure and improve system resilience [22].

4.4. Tailoring interventions to pathogen–antimicrobial ecological dynamics

4.4.1. Using evolutionary modeling to anticipate resistance trajectories

Evolutionary models predict how resistance traits evolve under varying antimicrobial pressures, helping institutions design interventions that prevent high-risk trajectories from materializing [26]. These models quantify how therapy duration, antimicrobial spectrum, and patient movement patterns influence resistance evolution, offering foresight into which organisms are most likely to proliferate under current prescribing norms [18].

4.4.2 Adaptive stewardship frameworks based on real-time modeling feedback

Adaptive stewardship leverages continuous modeling outputs to refine interventions dynamically. As resistance trends, workflow conditions, or prescribing behaviors shift, real-time feedback updates risk assessments and triggers adaptive policy adjustments [21]. This creates a learning stewardship system that adjusts strategies as conditions evolve rather than relying on static guidelines ill-suited to complex hospital ecosystems [23].

Table 1 Mapping of Stewardship Interventions to Model-Identified Leverage Points, With Predicted Impact Estimates

Model-Identified Leverage Point	Corresponding Stewardship Intervention	Predicted Impact on Utilization	Predicted Impact on Resistance Dynamics	Operational Considerations
Diagnostic delays leading to empiric broad-spectrum escalation	Rapid diagnostic testing, accelerated culture workflows, automated result routing	15–25% reduction in empiric broad-spectrum starts	Slower emergence of resistance due to earlier organism targeting	Requires investment in lab capacity; improved IT–lab integration
Prescribing clusters among high-influence clinicians or units	Targeted education, peer comparison dashboards, real-time decision nudges	10–30% reduction in inappropriate prescribing within targeted clusters	Reduced transmission of resistant organisms within cluster pathways	Must ensure supportive culture and non-punitive feedback processes
Workflow bottlenecks that create prolonged uncertainty	Streamlined consult workflows, improved staffing distribution, workflow redesign	20% decrease in delay-driven antimicrobial escalation	Fewer selection-pressure surges tied to operational strain	Requires cross-department coordination (ED, ICU, ID, pharmacy)
High-risk patient pathways with repeated diagnostic ambiguity	Embedded clinical decision support with pathway-specific guidance	10–20% improvement in narrowing/de-escalation adherence	Lower cumulative exposure to broad-spectrum agents	Integration with EHR pathways needed; periodic algorithm updates
Rising drift in antimicrobial intensity or duration across units	Unit-level monitoring dashboards, audit-and-feedback, escalation-limiting policies	10–15% reduction in mean treatment duration	Stabilization of resistance trendlines; fewer MIC increases over time	Benefits from real-time analytics rather than retrospective reviews
Ecological hotspots of resistant organism transmission	Enhanced isolation protocols, targeted decolonization, environmental cleaning cycles	Lower incidence of MDRO colonization in hotspot areas	Interrupted resistance propagation across departments	Needs coordination with infection prevention and environmental services
Stocking patterns driving substitution with broader agents	Formulary optimization, tiered access controls, smart inventory planning	5–12% reduction in unnecessary broad-agent substitution	Reduced unintended selective pressure due to stockouts	Close pharmacy–operations collaboration required
High variability in de-escalation practices	Automated reminders, time-based de-escalation checkpoints, pharmacist-led review	15–25% improvement in timely de-escalation	Lower aggregate antimicrobial exposure across episodes	Dependent on consistent adoption by clinical teams
Inefficient review processes for high-risk prescriptions	Automated routing of high-risk cases to stewardship teams	20–35% faster intervention and review	Earlier correction reduces resistance-driving exposure windows	Requires alert prioritization rules to avoid overload

5. Embedding systems modeling into clinical and operational workflows

5.1. Integrating models with EHRs, stewardship dashboards, and clinical decision support

5.1.1. Real-time prescribing risk scoring

Real-time prescribing risk scoring enables stewardship teams to identify inappropriate antimicrobial use as it emerges, rather than retrospectively. Predictive models embedded within EHR systems evaluate a range of inputs including presenting symptoms, diagnostic uncertainty markers, comorbidity profiles, and workflow delays to calculate the likelihood that a given prescription is unnecessary, overly broad, or misaligned with guidelines [29]. These scores update continuously as new data flows into the EHR, producing a dynamic risk signal that reflects evolving clinical circumstances rather than static rules.

To ensure usability, risk scores must appear within clinician workflows in intuitive formats such as color-coded indicators, context-sensitive prompts, or embedded rationale summaries [24]. Real-time scoring empowers clinicians to adjust prescribing decisions in the moment, while also enabling stewardship teams to target interventions toward the highest-risk situations. This functionality makes model-driven oversight more precise and less intrusive, supporting timely corrective action without disrupting care [31].

5.1.2. Dynamic dashboards for pharmacists, physicians, and stewardship committees

Dynamic dashboards synthesize risk scores, resistance trends, utilization patterns, and workflow metrics into an integrated decision-support environment usable by pharmacists, frontline physicians, infectious-disease specialists, and stewardship committees [27]. These dashboards surface essential insights such as unit-specific drift in broad-spectrum use, clusters of inappropriate therapy, or variation in prescribing practices across specialties [23].

To support rapid operational response, dashboards incorporate filtering and drill-down capabilities that allow teams to explore individual cases, compare departments, or track progress toward stewardship goals. Automated trend alerts highlight concerning shifts such as rising carbapenem use or declining de-escalation rates enabling early escalation to stewardship leadership [30].

By presenting model outputs in transparent, actionable formats, dashboards foster shared situational awareness across clinical and operational teams. This enhances the precision and coordination of stewardship interventions at both micro- and macro-levels [32].

5.2. Workflow orchestration and cross-department alignment

5.2.1. Ensuring model outputs drive timely action

Workflow orchestration ensures that model outputs translate into rapid clinical action rather than remaining informational artifacts. Automated triggers route high-risk prescribing events to pharmacists or ID specialists, initiating real-time review and intervention when needed [26]. Escalation logic increases alert prominence if conditions worsen such as diagnostic delays intensifying uncertainty or if recommended actions are not documented within defined intervals.

These mechanisms reduce stewardship lag and ensure that high-risk antimicrobial events receive immediate attention. Additionally, embedding model outputs at key workflow checkpoints triage, order entry, morning rounds ensures clinicians encounter decision-support at moments when prescribing choices are most likely to be influenced [23].

5.2.2. Communication pathways between stewardship, ID, pharmacy, and hospital operations

Effective implementation requires structured communication pathways linking stewardship teams, infectious-disease physicians, pharmacy leadership, nursing, and hospital operations. Model outputs must flow seamlessly across these groups to coordinate clinical review, adjust protocols, and mobilize operational support when large-scale patterns are detected [32].

For example, if forecast models predict rising broad-spectrum use, pharmacy leaders may need to adjust inventory planning, while ID specialists refine treatment algorithms. Similarly, projected workflow bottlenecks may require operational changes such as increasing diagnostic capacity or refining consult prioritization [28]. These communication pathways transform model insights into coordinated institutional action rather than isolated clinician-level changes [30].

5.3. Organizational governance and compliance structures

5.3.1. Oversight mechanisms for model validation and ethical use

Robust governance ensures that antimicrobial stewardship models are accurate, fair, and ethically deployed. Oversight committees including clinicians, data scientists, ethicists, and compliance officers review model performance, examine misclassification patterns, and monitor unintended consequences such as inequitable prescribing recommendations across patient groups [27].

Continuous validation against real-world outcomes prevents model drift and ensures the system evolves alongside changing resistance patterns, diagnostic technologies, and clinical workflows [25]. Ethical oversight safeguards patient autonomy and prevents overreliance on automated guidance, ensuring that human expertise remains central to decision-making [29].

5.3.2. Ensuring accountability and alignment with regulatory expectations

Regulatory frameworks increasingly require transparency in algorithmic systems, especially those influencing clinical treatment decisions. Hospitals must document data provenance, validation workflows, model-update procedures, and escalation policies to maintain compliance with accreditation bodies and national quality standards [23].

Accountability mechanisms such as audit logs, override tracking, and periodic governance reviews ensure that stewardship interventions guided by models remain clinically defensible and operationally consistent. This alignment strengthens institutional trust and supports safe integration of advanced analytics into antimicrobial governance structures [31].

5.4. Human-factors and implementation science considerations

5.4.1. Reducing clinician burden and alert fatigue

Model-driven alerts must be carefully calibrated to avoid overwhelming clinicians already facing substantial cognitive load. Prioritization rules, tiered severity levels, and suppression of low-value notifications help reduce alert fatigue [26]. Embedding recommendations inline with workflow rather than requiring context switches further minimizes burden and enhances adoption [24].

5.4.2. Building trust, training, and capacity for model-guided practice

Sustained implementation depends on clinician trust. Transparent logic explanations, case-based training, and opportunities for feedback help clinicians understand how models derive recommendations [30]. Regular communication between stewardship teams and frontline staff reinforces shared ownership of antimicrobial decisions. Training programs that build data literacy and modeling awareness strengthen the institution's capacity for model-guided stewardship practice [28].

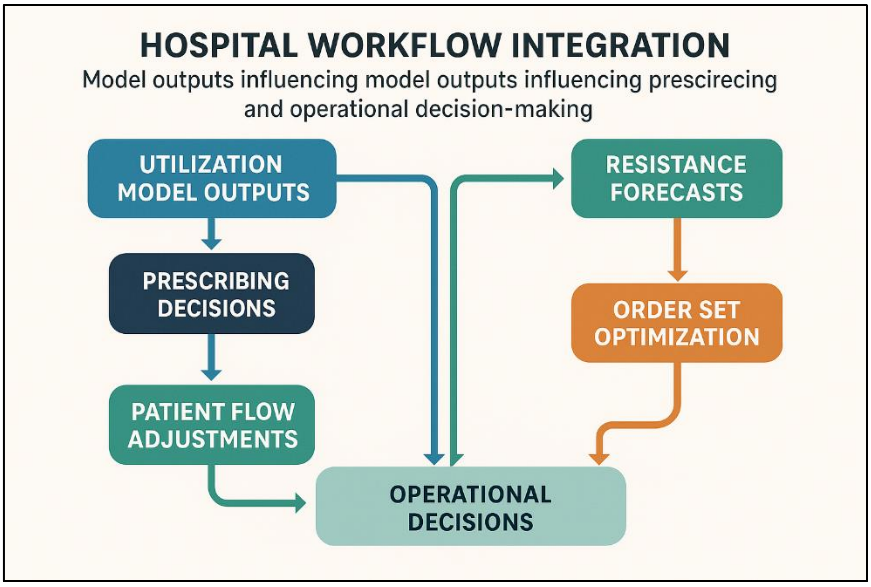

Figure 2 Hospital workflow integration diagram showing model outputs influencing prescribing and operational decision-making

6. Evaluation, performance outcomes, and lessons from deployments

6.1. Clinical outcomes and resistance suppression metrics

Systems-level antimicrobial stewardship models demonstrate substantial clinical impact by reducing inappropriate broad-spectrum use, slowing resistance emergence, and lowering infection rates across diverse hospital environments [29]. Real-time prescribing risk scores and simulation-driven recommendations enable clinicians to adjust therapy earlier, reducing unnecessary exposure windows that historically fueled selection pressure for resistant organisms [33]. Studies employing integrated modeling–stewardship frameworks have reported measurable declines in carbapenem use, shorter durations of empiric therapy, and improved de-escalation rates, outcomes that correlate strongly with resistance suppression at both patient and unit levels [28].

Moreover, resistance surveillance integrated into predictive analytics offers early insight into concerning ecological shifts such as rising MIC values or increasing colonization density allowing hospitals to intervene before resistant strains become entrenched [34]. Infection prevention programs also benefit: by linking prescribing behaviors to transmission dynamics, models help identify when reductions in antimicrobial pressure correspond with decreased hospital-acquired infections, including device-associated and multidrug-resistant organism episodes. These improvements not only enhance patient safety but also mitigate downstream burdens such as prolonged length of stay, isolation requirements, and need for toxic salvage regimens [31]. Collectively, these outcomes demonstrate that systems-level stewardship is capable of producing clinically meaningful resistance suppression across care settings [35].

6.2. Operational and economic impacts

Beyond clinical outcomes, system-level models generate substantial operational and financial benefits. Reductions in unnecessary antimicrobial use translate directly into lower drug utilization costs, particularly for high-cost broad-spectrum agents such as carbapenems and extended-spectrum agents [30]. Forecasting models support more efficient inventory planning, reducing wastage and preventing stockouts that previously disrupted clinical operations [32].

Workflow efficiency improves as well. By identifying diagnostic bottlenecks, staff-distribution imbalances, and high-risk prescribing scenarios, models guide targeted operational changes that smooth patient flow and improve decision timeliness [28]. Real-time alerts enable pharmacists and stewardship teams to prioritize cases with the highest potential impact, reducing review burden and preventing duplication of effort [33].

Economically, hospitals report savings related not only to reduced antimicrobial purchasing but also to averting costly complications such as resistant infections, prolonged admissions, or transfer to higher-acuity units [35]. These combined operational and financial gains make model-driven stewardship a compelling strategy even for resource-constrained hospitals, as investments in analytics infrastructure often pay for themselves through downstream efficiencies [31].

6.3. Scalability across diverse hospital infrastructures

Scalability remains a critical consideration as hospitals differ widely in technological maturity, staffing capacity, and data interoperability. Systems-level stewardship models can be adapted across low-resource, mid-tier, and high-tech environments by adjusting model complexity and data requirements [28]. For example, hospitals without advanced EHR integration can deploy simplified rule-based or statistical models, while larger institutions benefit from full machine learning pipelines and simulation engines [34].

Interoperability challenges such as inconsistent coding standards or siloed diagnostic systems remain barriers to universal adoption, yet modular architectures and standardized data models increasingly enable cross-platform implementation [32]. Adaptive scaling approaches ensure that model insights remain actionable even when computational resources or data depth vary. Ultimately, successful scalability depends on aligning modeling architecture with institutional readiness, ensuring both technical feasibility and operational absorption capacity [29].

Table 2 Summary of Clinical, Operational, and Financial Outcomes Across System-Level Stewardship Deployments

Outcome Category	Measured Outcome	Observed Impact Range	Mechanisms Driving Improvement	Implementation Considerations
Clinical Outcomes	Reduction in broad-spectrum antimicrobial use	10–30% decrease across ICUs, ED, and medical wards	Real-time prescribing risk scores, early diagnostic clarification, decision-support nudges	Requires integration with EHR and rapid diagnostic pathways
	Increased de-escalation rates	15–25% improvement in timely narrowing	Automated de-escalation checkpoints, pharmacist-driven reviews	Depends on clinician acceptance and consistent workflow exposure
	Declines in resistant organism incidence	8–20% reduction in MDRO colonization or infection rates	Lower selection pressure, hotspot identification, targeted interventions	Strongest effects in units with high antimicrobial turnover
	Reduced length of stay for infection-related admissions	5–12% reduction	Earlier appropriate therapy, fewer complications, reduced resistance-driven delays	Benefits from coordinated stewardship + infection prevention alignment
Operational Outcomes	Improved workflow efficiency	10–18% reduction in time-to-intervention for high-risk prescriptions	Automated routing of alerts, streamlined consult pathways	Requires stable IT infrastructure and stewardship manpower
	Faster diagnostic-to-treatment alignment	Up to 30% improvement in concordance	Prioritized processing, reduced bottlenecks, tighter lab–clinical integration	High diagnostic capacity amplifies gains
	Enhanced cross-department coordination	Qualitative improvements in communication and escalation consistency	Shared dashboards, unified situational awareness platforms	Cultural readiness and governance structures are key
Financial Outcomes	Reduced antimicrobial expenditure	12–22% annual cost savings	Decreased broad-spectrum use, shorter	Most impactful in high-volume tertiary centers

			durations, fewer unnecessary courses	
	Lower costs from avoided resistant infections	Significant downstream savings (varies by pathogen burden)	Fewer MDRO cases, reduced isolation needs, minimized salvage therapy	Financial benefits increase with institution size and baseline resistance rates
	Optimized inventory management and reduced wastage	8–15% reduction in expired or unused stock	Forecasting-driven procurement, smarter substitution prevention	Dependent on pharmacy–operations collaboration

7. A unified systems-level stewardship framework

7.1. Multi-layer integration of modeling, surveillance, and intervention

A unified systems-level stewardship framework integrates surveillance, modeling, and targeted intervention into a continuously adaptive ecosystem rather than a collection of discrete initiatives. Central to this integration is the merging of prescribing analytics, resistance surveillance data, and operational workflow signals into a single intelligence layer capable of monitoring system health in real time [36]. Unlike traditional stewardship, which often depends on retrospective audits, multi-layer approaches allow hospitals to detect early deviations, intervene before patterns worsen, and track downstream ecological effects as they unfold [34].

Key to this model is continuous feedback. Insights from predictive analytics inform operational adjustments, which then reshape prescribing patterns, creating new data that refine subsequent model iterations [39]. This cyclical information flow strengthens institutional resilience by ensuring stewardship strategies evolve alongside clinical, microbial, and operational conditions.

Intervention layers from decision-support nudges to rapid diagnostics and workflow redesign are orchestrated through shared situational awareness platforms accessible to clinicians, pharmacists, infection-prevention teams, and administrators [37]. This alignment ensures stewardship is not limited to isolated clinician behavior but becomes a system-wide behavioral, operational, and ecological optimization process. Through this multi-layer integration, stewardship transforms from episodic oversight into an adaptive, ecosystem-level management strategy capable of responding dynamically to emerging resistance threats [40].

7.2. Future directions: federated learning, predictive evolutionary modeling, and autonomous stewardship agents

Next-generation stewardship will increasingly depend on technologies that enable anticipatory, decentralized, and scalable intelligence. Federated learning, for example, allows institutions to train predictive antimicrobial utilization and resistance models across distributed datasets without sharing raw patient information, thus preserving privacy while generating more robust and generalizable models [35]. Such architectures enable system-wide learning across networks of hospitals, strengthening situational awareness and resistance forecasting capabilities.

Predictive evolutionary modeling emerges as another frontier, offering the ability to simulate how resistance traits may evolve under different antimicrobial pressures, patient flows, or ecological disruptions [38]. These models help institutions anticipate the next generation of resistant organisms rather than merely reacting to existing ones.

Autonomous stewardship agents AI-driven decision-support systems capable of delivering real-time recommendations represent a further shift toward proactive antimicrobial management. These agents continuously analyze prescribing data, workflow conditions, diagnostic status, and ecological signals to offer context-aware guidance, escalating concerns when patterns indicate high-risk misuse [34]. By transitioning stewardship from reactive oversight to anticipatory governance, these technologies redefine how hospitals respond to complex AMR dynamics [40].

7.3. Policy, workforce, and institutional readiness considerations

Realizing the full potential of systems-level stewardship requires readiness across policy, workforce capacity, and institutional governance. Policymakers must support standards for data interoperability, algorithmic transparency, and cross-institutional learning frameworks that enable federated analytics without compromising patient privacy [36].

Institutions must likewise invest in workforce development equipping clinicians, pharmacists, data scientists, and administrators with the competencies needed to interpret and operationalize model outputs effectively [39].

Governance structures should ensure clear accountability for model deployment, validation, and ongoing monitoring, supported by dedicated stewardship committees capable of overseeing dynamic, data-driven systems [37]. Finally, hospitals must assess their maturity level and readiness to adopt advanced analytics, ensuring infrastructure, culture, and leadership alignment before large-scale implementation [40]. Without these foundational elements, even sophisticated models risk limited impact or operational resistance.

8. Conclusion

This article has demonstrated that antimicrobial stewardship must evolve beyond traditional, prescriber-focused interventions toward a systems-level paradigm capable of addressing the complex clinical, operational, and ecological forces that drive antimicrobial use. By integrating modeling, surveillance, workflow analysis, and predictive analytics, hospitals gain a more complete understanding of how prescribing decisions emerge, how resistance evolves, and where leverage points exist for effective intervention. This systems-oriented framing represents a significant conceptual advancement, shifting stewardship from reactive auditing to proactive, intelligence-driven management.

The strategic importance of systems-level modeling lies in its ability to unify previously siloed data streams EHR prescribing patterns, microbiology trends, operational workflows, and ecological indicators into a coherent analytical architecture. This integration allows institutions to detect drift, anticipate misuse, and intervene before resistance becomes entrenched. Such foresight is essential as hospitals face rising complexity: faster patient turnover, diagnostic uncertainty, workforce strain, and the continuous emergence of multidrug-resistant organisms. Modeling transforms these challenges into actionable insights, strengthening institutional resilience and supporting more adaptive stewardship practices.

Clinically, systems-level approaches improve decision quality at the bedside, reducing unnecessary antimicrobial exposure and suppressing resistance trajectories. They bolster infection prevention capabilities by connecting prescribing behavior to transmission pathways and ecological consequences. Organizationally, these models enhance coordination across departments, streamline workflows, reduce avoidable costs, and support consistent governance. Their ability to highlight structural contributors diagnostic delays, bottlenecks, staffing patterns positions stewardship as a core operational strategy rather than solely a clinical responsibility.

Looking ahead, the field stands at the threshold of significant innovation. Federated learning, predictive evolutionary modeling, and autonomous decision-support agents promise to expand the predictive power, scalability, and anticipatory intelligence of stewardship systems. These emerging technologies will reshape how hospitals interpret risk, deploy resources, and respond to evolving microbial threats. Future research must explore how these tools can be safely integrated, how clinical trust can be cultivated, and how regulatory frameworks can support responsible adoption.

Ultimately, systems-level modeling offers a transformative pathway toward more effective, efficient, and sustainable antimicrobial stewardship. By embracing these analytical advances, healthcare institutions can better protect patients, preserve antimicrobial efficacy, and strengthen their defense against the accelerating threat of resistance.

References

[1] Garcia E, Ly N, Diep JK, Rao GG. Moving from point-based analysis to systems-based modeling: integration of knowledge to address antimicrobial resistance against MDR bacteria. Clinical Pharmacology & Therapeutics. 2021 Nov;110(5):1196-206.

[2] Daniel Akanbi. LEADING DIGITAL REINVENTION INITIATIVES COMBINING DATA ARCHITECTURE MODERNIZATION, INTELLIGENT PROCESS MINING, AND SCALABLE PLATFORM INTEGRATION ACROSS DIVERSE ORGANIZATIONAL ENVIRONMENTS. International Journal Of Engineering Technology Research & Management (IJETRM). 2021Dec21;05(12):360–73.

[3] Yusuf O, Taiwo M. Quantifying economic impact of COVID-19-induced disruptions in Nigeria's medicine supply chains: prices, availability and out-of-pocket burdens. World J Adv Res Rev. 2020;7(3):357-371. doi:10.30574/wjarr.2020.7.3.0346.

[4] Schueller J, Kiggundu N, Doering O, Dale B. Engaging Challenges. Organization (ISCO). 2015 May;31.

[5] National Research Council, Board on Global Health, Global Affairs, Security, Cooperation, Committee on Advances in Technology, the Prevention of Their Application to Next Generation Biowarfare Threats. An international perspective on advancing technologies and strategies for managing dual-use risks: report of a workshop. National Academies Press; 2005 Dec 8.

[6] Sitterding MC, Miller C, Marshall ES. Practice Models: Design, Implementation, and Evaluation. TRANSFORMATIONAL. 2016 Aug 26:99.

[7] Lubin IM, Astles JR, Shahangian S, Madison B, Parry R, Schmidt RL, Rubinstein ML. Bringing the clinical laboratory into the strategy to advance diagnostic excellence. diagnosis. 2021 Aug 1;8(3):281-94.

[8] Rumbidzai Derera. HOW FORENSIC ACCOUNTING TECHNIQUES CAN DETECT EARNINGS MANIPULATION TO PREVENT MISPRICED CREDIT DEFAULT SWAPS AND BOND UNDERWRITING FAILURES. International Journal of Engineering Technology Research & Management (IJETRM). 2017Dec21;01(12):112–27.

[9] Graber CJ, Jones MM, Goetz MB, Madaras-Kelly K, Zhang Y, Butler JM, Weir C, Chou AF, Youn SY, Samore MH, Glassman PA. Decreases in antimicrobial use associated with multihospital implementation of electronic antimicrobial stewardship tools. Clinical Infectious Diseases. 2020 Aug 22;71(5):1168-76.

[10] Milstein B, Stojicic P, Auchincloss E, Kelleher C. Civic Life and System Stewardship on the Job: How Can Workers in Every Industry Strengthen the Belonging and Civic Muscle Everyone Needs to Thrive?. The Good Society. 2020 Apr 9;29(1-2):42-73.

[11] EXCHANGE M, NETWORK S. 28th Annual Meeting of the Pediatric Pharmacy Administrative Group on Ambulatory Care and Pediatric Intensive Care, April 10-11, 2019, Oklahoma City, OK. J Pediatr. 2019;24(4):330-72.

[12] Zingg W, Holmes A, Dettenkofer M, Goetting T, Secci F, Clack L, Allegranzi B, Magiorakos AP, Pittet D. systematic review and evidence-based guidance on organization of hospital infection control programmes (SIGHT) study group. Hospital organisation, management, and structure for prevention of health-care-associated infection: a systematic review and expert consensus. Lancet Infect Dis. 2015 Feb;15(2):212-4.

[13] Akanbi D. Building automated decision engines that merge operational intelligence with workflow robotics to significantly elevate enterprise throughput, accuracy, and performance stability. *International Journal of Computer Applications Technology and Research*. 2020;9(12):487-499.

[14] National Research Council, Division on Earth, Board on Life Sciences, Committee on a New Biology for the 21st Century, Ensuring the United States Leads the Coming Biology Revolution. A new biology for the 21st century. National Academies Press; 2009 Dec 20.

[15] Udeh NC. *Building sustainable SME banking strategies that expand market access, boost client retention, and support economic inclusion*. International Journal of Financial Management and Economics. 2018;1(1):126-135. doi:10.33545/26179210.2018.v1.i1.674.

[16] Daughton CG. Drugs and the environment: stewardship & sustainability. US Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory; 2010 Sep 12.

[17] Wizemann T, Nass SJ, Andrada A, Amankwah FK, National Academies of Sciences, Engineering, and Medicine. Proceedings of a Workshop. InThe Role of NIH in Drug Development Innovation and Its Impact on Patient Access: Proceedings of a Workshop 2019 Nov 14. National Academies Press (US).

[18] Eze Dan-Ekeh. DEVELOPING ENTERPRISE-SCALE MARKET EXPANSION STRATEGIES COMBINING TECHNICAL PROBLEM-SOLVING AND EXECUTIVE-LEVEL NEGOTIATIONS TO SECURE TRANSFORMATIVE INTERNATIONAL ENERGY PARTNERSHIPS. International Journal Of Engineering Technology Research & Management (IJETRM). 2018Dec21;02(12):165–77.

[19] National Academies of Sciences, Medicine, Division of Behavioral, Social Sciences, Board on Environmental Change, Medicine Division, Division on Earth, Life Studies, Water Science, Technology Board, Board on Life Sciences. Science breakthroughs to advance food and agricultural research by 2030. National Academies Press; 2019 Mar 21.

[20] Rockne RC, Hawkins-Daarud A, Swanson KR, Sluka JP, Glazier JA, Macklin P, Hormuth DA, Jarrett AM, Lima EA, Oden JT, Biros G. The 2019 mathematical oncology roadmap. Physical biology. 2019 Jun 19;16(4):041005.

[21] Lui LM, Majumder EL, Smith HJ, Carlson HK, Von Netzer F, Fields MW, Stahl DA, Zhou J, Hazen TC, Baliga NS, Adams PD. Mechanism across scales: a holistic modeling framework integrating laboratory and field studies for microbial ecology. Frontiers in microbiology. 2021 Mar 24;12:642422.

[22] Kennedy MC, Pallotti P, Dickinson R, Harley C. 'If you can't see a dilemma in this situation you should probably regard it as a warning': a metasynthesis and theoretical modelling of general practitioners' opioid prescription experiences in primary care. British Journal of Pain. 2019 Aug;13(3):159-76.

[23] Biteen JS, Blainey PC, Cardon ZG, Chun M, Church GM, Dorrestein PC, Fraser SE, Gilbert JA, Jansson JK, Knight R, Miller JF. Tools for the microbiome: nano and beyond. ACS nano. 2016 Jan 26;10(1):6-37.

[24] Nwenekama Charles-Udeh. Leveraging financial innovation and stakeholder alignment to execute high-impact growth strategies across diverse market environments. Int J Res Finance Manage 2019;2(2):138-146. DOI: 10.33545/26175754.2019.v2.i2a.617

[25] National Research Council, Division on Earth, Committee on Twenty-First Century Systems Agriculture. Toward sustainable agricultural systems in the 21st century. National Academies Press; 2010 Jul 25.

[26] Fernández L, Cima-Cabal MD, Duarte AC, Rodriguez A, García P, García-Suárez MD. Developing diagnostic and therapeutic approaches to bacterial infections for a new era: implications of globalization. Antibiotics. 2020 Dec 16;9(12):916.

[27] Hull CM, Purdy NJ, Moody SC. Mitigation of human-pathogenic fungi that exhibit resistance to medical agents: can clinical antifungal stewardship help?. Future microbiology. 2014 Mar 1;9(3):307-25.

[28] Payumo J, Alocilja E, Boodoo C, Luchini-Colbry K, Ruegg P, McLamore E, Vanegas D, Briceno RK, Castaneda-Sabogal A, Watanabe K. Next Generation of AMR Network. Encyclopedia 2021, 1, 871–892 [Internet]. 2021

[29] Imamovic L, Sommer MO. Use of collateral sensitivity networks to design drug cycling protocols that avoid resistance development. Science translational medicine. 2013 Sep 25;5(204):204ra132-.

[30] Köser CU, Ellington MJ, Peacock SJ. Whole-genome sequencing to control antimicrobial resistance. Trends in Genetics. 2014 Sep 1;30(9):401-7.

[31] Billington JK. A new product development partnership model for antibiotic resistance. American Journal of Law & Medicine. 2016 May;42(2-3):487-523.

[32] Pulia M, Redwood R, May L. Antimicrobial stewardship in the emergency department. Emergency medicine clinics of North America. 2018 Sep 6;36(4):853.

[33] Wallace MJ, Fishbein SR, Dantas G. Antimicrobial resistance in enteric bacteria: current state and next-generation solutions. Gut microbes. 2020 Nov 9;12(1):1799654.

[34] Payumo J, Alocilja E, Boodoo C, Luchini-Colbry K, Ruegg P, McLamore E, Vanegas D, Briceno RK, Castaneda-Sabogal A, Watanabe K, Gordoncillo MJ. Next generation of amr network. Encyclopedia. 2021 Aug 26;1(3):871-92.

[35] McEwen SA, Collignon PJ. Antimicrobial resistance: a one health perspective. Antimicrobial resistance in bacteria from livestock and companion animals. 2018 Oct 1:521-47.

[36] Ahmed FA. Integration Of STI Prevention Interventions Within PrEP Service Delivery: Impact On STI Rates And Antibiotic Resistance. International Journal of Scientific Interdisciplinary Research. 2021 Jun 27;2(2):63-97.

[37] Knight GM, Costelloe C, Murray KA, Robotham JV, Atun R, Holmes AH. Addressing the unknowns of antimicrobial resistance: quantifying and mapping the drivers of burden. Clinical Infectious Diseases. 2018 Feb 1;66(4):612-6.

[38] Moehring RW, Anderson DJ. Antimicrobial stewardship as part of the infection prevention effort. Current infectious disease reports. 2012 Dec;14(6):592-600.

[39] Eze Dan-Ekeh. Engineering high-value commercialization frameworks integrating technical innovation with strategic sales leadership to drive multimillion-dollar growth in global energy markets. World J Adv Res Rev. 2019;4(2):256-268. doi:10.30574/wjarr.2019.4.2.0152

[40] Charani E, McKee M, Ahmad R, Balasegaram M, Bonaconsa C, Merrett GB, Busse R, Carter V, Castro-Sanchez E, Franklin BD, Georgiou P. Optimising antimicrobial use in humans–review of current evidence and an interdisciplinary consensus on key priorities for research. The Lancet Regional Health–Europe. 2021 Aug 1;7.