Natural Resources for Human Health

eISSN: 2583-1194

Original Research

Received 28 April 2026
Revised 26 May 2026
Accepted 16 June 2026

Natural Resources for Human Health 2026, Vol. 6 (5): 59–71

KEYWORDS: Antimicrobial Stewardship Program; ASP; Surgical Site Infections; SSIs; Review.

Antimicrobial Stewardship Program Approaches, Barriers, and Novel Strategies for Combating Surgical Site Infections

Faisal Miqad K. Albaqami

Department of Biology, Faculty of science, Islamic University of Madinah, Madinah 42351, Saudi Arabia, falbaqami@iu.edu.sa, https://orcid.org/0000-0003-4909-1081

ABSTRACT: Surgical site infections (SSIs) are among the most critical types of infections encountered in hospital settings, occurring before, during, or after surgical procedures. Antimicrobial resistance associated with these infections is highly prevalent in healthcare environments, posing a significant challenge to patient safety and clinical outcomes. Therefore, the implementation and establishment of antimicrobial stewardship programs (ASPs) are fundamentally important to combat this resistance. These programs provide a structured approach to optimizing antibiotic prescribing, reducing the costs associated with antimicrobial use, and minimizing the development of microbial resistance. However, several barriers and challenges may hinder the effective establishment of these programs. Consequently, innovative strategies must be developed and implemented to overcome these obstacles and enhance the quality and effectiveness of antimicrobial stewardship programs in hospitals. This review aims to provide an overview of the key criteria for establishing antimicrobial stewardship programs to combat surgical site infections and their resistance patterns. It also highlights novel approaches to reducing the challenges faced by healthcare professionals during the implementation of these programs.

INTRODUCTION

A surgical site infection (SSI) is an infection that develops at the site of a surgical procedure. It usually occurs within 30 days after surgery [1]. However, when an implant or prosthetic device is involved, the infection may develop up to one year after the procedure [2].

SSIs remain a major cause of illness and death in modern healthcare systems. They continue to pose a serious global health challenge, particularly in the Middle East and North Africa region, where they account for a considerable proportion of hospital-acquired infections. The incidence of SSIs ranges from approximately 1% to 30%, depending on the type and complexity of the surgical procedure, the patient's health status, and other clinical risk factors [3].

The effects of SSIs can be severe. They are associated with increased mortality, unexpected hospital readmissions, additional medical procedures, and prolonged recovery. Patients who develop an SSI may remain in the hospital for an additional 10 to 11 days compared with patients who recover without infection. These infections also impose substantial financial and operational burdens on patients, healthcare professionals, and healthcare institutions [4].

Antimicrobial Stewardship Programs have become an essential strategy for improving the use of antimicrobial medications, enhancing patient outcomes, and limiting the development of antimicrobial resistance [5]. These programs involve coordinated actions to ensure that patients receive the most appropriate antimicrobial agent at the correct dose, via the most suitable route, and for the necessary duration. Treatment decisions should also consider the patient's individual characteristics, the type of infection, and local patterns of antimicrobial resistance [6].

Antimicrobial stewardship programs are a key component of comprehensive strategies to reduce the incidence of surgical site infections and limit complications caused by antimicrobial-resistant infections [7]. Antimicrobial stewardship is an organised approach implemented across healthcare institutions to promote and monitor the responsible use of antimicrobial medications. Its main purpose is to ensure that these treatments remain effective for both current and future patients [8]. This review aims to provide an overview of the key criteria for establishing antimicrobial stewardship programs to combat surgical site infections and their resistance patterns. It also highlights novel approaches to reducing the challenges faced by healthcare professionals during the implementation of these programs.

OVERVIEW OF SURGICAL SITE INFECTIONS

A surgical site infection (SSI) is an infection that develops at the surgical site. It may affect the skin and subcutaneous tissue or extend into deeper tissues, organs, or body spaces [9]. Depending on the type of surgical procedure, an SSI may occur within 30 or 90 days after surgery. These infections are classified according to how deeply they involve the surgical site [10].

SSIs place a considerable burden on both patients and healthcare systems. Previous estimates suggest that treating an SSI may cost approximately £10,523 per patient. They are also among the most common causes of unexpected hospital readmission following surgery.

The incidence of SSIs varies considerably depending on the location of the operation and the classification of the surgical wound, with reported rates ranging from 5% to 30%. In the United States, it is estimated that SSIs develop in approximately 2% to 5% of patients undergoing inpatient surgical procedures each year [11].

These infections can lead to serious complications, prolonged recovery, increased illness, and a higher risk of death. Although preventive measures have helped reduce SSI rates over time, they remain a major concern. As the population ages and more patients undergo increasingly complex surgical procedures, the number of people at risk of developing SSIs is likely to rise [12].

Surgical site infections are classified according to the depth and anatomical location of the affected tissues [13]. They may involve only the skin and subcutaneous tissue, extend into the deeper soft tissues of the incision, or affect an organ or body space involved in the surgical procedure. This classification is important because the severity, clinical presentation, diagnostic approach, and management of infection may differ between the three categories [9]. The main types of surgical site infection are summarized in Table 1.

The development of a surgical site infection is influenced by several interacting factors related to the patient, the surgical procedure, and the healthcare environment. Patient-related factors include advanced age, diabetes, obesity, smoking, malnutrition, immunosuppression, and poor glycemic control [14]. Procedure-related factors include prolonged or emergency surgery, contaminated wounds, excessive blood loss, inadequate skin preparation, and inappropriate antibiotic prophylaxis. Environmental and healthcare-related factors, such as poor sterile technique, inadequate hand hygiene, improper instrument sterilization, and suboptimal postoperative wound care, may also increase the risk of infection [15]. These major risk-factor categories are illustrated in Figure 1.

Table 1 Types of Surgical Site Infection (SSI) [16, 17]

Type of SSI	Definition	Structures Involved	Common Features
Superficial Incisional SSI	Infection occurs at the surface of the surgical incision	Skin and subcutaneous tissue	Redness, warmth, swelling, pain, tenderness, pus or discharge from the wound
Deep Incisional SSI	Infection extends deeper than the skin and subcutaneous layer	Fascia and muscle layers	Fever, pain, swelling, wound separation, abscess formation, deep discharge
Organ/Space SSI	Infection develops in any organ or body space opened or manipulated during surgery	Organs, cavities, or spaces involved in the operation	Fever, localized pain, abscess, drainage from drains, evidence of infection on imaging or reoperation

Surgical-site infection microbiology varies by the type of operation, wound contamination class, local antimicrobial-resistance patterns, and patient risk factors. Therefore, the list below is an approximate clinical ranking, rather than a universal prevalence ranking. In European SSI surveillance for 2023, *Staphylococcus aureus*, coagulase-negative staphylococci, *Escherichia coli*, and *Enterococcus* species were among the most frequently reported organisms (Table 2).

Table 2 Major bacterial and fungal pathogens causing hospital-acquired SSIs [18-22]

Pathogen	Type	Common surgical settings	Major clinical or resistance concern
***Staphylococcus aureus*, including MRSA**	Gram-positive bacterium	Cardiac, orthopedic, vascular, breast, neurosurgical and other clean operations	One of the leading causes of SSI. MRSA strains limit β-lactam treatment options and may cause deep wound infection, bacteremia and implant infection.
Coagulase-negative staphylococci, especially *S. epidermidis*	Gram-positive bacteria	Prosthetic-joint, cardiac-device, spinal and vascular-graft surgery	Normal skin organisms that readily form biofilms on implants, prostheses, sutures and other foreign material.
Escherichia coli	Gram-negative bacterium	Colorectal, abdominal, hepatobiliary, gynecological and urological surgery	Important endogenous intestinal pathogen; ESBL-producing and occasionally carbapenem-resistant strains complicate treatment.
Enterococcus faecalis* and *E. faecium	Gram-positive bacteria	Colorectal, abdominal, pelvic, transplant and hepatobiliary surgery	Frequently involved in polymicrobial organ-space infections. VRE, particularly resistant *E. faecium*, is a major hospital concern.
Klebsiella pneumoniae	Gram-negative bacterium	Abdominal, colorectal, transplant, trauma and ICU-associated surgery	ESBL and carbapenemase-producing strains—including KPC, NDM and OXA-48-like organisms—may be multidrug resistant [23].
Pseudomonas aeruginosa	Gram-negative bacterium	Burns, trauma, vascular surgery, moist wounds and prolonged hospitalization	Can persist in moist hospital environments and develop multidrug resistance during therapy; deep infections can be difficult to eradicate.
***Enterobacter cloacae* complex**	Gram-negative bacterium	Abdominal, hepatobiliary, transplant and device-associated surgery	Possesses inducible AmpC β-lactamase and may acquire ESBLs or carbapenemases, producing treatment failure with some cephalosporins.
Acinetobacter baumannii	Gram-negative bacterium	Trauma, burns, neurosurgery and ICU-associated postoperative wounds	Survives for prolonged periods on hospital surfaces. Carbapenem-resistant *A. baumannii* is especially difficult to treat.
Proteus mirabilis	Gram-negative bacterium	Abdominal, colorectal, perineal and urological surgery	Often occurs in polymicrobial wounds and may carry ESBL or other acquired resistance mechanisms.
***Bacteroides fragilis* group**	Anaerobic Gram-negative bacteria	Colorectal, appendiceal, pelvic and other gastrointestinal surgery	Major component of intestinal flora and an important cause of deep abscesses and polymicrobial organ-space SSIs. Anaerobic culture may be required.
β-Hemolytic streptococci, including *Streptococcus pyogenes*	Gram-positive bacteria	Obstetric, gynecological, soft-tissue and general surgery	Less frequent than staphylococci, but capable of producing rapidly progressive cellulitis, necrotizing infection and toxic shock [24].
Serratia marcescens	Gram-negative bacterium	Cardiac, neurosurgical, ophthalmic and device-associated procedures	Can cause hospital clusters linked to contaminated solutions, equipment or environmental reservoirs; may express

			AmpC and additional resistance mechanisms.
Candida albicans	Yeast	Gastrointestinal surgery, anastomotic leakage, recurrent abdominal surgery, transplantation and prolonged ICU admission	The dominant fungal cause of postoperative wound and intra-abdominal fungal infection; usually affects critically ill or immunocompromised patients [25].
Non-*albicans Candida*—especially *C. glabrata*, *C. parapsilosis* and *C. tropicalis*	Yeasts	Abdominal surgery, transplantation, parenteral nutrition, central-line exposure and prolonged broad-spectrum antibiotic use	Some species have reduced azole susceptibility or acquire echinocandin resistance. *C. parapsilosis* is particularly associated with devices and healthcare transmission.
***Candida auris* and postoperative molds such as *Aspergillus* spp.**	Yeast and filamentous fungi	High-risk ICU patients, cardiac or spinal surgery, immunosuppression and occasional hospital environmental outbreaks	*C. auris* can spread between hospitalized patients and is often antifungal resistant. Postoperative aspergillosis is rare but may cause severe deep wound, mediastinal, bone or spinal infection.

Bacteria account for the great majority of SSIs, *particularly staphylococci, Enterobacterales, enterococci* and non-fermenting Gram-negative bacilli. Fungal SSIs are less common but should be considered in immunocompromised patients, transplant recipients, patients with gastrointestinal leakage, prolonged ICU admission, repeated surgery or failure to improve with antibacterial treatment. Definitive management should be based on properly collected deep-tissue or organ-space cultures, antimicrobial susceptibility testing, local antibiogram data, and adequate surgical source control.

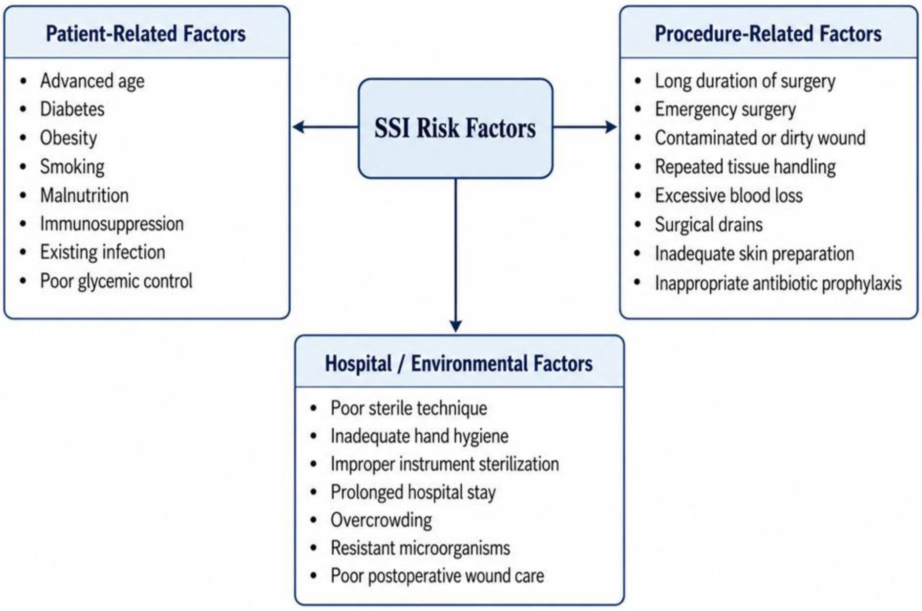

Figure 1 The most commonly reported risk factors of SSIs [17, 26]

PRINCIPLES OF ANTIMICROBIAL STEWARDSHIP PROGRAMS

Antimicrobial stewardship refers to coordinated interventions intended to improve and measure antimicrobial use by ensuring the selection of the most appropriate agent, dose, route, and duration [27]. In SSI care, stewardship applies to two distinct clinical situations: perioperative antimicrobial prophylaxis, which is administered to prevent an infection, and therapeutic antimicrobial treatment, which is used when an SSI has already developed. Prophylactic antibiotics should not be continued as treatment unless there is clinical evidence of infection. Similarly, treatment of an established SSI should not rely on antibiotics alone when drainage, debridement, removal of infected material, or another source-control procedure is required [28] (Table 3).

Table 3 Principles of Antimicrobial Stewardship Programs Used in SSI Prevention and Management [29-35]

Stewardship principle	Application to surgical site infections	Practical implementation and indicators
Leadership commitment and accountability	Hospital leadership should recognize appropriate surgical antimicrobial use as a patient-safety priority and provide the personnel, authority, information technology, and financial resources required for implementation. A named physician and pharmacist should be responsible for stewardship outcomes.	Establish a multidisciplinary SSI and antimicrobial stewardship committee involving surgery, infectious diseases, pharmacy, microbiology, anesthesia, nursing, infection prevention, and quality-improvement personnel. Monitor whether responsibilities, policies, and escalation pathways are clearly assigned.
Clear distinction between prophylaxis and treatment	Perioperative prophylaxis is intended to prevent SSI and should not be automatically extended because a procedure was complicated, a drain remains in place, or the patient is considered high risk. Therapeutic antibiotics should be initiated only when clinical findings support an established or strongly suspected infection.	Require clinicians to document the indication as "surgical prophylaxis" or "treatment of established infection." Use automatic stop dates or separate electronic order sets for prophylaxis and treatment.
Procedure-specific antimicrobial selection	The prophylactic agent should cover the organisms most likely to contaminate the surgical site during the specific procedure. The narrowest effective regimen should be selected according to evidence-based recommendations, surgical site, wound classification, institutional resistance patterns, and individual patient factors.	Develop procedure-specific prophylaxis guidelines and order sets. Measure the percentage of operations in which the recommended agent was administered. Avoid unnecessarily broad-spectrum or combination prophylaxis.
Appropriate management of antimicrobial allergies	A complete allergy history should be obtained because an inaccurate β-lactam allergy label may lead to the use of less effective or unnecessarily broad alternatives. Allergy assessment can help patients receive first-line prophylaxis safely when appropriate.	Document the nature, timing, severity, and previous management of the reported reaction. Establish referral, testing, or de-labelling pathways for patients with uncertain histories of β-lactam allergy.
Correct timing of surgical prophylaxis	The antimicrobial should achieve effective tissue concentrations before microbial contamination occurs. For most agents, administration should begin within 60 minutes before incision. Agents requiring prolonged infusion, including vancomycin and fluoroquinolones, may be started within 120 minutes before incision.	Record the start time of antimicrobial administration and the incision time. Calculate the percentage of procedures in which prophylaxis was administered within the recommended interval. Ensure administration is completed appropriately before inflating the tourniquet, when relevant.
Dose optimization and intraoperative redosing	Prophylactic dosing should account for patient weight, age, renal function when relevant, pharmacokinetic properties, and the agent being used. Intraoperative redosing may be required	Include weight-based dosing and redosing intervals in surgical order sets. Document the initial dose, patient weight, procedure duration, blood loss, and any intraoperative

	during prolonged procedures or after substantial blood loss to maintain effective tissue concentrations.	redoses. Audit missed or delayed redosing opportunities.
Prompt discontinuation of prophylaxis	Routine prophylactic antibiotics should be discontinued after incisional closure in the operating room. Continuing prophylaxis after closure has not been shown to provide additional SSI prevention, including when surgical drains remain in place, and may increase antimicrobial resistance, *Clostridioides difficile* infection, renal injury, and other adverse effects.	Use automatic discontinuation orders and electronic alerts. Measure the percentage of prophylactic regimens stopped at closure. Investigate prolonged postoperative prophylaxis and provide feedback to the responsible clinical team.
Source control before unnecessary antimicrobial escalation	Management of an established SSI should focus on opening the infected incision, removing sutures when appropriate, draining purulent material, debriding devitalized tissue, and addressing infected implants or deeper collections. Antibiotics cannot compensate for inadequate source control.	Arrange early surgical assessment and drainage or debridement when required. Document whether source control was achieved and whether further imaging or intervention is necessary. Systemic antibiotics may not be required for a limited superficial SSI without systemic manifestations after adequate drainage.
Diagnostic and microbiological stewardship	Appropriate wound, tissue, fluid, or blood specimens should be obtained when microbiological results are likely to guide management, particularly in deep, severe, recurrent, implant-associated, or treatment-resistant infection. Superficial swabs that are likely to reflect colonization should be interpreted with caution.	Whenever clinically safe, collect specimens before starting or changing antimicrobial therapy. Clearly identify the specimen source and request susceptibility testing. Review results promptly and distinguish infection from colonization or contamination.
Evidence-based empiric treatment	When systemic antimicrobial therapy is indicated, the initial regimen should cover the organisms expected from the type and anatomical location of surgery, the severity of infection, prior antimicrobial exposure, colonization history, presence of prosthetic material, and local resistance data. Broad-spectrum treatment should be reserved for patients whose clinical characteristics justify it.	Develop facility-specific SSI treatment pathways linked to the local antibiogram. Document infection severity, suspected source, relevant resistance risks, previous cultures, and the rationale for broad-spectrum or anti-MRSA coverage.
Early review and de-escalation	Empiric therapy should be reassessed when microbiological and clinical information becomes available. Treatment should be narrowed to the most targeted effective agent, changed if resistance is identified, or discontinued when infection is no longer considered likely.	Conduct an antimicrobial “time-out,” commonly within 48–72 hours, assessing diagnosis, cultures, source control, spectrum, dose, route, adverse effects, interactions, and planned duration. Use prospective audit and feedback or preauthorization for selected broad-spectrum agents.
Optimal route and shortest effective duration	Intravenous therapy should be changed to an appropriate oral agent when the patient is clinically stable, gastrointestinal absorption is reliable, source control is adequate, and an active oral option is available. Treatment should continue only for the	Require a review date and expected stop date on every therapeutic antimicrobial prescription. Monitor intravenous-to-oral conversion, excessive durations, unnecessary outpatient intravenous therapy,

	shortest duration supported by the type and depth of infection, clinical response, microbiological findings, and adequacy of source control.	and antibiotics continued after resolution of the infection.
Surveillance, tracking, reporting, and feedback	Stewardship programs should monitor both antimicrobial-use processes and SSI outcomes. Data should be stratified by surgical procedure, department, surgeon or unit when appropriate, while considering patient- and procedure-related risk factors.	Measure appropriate agent selection, dose, timing, redosing, discontinuation, antimicrobial consumption, resistance patterns, adverse events, and risk-adjusted SSI rates. Regularly report results to surgical teams, pharmacists, nurses, infection-prevention staff, and hospital leadership [22].
Education combined with active interventions	Education should reinforce appropriate prophylaxis and SSI treatment but should not be the only stewardship intervention. Sustainable improvement generally requires education combined with clinical guidelines, order sets, reminders, audit, feedback, and accountability.	Provide case-based education for surgeons, anesthesiologists, nurses, pharmacists, residents, and operating-room staff. Focus educational feedback on locally identified prescribing problems and recurrent deviations from SSI protocols [20].

DIAGNOSTIC STEWARDSHIP IN SURGICAL INFECTIONS

Diagnostic stewardship in surgical infections ensures that the right test is obtained from the right patient, specimen, site, and time, with results interpreted in clinical context. Evaluation begins with assessment of wound findings, systemic illness, procedure type, implanted material, and need for imaging or source control [26]. When indicated, deep-tissue, aspirate, fluid, or blood cultures should be collected before antibiotics are administered, and low-value superficial swabs should be avoided. Laboratories should provide rapid identification and susceptibility results. Clinicians should reassess therapy when results return, narrowing, stopping, or modifying antimicrobials. This approach improves diagnostic accuracy, supports source control, reduces unnecessary treatment, resistance, adverse events, and costs [36].

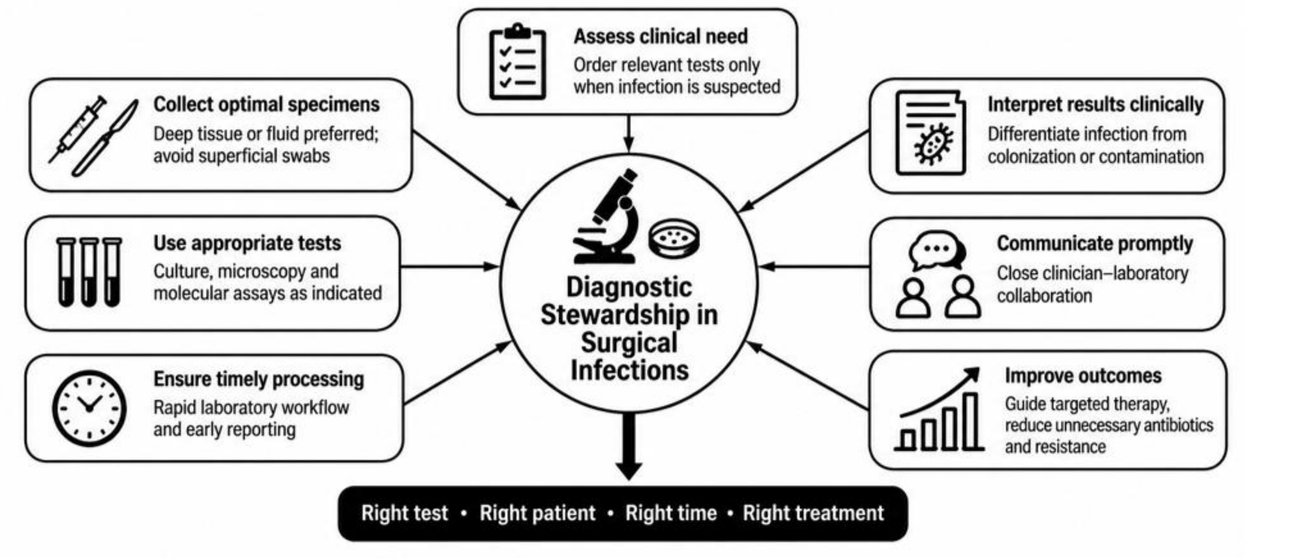

Figure 2 Diagnostic Stewardship in Surgical Site Infections [33]

BARRIERS TO EFFECTIVE ANTIMICROBIAL STEWARDSHIP

Antimicrobial stewardship is an essential part of preventing and managing surgical site infections (SSIs) [37]. Its purpose is not simply to reduce antibiotic use, but to ensure that surgical patients receive the correct antimicrobial agent, at the appropriate dose and time, and for the shortest effective duration. Successful stewardship, therefore, depends on coordinated action among surgeons, anesthetists, pharmacists, nurses, microbiologists, infection-prevention teams, and hospital administrators [3, 38]. However, several organizational, clinical, behavioral, and resource-related barriers can limit the effectiveness of antimicrobial stewardship in surgical settings (Table 4).

Table 4 Barriers to Effective Antimicrobial Stewardship in Combating Surgical Site Infections [38-40]

Barrier	How the Barrier Affects Antimicrobial Stewardship and SSI Prevention
Limited leadership commitment and institutional support	Antimicrobial stewardship programs often struggle when hospital leaders do not provide sufficient authority, funding, staffing, information technology, or protected time for staff. Without visible leadership support, stewardship activities may be treated as optional rather than as an essential patient-safety responsibility. This makes it difficult to enforce surgical prophylaxis policies, organize regular reviews, or hold clinical departments accountable for inappropriate prescribing.
Shortage of trained personnel and specialist expertise	Many hospitals have an insufficient number of infectious-disease physicians, clinical pharmacists, microbiologists, infection-control practitioners, and trained nurses. Existing staff may also be overwhelmed by routine clinical responsibilities. As a result, stewardship teams may be unable to promptly review antibiotic prescriptions, advise surgical teams, monitor prophylaxis, or support early modification of treatment when microbiological results become available.
Absence of clear, locally adapted clinical guidelines	National or international guidelines may not fully reflect local resistance patterns, available antibiotics, hospital resources, or the types of surgery commonly performed in a particular facility. When clinicians consider guidelines unrealistic or unsuitable for their setting, they may rely on personal experience or habitual prescribing. This can lead to inconsistent antibiotic selection, unnecessary use of broad-spectrum agents, and prolonged postoperative prophylaxis. WHO guidance recognizes that SSI recommendations often require careful local adaptation.
Knowledge gaps and inadequate continuing education	Some healthcare professionals may not be fully familiar with the recommended antibiotic, dose, administration time, intraoperative redosing requirements, or appropriate duration of surgical prophylaxis. Others may confuse prophylaxis with treatment and continue antibiotics after surgery without a confirmed infection. When education is irregular or limited to one professional group, the entire surgical team may not share the same understanding of appropriate antibiotic use.
Fear of SSIs and the belief that more antibiotics provide greater protection	Surgeons and other clinicians may continue antibiotics for several days because they fear that stopping them early will expose the patient to an SSI. Concerns about wound contamination, inadequate sterilization, poor infection-control practices, severe complications, patient dissatisfaction, or professional blame may reinforce this behavior. However, prolonged prophylaxis can expose patients to adverse effects and promote antimicrobial resistance without necessarily providing additional protection against SSIs.
Professional hierarchy and resistance to changing established practice	Surgical settings often have strong professional hierarchies. Junior doctors, pharmacists, nurses, or anesthetists may recognize inappropriate antibiotic prescribing but feel uncomfortable questioning a senior surgeon's decision. Some surgeons may also consider antimicrobial prescribing to be part of their individual professional autonomy. These cultural barriers can prevent constructive discussion, reduce acceptance of stewardship recommendations, and allow outdated practices to continue.
Poor multidisciplinary communication and unclear responsibility	Effective surgical prophylaxis requires coordination between the surgeon who selects the antibiotic, the anesthetist or nurse who administers it, the pharmacist who verifies the prescription, and the ward team responsible for discontinuation. When roles are unclear,

	doses may be delayed, repeated unnecessarily, or continued after surgery because each professional assumes that another person is responsible. Poor communication during handovers further increases the risk of inappropriate antibiotic use [41].
Operating-room workflow and logistical difficulties	Emergency procedures, rapidly changing operating schedules, delayed patient transfers, incomplete documentation, medication shortages, and heavy workloads can interfere with correct prophylaxis. Antibiotics may be given too early, after the incision, or not at all. In long operations, required intraoperative redosing may be forgotten. These failures reduce the preventive value of antimicrobial prophylaxis even when an appropriate antibiotic has been selected.
Limited microbiology and diagnostic capacity	When culture collection is delayed, laboratory services are unavailable, or susceptibility results take too long, clinicians must rely heavily on empirical treatment. This frequently encourages the continued use of broad-spectrum antibiotics because clinicians lack reliable evidence to narrow or discontinue therapy. Inadequate laboratory capacity also makes it more difficult to distinguish a true SSI from postoperative inflammation, colonization, or contamination [42].
Weak surveillance, auditing, feedback, and information systems	Hospitals cannot improve what they do not consistently measure. Without reliable data on antibiotic selection, timing, duration, resistance patterns, and SSI rates, stewardship teams may be unable to identify recurring problems or demonstrate the effectiveness of interventions. A lack of timely, non-punitive feedback also means that clinicians may remain unaware of their prescribing patterns or how these patterns compare with established standards. Tracking and regular reporting are therefore central components of effective hospital stewardship.

The barriers to effective antimicrobial stewardship in surgical care are not caused solely by clinicians. They usually arise from a combination of limited resources, fragmented systems, professional culture, fear of postoperative infection, and uncertainty about who is responsible for antibiotic decisions. Addressing these barriers requires more than distributing guidelines. Hospitals need committed leadership, locally appropriate protocols, accessible microbiology services, continuous education, multidisciplinary teamwork, and regular feedback based on prescribing and SSI data. When these elements work together, antimicrobial stewardship becomes a practical tool for protecting surgical patients while also reducing unnecessary antibiotic exposure and antimicrobial resistance [19, 43-46].

NOVEL AND EMERGING STRATEGIES FOR OVERCOMING STEWARDSHIP BARRIERS

Overcoming antimicrobial stewardship barriers requires moving beyond traditional policies toward systems that make appropriate prescribing easier, faster, and more acceptable in everyday surgical practice. One emerging approach is embedding real-time clinical decision support within electronic health records [39]. These platforms can recommend the appropriate prophylactic agent, dose, timing, redosing interval, and discontinuation point according to the procedure, patient allergies, renal function, body weight, and local resistance patterns. Automated alerts can also identify prolonged postoperative prophylaxis or unnecessary broad-spectrum treatment, allowing pharmacists and clinicians to intervene before inappropriate use becomes routine [47].

Artificial intelligence and machine-learning tools may further personalize stewardship. By combining microbiology results, previous antibiotic exposure, local antibiograms, comorbidities, and surgical risk factors, predictive models can estimate the probability of resistant infection and support more targeted empirical therapy [21]. However, these systems should remain explainable, locally validated, and supervised by clinicians to prevent automation bias. Their role is to strengthen professional judgment rather than replace it [42, 48].

Rapid molecular diagnostics and accelerated antimicrobial susceptibility testing offer another important strategy. Earlier identification of pathogens and resistance markers can shorten the period of diagnostic uncertainty that often drives unnecessary broad-spectrum prescribing [49]. Diagnostic stewardship should accompany these technologies by ensuring that appropriate specimens are collected before treatment, contaminated samples are minimized, and results are interpreted promptly. Linking laboratory alerts directly to stewardship teams can trigger rapid de-escalation, escalation, or antibiotic discontinuation [50].

eISSN: 2583-1194

Behavioral and implementation strategies are equally important. Peer comparison dashboards, individualized prescribing feedback, accountable justification, and carefully designed electronic prompts can influence clinical behavior without creating a punitive environment [51]. Surgical champions can increase trust by presenting stewardship as a shared patient-safety responsibility rather than an external restriction. Brief multidisciplinary "antibiotic time-outs" after surgery can help surgeons, anesthetists, pharmacists, nurses, microbiologists, and infection-prevention staff reconsider whether treatment remains necessary [52].

New stewardship models are also becoming more flexible. Tele-stewardship enables infectious disease specialists and pharmacists to support smaller or resource-limited hospitals remotely through virtual consultations, prescription reviews, and case conferences. Pharmacist-led protocols can authorize dose optimization, intravenous-to-oral conversion, allergy assessment, culture follow-up, and timely discontinuation. Nurse-led surveillance can improve recognition of missed prophylaxis, delayed administration, and continuation of postoperative antibiotics.

The most promising future model is therefore adaptive, data-driven, multidisciplinary, and human-centered [53]. Technology can provide speed and precision, but sustainable improvement depends on trusted leadership, clear accountability, constructive feedback, and workflows designed around the realities of surgical care. It must also remain equitable, ensuring that hospitals with limited laboratory, staffing, financial, or digital capacity can adopt scalable interventions without widening existing differences in access, prescribing quality, surgical outcomes, and patient safety across diverse healthcare settings [53].

Finally, stewardship should be integrated with SSI prevention rather than treated as an isolated pharmacy program. Combined dashboards can track antibiotic timing, prophylaxis duration, surgical infections, resistance, adverse events, and compliance by procedure. Locally adapted pathways, continuous education, simulation, and gamified training can make recommendations more practical and memorable. Patient engagement is also emerging as a useful tool: explaining why longer antibiotic courses are not always safer may reduce pressure on clinicians to prescribe unnecessarily [54].

ASSESSMENT OF PROGRAM EFFECTIVENESS

Assessing the effectiveness of an antimicrobial stewardship program is essential to determine whether its interventions are improving antibiotic use, reducing surgical site infections, and supporting patient safety. Regular evaluation also helps identify performance gaps and guides continuous program improvement [10].

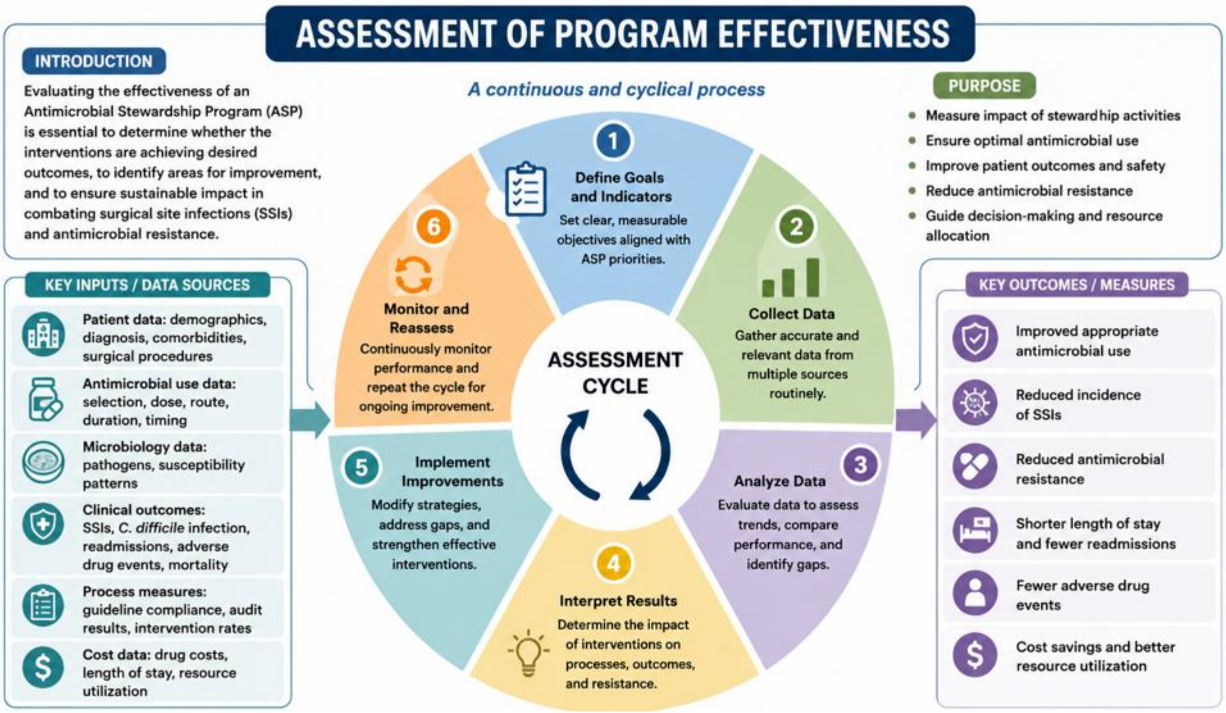

Figure 3 A diagram summarized the ASP effectiveness assessment [55, 56]

A structured and continuous assessment process allows healthcare teams to measure progress, refine stewardship strategies, and sustain positive outcomes. Effective evaluation ultimately strengthens antimicrobial use, reduces resistance, and improves the quality of surgical care.

CONCLUSION AND RECOMMENDATIONS

In conclusion, surgical site infections remain a significant healthcare burden, further complicated by the rising prevalence of antimicrobial resistance. The implementation of antimicrobial stewardship programs is essential for optimizing antibiotic use, improving patient outcomes, and reducing healthcare costs. Despite their importance, the successful establishment of these programs is often hindered by multiple institutional and practical barriers. Addressing these challenges requires a multidisciplinary approach, strong institutional support, and the integration of innovative and evidence-based strategies.

It is recommended that healthcare institutions prioritize the development and strengthening of antimicrobial stewardship programs by ensuring adequate training for healthcare professionals, enforcing standardized prescribing guidelines, and promoting continuous surveillance of antimicrobial use and resistance patterns. Additionally, leveraging advanced technologies, enhancing interprofessional collaboration, and implementing tailored interventions can further improve program effectiveness. Future research should focus on evaluating the impact of these strategies in diverse clinical settings to ensure sustainable and scalable solutions for combating surgical site infections and antimicrobial resistance.

Author contributions

………….. contributed to conceptualization, data curation, formal analysis, methodology, supervision, writing - original draft, review, and editing. ……………………………. contributed to conceptualization, project administration, methodology, resources, visualization, validation, and investigation.

Data availability

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Conflict of interest

The authors declare they have no conflict of interest.

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