DATA COLLECTION FOR LIFE CYCLE ASSESSMENT OF BIOMEDICAL SOLID WASTE TREATMENT AND DISPOSAL: A CASE STUDY IN ULAANBAATAR, MONGOLIA

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ABSTRACT
The safe and environmentally friendly management of healthcare waste (HCWM) is a significant concern in many low and lower-middle income countries. Despite recent and ongoing efforts to improve treatment technologies and waste disposal in Mongolia, the current HCWM system in Ulaanbaatar city still presents important margins for improvement. Currently, a private company manages the collection, transport, treatment and disposal of healthcare waste from most of the hospitals in the city through a private–public partnership. The waste is transported to a decentralised site consisting of an autoclave, an incinerator and a landfill, where some environmental concerns exist. As part of a UNICEF project, three electric sterilisers based on frictional heat technology were installed in three hospitals in Ulaanbaatar to treat biomedical waste on-site in a more sustainable way than incineration and landfill. The sterilised output material is reduced in volume by 70% and is disposed of as common waste in landfills. Our study aims to conduct a preliminary life cycle assessment (LCA) to compare the environmental impacts of the current HCWM system in Ulaanbaatar with the new on-site sterilisation. This paper aims to define the goals and scope of the LCA and the inventory analysis to understand all the input data required to conduct the LCA. The analysis is being carried out in a context of data scarcity, where only a few similar studies exist. Therefore, a combination of local data collection, literature, LCA databases and previous LCA studies on the same steriliser must be used. Further research could combine the results of the LCA with an economic and social sustainability analysis to support key stakeholders in the health and environment sectors in decision-making processes to improve the HCWM system in Ulaanbaatar.
Keywords: healthcare waste management, incineration, biomedical waste sterilisation, life cycle assessment, inventory form, sustainable development.

1 INTRODUCTION

Healthcare waste (HCW) is defined as the totality of the waste produced in every kind of healthcare facility. It is estimated that between 75% and 90% of HCW is comparable to municipal common waste, while the remaining 10–25% is classified as hazardous waste, commonly referred to as medical or biomedical solid waste (BSW) [1]. This waste may pose various environmental and health risks [2], [3]. The management of healthcare waste (HCWM) is a complex topic that encompasses not only the technical procedures but also adequate regulatory frameworks, responsibilities among public and private stakeholders, environmental, economic, and social aspects. A lack of awareness among health professionals and the general population regarding the improper handling of HCW, the absence of an effective regulatory framework and national policy, and financial strains represent the major impediments to the implementation of adequate HCWM, particularly in

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developing countries [4]–[7]. The majority of developing Asian countries encounter a combination of these impediments to effectively manage HCW, especially in the implementation of the legislation [8], [9].

Mongolia is classified as a lower middle-income country [10], with a Human Development Index value for 2022 of 0.741, which places the country in the High Human Development category and positions it at 96 out of 193 countries and territories [11]. There is a lack of consistency in the management options for HCW in Mongolia, despite the issuance of several laws and orders [12]. Furthermore, the capital city of Ulaanbaatar is subject to elevated levels of air pollution due to the wind-blown dust, coal combustion for heating buildings and traditional gers, vehicles and coal-fuel combined heat and power plants [13]. The combustion sources (coal combustion, motor vehicles, forest fires) contribute most of the fine fraction of particulate matter, particularly during the winter months, due to the heating processes [14]. The incineration of HCW and the use of obsolete treatment technologies contribute to increase air pollution. In such fragile context, UNICEF is supporting the Mongolian Ministry of Health (MoH) in the planning of sustainable and context-specific solutions for HCWM of healthcare centres countrywide. In 2023, UNICEF and the MoH started the project 'Medical Waste Treatment Equipment for Health Facilities in Mongolia' with the objective of installing 51 technologies for medical waste treatment in HCFs across the country.

The objective of this study is to compare the environmental impact of different HCWM systems. The focus is on the choice of treatment technology, as well as the on-site or off-site nature of the process (and thus the necessity of a transport step). To achieve this, an LCA methodology is applied to the Ulaanbaatar case study, comparing the current HCWM system and improved scenarios using the new treatment technologies provided by the UNICEF project. This paper is limited to the first part of the study, namely the context analysis and the preparation of the LCA study. The aim of the paper is to define the goals and scope of the LCA and the inventory analysis, collecting all the input data required to conduct the LCA. The analysis is being carried out in a context of data scarcity, where only a few similar studies exist but not applied to HCWM.

2 LITERATURE REVIEW

2.1 Life cycle assessment on HCWM

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 [15]. To standardise the methodology, ISO 14040:2006 and ISO 14044:2006 are the two main standards, respectively on principles and framework, and requirements and guidelines. There are four phases in an LCA study: the goal and scope definition, the inventory analysis, the impact assessment, and the interpretation. The present paper aims to analyse the first two phases of the LCA, namely the goal and scope definition and the inventory analysis. As for the life cycle inventory (LCI) phase it involves the collection of the data necessary to meet the goals of the defined study. This data set is a compilation of inputs and outputs related to the function or product generated by the process. Data collection and compilation are often the most work- and time-consuming steps in LCAs [16], as we will see in the present paper.

Few studies have been conducted to assess the environmental impacts related to HCWM systems. Some studies analyse the entire management chain, comparing the presence or absence of some specific phases like sorting and recycling [17] or considering different management systems [18]–[20], energy recovery [21]. Some other papers [22]–[24] analyse HCWM systems during the COVID-19 pandemic. A significant part of the LCA studies on HCW focuses on treatment technologies comparison, considering the transport phase (if present) and different techniques [25]–[27]. Papers comparing incineration and sterilisation techniques [28], [29] shows that the environmental impact of the sterilisation process remained negligible relative to the combustion process.

2.2 Treatment processes and technologies for BSW

The treatment phase, if not properly designed, could be the most crucial step as for the environmental impact. Many treatment techniques have been developed, and they can be classified in five basic processes: thermal, chemical, irradiation, biological and mechanical [1]. In the present study, we will focus on three treatment technologies: incinerator, autoclave and electric steriliser based on frictional heat technology (FHT).

Incineration is the most widely used process for the treatment of HCW because it can destroy or inactivate the waste with a significant (>90%) reduction in mass and volume [30]. Moreover, low-cost small-scale incinerators could be the most economically sustainable alternative to open burning for public hospitals in developing contexts. Nevertheless, one of the disadvantages of medical waste incineration is the emission of pollutants into the atmosphere, and incinerators without air pollution control (APC) systems represent one of the main sources of dioxins and furans [31]. Combined with the high heating value and halogenated plastics in the medical waste, the PCDD/PCDF formation potential is generally higher than for municipal solid waste [32]. Emission factors in air could be 40,000 times higher than a technological, continuous combustion with a sophisticated APC system, that can also have an emission factor in residues (bottom and fly ashes) reduced by 25%.

Many alternatives have been developed to incineration process. Among the low-heat-based processes, sterilisation of BSW can be performed using autoclaves. An autoclave consists of a metal vessel where the waste is loaded, with pipes and valves through which steam is introduced into and air is removed from the vessel. Steam is introduced into the chamber until the required pressure or temperature is reached – typically 121°C for at least 30 minutes. Additional steam is automatically fed into the chamber to maintain the temperature and pressure for a set period. A drying phase after treatment is added to protect the operator against steam when opening the door. After treatment, the waste is considered non-hazardous and can be disposed accordingly. It is common to shred the sterilised waste to reduce the volume amount. Waste treatment autoclaves must also treat the air and the resulting condensate before releasing them [33]. Waste treatment autoclave can range in size from about 20 litres to over 20,000 litres per cycle. They operate in a batch mode.

Frictional heat can also be used to sterilise BSW, and it is listed among the best available techniques [1]. The patented technology employs the heat generated by the shredding action to sterilise the waste without persistent organic pollutant emissions into the atmosphere. The machine is composed of three parts: steriliser, filter and electronic unit. Waste is loaded into a stainless-steel vessel with rotating blades at the bottom, where the treatment is carried out under negative pressure and in absence of chemicals. During the cycle, the internal rotor rotates rapidly, shredding the waste and raising the temperature to 100°C. Water turns to steam that goes through condensers and filters. When the humidity has been eliminated, the temperature starts to rise again reaching a peak of 150°C. In the last phase of the cycle a water spray cools the waste down to around 95°C. The output sterilised waste is automatically uploaded in a plastic bag. The sterile, finely ground, dry and unrecognisable residue is

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significantly reduced in weight (around 20%) and volume (around 75%) and could be disposed of as common municipal waste [31].

3 MATERIALS AND METHODS

The present study represents the first LCA on HCWM in Mongolia. This section outlines the methodology employed to develop the current state of the art and to collect data for the inventory form of the LCA. The LCA requires a substantial amount of data, and there is limited information in the existing literature regarding the status of HCWM in Ulaanbaatar. After the fieldwork for data collection, the data collected on the field were integrated with data from literature and databases provided by the software used for the LCA.

3.1 Developing the state of art

The production and characterisation of HCW in Ulaanbaatar were previously analysed in a paper published prior to the COVID-19 pandemic [34]. One of the immediate and direct consequences of the pandemic was an increase in the volume of waste generated at healthcare facilities, including hazardous waste, particularly due to the increased use of personal protective equipment (PPE) [35]. Therefore, the preceding studies on HCW production are not reliable nowadays. As for the management chain, after the segregation and storage phases within healthcare facilities, the municipal service collects the common waste, whereas the BSW is collected by a private company, Element Medical LCC (EM), transported to a treatment site, and finally disposed of in the municipal landfill [34], [36], [37].

To develop the state of the art, a team from the University of Trento and the National University of Mongolia conducted a series of semi-structured interviews, visits, and meetings. The following stakeholders were interviewed: the three hospitals where the Newster Group™ (NW) sterilisers have been installed, the MoH, EM company, and the company that installed the sterilisers. The interviews were conducted in Mongolian. A simultaneous translation was provided in English to facilitate the immediate acquisition of pertinent information. The interviews were recorded with the consent of the interviewees. Following the interviews, some data remained unavailable due to the inability of the interviewees to provide precise information, particularly regarding quantitative data (e.g., average kg of waste produced daily, energy and water consumption of the treatment facilities, details on spare parts, etc.). It was necessary to send a module to be completed with quantitative data, and a formal letter was required by the hospital to obtain data regarding the waste production.

As part of the UNICEF Project on Medical Waste Treatment Equipment, three electric sterilisers based on FHT, produced by NW, have been installed in three hospitals: the National Centre for Maternal and Child Health (NCMCH), the National Second Central State Hospital, and the National Centre for Zoonotic Diseases. The interviews were conducted at the above-mentioned hospitals. The NCMCH was identified as the most suitable hospital for the machine, and the hospital that provided more data about the use of the steriliser. Consequently, the LCA will consider the case study of HCWM in this hospital.

Chemical waste will not be analysed in this paper due to its low production in all the hospitals of the city (e.g., in May 2024 there was no collection of them, see Fig. 1). Moreover, the different scenarios would treat chemicals in the same way at EM treatment site, due to the impossibility to insert them into the NW steriliser.

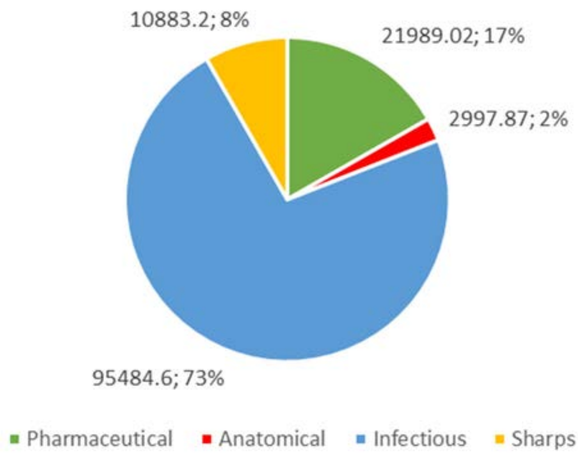

Figure 1: BSW (kg and percentages) collected and treated by EM in May 2024.

3.2 LCA

The software selected for the LCA analysis is SimaPro, version 9.5.0.2. In SimaPro, the Ecoinvent 3 database was employed. This paper investigates the initial two stages of the LCA, namely the definition of goals and scope and the inventory analysis. Consequently, the subsequent section will present the state of the art and the three scenarios considered (including the system boundaries), the functional unit (FU) and the inventory form.

4 RESULTS

4.1 Scenarios: state of art and future development

The LCA necessitates the delineation of precise system boundaries and a comprehensive qualitative and quantitative description of the scenarios to be analysed. A comparison was conducted between the standard BSWM system employed in Ulaanbaatar and an enhanced scenario using the electric steriliser installed through the UNICEF project. Currently, the steriliser is not treating all the BSW produced by the hospital, but rather a proportion of it. For this reason, three distinct scenarios were analysed, as detailed in the following sections.

4.1.1 Scenario 1

In the present scenario, graphically described in Fig. 3, all the waste produced at the NCMCH is collected and treated by EM. Inside the hospital, the waste is segregated in common waste and five categories of hazardous waste: anatomical, sharps, infectious, pharmaceutical, chemical. The municipality is responsible for the collection and transport of common waste up to the municipal landfill. As for the BSW, EM bears responsibility for its collection, transportation, treatment, and final disposal. At the NCMCH, the sorted BSW is collected in a designated room and placed into yellow polypropylene rigid containers. EM collects the waste every day (except on Sunday) inside the yellow containers, giving back the sterilised ones. The vehicles employed for the transportation of the BSW are classified as Euro 3 and utilise either gas or fuel, with a total capacity of a maximum of 1.5 tons. The mean distance travelled by a truck per day is around 25 km.

The company has stated that approximately 4.5–5 tons of BSW are collected daily, 6 days a week. Fig. 1 illustrates the quantities recorded in May 2024.

The NCMCH is situated at 13.6 km from the designated treatment site, which is located in close proximity to the municipal landfill. The treatment site comprises the following facilities: EM’s offices, a truck park, various storage areas for BSW and sterilised waste, an autoclave, a waste shredder, and an incinerator. The type of waste determines the treatment method employed: sterilisation with an autoclave for sharps and infectious waste, incineration for anatomical waste, and cementation for chemicals. Subsequent to the autoclave treatment, the sterilised waste is conveyed to a shredder with the objective of reducing its volume. The pharmaceutical waste is conveyed directly to the shredder, bypassing the autoclave. All facilities are operational 6 days a week.

The autoclave is a Chinese model with a maximum capacity of 300 kg per cycle. The apparatus comprises a main horizontal chamber, a steam generator, a pump for the steam, and a filter group (see Fig. 2). On a daily basis, the facility processes between 3,000 and 5,000 kg of infectious and sharps waste, operating between 10 and 15 cycles over a period of approximately 5–6 hours. The volume reduction of the waste is minimal. Therefore, the sterilised waste and pharmaceutical waste are subjected to a shredding process prior to final disposal in a landfill. The maximum capacity of the shredder is 2 tons per hour; however, it typically operates for a total of 4 hours per day. Subsequently, the waste is conveyed directly to a compressor truck (Euro 3), which has a maximum capacity of 2 tons. On average, the truck goes to the landfill two or three times per day, with an average distance of 10 km.

Figure 2: EM’s autoclave (left) and incinerator (right).

As for the incinerator, an average of 110 kg of anatomical waste is processed every day. The incinerator is of Chinese manufacture and is of the single-chamber type, equipped with a filter group (see Fig. 2). An additional ventilation system is provided by a fan. The filtration process is purely mechanical, employing a double system of grids with the capacity to capture materials of up to 9 nm in size. Energy is expended for the operation of the fans, the gas compressors for the filters, and the cooling of the flue gases. The temperature reached in the combustion chamber exceeds 850°C, while the temperature of the flue gases is reduced to 250°C. The fuel employed is diesel. On average, 45 kg of bottom ashes are removed daily.

Finally, the ashes and the sterilised shredded waste are deposited in a designated area of 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. Additional data necessary for the LCA have been provided by EM but are not reported in the paper. These include: the model of the trucks and the compressor, fuel consumption for the trucks and the incinerator, water and energy consumption for the autoclave, energy consumption for the shredder and the incinerator, spare parts for the autoclave, the shredder and the incinerator, and emission in air of the incinerator (NO_x, SO_2, CO, TSP expressed in mg present in 1 m^3 of flue gas). The volume of flue gas generated by the waste will be calculated to associate the mg of pollutants to the kg of waste burnt.

4.1.2 Scenario 2

The installation of the NW15 electric steriliser based on the FHT system at the NCMCH was completed in November 2023. The hospital produced an average of 250 kg of BSW per day. Each sterilisation cycle performed at the hospital has processed between 22 and 25 kg of BSW in approximately 40 minutes. In consideration of the additional time required for loading and unloading the machine, each cycle can be expected to take up to an hour. Consequently, to treat 250 kg of BSW, the machine should be operated for 10–12 cycles over a period of 10–12 hours. This scenario considers the on-site treatment of the total amount of BSW produced by the hospital, except for the chemicals. The machine can treat infectious, sharps and anatomical waste, with a maximum of 20% of the total weight permitted for anatomical waste. A recirculation system for water has been installed; however, the machine requires additional water to cool the waste, with an average consumption of 11 litres per hour. The average energy consumption is approximately 12 kWh. Additionally, data regarding the necessary spare parts and consumables, as well as the input of an enzymatic solution for odour control and wastewater, were collected.

The primary output of the machine is sterilised shredded waste that can be managed as common waste by the municipality. The final weight of the output is around 80% of the initial BSW, which equates to a total of an additional 200 kg of common waste to be collected. The collection of common waste is conducted daily; however, further information regarding the means of transport would be required in order to complete the study. The final destination for the BSW is the municipal landfill, situated at a distance of 14 km from the hospital. The characteristics of the landfill are identical to those described in Scenario 1. Fig. 3 provides a graphical representation of this scenario.

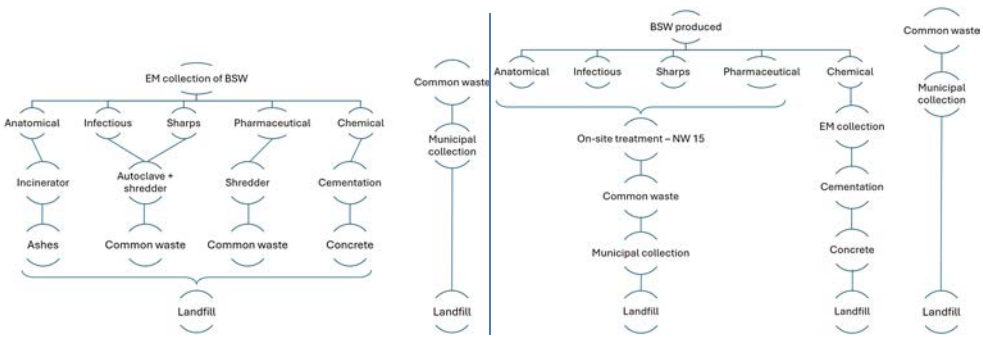

Figure 3: Graphical representation of Scenario 1 and 2 management systems.

4.1.3 Scenario 3

Given the current working hours of the waste operator in the hospital, it is estimated that a maximum of seven cycles per day could be performed. Therefore, around 125 kg of BSW could be treated per day, almost the half of the daily production. The present scenario considers this situation with 50% of the waste treated locally with the steriliser as in Scenario 2 and the remaining 50% of the waste collected and treated by EM as in Scenario 1.

Figure 4: NW15 steriliser installed at the NCMCH.

4.2 The functional unit

The choice of the FU is based on the findings of previous LCA studies conducted by NW. Considering the waste treated with the NW steriliser, it is possible to quantify a range of information for each cycle performed. Accordingly, the initial FU selected is 20 kg of BSW, which represents the load of a cycle. From this, it is possible to evaluate the impacts derived from the total amount of BSW produced on a daily or annual basis.

4.3 The inventory form

The present section reports the tables for the inventory form. There are two main parts for each process, namely the input and output (Tables 1–3).

5 DISCUSSION AND CONCLUSIONS

The LCA will be based on the data collected and any further information provided by the Ecoinvent database. Additional data is lacking regarding the municipal vehicle utilised for the collection of general waste, as well as certain spare components of the incinerator and autoclave. It should be noted that only the principal spare parts have been specified, without any indication of the duration for which they are required. Accordingly, we will refer to the general information provided in the Ecoinvent database. An alternative approach would be to exclude the consumables associated with spare parts from the scenario 1 calculations, which would result in a minimal reduction in the overall impact. Furthermore, it would be beneficial to consider the import of technologies and the associated impact of transporting a machine from China or from Italy to Mongolia.

The NCMCH represents an appropriate case study for the analysis of one of the first transitions to a more sustainable HCWM system in Mongolia. The machine is suitable for the context and the type of waste produced, and the operator reported no issues in using it. As evidenced by the results of the three interviews conducted, EM company is currently

Table 1: NW15 steriliser inventory form.

NW15 INPUT				
	Name	**Description**	**Quantity**	**Unit**
Material 1	HCW	Infectious solid waste HP9		kg/cycle
Material 2	Plastic bags	Polypropylene bags		kg/cycle
Material 3	Consumables	Spare parts, listed materials		kg/cycle
Material 4	Active air	Anti odour enzymatic solution		kg/cycle
Material 5	Water	Tap water		l/cycle
				l/h
Energy 6	Energy consumption	Power supply		kWh/cycle
				kWh
NW15 OUTPUT				
	Name	**Description**	**Quantity**	**Unit**
Material 1	Sterilised flocs	General waste EWC 20.03.01 HP9		kg/cycle
Material 2	Sewage wastewater	Grey wastewater		l/cycle
Material 3	Absolute filter	Paper		kg/cycle
Material 4		Iron		kg/cycle
Material 5	Consumables	Mix material		kg/cycle
Material 6	Activate carbon pellet	Mineral		kg/cycle

Table 2: Autoclave and shredder inventory form.

AUTOCLAVE INPUT				
	Name	**Description**	**Quantity**	**Unit**
Material 1	HCW	Infectious solid waste HP9		kg/cycle
Material 2	Plastic bags	Polypropylene bags		kg/cycle
Material 3	Consumables	Steam generator		kg/cycle
Material 4	Water	Tap water		l/day
				l/cycle
Energy 5	Energy consumption	Power supply		kWh
AUTOCLAVE OUTPUT				
	Name	**Description**	**Quantity**	**Unit**
Material 1	Sterilised waste	General waste EWC 20.03.01 HP9		kg/cycle
Material 2	Wastewater			l/cycle
Material 3	Consumables			kg/cycle

Table 2: Continued.

SHREDDER INPUT				
	Name	**Description**	**Quantity**	**Unit**
Material 1	Sterilised waste	Autoclave output + pharmaceutical waste		kg/cycle
Material 2	Consumables in the waste	Autoclave output material 3		kg/cycle
Material 3	Steel consumables	Blades consumables		kg/cycle
Energy 4	Energy consumption			kWh
SHREDDER OUTPUT				
	Name	**Description**	**Quantity**	**Unit**
Material 1	Sterilised shredded waste	Common waste		kg/cycle
Material 2	Consumables in the waste			kg/cycle
Material 3	Steel consumables	Blades consumables		kg/cycle
Transport 4	From shredder to landfill	With compactor truck		km

Table 3: Incinerator inventory form.

INCINERATOR INPUT				
	Name	**Description**	**Quantity**	**Unit**
Material 1	Anatomical waste	Infectious solid waste HP9		kg/day
Material 2	Consumables	Filter		kg/day
Material 3	Diesel			l/week
				l/day
Energy 4	Energy consumption	Power Supply		kWh
INCINERATOR OUTPUT				
	Name	**Description**	**Quantity**	**Unit**
Material 1	Ashes			kg/day
Material 2	NO_x	Pollutants in the flue gas		mg/m^3
Material 3	SO_2			mg/m^3
Material 4	CO			mg/m^3
Material 5	TSP			mg/m^3
Material 6	Consumables	Filter		kg/day
Transport	From incinerator to landfill	Compactor truck		km

providing a satisfactory service to the hospitals. Given the lack of treatment technologies for waste in Mongolia, including municipal ones, the company is offering a crucial service. However, it is possible that autoclaves and incinerators may have an environmental impact that is considerably higher than that of the NW steriliser. It is therefore important to quantify the impact through an LCA. While the environmental impact information is obtained, further research could combine the results of the LCA with an economic and social sustainability analysis. This would enable key stakeholders in the health and environment sectors to make informed decisions that would lead to improvements in the HCWM system in Ulaanbaatar.

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