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Catheter-Associated Urinary Tract Infections among Hospitalized Adults: A PRISMA-Guided Systematic Review of Epidemiology, Risk Factors, Microbiology, and Prevention Strategies, 2015–2024

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Abstract:

Background: *Catheter-associated urinary tract infection (CAUTI) remains a major device-associated healthcare infection and a measurable indicator of inpatient device safety. Although prevention guidance is well established, CAUTI persists because catheter insertion, maintenance and removal decisions are distributed across multiple clinical actors and daily workflows.*

Objective: *To synthesize evidence published between 2015 and 2024 on the epidemiology, risk factors, microbiology and prevention of CAUTI among hospitalized adult patients, with emphasis on practical implementation in resource-limited hospitals.*

Methods: *A PRISMA-guided systematic review was conducted using PubMed, Web of Science and Google Scholar. English-language studies involving adult hospitalized patients with indwelling urinary catheters were eligible when they reported CAUTI incidence, risk factors, microbiological findings or prevention interventions. Sixteen studies were included and synthesized narratively because designs and outcome denominators were heterogeneous.*

Results: *The review identified catheter duration as the main modifiable risk factor for CAUTI. Rates ranged from about 1–5 infections per 1,000 catheter-days in general wards. Higher baseline rates were reported in intensive care units. Risk increased with female sex, older age, diabetes, neurologic impairment and immobility. Critical illness, non-ideal insertion conditions and drainage-system disruption also contributed. Microbiology showed Gram-negative bacilli, Enterococcus spp., Candida spp., biofilm and multidrug resistance. Multicomponent bundles achieved the strongest reductions, including zero or near-zero CAUTI periods in some units.*

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Conclusion: *CAUTI prevention is primarily an exposure-control and governance problem. The most practical strategy is not expensive technology alone, but disciplined catheter-day reduction, multidisciplinary accountability, diagnostic stewardship, and a simple bundle that can be reliably implemented in low-resource hospitals.*

Keywords: catheter-associated urinary tract infection; CAUTI; hospitalized adults; infection prevention; urinary catheter; prevention bundle; biofilm; antimicrobial stewardship

1. INTRODUCTION

Catheter-associated urinary tract infection (CAUTI) is a preventable but persistent healthcare-associated infection in hospitalized adults. The clinical importance of CAUTI derives from three linked features: the widespread use of indwelling urinary catheters, the rapid emergence of bacteriuria and biofilm on catheter surfaces, and the capacity of urinary infection to progress to bacteremia, sepsis, prolonged admission, and avoidable antimicrobial exposure. Although urinary catheters are often necessary for acute urinary retention, selected perioperative situations and accurate monitoring of urine output in unstable patients, they are also frequently inserted or retained without a continuing evidence-based indication [1,2].

The infection prevention problem is therefore not only microbiological; it is also behavioral, organizational, and procedural. A catheter bypasses normal host defense, connects the external environment to the bladder, and provides a surface for microbial adherence. The risk is cumulative because every additional catheter day expands the opportunity for ascending contamination and biofilm maturation. This mechanism explains why catheter dwell time repeatedly appears as the dominant modifiable risk factor in contemporary CAUTI literature [2,5,10].

CAUTI is also a useful indicator of health-system discipline. A hospital may possess guidelines, but patients remain at risk when indications are not documented, insertion technique is inconsistent, drainage systems are opened unnecessarily, bags are positioned incorrectly, and responsibility for catheter removal is unclear. In resource-limited settings, where staffing constraints, supply interruptions and weak surveillance systems can intensify device-associated infection, CAUTI prevention requires simple and reproducible processes rather than expensive technology [3,4,12,13,14,15].

This systematic review synthesizes evidence published from 2015 to 2024 on CAUTI epidemiology, risk factors, microbiology, and prevention among hospitalized adults. The central review question was: among adult inpatients with indwelling urinary catheters, what contemporary evidence describes CAUTI incidence, associated risk factors, microbiological patterns, and effective prevention strategies? The operational hypothesis was that CAUTI occurrence is driven primarily by modifiable device exposure, especially catheter duration, and that multicomponent prevention bundles reduce infection more consistently than isolated technical measures.

2. MATERIALS AND METHODS

This article was prepared as a PRISMA-guided systematic review of published evidence. The methodology emphasized transparent study identification, predefined eligibility

criteria, systematic extraction, and narrative synthesis because the included evidence differed substantially in design, setting, outcome definitions and denominator structure. Eligible publications included adult hospitalized patients with indwelling urinary catheters and reported at least one CAUTI-relevant outcome: incidence, prevalence, risk factor analysis, microbiological profile, antimicrobial resistance, diagnostic stewardship, or prevention/intervention results. Observational studies, surveillance studies, quality-improvement projects, systematic reviews, clinical reviews, and consensus guidance were considered when they provided extractable information applicable to adult inpatient care. Pediatric or neonatal studies, outpatient-only studies, long-term-care-only studies, case reports, conference abstracts without adequate data and articles not focused on catheter-associated infection were excluded [1,2,3,4,5,10].

PubMed, Web of Science and Google Scholar were searched for English-language sources published between January 2015 and June 2024. Search terms combined controlled and free-text concepts including catheter-associated urinary tract infection, CAUTI, indwelling urinary catheter, urinary catheter risk factors, prevention bundle, nurse-driven removal, antimicrobial stewardship, biofilm, and hospitalized patients. Reference lists of key articles and infection prevention guidance were screened manually to improve retrieval of relevant evidence [5,10].

Titles and abstracts were screened for relevance to adult inpatient CAUTI. Full texts were then assessed against the eligibility criteria. Extracted data included author, year, setting, study design, population, sample size, or evidence base, CAUTI definition where available, risk factors, microbiological results, prevention bundle elements, and intervention outcomes. Extracted findings were organized into thematic domains: epidemiology, risk factors, microbiology, prevention bundles, and stewardship.

Observational evidence was interpreted according to selection, comparability, and outcome limitations; quality-improvement projects were assessed for pre-post design limitations, secular trends, and sustainability of effect; reviews and guidelines were assessed for transparency, recency, and practical applicability. The synthesis classified evidence strength qualitatively as strong, moderate, or context-dependent, based on consistency across designs, biological plausibility, and implementation relevance.

The review was not registered prospectively because the work originated as an academic student systematic review. This limitation was handled by documenting the review question, eligibility criteria, selection flow, and synthesis procedure explicitly in the manuscript. No ethical approval was required because the review used published literature only and did not involve direct contact with human participants or identifiable patient data.

3. RESULTS

3.1 Study selection and PRISMA flow

The search identified 115 records. After title and abstract screening, 30 full-text reports were assessed for eligibility. Fourteen full-text reports were excluded because they did not involve the target adult hospital population, lacked extractable CAUTI data, were not CAUTI-specific, were guideline/editorial material unsuitable for inclusion in the empirical synthesis, or were non-English without usable data. Sixteen studies were included in the qualitative narrative synthesis (Figure 1).

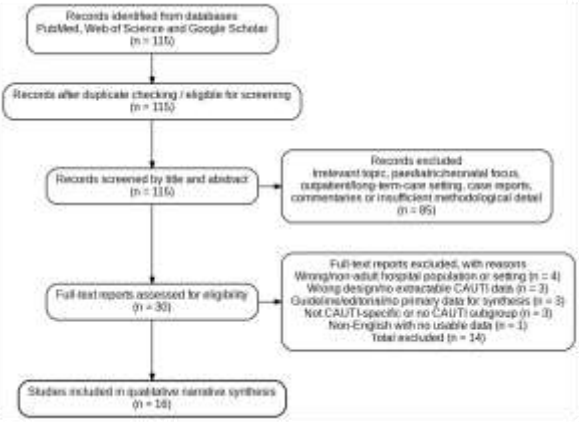

Figure 1. PRISMA flow diagram for study selection.

3.2 Characteristics of the included evidence

The 16 included sources represented a mixture of observational cohorts, cross-sectional hospital studies, quality-improvement interventions, systematic reviews, clinical reviews, and consensus guidance. This mixed evidence base is appropriate for CAUTI because prevention depends on both epidemiological risk estimation and implementation science. The included studies covered general hospital wards, surgical patients, cardiac and adult ICUs, safety-net hospitals, and lower-resource healthcare environments (Table 1) [1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16].

Table 1. Characteristics and contribution of the 16 included studies.

Evidence source	Design / setting	Sample or evidence base	Principal contribution to synthesis
Kuy et al. 2020	Retrospective surgical cohort, USA	20,467 surgical patients	Showed residual CAUTI occurrence despite guideline compliance; challenged simplistic use of CAUTI as an absolute never-event.
Trautner et al. 2015	Stewardship intervention, US VA system	Multi-hospital program	Reduced unnecessary urine cultures and antibiotic treatment for catheter-associated asymptomatic bacteriuria.
Letica-Kriegel et al. 2019	Large time-to-event cohort, USA	Large multicenter dataset	Quantified the non-linear increase in CAUTI risk with catheter dwell time.
Gupta et al. 2023	Pre-post QI intervention, cardiac ICU	Unit-level project	Coordinated strategy and nursing empowerment reduced CAUTI towards zero.

Evidence source	Design / setting	Sample or evidence base	Principal contribution to synthesis
Taha et al. 2017	Pre-post QI project, medical units	Hospital wards	Education, audits, and daily review reduced CAUTI rates after bundle implementation.
Mitchell et al. 2021	Systematic review and meta-analysis	69 studies	Assessed meatal cleaning strategies and supported antiseptic cleaning as a modest adjunct.
Van Decker et al. 2021	QI bundle, safety-net centre	Critical care units	Demonstrated large sustained CAUTI reduction through rapid-cycle testing and standardized tools.
Oumer et al. 2021	Cross-sectional hospital study, Ethiopia	Hospitalized catheterized patients	Estimated incidence, associated factors, and drug-resistance patterns in a low-resource setting.
Ramadan et al. 2021	Microbiological study, Egypt	CAUTI catheter/urine isolates	Reported high biofilm-dependent CAUTI and stronger resistance among biofilm-producing isolates.
Saint et al. 2018	Prospective patient-reported cohort, USA	2,076 adult patients	Showed infectious and non-infectious catheter complications, including sex-related differences in harm.
Ling et al. 2023	APSIC guideline/consensus	Asia-Pacific evidence base	Provided practical bundle guidance: avoid unnecessary catheterization, aseptic insertion, and early removal.
Rubi et al. 2022	Narrative review	Current overview	Summarized CAUTI pathogenesis, diagnosis, and prevention with emphasis on catheter duration.
Chenoweth 2021	Clinical review	Adult UTI update	Clarified diagnostic and management principles for urinary tract infection in modern hospital practice.
Odabasi and Mert 2020	Clinical review	Adult candiduria/UTI	Supported catheter removal and selective antifungal treatment for Candida urinary tract infection.
Scruggs-Wodkowski et al. 2024	Clinical review	Device-associated urinary infection	Reinforced modern emphasis on alternatives, short dwell time, and diagnostic stewardship.

Evidence source	Design / setting	Sample or evidence base	Principal contribution to synthesis
Kranz et al. 2020	Systematic review	Adult CAUTI prevention/treatment	Synthesized preventive strategies and treatment options with device minimization as core principle.

3.3 Epidemiology and patient burden

CAUTI remains one of the most frequent device-associated infections affecting hospitalized adults. Reported incidence varied by setting, denominator, and baseline device-utilization ratio. General wards commonly reported lower rates than critical care units, while ICUs and high-dependency units had higher baseline rates because patients were more severely ill, required closer urine output monitoring and often experienced longer catheter dwell time. Resource-limited settings reported additional vulnerability because staffing, surveillance and supply constraints may compromise daily catheter review, aseptic insertion, and maintenance auditing (Oumer et al. 2021) [1,3,4,6,12].

The patient burden extends beyond infection. Catheterization may cause discomfort, urgency, urethral trauma, hematuria, restricted mobility, and dignity-related harms even when symptomatic CAUTI does not develop (Saint et al. 2018). This broader harm profile strengthens the argument that indwelling catheterization itself should be treated as an invasive device exposure requiring daily justification [4].

3.4 Patient-level and device-related risk factors

The clearest and most reproducible risk factor was prolonged catheterization. In the large time-to-event analysis by Letica-Kriegel et al. (2019), CAUTI risk increased non-linearly with duration: infection-free survival was approximately 97.3% at 10 days, 88.2% at 30 days and about 72% at 60 days of continuous catheterization. This pattern supports the central prevention principle that reducing catheter-days is more important than relying on treatment after infection occurs [3,4,6].

Other patient-level risks included female sex, advanced age, diabetes mellitus, severe comorbidity, immobility, neurologic impairment, and critical illness. These factors should not be interpreted as isolated determinants only; they often operate by increasing the likelihood and duration of catheterization. Device-related and practice-related risks included insertion outside controlled environments, breach of aseptic technique, poor securement, obstruction or dependent loops in drainage tubing, unnecessary opening of the closed drainage system and absence of daily indication review (Kuy et al. 2020; Oumer et al. 2021; Saint et al. 2018) [3,4,6,12].

3.5 Microbiology, biofilm, and antimicrobial resistance

The microbiological synthesis showed that CAUTI is not merely a simple ascending infection. Gram-negative enteric bacilli, especially Escherichia coli and Klebsiella spp., were prominent pathogens, while Enterococcus spp., Pseudomonas aeruginosa and Candida spp. were also clinically important. Candida in catheterized patients was frequently related to colonization, antibiotic pressure, and critical illness; therefore, catheter removal or replacement and diagnostic stewardship are often more appropriate

than immediate antifungal therapy unless high-risk criteria are present (Odabasi and Mert 2020) [6,7,8,9].

Biofilm is the mechanistic bridge between catheter duration and treatment difficulty. Biofilm-producing organisms adhere to catheter surfaces, form a protective matrix, and become less susceptible to host immunity and antimicrobial agents. The microbiological evidence, particularly from lower-resource and device-focused studies, emphasized high levels of multidrug resistance and frequent biofilm formation (Oumer et al. 2021; Ramadan et al. 2021). This finding shifts the prevention priority away from antibiotic reliance and towards device avoidance, early removal, and replacement of long-standing catheters when true infection occurs [6,7,8,9].

3.6 Prevention and quality-improvement interventions

The most effective interventions were multicomponent bundles rather than single isolated steps. Core elements included appropriate indication documentation, aseptic insertion by trained staff, closed drainage maintenance, catheter securement, daily necessity review, nurse-driven removal, automatic stop orders, alternatives to urethral Foley catheters and continuous education with audit feedback. Studies from cardiac ICU, medical wards and safety-net critical care settings reported large reductions in CAUTI after embedding such bundles into daily workflow (Gupta et al. 2023; Taha et al. 2017; Van Decker et al. 2021) [5,13,14,15].

The mechanism of bundle success is straightforward: the bundle reduces both exposure time and contamination opportunities. It also assigns operational responsibility. In hierarchical clinical environments, nurse-driven removal is especially important because it transforms catheter removal from a delayed physician-dependent decision into a protocolized patient-safety action. Diagnostic stewardship is a complementary intervention because unnecessary urine cultures and inappropriate treatment of asymptomatic bacteriuria inflate antimicrobial use without improving outcomes (Trautner et al. 2015) [5,13,14,15].

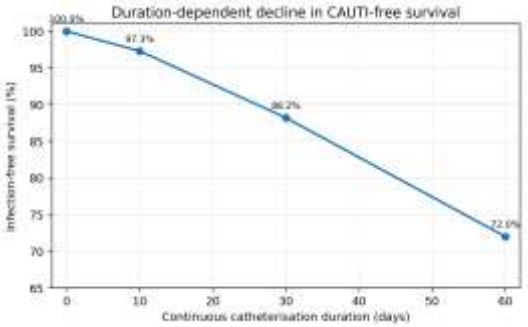

Figure 2. Duration-dependent decline in infection-free survival among continuously catheterized patients.

Table 2. Evidence synthesis matrix and implementation interpretation.

Domain	Main synthesized finding	Evidence strength	Practical implication
Epidemiology	CAUTI remains a common healthcare-associated infection; rates are usually higher in critical care than in general wards.	Moderate to strong	Use catheter-days and device-utilization ratios as routine IPC indicators.
Duration of catheterization	Dwell time was the most consistent modifiable determinant; CAUTI-free survival fell progressively over days to weeks.	Strong	Apply daily necessity review, stop orders and nurse-driven removal.
Patient susceptibility	Female sex, older age, diabetes, immobility, severe comorbidity, and ICU admission repeatedly increased risk.	Moderate	Priorities high-risk patients for daily review and early catheter alternatives.
Insertion and maintenance	Non-controlled insertion settings, broken closed drainage, obstruction, poor securement, and suboptimal hygiene increased exposure to ascending contamination.	Moderate	Use insertion checklists, closed drainage, bag-below-bladder positioning, and securement audits.
Microbiology	Gram-negative bacilli, Enterococcus spp., Candida spp., biofilm, and multidrug resistance were central findings.	Moderate	Remove/replace long-standing catheters during true CAUTI and avoid treating colonization.
Prevention bundles	Multicomponent bundles commonly reduced CAUTI by large margins and sometimes achieved zero-event periods.	Strong for bundle approach	Bundle implementation should be multidisciplinary, nurse-led and monitored through feedback.

Table 3. Practical CAUTI prevention bundle for resource-limited hospitals.

Bundle component	Operational action	Priority	Low-resource implementation
Avoid unnecessary insertion	Approved indication checklist before catheterization	High	Printed checklist at trolley/ward; document indication in notes.
Aseptic insertion	Hand hygiene, sterile field, trained inserter, and appropriate antisepsis	High	Low-cost training and competency observation.
Closed drainage maintenance	No unnecessary disconnection; unobstructed tubing; bag below bladder level	High	Nursing shift checklist and immediate correction.
Daily necessity review	Remove unless a valid indication persists	Very high	Add to ward round and nursing handover forms.
Nurse-driven removal	Pre-authorized removal if criteria are not met	Very high	Written protocol signed by hospital leadership.

Bundle component	Operational action	Priority	Low-resource implementation
Catheter alternatives	Condom catheters, female external devices, or intermittent catheterization where feasible	Context-dependent	Use alternatives first for incontinence or non-critical monitoring.
Diagnostic stewardship	Culture only when symptoms/signs support CAUTI; avoid treating CA-ASB	High	Laboratory request form should require symptoms/indication.
Audit and feedback	Monthly CAUTI rate, catheter-days, compliance, and root-cause review	High	Simple paper tally or spreadsheet dashboard.

4. DISCUSSION

4.1 Principal interpretation

This systematic review supports a strong and clinically actionable interpretation: CAUTI prevention is primarily an exposure-control problem. The indwelling urinary catheter simultaneously creates a conduit for ascending microorganisms, a foreign surface for microbial attachment and a repeated care interface where lapses in asepsis can occur. Therefore, the most powerful prevention strategy is not late treatment after infection becomes established, but disciplined avoidance of unnecessary catheterization and early removal of catheters that are no longer clinically justified.

The consistency of catheter duration as a risk factor across epidemiological, clinical and implementation studies makes catheter-days the most meaningful operational target for hospitals. This is important because catheter-days are measurable, modified, and directly linked to clinical workflow. In practical IPC terms, CAUTI reduction should be monitored not only by infection counts, but also by catheter utilization ratio, daily indication documentation, proportion of catheters removed within 48-72 hours when indications expire and compliance with closed drainage maintenance [3,5,13,14,15]. The epidemiological evidence and microbiological evidence converge around the same mechanism. With increasing catheter dwell time, microorganisms have greater opportunity to ascend along internal or external catheter surfaces and establish biofilm. Once biofilm matures, the device becomes a persistent microbial reservoir that is less responsive to host immunity and less penetrable by antimicrobial therapy. This explains why prolonged catheterization is not simply a statistical predictor; it is biologically embedded in the pathogenesis of CAUTI [6,7,8,9].

The pathogen profile reported in the included evidence, especially Escherichia coli, Klebsiella spp., Enterococcus spp., Proteus spp., Pseudomonas aeruginosa and Candida spp., reinforces the need for prevention rather than dependence on empirical therapy. In hospitals with high antimicrobial pressure, these organisms may be multidrug resistant, and treatment becomes increasingly uncertain. Biofilm-associated infection also means that antimicrobial therapy without catheter removal or replacement may fail because the colonized device continues to seed the urinary tract [6,7,8,9]. The evidence explains why single interventions have limited effect when applied alone. Excellent insertion technique cannot compensate for unnecessary catheter retention.

Antiseptic meatal cleaning cannot overcome weeks of device exposure. Antibiotics cannot reliably eradicate organisms protected within mature catheter biofilm. In contrast, prevention bundles work because they interrupt several points in the causal chain: they reduce inappropriate insertion, standardize sterile technique, maintain a closed drainage pathway, force daily reassessment, empower nurses to remove unnecessary devices and reduce unnecessary cultures and antimicrobial treatment [6,7,8,9].

The most effective programs also change responsibility. They convert catheter management from a passive default into an active daily clinical decision. A catheter should not remain in place because nobody has asked about it; it should remain only because a valid indication is documented on that day. This accountability principle is particularly important in busy wards, emergency units, and ICUs where catheters inserted during acute care may persist after the original indication has been resolved. CAUTI is a multidisciplinary safety problem rather than a nursing-only, microbiology-only or physician-only issue. Physicians determine indications and respond to deterioration; nurses insert, maintain, observe, and often identify unnecessary continuation first; laboratory teams influence urine culture quality and diagnostic stewardship; pharmacists guide antimicrobial selection and stewardship; IPC teams provide surveillance, audit, and feedback; and hospital leadership provides supplies, staffing and authority for protocol implementation. Sustainable reduction therefore requires governance, not merely technical instruction [8,9].

The implication is that CAUTI prevention should be embedded in unit-based quality systems. A practical governance model would include an approved indication checklist, insertion competency assessment, daily catheter review during ward rounds, nurse-driven removal criteria, monthly catheter-days reporting, unit feedback and escalation when preventable device retention is identified. In this model, the CAUTI bundle becomes a measurable safety process rather than an educational poster [3,5,13,14,15]. Diagnostic stewardship is central because catheter-associated asymptomatic bacteriuria is common and does not equal symptomatic infection. Treating colonization simply because urine culture is positive increases unnecessary antibiotic use, wastes laboratory capacity and promotes resistance. The review supports a conservative diagnostic approach: culture and treat when compatible clinical features are present, but do not treat bacteriuria or candiduria in a catheterized patient in the absence of clinical evidence of infection, except in recognized high-risk circumstances [8,9].

This distinction is especially important in settings where antimicrobials are frequently used empirically, and microbiology capacity is limited. A low-resource CAUTI program should therefore include clear criteria for when to send urine cultures, how to collect specimens aseptically, when to replace the catheter before culture and how to de-escalate therapy once results are available. Prevention and stewardship are inseparable: avoiding unnecessary catheters prevents infections, while avoiding unnecessary cultures prevents overdiagnosis and overtreatment [8,9]. The findings are highly relevant to resource-limited hospitals in Sudan, Egypt, and comparable settings. Expensive antimicrobial-coated catheters, electronic reminder systems, and continuous digital surveillance may be difficult to sustain during workforce shortages, supply-chain disruption, or conflict-related service instability. However, the highest-yield actions are affordable: hand hygiene, aseptic insertion training, indication checklists, closed

drainage discipline, securement, avoidance of kinks and dependent loops, a catheter-days tally, nurse-driven removal authority, and monthly feedback [3,5,13,14,15].

For low-resource implementation, the strongest practical option is a paper-based or simple electronic CAUTI bundle linked to nursing rounds. A one-page catheter indication and maintenance checklist can be attached to the patient file; catheter necessity can be reviewed during each morning round; and ward-level catheter-days can be counted manually. These measures require leadership, accountability, and repetition more than advanced technology. The review therefore supports a pragmatic prevention model that is feasible even when sophisticated infection surveillance software is unavailable [3,5,13,14,15]. Despite the strength of the review findings, limitations should be acknowledged. The included studies differed in design, population, denominator, and surveillance definitions. Quality-improvement studies are often vulnerable to secular trends, co-interventions, and the Hawthorne effect. Some included reviews and guidance documents were not primary studies but were retained because they provided implementation-relevant synthesis. The review was not registered in PROSPERO, and the English-language restriction may have excluded relevant regional evidence.

Future research should prioritize implementation studies in low- and middle-income hospitals, especially studies that evaluate the minimum effective CAUTI bundle under constrained staffing and supply conditions. Additional evidence is needed on female external urinary collection devices, patient comfort, skin complications, cost-effectiveness, and sustainability after the active project period ends. For hospitals in conflict-affected or fragile health systems, research should also evaluate how to maintain catheter safety practices when staff turnover, electricity interruption, laboratory limitations, and supply shortages are present.

Overall, the review indicates that CAUTI prevention is both scientifically coherent and operationally feasible. The evidence does not support reliance on expensive technology alone. It supports disciplined device governance: avoid unnecessary insertion, remove early, maintain asepsis, diagnose carefully and review performance continuously.

5. CONCLUSION

CAUTI among hospitalized adults remains common, harmful, and largely preventable. The dominant modifiable risk is catheter duration; consequently, daily catheter necessity review, nurse-driven removal, and alternatives to indwelling urethral catheterization should be treated as core safety interventions. Multicomponent bundles integrating aseptic insertion, closed drainage maintenance, early removal, staff education, audit feedback, and antimicrobial stewardship provide the most practical and evidence-supported route to sustained CAUTI reduction. For resource-limited hospitals, these interventions are realistic because they rely principally on disciplined workflow, accountability, and IPC leadership rather than costly technology [5,13,14,15].

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICAL APPROVAL

Ethical approval was not required because this article is a systematic review of previously published literature and did not involve direct contact with human participants or access to identifiable patient data.

DATA AVAILABILITY

All data relevant to this review were extracted from published studies and are summarized within the manuscript tables and figures.

AUTHOR CONTRIBUTIONS

Ibrahim Adil Ibrahim Aldaw, Abrar Mohammed Saied and Namarig Elbasri Mohamed Abdelrahman contributed to the thesis-stage literature search, screening, data extraction, and initial evidence synthesis. Sahar G. Elbager contributed academic leadership, institutional oversight, and critical review from the Faculty of Medical Laboratory Sciences, UMST. Mutaz Mohamed Ibrahim Ali contributed research consultation, manuscript restructuring, scientific editing, journal-targeted redesign, critical revision, and correspondence. All authors reviewed and approved the final manuscript for submission.

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