International Journal of Social Science Research and Review

http://ijssrr.com
editor@ijssrr.com
Volume 9, Issue 1
January, 2026
Pages: 46-62

Sustainable Approaches to Medical Waste Management for Better Public Health Outcomes

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http://dx.doi.org/10.47814/ijssrr.v9i1.3080

Abstract

Purpose: Medical waste disposal has become a significant issue worldwide, driven by public health concern, environmental safety and healthcare continuum. This work investigates sustainable management of infectious waste by examining technologies, governance models and stakeholder perceptions in different country context and opportunities for its circular economy.
Methodology/approach: This research applied the mixed methods to analyses sustainable medical waste management practices and its health impacts.
Results/findings: Results show that more advanced non-burn techniques, autoclaving and microwaving, are prevalent in high income countries and result in relatively good concomitant compliance of low emissions at the three cost types. Methods including incineration, open burning and burials are employed in middle and low-income countries that provide poor infection control with high degree of threats to the environment and public health. Comparisons between subsystem circularities, autoclaving, chemical disinfection and the rate of reuse are also discovered to be more effective in terms of reducing infection risk during health crises as well as environmental impact. Lack of enforcement, inadequate training and financial limitations still remain the major deficiencies in most parts. The necessity to incorporate non-burn technologies and strengthen governance and enforcement, incentivize circular economy innovations, establish surge capacity for future crises.
Limitations: The findings are constrained by a narrow focus on technological and economic factors and a cross-sectional design that precludes long-term impact assessment.
Contribution: Sustainable medical waste disposal is thus extremely critical in order to minimize environmental pollution and also to protect human health, while ensuring the sustainability of the healthcare system.

Keywords: *Medical Waste; Public Health; Sustainability; Non-burn Technologies; Recycling*

1. Introduction

Healthcare waste, also known as medical waste, is any type of waste that could cause harm to patients, the public, or to its handlers or carriers if not managed properly (Janik-Karpinska et al., 2023). This waste stream includes infectious, pathological, pharmaceuticals, chemicals, sharps and radioactive materials that if not handled appropriately, can pose negative impact to both human health and environment (Janik-Karpinska et al., 2023). The World Health Organization (WHO) reported that 15% of health-care waste is classified as hazardous; however, it has the greatest potential to harm human health by virtue of its infectious, toxic or radioactive characteristics (WHO/UNICEF, 2024). The acceleration in the demand of healthcare facilities, rising population and use of disposable medical products has amplified the problem of medical waste disposal particularly in lower and middle-income countries (Syed et al., 2012).

Medical waste that is improperly treated or disposed of can pose serious risks to health. Poor waste management may cause injuries and infections among those treating the waste, as well as exposure to hazardous substances from health workers involved in managing such type of waste, and also among scavengers/recyclers (Gutberlet & Uddin, 2017). However, open/uncontrolled dumping and burning of medical waste is common practice in many developing countries leading not only to soil and groundwater contamination but also environmental release of toxic pollutants dioxins and furans (Thiagarajan et al., 2025). Such practices, besides being a risk for public health, are not eco-friendly, unsustainable and cannot be justified against international obligation of sustainable development practices (Obaideen et al., 2022). The issue of medical waste management and disposal has been becoming increasingly noticeable over the past few years, particularly in light of the current another health emergencies and sustainability concerns (Shozib et al., 2025).

Healthcare waste management practices and policies are not unidimensional as they have to deal with economic, social and environmental aspects in order that medical waste be destroyed innocuously, without any doubt to prevent environment of our planet (Çelik et al., 2023; Halimuzzaman et al., 2024). In order of preference, the initiatives include waste reduction at its source, separation of wastes at where they are generated followed by their collection and transport safely to designated treatment or disposal; in addition to treatment using technology that is environment friendly, and safe disposal meeting public health norm (Quttainah & Singh, 2024; Sapkota et al., 2014). The use of alternative management strategies such as autoclaving, microwaving, chemical disinfection and advanced non-burn technologies has been increasingly considered instead of incineration (Mazzei & Specchia, 2023). Similarly, emphasis on circular economy initiative demands recycling, and energy recovery are gaining traction with healthcare facilities looking to be more environmentally responsible in the way they manage their waste and consume resources (Islam et al., 2024; Martin et al., 2024). Public health results depend largely on the functionality of medical waste disposal (Husaini et al., 2024). Poor systems also increase the risk of disease transmission in urban and peri-urban areas due to high population density and inadequate waste disposal sites (Rahaman et al., 2023). In contrast, sustainable management reduces the risk of infections and other diseases along with decrease in occupational hazards and environmental pollution leading to better health (Tulchinsky & Varavikova, 2014).

Despite all the significance of taking care, the handling of medical waste is confronted with several obstacles (Alshagrawi & Alahmari, 2025). Limited budget, poor facilities, weak regulations and shortage of trained staff are still the barriers for most of the countries, particularly low and middle-income nations (Puchalski Ritchie et al., 2016). Furthermore, lack of knowledge on the part of healthcare workers and people in communities has led to inadequate segregation and unsafe disposal (Ibrahim et al., 2023). These challenges need to be met by coordinated policies and cooperation across sectors, support for advanced treatment technologies, and capacity-building. Global cooperation refers to multilateral/ international collaboration that is carried out according to a global framework in order to assist the national government as they work on improving practices of waste management.

2. *Literature Review*

2.1 The Problem of Unsustainable Medical Waste Management

According to WHO, medical waste means any waste produced during diagnosis, treatment, or immunization of human beings or animals or in research undertaken during the provision of health services (Prüss et al., 2014). It is usually divided into non-hazardous (general) and hazardous (infectious, pathological, pharmaceutical, genotoxic, chemical and radioactive). Although non-hazardous waste remains in the majority, the hazardous portion which is in many cases 10-25% of total amount creates more risk (Janik-Karpinska et al., 2023). Traditional disposal of this waste, primarily in low and middle-income countries (LMICs), has been with crude and hazardous practices. Open dumping and uncontrolled burning are rampant resulting in widespread environmental pollution and pathways for direct human exposures to a range of health hazards (Ferronato & Torretta, 2019). The gap in source separation practices is also one of the major issues identified by a number of studies (Ferdous et al., 2020). Without correct source segregation (in a ward/clinics), then whole fraction of waste might become contaminated with an infectious material and the amount would increase while it needs to be handled at high risk. A research conducted by Barua & Hossain (2021) in Bangladesh reported contamination of general waste with sharps and infectious materials which increased the risk of infection through wastes among handlers and scavengers.

2.2 Waste Minimization and Source Segregation

This is one of the most basic features of any sustainable system, and can be adapted in management of waste which focuses only on reducing generation at source (Hajam et al., 2023). Operational and behavioral changes such as the use of reusable medical devices where possible and appropriate, rational procurement to reduce over-packaging, and increasing staff awareness could be mentioned as how such vision may become true (Hoveling et al., 2024). However, rigorous source segregation is the most efficient intervention for safety improvement and cost reduction (Alshemari et al., 2025). By discarding waste in dedicated, color-coded bins (e.g., yellow for infectious waste, red for sharps and black for common garbage), the amount of rubbish to be sent up to specialist treatment is greatly reduced and therefore subsequent operations become safer and cheaper. Various research has proved a strong relation between better segregation practices and the reduction in processing costs of waste (Adam et al., 2025).

2.3 Environmentally Sound Treatment Technologies

Incineration has been the primary option for hazardous medical waste treatment in the past because it can effectively eliminate pathogens; however, its emissions of toxic pollutants like dioxins, furans and heavy metals have led to significant environmental and health issues (Alvim-Ferraz, 2003), resulting in more environmentally friendly alternatives. Of these, sterilization of infectious waste and sharps through autoclaving by high-pressure wet steam has been very efficient to reduce the decay in a form that does not emit harmful air although disposed to dumps (Rutala & Weber, 2015). Microwave, like inducing microparticle heat, applies microwave energy to sterilize infectious waste in an ecological way and disinfection with chemicals such as sodium hypochlorite is efficient for some infectious wastes but creates liquid effluent which should be managed carefully to prevent water pollution (Zimmermann, 2017). For pharmaceutical and chemical waste there exist forms of encapsulation and inertization, with the former as solidifying waste into cement or plastic blocks while the latter is mixing waste with stabilizing agents including cement to reduce solubility and mobility (Prüss et al., 2014). A review by Hussein Emad et al. (2023) highlighted that non-incineration technologies, including but not limited to autoclaving, provide the optimum tradeoff between environmental safety, economic efficiency and public acceptability and were thus crucial for sustainable medical waste management.

2.4 Reduction of Direct Health Risks

The most direct health benefit is a decrease in exposure to infectious hazards on the job and in the community. Blenkharn (2009) research on sharps injuries concluded that the correct segregation and disposal of the sharp containers can reduce the level of sharp injuries among health care workers and waste handlers which would help in reducing the transmission risk of bloodborne diseases like Hepatitis B, C and HIV. Apart from infectious threats, contact with hazardous heavy metals (such as lead or mercury) and cancer-causing dioxins due to uncontrolled burning bear serious long-term health threats such as neurological impairment, kidney failure, and cancers of various kind (Witkowska et al., 2021). Sustainable practices directly protect human health by reducing or regulating these dangerous disposal practices.

2.5 Mitigation of Environmental Contamination

The health of the environment and human health are indivisible. Waste practices that are not sustainable result in air, soil, and water pollution. Open burning and traditional incineration emit a mix of hazardous pollutants that form the root cause of air pollution and acid rain (Krecl et al., 2021). Contaminated liquid leachate from open landfills contaminates groundwater and surface water, resulting in pollution of drinking water sources and aquatic habitats (Parvin & Tareq, 2021). Sustainable practices interrupt this cycle of environmental loss through waste processing prior to disposal, and containment of final residues in sanitary landfills, protecting public health from potential indirect exposures over the long term (Oluwagbayide et al., 2024).

2.6 Policy, Regulation, and Stakeholder Engagement

There must be a good policy and enforcement mechanism for the medical waste management as well all-inclusive participation if any system should be sustainable. WHO provides international guidelines, however the implementation and enforcement of such regulations is crucial at the national and local level (Prüss et al., 2014). A study by Tazzie et al. (2025) in Ethiopia found that existing national guidelines, insufficient financial commitment, limited training and enforcement were the significant barriers to implementation. This speaks for the requirement of political will and also resources. Second, there is the value of education and training. However, having a trained and educated personnel such as physicians, nurses, waste handlers and administrators is crucial to implement laws and regulations in support of the overall activities (Alharbi & Aloyuni, 2023). Public education and community participation campaigns are indispensable as well to discourage illegal disposal and foster a sense of ownership towards the good health of people in general (Kitole et al., 2024).

2.7 Research Gap

However, there has been relatively little discussion on general medical waste management; this remains at a deficit in comparison to the literature given its importance for sustainable and health-based interventions. While there are numerous studies that address technical issues (alternatives to incineration, sterilization, possibilities for waste-to-energy and others), little is known through scientific research on their financial sustainability, environmental trade-offs or technological options for the same under different social-economic configurations especially in low and middle-income countries. There are not many life cycle assessment studies comparing individual technologies, so it is difficult to determine what measures can be taken that are both epidemiologically sensitive and cheap, environmentally friendly. In addition, circular economy principles (reduction at source, re-use of medical products and safe recycling) are not fairly implemented into regular health care waste management. While policy and governance systems are sound at the higher level, they fail to be operationalized due to weak implementation, inadequate training and low awareness in community. However, there are few studies on how to build resilience and surge capacity in medical waste management. It is thus necessary to break down the silos and endeavor to piece together interdisciplinary knowledge on technology, policy, economics and behavioral change etc., by which holistically sustainable approaches can be framed so that there are environmental safeguards as well as better public health outcomes.

2.8 Research Questions

a) How can sustainable strategies for the management of medical and health care waste protect environmental safety, economic viability, and public health under the diverse socio-economic situations?
b) What is the relative life-cycle environmental impacts, cost-effectiveness, and scalability of alternative treatment technologies for use with low and middle-income countries?
c) How can circular economy-based approaches, e.g., waste prevention at source, sound reuse or recycling be relevant to health care systems without endangering infection control and occupational safety?
d) Which policy, governance and capacity-building approaches can be used to narrow the gap between international guidance and local implementation towards sustainable medical waste management?
e) What are strategies to make medical waste management systems more robust in response to health emergencies (i.e., pandemics) without sacrificing surge capacity, and still contribute toward sustainability and health outcomes?

2.9 Research Objectives

a) To explore and evaluate sustainable medical waste management initiatives with an optimal compromise between environmental safety, economic viability, and public health protection in divergent socio-economic settings.
b) To investigate alternative treatment technologies such as autoclaving, microwaving, chemical disinfection and advanced non-burn methods by taking a life-cycle perspective to assess their environmental, economic and technical feasibility.
c) To explore the opportunities and challenges of integrating elements of circular economy (waste minimization, reuse, recycling etc.) in healthcare systems without compromising infection prevention, control or occupational health.
d) To examine policy and governance options which can narrow the disconnect between international norms and local practice including enhancing regulation, capacity strengthening and community awareness.
e) To explore ways of increasing the resilience of healthcare waste management systems in pandemic-type outbreaks to surge as well as long-term performance.

3. Methodology

This article applied the mixed methods, namely a systematic review of the literature; comparative life cycle assessment and policy analysis to analyses sustainable medical waste management practices and its health impacts. The aim of the study was conceived on the overall principles of identification, analysis and proposing potential environmentally sustainable, economically affordable, as well as health-oriented waste management alternatives.

3.1 Literature Review Process

A systematic review of the literature was conducted to collect information on best practices for waste management, treatment technology options, policy considerations and public health impacts. The search was performed in Scopus, Web of Science, PubMed and Google Scholar databases with keywords and terms such as “medical waste management”, “healthcare waste treatment”, “sustainable approaches”, “circular economy in healthcare” and “Public health outcomes”. Articles from 2000 to 2025 were assessed to account for historical and novel approaches. The following were the inclusion criteria: peerreviewed articles, policy documents and technical reports that stated to deal with strategies or technologies of medical waste management and health effects. If they only covered industrial MSW or municipal solid waste (without healthcare-specific data), these studies were excluded. Records were screened for title and abstract first, and then full text, leaving the final document set of around 150 relevant documents for synthesis.

3.2 Comparative Technology Assessment

All treatment technology evaluations were conducted using an ISO 14040/44 standards-based life cycle assessment (LCA) approach. Four common methods (autoclave, microwave, chemical disinfection and alternative incineration technologies including plasma gasification (and a range of non-combustion approaches)) were evaluated. The system function included waste separation, collection, treatment and final disposal. Data for the LCA was organized from significant cases, technical publications and peer reviews. The following KPIs were examined: greenhouse gas emissions (kg CO_2-eq/ton waste), energy demand (kWh/ton), operational cost (USD ton^{-1}), treatment performance (% inactivated pathogens) and pollutant generation. When available, we added context to LMIC data for assessing adaptability under resource-limited settings.

3.3 Circular Economy Evaluation

The feasibility of the circular economy for several areas has been considered by an analysis of the case studies on waste reduction, medical supplies re-use, plastics recycling and recovery of energy from medical waste. Qualitative content analysis analyzed results such as percentage reduction in waste, safety and acceptability by healthcare workers gleaned from sources reported on by authors. Lessons from COVID-19 in healthcare, reuse of products (including devices) and recycling healthcare and medical waste have been both highly promising as well as highly limiting.

3.4 Policy and Governance Analysis

Policy papers and legislation were examined to assess governance approaches for medical waste. We compared the WHO "Blue Book" international guidelines to national policies from selected case study countries with diverse income levels. A framework analysis was used to describe enforcement, training, infrastructure and community engagement strengths, gaps and barriers. To confirm the analysis, online-based semi-structured interviews with 15 stakeholders such as health care provider administrators, waste handlers and environmental regulatory officials, were taken place. Interviews were approved ethically by the appropriate institutional review board; informed consent was obtained from all interviewees.

3.5 Resilience Assessment during Health Emergencies

In response to the surge-capacity aspect, the current study evaluated medical waste management during the COVID-19 pandemic. Secondary data were pooled from WHO and national health ministries for waste volumes, emergency disposal practices, and coping strategies. These were cross-referenced with resilience indicators such as scalability, flexibility, environmental and occupational safety. Using these lessons, a conceptual framework focused on resilience in public health emergencies was created, weaving sustainability of the system and preparedness into a single whole.

3.6 Data Synthesis and Analysis

Findings collected from all sources (literature, LCA and case studies, policy review and interviews) were synthesized through thematic and comparative analysis. Qualitative data were coded in NVivo software and environmental and economic points were quantified with Excel and OpenLCA software. Use of triangulation for validation, especially by cross-verifying results across data sources and methods.

The ultimate literature synthesis included the evidence of best sustainable practices in medical waste with respect to public health and environmental protection.

4. Results and Discussion

4.1 Results

4.1.1 Sustainable Practices in Medical Waste Management

Table 1 shows the differences in waste management process among different income countries. In high-income nations, advanced non-burn technologies, including autoclaving, microwaving and recycling are being increasingly used offering the benefits of high compliance and reduction in emissions; however, their costs as well as energy requirements are high. While middle-income countries use mainly autoclaving and incineration with minimum recycling activities, acceptance of these methods is weak due to lack of enforcement and non-standardized management of waste. In contrast, open burning, burial and donor-provided autoclaves (which can appear inexpensive at the start but are associated with significant health burdens and environmental pollution through soil and air contamination) remain main methods of sterilization in resource-poor countries.

Table 1. Distribution of sustainable practices across income groups.

Country group	Common practices	Advantages	Limitations
High-income	Autoclaving, microwaving, advanced non-burn methods, and recycling	High compliance, lower emissions	High cost, energy intensity
Middle-income	Mix of autoclaving and incineration, limited recycling	Moderate infection control	Weak enforcement, variable segregation
Low-income	Open burning, burial, donor-provided autoclaves	Low upfront cost	Severe health risks, soil/air contamination

4.1.2 Comparative Evaluation of Treatment Technologies

Autoclaves demonstrated the high pathogen inactivation, while it has average greenhouse gas (GHG) emissions and moderate energy consumption, which makes them highly feasible for LMICs as value-for-money (Table 2). Microwave irradiation is also the equivalent level of disinfection (99.5%); however, it demands higher energy and expenses, such that it is impractical to produce at certain moderate degrees. Chemical disinfection demonstrates excellent inactivation of pathogens (98.5%) with reduced energy requirement and lower costs, which is highly suitable for LMICs. Incineration, despite an excellent inactivation rate (99.9%), it has very high GHG emissions and requires substantial energy use, causing environmental issues while keeping intermediate feasibility for LMICs. Plasma gasification is extremely efficient (with the lowest emissions) but suffers from excessively high energy requirements and costs, thus rendering this technology unfeasible in resource-scarce environments.

Table 2. Comparative performance of treatment technologies

Technology	Pathogen inactivation (%)	GHG emissions (kg CO_2-eq/ton)	Energy use (kWh/ton)	Cost (USD/ton)	Feasibility in LMICs
Autoclaving	99.9	120	220	95	High
Microwaving	99.5	150	240	110	Moderate
Chemical disinfection	98.5	180	180	85	High
Incineration (modern)	99.9	650	500	150	Moderate
Plasma gasification	99.9	80	750	350	Low

4.1.3 Integration of Circular Economy Principles

The results of combining circular economy strategies with medical waste management in various regions are shown in Table 3. In Europe, the use of reusable gown materials and PPE reduced waste by 35%, saving 28% costs but evolve at high cost for sterilization. In India, a pilot plastic recycling program reduced waste by 22 percent and saved 15 percent, but contamination fears prevented roll-out. Japan’s waste-to-energy recovery approach was most successful with the greatest reduction in waste (45%) and savings in cost (30%), but would require investment for infrastructure. Centralized autoclaving with recycling integration in Kenya reached low reduction (18%) and cost savings (12%) levels, due to poor segregation performance.

Table 3. Outcomes of circular economy applications in healthcare waste management.

Circular strategy	Region	Waste reduction (%)	Cost savings (%)	Constraints
Reusable gowns and PPE	Europe	35	28	High sterilization cost
Plastic recycling pilot	India	22	15	Contamination risks
Waste-to-energy recovery	Japan	45	30	High infrastructure demand
Centralized autoclave + recycling	Kenya	18	12	Limited segregation

4.1.4 Policy and Governance Mechanisms

The USA and Germany both exhibit a high coherence to the WHO guiding principles with strong regulation, substantial training initiatives and an advanced level of public awareness; however, the USA is hampered by disposal costs while Germany has insufficient recycling capacity (Table 4). India, on the other hand, shows moderate policy alignment with weak enforcement, inadequate training and only moderate public awareness; poor segregation has been found to be a significant need. Kenya has the weakest enforcement, the lowest training and little public awareness because of infrastructure deficiencies. Bangladesh shows a moderate fit and weak monitoring, low training, and awareness; the main limitations are related to insufficient funds.

Table 4. Comparative governance frameworks in selected countries.

Country	Policy alignment with WHO	Enforcement	Training programs	Public awareness	Key gaps
USA	High	Strong	Extensive	High	High disposal cost
Germany	High	Strong	Extensive	High	Limited recycling capacity
India	Moderate	Weak	Limited	Moderate	Poor segregation
Kenya	Low	Weak	Minimal	Low	Infrastructure deficit
Bangladesh	Moderate	Weak	Limited	Low	Funding, weak monitoring

4.1.5 Stakeholder Perspectives on Implementation Challenges

The healthcare executives considered high technology costs as one of the major barriers and recommended subsidies and having centralized facilities to save costs (Table 5). Waste handlers mentioned the type of threats they face at work, including no personal protective equipment (PPE) and frequent sharps injury, requiring measures such as adequate provision of PPE and training. Regulators identified enforcement as a weakness that continues to exist and one which needs stronger regulations and monitoring. Community leaders, meanwhile, expressed health worries from pollution and said awareness campaigns should be run to engage and inform the public.

Table 5. Stakeholder-identified challenges and suggested solutions.

Stakeholder group	Reported challenges	Suggested solutions
Healthcare administrators	High technology costs	Subsidies, centralized facilities
Waste handlers	Lack of PPE, sharps injuries	Provision of PPE, training
Regulators	Weak enforcement	Stronger laws, better monitoring
Community leaders	Health risks from pollution	Awareness campaigns

4.1.6 Resilience in Health Emergencies

The high-income countries found a 3–5 multiplication factor for waste and met this through mobile autoclaves and centralised treatment hubs that only raised environmental impact to moderate levels, albeit with reasonable overall effectiveness (Table 6). The middle-income countries recorded four to seven times increase largely using incineration and temporary burials, that were efficient but anyone with environmental concerns opted them at best. Conversely, open burning in low-income countries has increased the most (5-10 times that of baseline) and it can be surmised that this has directly led to widespread environmental damage with very few benefits.

Table 6. Medical waste surge and management during COVID-19.

Country group	Surge magnitude (× baseline)	Response strategy	Environmental impact	Effectiveness
High-income	3-5×	Mobile autoclaves, hubs	Moderate	High
Middle-income	4-7×	Incineration, temporary burial	Significant	Moderate
Low-income	5-10×	Open burning, uncontrolled dumping	Severe	Low

4.1.7 Sustainable and Unsustainable Practices

The advantages of using sustainable measures are easily noticeable in the sense of better infection control, lower rates of injuries by sharps, environmental impact that is low to moderate and economic viability that increases with time through savings and overall efficacy (Table 7). They are also key drivers in strengthening system resilience and health system capacity to respond to crises. Conversely, unsustainable practices are co-interlinked with low infection control and high exposure risk; high environmental burden (air/water pollution), weak financial sustainability (with hidden health costs) and overall system resilience for the critically ill.

Table 7. Comparative outcomes of sustainable and unsustainable approaches.

Outcome dimension	Sustainable practices	Unsustainable practices
Infection control	High (low sharp injuries)	Low (high exposure risk)
Environmental impact	Low to moderate	High (emissions, contamination)
Economic feasibility	Moderate to high	Low (hidden costs of illness)
System resilience	Strong	Weak

4.1.8 Integrated Framework for Sustainable Medical Waste Management

Technology drives non-burn systems, autoclaving and other scalable technologies that could help reduce infection risks and emissions (Table 8). Carriers prioritize enhanced policy compliance, employee training and community activation which leads to safer workplaces and greater compliance. Adopting principles of the circular economy, such as reuse and safe recycling or energy recovery, would be a step towards greater resource efficiency and away from waste disposal. Finally, capacity surges and emergency hubs provide resilience for health emergencies while eliminating the habit of dumping people into emergencies.

Table 8. Proposed framework for sustainable medical waste management.

Component	Key actions	Expected health outcomes	Environmental benefits
Technology	Promote non-burn methods, expand autoclaving, adopt scalable innovations	Lower infection risks	Reduced emissions
Governance	Enforce policies, train staff, engage communities	Safer workplaces	Higher compliance
Circular economy	Promote reuse, safe recycling, and energy recovery	Resource efficiency	Reduced landfill load
Resilience	Develop surge capacity, emergency hubs	Preparedness for crises	Avoid emergency dumping

4.2 Discussion

This study informed sustainable alternatives for medical waste management, variations in practice among income levels, comparative efficacy of treatment technologies, circular economy values consideration, governance and policy measures and stakeholder perceptions on local governments' resilience strategies towards bio-medical waste management during health pandemics and way forward an integrated sustainability approach. Results showed that in high-income countries, advanced non-burn technologies and recycling with strong regulation and enforcement are prevalent. These results are also in accordance with the WHO recommendations for non-burn alternatives as strategy to reduce environmental emissions (Prüss et al., 2014). Other studies (Baaki et al., 2022; Khan et al., 2019) also assert that those with high capacity in finance and institutions prefer safe and clean technologies, while poor ones engage in open burning as well as burial. Consistent with our findings, many LMICs like Bangladesh, Nigeria and Nepal are still depending on low cost and high risk sources where poor segregation practice has exacerbated the situation (Mmereki et al., 2024). This further highlights the disparity that exists globally in access to safe facilities for treating medical waste.

Autoclaving was the most optimal in vitro ETP technology, which provides a combination of high pathogen reactivation and low GHG emissions, besides medium cost for LMICs. These results are in agreement with previous LCA studies (Ferdowsi et al., 2013; Sharifi et al., 2024), where autoclaving was found to be cost-effective, compared to incineration in low-resource settings. The plasma technology presented the lowest emissions; however, it is an uneconomical technology and this brings attention to reports of Kumar et al. (2020), having claimed that advanced waste-to-energy systems usually are not financially viable in LMICs despite their environmental performance. The persistence of incineration in some settings emphasizes the tension between priorities for infection control and environmental sustainability, resembling previous concerns expressed by Windfeld & Brooks (2015).

The best in vitro ETP technology was autoclaving, as it came through with high pathogen reactivation and low GHG emission along with medium cost for LMICs. These findings are consistent with other LCA studies (Ferdowsi et al., 2013; Sharifi et al., 2024), that showed sterilization through autoclave, is more cost effective compare to incineration in a low resources settings. The plasma process had the least emissions but it is an expensive technology and this draws reference to the publication by Kumar et al. (2020), who argued that advanced waste-to-energy technologies normally are not economically viable in LMICs despite its environmental efficiency. Incineration remained an issue in some areas, reflecting the balance of infection control and environmental sustainability priorities as discussed previously by Windfeld & Brooks (2015).

The incorporation of circular economy concepts as reusable PPE, plastic recycling and waste-to-energy recovery exhibited high potential in terms of waste reduction and cost savings. This is in line with Hasibuan et al. (2025) observations that a circular design approach not only improves resource efficiency but also reduces the waste produced. Nevertheless, risks of contamination and infrastructure deficits are still substantial obstacles, especially in LMICs. Parallel challenges were reported in the context of the COVID-19 pandemic, with reuse and recycling programs disrupted because handling was associated with risk of infection (Talukdar et al., 2024). The success of the Japanese waste-to-energy model, particularly with respect to its infrastructure and investment, augments previous evidence that integration of the circular economy is a contextual issue (Ferronato & Torretta, 2019). Comparison of governance frameworks showed that, while international high-income countries have strong alignment policies with WHO standards, low-middle income countries (LMICs) are suffering from weak enforcement, lack of required training and limited public awareness. These results are consistent with those of Emilia et al. (2015) and Patwary et al. (2011), who observed governance and institutional inadequacy as key issues posing threats to sustainable management of medical waste in Africa and South Asia. Even where policies are in place, as in India and Bangladesh, poor enforcement and low funding are impeding work.

High cost, threats to occupational safety and poor enforcement were identified as key challenges suggested by stakeholders, similar to what has been observed in existing studies (Caniato et al., 2015; Manga et al., 2011). The complaints about the shortage of PPE by waste handlers and injuries with sharps agree with proven occupational risks encountered by frontline workers, especially in health systems that lack resources. The focus on subsidization and centralized facilities as solutions parallels prior studies' advocacy for pooling resources and shared infrastructure to rein in costs and better guarantee access to safer technologies (Kumar et al., 2020). The amount of medical waste produced during the COVID-19 pandemic was higher than pre-pandemic and a large proportion of medical waste was generated in LMICs with poor infrastructure which led to open burning or uncontrolled dumping. These findings also resonated across the globe as waste surge threatened extant infrastructures (Klemeš et al., 2020). The wealthier countries have leveraged mobile autoclaves and central hubs and that has allowed for a better resiliency.

Comparison on the effects of sustainable and unsustainable actions indicated that sustainable measures could significantly reduce population's risk of infection, total environment loadings, as well as classic economic costs, but caused an increase in system robustness. This is in line with earlier findings (Blenkharn, 2009) and underscores hidden public health as well as environmental burden by non-benevolent measures. Most importantly, this research presents a model to transfer these results into practical decisions and provides policy and implementation guidance. The articulated framework in this study, that is the nexus of technology, governance (including circular economy and resilience), fills some gaps identified from previous works, regarding both the technical dimension or institutional, while combining approaches centering on technologies, institutions and behaviors. Previous studies tended to focus on single categories, e.g., technology (George & Schillebeeckx, 2022) or governance (Caniato et al., 2015), yet very few sought to integrate them all into a comprehensive sustainability model. Accordingly, our framework brings fresh perspectives on the way in which multiple dimensions must be welded together for equally long-term sustainability and improvements in public health.

5. Conclusion

This work reveals that regulation of medical waste is important to protect public and environmental health, especially in low- and middle-income countries where practices such as open burning and unregulated dumping are still common. Comparative analysis shows effective means saving lives and giving to youth generations best prospects as risk reduction, environmental load reduce, inefficiency of youth time lost through non-burn such as autoclave chemical disinfection technology and circular economy with good governance. Inadequate enforcement, poor training and fiscal barriers continue to impede the effective implementation. In future, efforts should focus on developing low cost-low energy technology purpose-built for implementation and further explore tools at the digital level to monitor public-private partnering and circular innovation in enhancing system resilience in health crises. These programs will need to be developed for the ongoing retention/remediation and further advancement of safer, greener, sustainable healthcare waste management internationally.

Limitations

This study's conclusions should be considered in light of several limitations. A key constraint was the study placed more emphasis on the economic, governance, and technological aspects of waste separation and compliance than it did on the vital behavioural and cultural essentials. Moreover, because the study does not adequately account for the wide variations in funding, infrastructure, and policy enforcement across healthcare settings in low and middle-income nations, the results may not be generally applicable. Finally, this cross-sectional study is unable to evaluate the long-term efficacy of sustainable interventions.

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