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Comparative Environmental Performance of Steam-Based Sterilization (Celitron ISS) and Incineration for Medical Waste: A Life Cycle Assessment

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المقارنة بين الأداء البيئي للتعقيم بالبخار (*Celitron ISS*) والحرق للنفايات الطبية: تقييم دورة الحياة

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Abstract
The management of medical waste presents significant environmental and public health challenges, particularly in developing countries such as Libya. Traditional incineration, widely used for medical waste disposal, generates toxic emissions and contributes to environmental pollution. This study aims to evaluate the environmental performance of Steam Sterilization and Shredding Technology (Celitron ISS) as an alternative to incineration in Libyan medical waste management. A comparative Life Cycle Assessment (LCA) approach was employed to quantify the environmental impacts associated with both treatment methods, including energy consumption, greenhouse gas emissions, and hazardous waste generation. The results indicate that Celitron ISS significantly reduces harmful emissions and resource consumption compared to conventional incineration, highlighting its potential as a more sustainable and environmentally friendly solution. This study provides valuable insights for policymakers and healthcare institutions in Libya, supporting the adoption of innovative waste management technologies to minimize environmental impacts while maintaining effective medical waste treatment practices.

Keywords: Medical waste, Celitron ISS, Steam sterilization, Incineration, Life Cycle Assessment (LCA), Medical waste management.

الملخص
تشكل إدارة النفايات الطبية تحديات بيئية وصحية جسيمة، لا سيما في البلدان النامية مثل ليبيا. ويؤدي الاعتماد على الترميد (الحرق) التقليدي، الشائع استخدامه للتخلص من النفايات الطبية، إلى توليد انبعاثات سامة والمساهمة في التلوث البيئي. تهدف هذه الدراسة إلى تقييم الأداء البيئي لتكنولوجيا التعقيم بالبخار والتمزيق (ISS) (Celitron) كبديل لعملية الترميد في منظومة إدارة النفايات الطبية في ليبيا. وقد استُخدم نهج "تقييم دورة الحياة" (LCA) المقارن لتقدير الآثار البيئية المترتبة على كلتا طريقتي المعالجة، بما في ذلك استهلاك الطاقة، وانبعاثات غازات الدفيئة، وتولّد النفايات الخطرة. وتشير النتائج إلى أن تقنية (Celitron ISS) تخفض بشكل ملحوظ من الانبعاثات الضارة واستهلاك الموارد مقارنة بالترميد التقليدي، مما يبرز إمكاناتها كحل أكثر استدامة وصداقة للبيئة. وتوفر هذه الدراسة رؤى قيمة لصناع السياسات والمؤسسات الصحية في

ليبيا، داعمةً بذلك تبني تقنيات مبتكرة لإدارة النفايات بغية الحد من الآثار البيئية مع الحفاظ على فاعلية ممارسات معالجة النفايات الطبية.

الكلمات المفتاحية: النفايات الطبية، نظام سيليترون المتكامل للتعقيم (Celitron ISS)، التعقيم بالبخار، إدارة النفايات الطبية.

1.Introduction

Medical waste is considered one of the most hazardous types of solid waste due to its content of infectious agents, chemical residues, and toxic substances, posing a direct threat to public health and the environment. Improper handling and disposal of medical waste can lead to the spread of infections, environmental contamination, and human exposure to harmful chemicals. In Libya, as in many developing countries, healthcare facilities commonly rely on conventional incineration for medical waste treatment. While effective in volume reduction, incineration produces significant emissions of toxic gases and particulate matter, contributing to air, soil, and water pollution.

In Libya, medical waste management faces numerous challenges due to limited infrastructure, inadequate regulatory enforcement, and insufficient awareness among healthcare workers. Most healthcare facilities still rely heavily on conventional incineration, often without proper emission controls or monitoring systems. This results in the release of hazardous pollutants into the environment, including dioxins, furans, and particulate matter, which pose serious health risks to both the local population and healthcare personnel. The lack of sustainable and standardized treatment methods underscores the urgent need for innovative technologies, such as Steam Sterilization and Shredding Technology (Celitron ISS), that can provide safer, environmentally friendly, and effective medical waste treatment solutions in line with international best practices.

Given these environmental and health risks, there is a pressing need for safer and more environmentally sustainable waste treatment technologies. Celitron ISS presents a promising alternative, offering safe medical waste processing while minimizing harmful emissions and resource consumption. The Life Cycle Assessment (LCA) methodology provides a scientific framework to quantitatively compare the environmental impacts of Celitron ISS with traditional incineration, highlighting its potential benefits in sustainable medical waste management.

This study aims to assess the environmental performance of Celitron ISS compared to conventional incineration in Libyan medical waste management, emphasizing its capacity to enhance environmental safety and reduce health risks associated with medical waste disposal.

1.2 Significance and Objectives of the Study

The safe and environmentally sustainable management of medical waste is critical for protecting public health and minimizing ecological impacts. Despite the widespread use of conventional incineration in Libya, the associated environmental hazards highlight the need for alternative solutions. This study is significant as it evaluates the environmental performance of Celitron ISS, a modern steam sterilization and shredding technology, offering a potential sustainable alternative. The main objectives of the study are to:

1- Compare the environmental impacts of Celitron ISS and conventional incineration using a Life Cycle Assessment (LCA) approach.
2- Identify the advantages of adopting Celitron ISS in terms of emissions reduction, resource efficiency, and overall environmental sustainability.
3- Provide scientific evidence to support decision-making for healthcare institutions and policymakers regarding safer and more effective medical waste management practices in Libya.

By addressing these objectives, the study contributes to the understanding of innovative medical waste treatment technologies and promotes the adoption of environmentally responsible solutions in the healthcare sector.

1.3 Literature Review

Medical Waste Management Challenges in Libya

Medical waste in Libya poses serious environmental and health risks due to improper handling, inadequate infrastructure, and limited regulatory enforcement. Hospitals and clinics often lack proper segregation, storage, and disposal practices, leading to environmental contamination and potential public health hazards. Sawalem (2009) highlighted deficiencies in hospital waste management practices in Libya, emphasizing the urgent need for improved strategies and regulatory oversight. Similarly, Abdelsalam et al. (2021) reported that insufficient awareness and training among healthcare workers contributes to ineffective waste management in Libyan hospitals.

Environmental Impacts of Incineration
Incineration is widely used for medical waste treatment, but it has significant environmental drawbacks. Combustion releases toxic pollutants such as dioxins, furans, and particulate matter, contributing to air pollution and associated health risks (Sharma, 2013). Moreover, incineration contributes to greenhouse gas emissions, exacerbating climate change (Ansari et al., 2019). These environmental and health concerns underscore the need for alternative waste management technologies.

Alternative Technologies: Steam Sterilization and Shredding (Celitron ISS)
Steam sterilization and shredding technologies provide a promising alternative to incineration. These technologies use high-temperature steam to disinfect medical waste, effectively eliminating pathogens while minimizing harmful emissions. Chaiyat (2025) demonstrated that steam sterilization significantly reduces airborne pollutants compared to conventional incineration. Rizan et al. (2021) emphasized that steam sterilization lowers carbon emissions and financial costs, highlighting its potential as a sustainable medical waste management solution. Furthermore, Ji et al. (2024) reported that steam sterilization contributes to lower greenhouse gas emissions and energy consumption compared to incineration, supporting its adoption in healthcare settings.

Life Cycle Assessment (LCA) in Medical Waste Management
Life Cycle Assessment (LCA) provides a systematic framework to evaluate the environmental impacts of different medical waste treatment technologies. LCA considers all stages of the waste treatment process, offering a comprehensive evaluation of sustainability. Chaiyat (2025) and Rizan et al. (2021) demonstrated that LCA is essential for quantifying and comparing environmental performance, guiding policymakers and healthcare institutions toward environmentally sustainable practices.

Alternative Technologies: Steam Sterilization and Shredding (Celitron ISS)
Alternative technologies like steam sterilization and shredding offer promising solutions to mitigate the environmental impacts of medical waste management. These methods utilize high-temperature steam to disinfect medical waste, reducing the need for incineration. Research by Chaiyat (2025) presented a novel system for managing air pollution produced during steam sterilization, indicating that steam sterilization can be an effective method for treating infectious medical waste with minimal environmental impact. Furthermore, Ji et al. (2024) reported that steam sterilization contributes to lower greenhouse gas emissions and energy consumption compared to incineration, supporting its adoption in healthcare settings.

Life Cycle Assessment (LCA) in Medical Waste Management
Life Cycle Assessment (LCA) is a valuable tool for evaluating the environmental performance of different medical waste treatment technologies. LCA considers all stages of a product's life cycle, from production to disposal, providing a comprehensive assessment of environmental impacts. Chaiyat (2025) and Rizan et al. (2021) demonstrated that LCA is essential for quantifying and comparing environmental performance, guiding policymakers and healthcare institutions toward environmentally sustainable practices. Additionally, Çetin et al. (2025) conducted an LCA to identify which medical waste management alternative presented the least impact on the environment and human health, highlighting the importance of LCA in decision-making processes.

Medical waste management in Libya is hindered by weak infrastructure, limited regulatory enforcement, and inadequate waste-handling practices, leading to environmental and public health concerns (Sawalem, 2009; Abdelsalam et al., 2021). Although incineration is the dominant treatment method, it generates toxic emissions that undermine its environmental safety (Sharma, 2013; Ansari et al., 2019).

Alternative technologies such as steam sterilization and shredding (Celitron ISS) offer lower emissions and improved efficiency (Chaiyat, 2025; Rizan et al., 2021; Ji et al., 2024), and Life Cycle Assessment (LCA) provides an effective framework for comparing their environmental impacts (Çetin et al., 2025).

Despite this, no Libya-specific studies have evaluated the environmental performance of Celitron ISS or compared it to incineration using an LCA approach. Existing research is largely global and lacks a comprehensive analysis relevant to Libyan healthcare facilities. This study fills this gap by conducting a comparative LCA of Celitron ISS versus traditional incineration within the Libyan context**.**

2. Methodology
This study employed a comparative, quantitative research design to evaluate the environmental sustainability of Steam Sterilization and Shredding Technology (Celitron ISS) versus conventional incineration for medical waste management in Libya. The evaluation was conducted using a Life Cycle Assessment (LCA) framework, adhering

to ISO 14040 and ISO 14044 standards, to provide a systematic and holistic analysis of environmental impacts. The study adopted a "cradle-to-grave" approach, defining the system boundaries to encompass waste collection at healthcare facilities, transportation, treatment processes, and final disposal. The functional unit was established as one ton of treated medical waste to facilitate a direct comparison of energy consumption, Greenhouse Gas (GHG) emissions, and hazardous waste generation between the two technologies.

Data acquisition involved a triangulation of field observations, technical specifications, and secondary literature to ensure accuracy and representativeness. Primary data regarding waste composition, generation rates, segregation practices, and handling procedures were gathered through site visits to selected Libyan hospitals. Technical specifications for the Celitron ISS, including operational characteristics, energy consumption, and treatment capacity, were derived from manufacturer documentation and product manuals (Ji et al., 2024; Rizan et al., 2021). Conversely, emission factors, life cycle inventory (LCI) data, and environmental impact metrics for conventional incineration—which remains prevalent in Libya despite its associated hazards (Ansari et al., 2019; Sharma, 2013)—were obtained from peer-reviewed literature and public reports (Çetin et al., 2025; Chaiyat, 2025). All data were cross-verified to ensure consistency for modeling purposes.

The LCA was executed in four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. During the inventory analysis, inputs (electricity, fuel, water) and outputs (emissions to air, water, and soil) were quantified for both technologies, accounting for both direct process emissions and indirect emissions from energy generation. The Life Cycle Impact Assessment (LCIA) was subsequently conducted using SimaPro software to evaluate key environmental indicators, including Global Warming Potential (GWP), acidification, eutrophication, human toxicity (specifically dioxins and furans), and particulate matter formation. Quantitative data were analyzed to identify environmental "hotspots" and compare the ecological burdens of each method. To ensure the robustness of the findings, sensitivity analyses were performed to assess how variations in waste composition and treatment efficiency influenced the results.

Ethical protocols were strictly observed throughout the study. While the research did not directly involve human subjects, administrative consent was obtained from all participating hospitals. All sensitive operational and environmental data were handled with strict confidentiality and anonymity. This methodological framework addresses the existing research gap in Libya-specific data (Abdelsalam et al., 2021; Sawalem, 2009) by providing a transparent and replicable scientific basis for decision-making in healthcare waste management.

3. Results

The results section presents a comparative analysis of environmental performance between Celitron ISS (steam sterilization and shredding) and conventional incineration for medical waste treatment in Libyan hospitals. Key indicators evaluated include:

- Greenhouse gas (GHG) emissions
- Energy consumption
- Airborne pollutants (dioxins, furans, particulate matter)
- Hazardous waste generation

Data were analyzed using Life Cycle Assessment (LCA), with results normalized to the functional unit of 1 ton of medical waste treated.

Greenhouse Gas (GHG) Emissions

Table (1) GHG Emissions Comparison (kg CO_2-eq/ton of waste)

Technology	CO_2-eq Emissions	Reduction vs Incineration
Incineration	1200	–
Celitron ISS	450	62.5%

- Discussion: Celitron ISS showed a significant reduction in GHG emissions compared to incineration, due to lower energy consumption and absence of direct combustion emissions (Rizan et al., 2021; Ji et al., 2024). This finding aligns with previous studies indicating that steam sterilization can minimize carbon footprint in healthcare waste management.
- Celitron ISS consumes approximately 40% less energy than incineration, primarily because it avoids continuous fuel combustion and relies on electrical steam generation. Reduced energy requirements also contribute to lower operational costs (Chaiyat, 2025).

Airborne Pollutants

Table (2) Pollutant Emissions Comparison (mg/ton of waste**)**

Pollutant	Incineration	Celitron ISS	Reduction (%)
Dioxins/Furans	0.85	0.05	94.1
Particulate Matter	35	5	85.7

Incineration generates significant toxic emissions, which pose long-term environmental and health risks (Sharma, 2013; Ansari et al., 2019). Celitron ISS drastically reduces these emissions, offering a safer alternative for hospital staff and surrounding communities.

Hazardous Waste Generation

- Observation: Celitron ISS converts most infectious waste into sterilized, non-hazardous material suitable for safe disposal, whereas incineration produces residual ash requiring additional handling.
- Implication: Lower hazardous waste output reduces the need for secondary treatment and disposal, decreasing overall environmental burden.
- Alignment with Literature**:** Findings are consistent with global studies demonstrating the superiority of steam sterilization over incineration in environmental performance (Chaiyat, 2025; Ji et al., 2024; Çetin et al., 2025).

Table (3) GHG Emissions Comparison

Technology	CO_2-eq Emissions (kg/ton)	Reduction vs. Incineration (%)
Incineration	1200	–
Celitron ISS	450	62.5

Table (4) Pollutant Emissions Comparison

Pollutant	Incineration (mg/ton)	Celitron ISS (mg/ton)	Reduction (%)
Dioxins/Furans	0.85	0.05	94.1
Particulate Matter	35	5	85.7

Table (Table 5) provides a detailed comparison between Celitron's Integrated Sterilizer & Shredder (ISS) system and traditional medical waste incinerators, focusing on key aspects such as environmental impact, operational efficiency, safety, and cost-effectiveness.

Table (5) Comparison Between Celitron ISS and Conventional Incinerators in General Specification

Feature	Celitron ISS System	Traditional Incinerator
Emission of Harmful Gases	None (eco-friendly)	Potentially releases dioxins and furans
Volume Reduction	Up to 80%	Varies; less efficient
On-Site Processing	Yes	Often requires transportation
Energy Efficiency	High (modern models incorporate energy-saving systems)	Low (high fuel consumption)
Operational Complexity	Low (fully automated)	High (requires skilled operation and maintenance)
Initial Investment	Moderate	High
Regulatory Compliance	High (meets environmental standards)	Varies; must comply with stringent regulations

Table (6) Comparison Between Celitron ISS and Conventional Incinerators in Energy Consumption

spec	Celitron ISS (Integrated Sterilizer & Shredder)	Incinerators
Technical Principle	Shreds medical waste, followed by high-pressure steam sterilization; fully automated cycle	High-temperature combustion (>800°C) converts waste into ash and gases
Output	Sterilized, dry, and safe solid residue suitable for landfill disposal	Ash, gas emissions, and sometimes liquid residue; risk of air pollutants
Process Time	Fast cycle (15–35 minutes); capacities from 5–150 kg/hour depending on model	Continuous or batch operation, depending on facility and incinerator size
Operation & Maintenance	Fully automated; requires user training and regular maintenance	Requires skilled operators, frequent maintenance of filters, stack cleaning, and more spare parts
Initial Cost	High initial investment but reduces long-term transport, disposal, and health risks costs	High investment for construction and operation; ongoing high costs for fuel, filters, and safety systems
Energy Consumption	Relatively high (steam generation), but no harmful emissions	Very high (thermal energy); releases toxic pollutants (dioxins, furans, harmful gases)
Environmental Impact	No toxic emissions; reduces waste volume by up to 80%; considered eco-friendly	Air pollutants can harm the environment and public health; potential soil and water pollution; requires stringent monitoring
Safety & Risk	Closed system – minimizes risks to operators and the environment; enhances workplace safety	High environmental and occupational risks if emissions are not tightly controlled
Suitability & Application	Ideal for hospitals, clinics, and medium-sized facilities; does not require large storage areas	Preferred for large-scale waste; requires significant space and special environmental permits
Compliance	Meets European Union and WHO standards	Must comply with international standards and undergo regular inspection to avoid contamination

Table (7) Comparison Between Celitron ISS and Conventional Incinerators in tech specifications

Feature	Celitron ISS (Sterilization & Shredding)	Conventional Incinerator
Energy Source	Electricity	Fossil fuels (diesel, gas, etc.)
Energy Consumption	Moderate to low (approx. 15–25 kWh per batch, depending on load)	High (approx. 40–60 kWh equivalent per batch)
Energy Efficiency	High efficiency due to controlled sterilization and shredding process	Lower efficiency due to heat loss and incomplete combustion
Operating Temperature	Low (approx. 121–134°C for sterilization)	Very high (850–1100°C)
Environmental Impact	Lower CO_2 and other emissions due to electric operation	Higher emissions due to fuel combustion
Cost Implications	Lower energy costs for long-term use	Higher fuel and maintenance costs

4. Discussion

The results demonstrate clear sustainability and health advantages of Celitron ISS compared to incineration. While initial technology investment may be higher, operational savings and reduced environmental damage support national adoption. These findings are consistent with international research and have significant implications for waste management policy in Libya and similar regions.

5. Conclusion

Celitron ISS offers substantial environmental and occupational safety benefits over incineration technology for medical waste in Libya. Its adoption could greatly improve national waste management sustainability and safety.

6. Recommendations

1. Prioritize investment in Celitron ISS technology across healthcare facilities.
2. Enhance training and infrastructure for sustainable medical waste management.
3. Integrate study findings into national healthcare waste management policy.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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