# ASSESSING ENVIRONMENTAL, ECONOMIC AND SOCIAL IMPACTS OF HEALTHCARE WASTE MANAGEMENT SYSTEMS: A CASE STUDY OF ULAANBAATAR, MONGOLIA

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ABSTRACT

The effective management of bio-hazardous solid healthcare waste, ensuring the protection of human health, environmental integrity and economic feasibility, remains a pressing issue of considerable relevance worldwide. In Mongolia, the treatment technologies and disposal practices of bio-hazardous waste have never previously been subjected to an impact assessment published in academic literature. The analysis of the emissions, costs and social impacts of this sector becomes crucial when considering the capital city of Ulaanbaatar, where air pollution, elevated population density and urban growth are central aspects. This paper aims to answer the following two questions: How can the impacts of the healthcare waste sector be assessed and quantified? And why is it important to do so? The paper reviews similar case studies to explore the methodologies that can be implemented to estimate the environmental, economic and social impacts of bio-hazardous healthcare waste management systems. The study then presents the methodologies applied to the Ulaanbaatar case study to conduct a life cycle sustainability assessment, evaluating the impacts of on-site treatment technologies for bio-hazardous healthcare waste installed in several hospitals in the capital city through an international cooperation project. The benefits and limitations of applying these methodologies to the case study are discussed. The paper remarks on the importance of conducting impact analyses for sustainable development. These analyses will provide decision-makers with quantitative and qualitative indicators from many stakeholders and experts, helping them to make efficient investments. Comments on the importance of integrating life cycle approaches with local environmental impact studies complete the work.

*Keywords: bio-hazardous waste, hospital waste, impact assessment, LCA, LCC, LCSA, medical waste, Mongolia, SLCA, sustainability.*

## 1 INTRODUCTION

Ensuring the environmental, economic and social sustainability of healthcare waste management (HCWM) systems remains an open challenge for many healthcare facilities (HCFs) worldwide [1]. HCWM is a complex topic that encompasses many technical procedures, but also adequate regulatory frameworks, effective implementation of strategies, clinical governance, responsibilities among public and private stakeholders and funding [2]. The rapid expansion of the healthcare sector to control diseases and treat patients has led to increased waste generation, alongside a rise in global per capita health spending of over 60% between 2000 and 2022, exceeding gross domestic product (GDP) growth [3]. Nonetheless, disparities are observed across income groups of countries and funding sources, exacerbating inequalities between high-income and low-income countries [4]. The majority of low- and middle-income countries encounter a combination of impediments to effectively manage healthcare waste (HCW), especially in the implementation of the legislation [5], [6], inadequate knowledge, attitude and practice among medical waste management personnel



WIT Transactions on Ecology and the Environment, Vol 267
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www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/EID260351

[7], [8], acceptance and finance of advanced technologies [9]. In particular, the bio-hazardous solid fraction of the HCW requires special management procedures due to its hazardous nature. Around the 15% of the HCW is regarded as bio-hazardous and mainly classified in the categories of sharps, infectious, pathological (or anatomical), pharmaceutical, chemical and radioactive waste [10]. Incineration and sanitary landfills are the most common process for bio-hazardous or biomedical solid waste management (BSWM) worldwide [11], [12]. The valorisation of biomedical solid waste (BSW) remains underexplored research field so far and most studies are mostly focusing on energy recovery from their combustion [13].

Identifying the best solution in the complex field of waste management by considering a holistic view of the potential impacts on the three pillars of sustainability may be challenging.

The sustainable development was first defined as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs [14]. An answer to questions on sustainability requires normative elements, such as trade-offs between economy and environment, and aspects of inter- and intra-generational equity [15]. When considering products, services and organizations' sustainability, a life cycle perspective (from extraction of raw material to end of life) brings powerful insights. This includes highlighting potential transfer of impacts among impact types, steps of the life cycle or stakeholder groups. It aims to provide increased knowledge on the 3Ps – three-pillar approach of sustainable development: people, planet, and profit [16]. As will be explored in Section 2, numerous life cycle assessments (LCA) have been conducted in the field of HCWM to assess the environmental impacts with diverse scopes and aims. Life cycle costing (LCC) and other cost analysis techniques have been commonly associated with LCA in order to understand whether enhanced environmental performance is also economically sustainable.

HCW has medical, sanitary, environmental, economic, logistic, cultural and financial implications, and the trade-offs between different factors act differently in different parts of the world [17]. For example, in the Binzhou District in China, specific HCW-related regulations were adopted after an outbreak of SARS (severe acute respiratory syndrome) [18]. In Ulaanbaatar, there is limited information in the existing literature regarding the status of HCWM [19]. The production and characterisation of HCW have been analysed in a paper published prior to the COVID-19 pandemic [20], therefore not reliable because of the increase of BSW registered worldwide [21]. According to the World Health Organization, in Mongolia, the Basel, Stockholm and Minamata Conventions have been ratified, a national legislation on BSWM exists, but limited description or guidance is provided in the technical guidelines concerning treatment and disposal of HCW [22]. Mongolia has undergone a significant economic transformation, shifting from an agriculture-based economy to one largely driven by mineral resources [23]. In recent years, air pollution has worsened considerably especially in the capital city of Ulaanbaatar, placing growing pressure on the country's already fragile environment [24], [25]. With a population density of 376.2 people per $km^2$, against the national population density of 2.3 people per $km^2$ [26], the rapid urbanisation in Ulaanbaatar is linked to several negative impacts. Numerous factors affect high levels of pollution, such as the population, overall vehicle numbers, industrial activity, number of power plants, metrological conditions and GDP output [27]. The cold climate worsens the problem as more coal is burned for heat and more frequent temperature inversions occur to limit atmospheric dispersion of pollutants [28]. On 29 December 2024, Ulaanbaatar, with a hazardous air quality index of 427, ranked 1st among 122 major global cities, and remained 11th even on 9 April 2025, well outside the heating season [29].

The paper reviews similar case studies to explore the methodologies that have been implemented in literature to estimate the environmental, economic and social impacts of


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BSWM systems. Particularly, the review aims to answer the following two questions: How can the impacts of the HCWM sector be assessed and quantified? And why is it important to do so? The study then presents the methodologies applied to the Ulaanbaatar case study to conduct a life cycle sustainability assessment (LCSA), evaluating the impacts of on-site treatment technologies for BSW installed in several hospitals in the capital city through an international cooperation project. The benefits and limitations of applying these methodologies to the case study are discussed, stressing on the importance of integrating Life Cycle approaches with local environmental impact studies. Finally, the paper remarks on the importance of conducting impact analyses for sustainable development, providing decision-makers with quantitative and qualitative indicators in order to make efficient investments.

## 2 LITERATURE REVIEW

Protecting the health of staff, patients, and the community, but also the environment, is the fundamental reason for implementing a system of safe waste management. The dominant HCW research themes have been identified and grouped in four areas by Ranjbari et al. [30], namely (i) HCW minimization, sustainable management and policy-making, (ii) incineration and environmental impacts, (iii) BSWM practices, and (iv) HCW handling, occupational safety and training. Many different criticalities can emerge during the entire waste chain: absence of HCW minimization, poor waste sorting, lack of structured management plans, equipment or training for workers, unsafe handling, polluting treatment technologies, unproper waste disposal [31]. Several studies have highlighted environmental measures for resource use minimization and HCW reduction, but few studies have used a holistic approach that includes the political, organizational and individual attempts toward sustainable waste management [32]. The methodologies to assess the different criticalities emerged in literature are many, both qualitative and quantitative. The number of HCW audits shows a general methodologic inconsistency: for example, in low-income contexts there is a greater propensity to utilise indirect methods to obtain data (i.e. interviews, questionnaires or surveys) in comparison to higher-income countries, where direct measurement necessitates greater effort, personnel and time [33]. Cross-sectional studies are widely used to assess HCWM practices and associated factors among healthcare workers inside hospitals [34]. Other studies provide guidelines for evaluating and assessing the quality of resources and waste management in HCFs, thereby enabling the principles of sustainable development to be addressed [35].

Many technical tools or quantitative methodologies exist to guide the choice of treatment solutions: manuals, as the overview of technologies for the treatment of infectious and sharp waste from health care facilities [36], combining multi-criteria decision making (MCDM) approaches to find the most appropriate solution from a technical, environmental, economic and social point of view [37], or from a multiple stakeholder perspective [38], or limited to expert decision-making employing the fuzzy-rough approach [39]. A recent review classified 101 papers using multi-criteria decision making analysis (MCDMA) into six groups: (a) selection of the most effective HCW treatment technology (59% of the papers considered), (b) identification of the best HCW disposal site, (c) assessment of the best-performing healthcare unit adopting ideal HCWM strategies, (d) selection of third party logistics providers, (e) identification of HCWM barriers and (f) evaluation of specific HCWM plans [40]. Among the many techniques used for MCDMA, the Analytic Hierarchy Process has been mostly preferred for solving HCWM problems, followed by Technique for Order Performance by Similarity to Ideal Solution (TOPSIS). MCDM methods have been developed to support the decision maker in their unique and personal decision process. Among the many different developed techniques, the fundamental idea of TOPSIS is that the


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best solution is the one which has the shortest distance to the ideal solution and the furthest distance from the anti-ideal solution [41].

### 2.1 Life cycle approaches in HCWM sector

LCA is a science-based methodology used to evaluate the environmental impact associated with a product or service considering cradle-to-grave approach, meaning the consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal [42]. The pandemic has led to an abrupt collapse of waste management chains, thus the application of LCA in waste management is crucial to prevent long-term risks [43]. Hospitals can have different motivations for carrying out LCA such as to measure the benefits in reusable dispositive instead of single-use ones, to classify and reduce their environmental impacts [44]. LCA has been widely used also as an effective decision-support tool by systematically comparing incineration and non-incineration treatments techniques [45], [46]. LCC is a technique that assesses costs over the life cycle of a product or a system [47]. LCA-coupled LCC is widely applied in eco-design, product improvement, decision-making and policy formulation. The LCC method has been used, for instance, to assess the economic impact caused by LCA comparing three commonly used disposal technologies in China, namely, pyrolysis, chemical disinfection and steam sterilization. Internal (i.e., company actual cost) and external cost (i.e., external market price on environmental emissions, human health protection, and land eco-remediation cost) were assessed [48]. The cost evaluation of each scenario through an LCC was associated with the functional unit (FU) of the LCA also in a study to evaluate the performance of different HCWM scenarios for small generators involving microwaving, autoclave, and lime disinfection [49].

A Scopus review using the keywords "healthcare waste" OR "medical waste" OR "hospital waste" OR "biomedical waste" AND "social life cycle assessment" OR "SLCA" returned only a single paper. The same review without "social" and "LCA" instead of "SLCA" returned 155 results. In the 1960s social indicators (SIs) were positioned as tools to measure social impact and gain more prominence to economic indicators [50], [51]. In the early 1990s, members of the LCA research community raised the importance of and an interest in assessing the social dimension of sustainability [52]. However, it was not until 2009 that first international ‘Guidelines for SLCA of Products’ was published jointly by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC). The social life cycle assessment (SLCA) is a methodology to evaluate the social and socio-economic aspects of products and services, assessing the potential and actual positive or negative impacts along their life cycle [53]. Subsequent researchers and practitioners have utilised these guidelines to evaluate the positive and negative social and socio-economic impacts of products over their lifecycle, and in 2020 the new ‘Guidelines for SLCA of Products and Organizations’ do not dictate one path but rather explain the strengths and challenges of different approaches to solve multiple questions [16]. Despite the critical role of the health sector and related stakeholders in ensuring the social sustainability of society, the current number of SLCA studies conducted in the HCW sector is critically low. A SLCA of two infectious HCWM supply chains has been conducted in Latvia, analysing a University Hospital pursuing treatment in a large-scale thermal plant and landfilling and a Regional Hospital pursuing treatment in a large-scale chemical plant followed by the use of the disinfected HCW as RDF in an energy generation plant [54].


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The need for a perspective that was wider than LCA was formalised into the LCSA framework. Presently, there are two main ways of conducting an LCSA: leading separate impact studies, each one addressing one of the three sustainability pillars (LCSA = LCA + LCC + SLCA), or conducting a single study on all these aspects [55]. A review on LCSA of municipal solid waste management systems showed that, among the analysed papers, 90% include environmental indicators and impact categories, 87% deal with the economic aspect of sustainability, and only 67% deal with the social impact [56].

## 3 ULAANBAATAR CASE STUDY

### 3.1 Study area

Over the past five decades, Ulaanbaatar has experienced steady population growth, which has driven rapid urban development [57]. It is the most populated city of Mongolia with more than 1.6 million inhabitants, which accounts for 48.7% of the total population of the country, with around 50% of these residents living in the so-called ger areas [58]. These are peri-urban districts relatively impoverished, lacking basic infrastructure such as tap water or central heating, where the city's population live in traditional dwellings called gers. The highest pollution levels are registered in the ger districts [59]. Due to the formation of unstructured urbanization of residential areas, pollution from pit latrines poses a risk to the urban environment and human health by infiltrating shallow water, being carried by floodwaters, and being released into the soil and the air [60]. In the 36th khoroo, Songinokhairkhan district, houses and gers are in close proximity to the municipal landfill. The landfill site lacks the requisite soil protection system, as well as leachate and biogas collection systems. The only form of protection is the daily covering of a 10 cm layer of soil. The district hosts also the plants where the BSW coming from the majority of the city's HCFs is treated. The treatment facilities are managed by Element Medical (EM) LCC, a company providing to HCFs the service of collection, transport, treatment and final disposal in landfill of BSW. In 2023, UNICEF Mongolia and the Mongolian Ministry of Health launched the project 'Medical Waste Treatment Equipment for Health Facilities in Mongolia' with the objective of 'using technical assistance through supplying the necessary equipment required for HCWM'. In particular, three electric sterilisers based on frictional heat treatment (FHT) produced by Newster Group™ (NW) have been installed in three hospitals in Ulaanbaatar, including the National Centre for Maternal and Child Health (NCMCH). Our study focuses on the comparison of impacts related to the two BSWM scenarios possible for the NCMCH: the EM off-site management scenario (BSW production and segregation at NCMCH, collection and transport by EM to their treatment facilities, incineration for anatomical waste, autoclave + shredding for infectious and sharps, transport to landfill) and the on-site management scenario in the hospital (BSW production and segregation at NCMCH, FHT sterilisation at the hospital, transport to landfill). The two scenarios analysed are detailed in [61]. The FU is the daily average production of BSW at the NCMCH.

### 3.2 LCSA for HCWM in Ulaanbaatar: The NCMCH case study

The approach we selected for the LCSA is the first presented by Kloepffer [55], namely the conduction of three separate LCA to evaluate environmental, economic and social impacts of the two management systems.

The LCA combines data from structured interviews and formal data request from the NCMCH, EM and NW with literature and databases. The LCA followed the ISO 14040/44,


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and environmental impacts were assessed using the ReCiPe 2016 method (hierarchical perspective) in SimaPro, based on Ecoinvent v3.9.1 data. The ReCiPe 2016 method was selected because of its global-scale characterization factors [62]. Eighteen midpoint impact categories have been assessed. Endpoint results were also calculated to estimate damages to human health, ecosystems, and resources, expressed in eco-indicator points (Pt). Despite the higher uncertainty associated with single scores, they support the comparison of alternatives and facilitate communication and integration with economic and SIs [63], [64].

A simplified cost assessment (CA) of the LCA flows was conducted due to data limitations and the project's scope, excluding revenues from HCWM. Costs were linked to the FU and LCA processes and grouped into operating (OPEX), capital (CAPEX), and environmental costs (ECs) [65]. OPEX and CAPEX were collected for each management process and expressed per kilogram of BSW, then scaled to the FU. CAPEX were annualised through linear depreciation over the equipment lifetime [66]. ECs were estimated by applying environmental price factors to the midpoint LCA results [67], [68].

The S-LCA was conducted following the reference scale approach of the UNEP S-LCA guidelines [16]. Stakeholder mapping was initially supported by a panel of 18 experts from academia, non-government organisations, hospitals, and the private HCWM sector, who identified the most relevant stakeholder groups and the corresponding impact categories and subcategories. Based on these results, specific questionnaires were developed for each stakeholder group and administered through short face-to-face interviews to assess the selected subcategories. In parallel, a questionnaire was distributed to the experts to evaluate their perception of stakeholders' social risks. Responses were converted into numerical scores using an ascending reference scale ranging from −2 (very negative performance) to +2 (very positive performance) [69]. Scores were then aggregated and weighted by dividing the sum of scores for each social theme by the number of responses received [70]. Two social impact matrices were subsequently developed: one based on local stakeholder responses and the other on expert evaluations.

For each assessment, some indicators have been selected for the MCDMA using the TOPSIS method. Particularly, the analysis includes a maximum of five indicators from the LCA, a maximum of five indicators from the SLCA and the three indicators from the CA.

## 4 DISCUSSION AND CONCLUSIONS

The choice of installing a modern treatment technology, whose emissions are in line with the Stockholm Convention's BAT/BEP guidelines as the FHT steriliser in a fragile context as Ulaanbaatar, follows the principles of sustainable development. Nevertheless, the transition towards sustainable HCWM requires significant financial investments and the sustainability of the project needs to be assessed and implemented locally. The objective of an LCSA assessment in this sense is dual. Firstly, the process enables the identification and quantification of negative and positive impacts of the current HCWM system and of the alternative one proposed by the project. Secondly, the generation of indicators is proposed as a means of guiding decision-makers in selecting the most suitable system for their context, integrating the local stakeholders' opinions and the visions of sustainable development projects.

The main limitations for the implementation of the study are many. First, due to data scarcity, the systems' boundaries resulted in a limited gate-to-gate approach, excluding the HCW sorting and production phases as well as the production of the treatment plants and their import. Second, even after limiting the study, lack of data and/or transparency have been noticed, especially regarding the consumptions or the costs of the processes. For example, the average water consumption for the autoclave and its average cost of annual maintenance


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were not known, resulting in possible inaccuracies linked to our estimation of the data based on literature. Difficulties have been found in reaching high numbers of interviews for the SLCA, both in the local stakeholders' case and in the international experts' case. As for the methodologies, the main limitations are:

- the lack of data referred to Mongolia in Ecoinvent database for the LCA, where the majority of the input/output process have been selected among 'rest of the world';
- the environmental prices we use in the CA refer to European context. This two first limitations underline the need of further local studies related to environmental impacts;
- the possibility of excluding some local important social hotspot when following the UNEP-SETAC guidelines;
- the selection of the indicators to be considered for the TOPSIS method, i.e. limiting the 18 midpoint categories to a maximum of five, therefore losing some information or risking including some subjective bias;
- LCSA has the potential to become a useful tool for the evaluation of circular economy solutions applied to waste management [71], [72] but scholars also evidence that sustainability assessments need further studies to be evaluated in a coherent and integrated way, instead of as the combination of separate studies on the environmental, economic and social burdens [56].

In conclusion, we emphasize the importance of conducting an impact assessment and actively involving stakeholders prior to the implementation of sustainable development projects. The FHT steriliser is currently not operational for several reasons. First, the legislation on BSWM has not yet been updated to regulate this new technology. Moreover, the NCMCH administration, waste operators and EM were not included as key stakeholders in the project, which may have contributed to a lack of interest in, or trust toward, the initiative. This consideration is particularly relevant in the context of international cooperation projects for sustainable development. In this regard, we recall the concept proposed by Freeman, one of the pioneers of stakeholder theory, who argued that sustainability is a multi-dimensional construct involving all key stakeholders, as well as the environment and society at large [73]. This perspective aligns well with life-cycle approaches, which recognize that the numerous and complex local and global aspects and impacts associated with the selection of BSW treatment technologies cannot be reduced solely to emissions to air.

## ACKNOWLEDGEMENTS

Thanks to the Ministry of Health of Mongolia, UNICEF Mongolia and Newster™ Group to have shared the information about the project 'Medical Waste Treatment Equipment for Health Facilities in Mongolia'. Thanks to the National Centre for Maternal and Child Health and to Element Medical LCC for sharing data about their facilities.

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