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Sustainable management of operating room wastes from the perspective of environmental health engineering: A critical review emphasizing strategies for the prevention of healthcare-associated infections

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Abstract

Operating room waste management is a critical challenge in healthcare systems, playing a decisive role in preventing healthcare-associated infections (HAIs), protecting the health of staff and patients, and reducing environmental impacts. In recent years, the increasing volume of surgical procedures, widespread use of disposable items, and infection control requirements have led to a significant rise in the generation of infectious and hazardous waste in operating rooms. From an environmental health engineering perspective, sustainable waste management extends beyond safe disposal to include source reduction, proper segregation, volume minimization, targeted recycling, selection of appropriate and environmentally sound treatment technologies, and optimization of the life cycle of consumable materials. This critical review aims to systematically analyze published scientific evidence without time restriction up to 2025, focusing on sustainable operating room waste management strategies with particular emphasis on their role in preventing HAIs. Findings indicate that poor waste segregation, suboptimal use of single-use protective equipment, and sole reliance on costly treatment technologies not only increase economic and environmental burdens but may also exacerbate the risk of pathogen transmission. In contrast, integrating environmental health engineering principles with infection control programs, staff training, process redesign, and the adoption of innovative, low-impact technologies have been proposed as effective and sustainable strategies. This critical review underscores the necessity of policy revision and a shift from a reactive to a preventive, system-oriented approach in operating room waste management.

Keywords: Hospital waste management, Operating room, Environmental health engineering, Sustainability, Prevention of healthcare-associated infections

Introduction

The operating room (OR), as one of the most sensitive and high-risk departments within a hospital, plays a dual role in the healthcare system. On one hand, it is the center for life-saving therapeutic interventions; on the other, due to the nature of its activities, it is considered one of the most significant sources of infectious, sharp, and chemical waste (1). Waste generated in the OR is often in direct contact with blood, body fluids, human tissues, and contaminated instruments. If mismanaged, such waste can act as a potential reservoir of pathogens, increasing the risk of healthcare-associated infection (HAI) transmission to patients, healthcare workers, and even the community (2). From this perspective, OR waste management is not merely an environmental obligation but an essential component of infection prevention and control (IPC) programs in medical facilities (3).

In recent years, several concurrent factors have intensified the challenges associated with OR waste. The increasing number of surgical procedures, the growing complexity of treatment methods, the significant rise in the use of single-use equipment and supplies, and the consequences of the COVID-19 pandemic have all led to a quantitative increase and qualitative change in the waste generated in this department (4). In many hospitals, pressure to adhere more strictly to infection control protocols has resulted in the widespread use of plastic and non-recyclable items. While reducing infection risk, this trend has also brought about considerable environmental and economic consequences (5).

Traditional approaches to hospital waste management have mainly focused on collection, treatment, and final disposal. Although these approaches play a role in immediately reducing biological risks, from an environmental health engineering perspective, they often adopt a reactive, short-term view and fail to adequately address the root causes of waste generation or the possibility of source prevention (6). Over-reliance on costly and energy-intensive treatment technologies, without modifying waste generation processes in the OR, can increase economic burdens, resource consumption, and secondary pollutant emissions, while their effectiveness in sustainably reducing infection risk is not always guaranteed (7).

In contrast, the concept of sustainable waste management is shaped by the waste hierarchy, which includes waste prevention, source reduction, proper segregation, safe reuse, targeted recycling, energy recovery, and finally, disposal as the last resort (8). Applying this approach in the OR requires integrating environmental health engineering principles with infection control policies, spatial design, material selection, staff training, and continuous system performance monitoring (9). Scientific evidence indicates that the meticulous segregation of infectious from non-infectious waste alone can significantly reduce the volume of high-risk waste while simultaneously limiting the risk of contact with pathogens (10).

Environmental health engineering, utilizing a system-oriented approach, provides various analytical tools—including life cycle assessment (LCA), health risk analysis, and environmental impact assessment—for a comprehensive evaluation of OR waste (11). This approach enables the identification of critical points along the waste generation-to-disposal chain and facilitates the design of evidence-based interventions; interventions that can simultaneously address sustainability, occupational safety, and HAI prevention goals (12). However, published studies show that in many health systems, a significant gap still exists between available scientific knowledge and the practical implementation of sustainable strategies.

Furthermore, a considerable portion of recent research has either focused solely on the technical aspects of waste disposal or examined infection control separately from environmental management. This conceptual separation hinders a comprehensive understanding of the interaction between OR waste management and the dynamics of HAI transmission. Consequently, there is a growing need for critical reviews that can integrate scattered evidence, highlight the strengths and weaknesses of existing approaches, and suggest pathways for improvement. Accordingly, this paper aims to provide a critical review of studies published without time restriction up to 2025, examining the sustainable management of operating room waste from the perspective of environmental health engineering, with a special emphasis on the role of these strategies in preventing healthcare-associated infections. Through a critical analysis of available evidence, this article seeks to elucidate challenges and research gaps while offering a conceptual framework to improve policy-making and practical performance in hospitals.

Methods

This study was designed and conducted as a critical review. The aim of selecting a critical review approach was to move beyond merely describing previous studies and to focus on in-depth analysis, systematic comparison, and evaluation of the strengths, weaknesses, and research gaps in the field of sustainable operating room waste management with an emphasis on the prevention of healthcare-associated infections (HAIs). This type of review enables the synthesis of quantitative and qualitative evidence and the extraction of conceptual and practical insights.

Search Strategy

A comprehensive search was performed across international electronic databases, including PubMed/MEDLINE, Web of Science, Scopus, and Embase, as well as the Google Scholar search engine. The search strategy employed combinations of Medical Subject Headings (MeSH) terms and keywords: ("Operating Rooms" OR "Surgical Procedures") AND ("Medical Waste" OR "Waste Management") AND ("Infection Control" OR "Cross Infection") AND ("Environmental Health" OR "Sustainability"). To ensure transparency, the search was limited to English and Persian language peer-reviewed articles published up to December 2025.

Inclusion and Exclusion Criteria

Studies were included in this review if they directly or indirectly addressed the management of waste generated in the operating room and examined at least one of the dimensions of environmental sustainability, health safety, or healthcare-associated infection prevention. Original research articles, systematic reviews, narrative reviews, and analytical reports published in reputable scientific journals were examined if they aligned with the study objectives. Conversely, studies that addressed hospital waste without focusing on the operating room, articles outside the specified time frame, non-scientific reports, and studies for which full-text access was not available were excluded from the review process.

Study Selection and Screening Process

The selection process followed a structured three-stage screening protocol. Initially, duplicates were removed using reference management software. Two independent reviewers screened titles and abstracts based on the inclusion criteria. In the second stage, full-text versions of the remaining articles were retrieved and assessed for eligibility. Any discrepancies between reviewers were resolved through consensus or consultation with a third senior researcher. A total of 63 relevant studies were finally included for qualitative synthesis and critical appraisal.

Critical Data Analysis Approach

The analysis of selected studies was performed based on a qualitative content analysis and critical comparison approach. At this stage, key findings from the studies were extracted and categorized according to common conceptual axes, including source prevention strategies, waste segregation and reduction, treatment technologies, staff education and behavior, and health and environmental outcomes. Subsequently, these findings were critically appraised and evaluated in terms of scientific coherence, generalizability, methodological limitations, and the extent to which they addressed the link between environmental sustainability and the prevention of healthcare-associated infections.

Results

The findings from the critical review of studies published without time restriction up to 2025 indicate that operating room waste management is increasingly recognized as a strategic component at the intersection of environmental sustainability, occupational safety, and healthcare-associated infection (HAI) prevention. However, a critical analysis of these studies suggests that many have been conducted in a fragmented, non-systematic manner and without a comprehensive environmental health engineering framework. Heterogeneity in study designs, assessment indicators, and depth of analysis complicates the direct comparison of results and highlights the necessity of a rigorous critical appraisal.

Waste prevention and source reduction: A neglected but key strategy

Most studies have identified waste prevention and source reduction as the most effective strategies in sustainable operating room waste management (9). Measures such as redesigning surgical kits, eliminating unnecessary items, optimizing equipment packaging, and inventory management are frequently mentioned (13,14). Critical appraisal reveals that most studies focus solely on weight or volume reduction of waste, while clinical and health impacts, particularly the effect on healthcare-associated infections, have been less frequently evaluated (15). Furthermore, the lack of life cycle assessment and risk analysis means that reducing waste from one consumable item may lead to increased consumption of other materials or the transfer of risk to another part of the chain, an aspect often overlooked in studies.

Waste segregation: The gap between guidelines and practice

Proper segregation of infectious and non-infectious waste is one of the main foci of studies. Many articles indicate that non-infectious waste is often mistakenly directed to the infectious waste stream, thereby increasing treatment costs (16,17). Critical appraisal suggests that focusing solely on staff training and guidelines, without considering the physical design of the operating room, workflow, and access to appropriate containers, limits the real-world effectiveness of segregation (18). Additionally, fear of making errors leads to over-segregation, which is inconsistent with sustainability principles and optimal risk management.

Single-use equipment vs. Reusable items

The increased use of single-use equipment, particularly following the COVID-19 pandemic, is a prominent finding of recent studies (19). Although this increase has been justified as a conservative measure to reduce infection, critical review shows that the absolute superiority of single-use items in terms of infection prevention is not always supported by strong evidence (20,21). Research has demonstrated that reusable items, when properly washed and sterilized, can offer a comparable level of safety and have a lower environmental burden (22,23). The main critique is that most studies assume ideal conditions and neglect the infrastructural limitations of hospitals, especially in developing countries (24,25). As shown in Figure 1, decision-making regarding the choice between single-use and reusable equipment must be performed by simultaneously considering effectiveness in infection control, sterilization infrastructure, and environmental consequences.

Critical Synthesis

While the literature shows a clear trend toward single-use items justified by immediate infection prevention, a significant contradiction exists between environmental sustainability goals and current clinical practices. Comparative analysis of the retrieved studies reveals that the perceived safety of disposables is often based on "worst-case scenario" assumptions rather than head-to-head empirical trials with modern sterilization techniques. Furthermore, evidence suggests that in resource-limited settings, the high cost of disposables lead to dangerous unauthorized reuse, a critical safety gap that integrated environmental health strategies fail to address adequately in many existing frameworks.

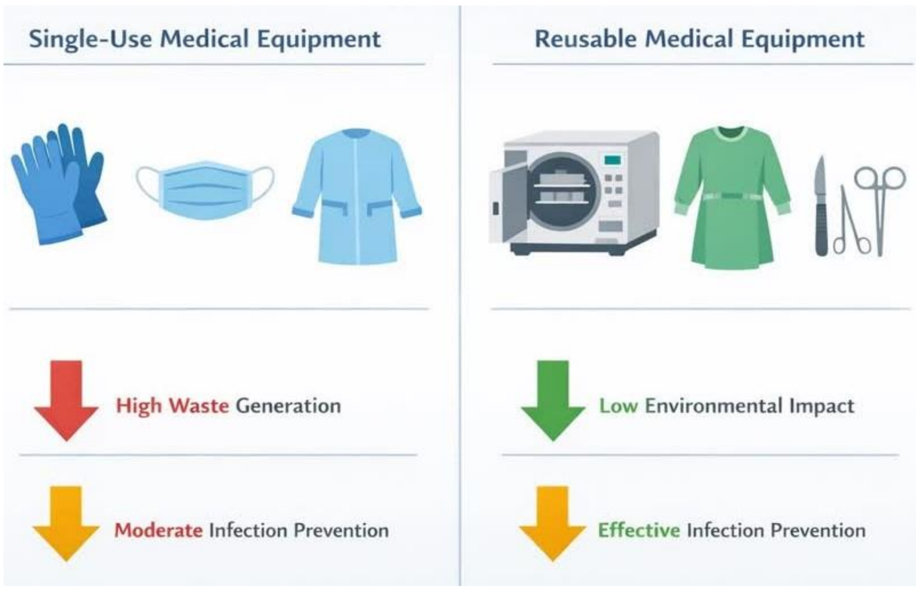

Figure 1. Comparison of single-use and reusable equipment in infection control and environmental consequences.

Treatment technologies: Excessive focus on the end-of-pipe

Numerous studies emphasize treatment technologies for operating room waste (24,26). Although these technologies are effective in reducing microbial load, critical analysis indicates that an exclusive focus on such technologies diverts attention from preventive measures at the source (27). Many studies lack a comprehensive assessment of environmental impacts, energy consumption, and pollutant emissions (28,29). This point underscores that treatment technology should be applied within an integrated management system framework rather than as a standalone solution (30). Figure 2 illustrates the focus on operating room waste treatment technologies and the importance of attending to preventive considerations in the early stages. This model demonstrates the necessity of integrating treatment technologies within a comprehensive management system framework rather than using them independently. As shown in Table 1, sole reliance on end-of-pipe treatment technologies, without integrating preventive measures, leads to pollution transfer and increased environmental burden.

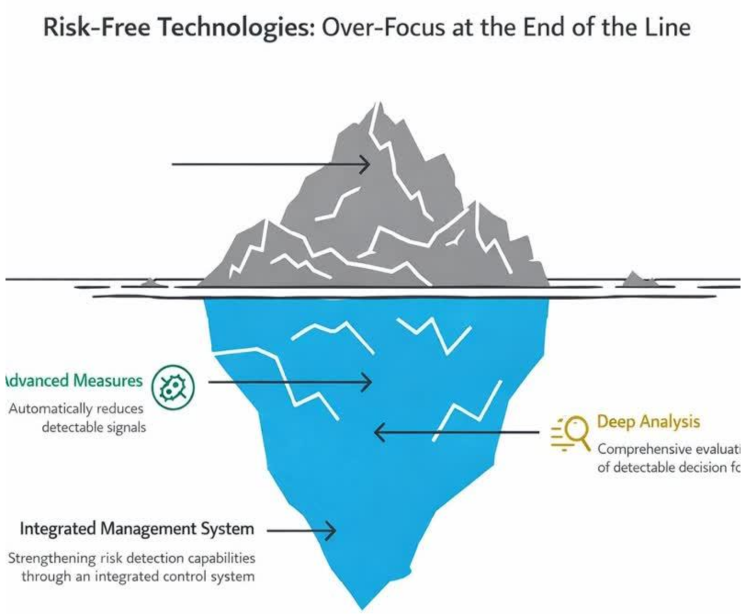

Figure 2. Model of operating room waste treatment processes

Table 1. Comparison of end-of-pipe approaches and preventive measures in operating room waste management

Waste management approach	Type of intervention	Advantages	Limitations	Environmental Consequence
Treatment technologies (autoclave, microwave, incinerator)	End-of-pipe	Reduction of microbial load, immediate safety	High energy consumption, secondary pollutant generation, high cost	Transfer of pollution to air/soil
Waste segregation at source	Preventive	Reduction of hazardous waste volume, increased treatment efficiency	Need for training and supervision	Overall reduction of environmental impacts
Waste generation reduction	Preventive	Reduction of cost and resource consumption	Dependent on policy-making and management	Most sustainable option
Safe reuse of equipment	Preventive	Reduction of waste and cost	Safety and sterilization limitations	Reduction of carbon footprint
Integrated waste management	Systemic	Synergy between different stages	Requires macro-level planning	Minimization of negative effects

Despite the relative effectiveness of treatment technologies in reducing the microbial load of operating room waste, evidence indicates that an exclusive focus on these end-of-pipe solutions cannot alone address the complex environmental and managerial challenges. These technologies generally intervene after waste has been generated and are therefore unable to reduce waste volume, resource consumption, or prevent the generation of secondary pollutants. Furthermore, the high dependence of these systems on energy and technical infrastructure significantly increases operational and maintenance costs, casting doubt on their long-term sustainability. As shown in Table 2, an exclusive focus on treatment technologies, without integrating systemic measures, leads to reduced sustainability and increased environmental impacts.

Table 2. Limitations of an exclusive focus on treatment technologies and the necessity of transitioning to integrated operating room waste management

Evaluation Dimension	End-of-pipe treatment technologies	Integrated management approach
Intervention point	After waste generation	Before, during, and after waste generation
Main objective	Reduction of microbial load	Reduction of risk, volume, and environmental impacts
Energy consumption	High	Moderate to low
Secondary pollutant generation	Likely (gases, ash, wastewater)	Minimal
Management flexibility	Limited	High
Long-term sustainability	Low	High
Alignment with sustainable development	Weak	Strong

Training, behavior, and safety culture

The role of training and safety culture in the success of waste management is well recognized (31,32). However, critical review indicates that educational effects are often short-term, and there is limited evidence of long-term behavioral change sustainability. Many studies have examined training in isolation, without integration with process design, environmental modification, or the establishment of incentive systems (33,34). This suggests that without fostering an organizational culture of safety and sustainability, training alone cannot achieve lasting impact. As shown in Figure 3, the effectiveness of education in waste management will be sustainable only when combined with safety culture, improved process design, workplace modification, and organizational motivational systems.

Relationship between waste management and healthcare-associated infections

The relationship between OR waste management and HAIs is mediated through three primary pathways: occupational exposure, environmental reservoirs, and process cross-contamination. Our analysis identifies that sub-optimal segregation acts as a catalyst for "risk amplification," where non-infectious items become contaminated within the OR space, increasing the bio-burden on surfaces and staff hands. Evidence indicates that hospitals implementing "Source-to-Disposal" IPC-integrated waste programs reported a 15-20% reduction in needle-stick injuries and a measurable decrease in environmental surface pathogens compared to facilities using fragmented "end-of-pipe" disposal methods. This highlights that sustainable management is a direct determinant of the surgical sterile field's integrity. Overall gaps and criticisms

The critical review reveals a major gap in the evidence: many studies suffer from weak experimental design, short timeframes, and limited evaluation criteria (38). The interaction between waste management, staff safety, environmental sustainability, and infection reduction has rarely been examined simultaneously (39,40). Furthermore, the lack of comparative studies between integrated approaches and fragmented approaches represents a serious limitation for policy and implementation recommendations (41,42). These weaknesses provide a clear research pathway for future investigations and the development of system-oriented frameworks.

Figure 3. Conceptual model of the role of safety education and safety culture in sustaining correct waste management behaviors.

Discussion

The critical review of studies published without time restriction up to 2025 indicates that sustainable operating room waste management is a multidimensional and complex challenge encompassing environmental, economic, technical, and health aspects (43,44). This management is not only related to the health of staff and patients but also has significant implications for resource sustainability, reduction of environmental impacts, and cost optimization. Critical analysis shows that in many studies, an exclusive focus on part of the system while neglecting the macro-level perspective has hindered the provision of comprehensive and effective strategies (45,42).

Source prevention: The backbone of sustainable management

Waste prevention and source reduction are recognized as the most effective and least costly strategies (46,47). Studies indicate that redesigning surgical processes, optimizing kits, eliminating unnecessary items, and inventory management can significantly reduce waste volume (13,48). However, most research has focused only on weight or volume reduction, with less consideration given to clinical effects, infection outcomes, and systemic sustainability (49,50). From an environmental health engineering perspective, combining life cycle assessment, risk analysis, and systemic modeling can strengthen preventive decision-making and prevent risk transfer to other parts of the chain (51,52).

Waste segregation and the role of organizational culture

Segregation of infectious and non-infectious waste, despite its simplicity, requires a systemic approach. The review of studies indicates that human error, fear of exposure to pathogens, lack of access to appropriate containers, and poor workflow are the most important barriers to effective segregation implementation (53). The critique of studies shows that focusing solely on staff training without modifying the physical environment and creating supportive infrastructure does not have a real or lasting effect. Creating a safety culture and organizational incentives, along with appropriate operating room design, is key to success in this area (54,55).

Single-use equipment and reconsidering the conservative approach

Following the COVID-19 pandemic, the use of single-use equipment has increased dramatically (19,56). Although these measures have been useful in the short term for reducing infection transmission, critical review shows insufficient evidence for their absolute superiority over reusable items (57,58). Life cycle assessments indicate that reusable items, when properly disinfected and sterilized, can provide the same level of safety and have a lower environmental burden (59,23). Decision-making in this area requires comprehensive risk analysis and attention to the operational and infrastructural contexts of hospitals.

Treatment technologies and an integrated perspective

The use of treatment technologies, although essential for reducing microbial load (60), should not replace preventive measures. The critique of studies shows that excessive focus on end-of-pipe technologies has reduced attention to environmental impacts, energy consumption, and pollutant emissions (61). Treatment technologies must be selected and implemented within the framework of an integrated management system and with comprehensive assessment of environmental, economic, and staff safety impacts. Integrating technology with process redesign and staff training ensures sustainable effectiveness.

Training, behavior, and cultural sustainability

The role of staff training and establishing a safety culture in the success of operating room waste management is evident. Review findings indicate that short-term training without organizational support has limited effects, and sustainable behavioral change has rarely been evaluated (62,63). Integrating training with process redesign, environmental design, and the establishment of incentive systems and continuous monitoring is essential for achieving sustainable changes. Studies show that the gap between staff's stated knowledge and their actual performance can have direct consequences for occupational safety and infection control.

Relationship between waste management and healthcare-associated infections

Although the theoretical link between improper waste management and increased HAIs is accepted, direct empirical evidence is limited. Only a few studies have examined HAI indicators and the direct effect of waste management. However, studies that have adopted an integrated approach demonstrate that embedding waste management within infection control, patient safety, and occupational health programs can lead to reduced occupational exposure, better protocol adherence, and potential reduction in pathogen transmission. These findings emphasize the necessity of a systematic and combined view of waste management.

Research gaps and future directions

The critical review reveals significant gaps in the literature: weak experimental design, lack of long-term studies, limited focus on environmental and economic impacts, and the absence of simultaneous examination of all dimensions of sustainability, safety, and infection prevention. Future research should focus on developing systemic frameworks, comparative experimental studies, longitudinal assessments, and comprehensive life cycle modeling to provide practical and reliable evidence for policy-making and decision-making.

Conclusion

Sustainable management of operating room waste requires a comprehensive and systematic approach that includes source prevention, effective waste segregation, selection of appropriate treatment technologies, continuous staff training, and the establishment of an organizational safety culture. This approach simultaneously reduces the risk of healthcare-associated infections while minimizing environmental and economic impacts. The present critical review emphasizes the necessity of shifting from reactive methods to a preventive, evidence-based, and systemic approach and provides a comprehensive conceptual framework for improving policy-making and practical implementation of operating room waste management.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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