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Research article

Life cycle analysis and environmental cost-benefit assessment of utilizing hospital medical waste into heavy metal safe paving blocks

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Abstract: This research explored the life cycle analysis and environmental cost-benefit assessment of converting ash waste from hospital medical waste incineration into environmentally safe paving block raw materials. The growing concerns about medical waste disposal and its environmental impact necessitate innovative solutions for sustainable waste management. This research aimed to evaluate the feasibility and environmental implications of reusing hospital waste into raw materials for paving block mixtures. This research, a comprehensive life cycle analysis, examined the environmental impacts of medical waste collection for the production and use of paving blocks. Additionally, we conducted an environmental cost-benefit assessment to ascertain the economic feasibility and potential environmental impact forecasts of this recycling approach. The research results show that converting hospital medical waste ash into mixed raw materials for paving blocks not only immobilizes heavy metals but also provides a sustainable alternative for non-building materials. These findings highlight the potential for significant environmental and economic benefits, making this approach a promising strategy for waste management and sustainable construction practices. The cost of preventing environmental damage (eco-cost) in the process of converting ash from the incineration of medical waste into a mixture of raw materials for paving blocks is IDR 600,180.9 per cycle.

Keywords: ash medical waste; life cycle assessment; paving blocks

1. Introduction

Medical waste is increasing in several countries due to the COVID-19 pandemic that started in 2019 [1]. The increasing population growth in developing countries is causing problems in handling medical waste [2]. The problems caused by medical waste are growing exponentially as it has a dual effect, first polluting the environment and second spreading disease, which impacts human health and the environment. If proper disposal is not done, it will result in harmful effects such as radiological [3], genetic, and chemical toxicity, infectivity, and others [4]. According to the World Health Organization (WHO), 10%–25% of medical waste is considered hazardous [5]. Different treatment methods are used according to the type of medical waste, such as incineration, landfilling, autoclaving, radiation, and recycling [4,6–9]. Improper management of medical waste is standard due to the high cost of waste disposal, even though the public is well aware of the potential health risks. About two-thirds of medical waste is currently disposed of in an unsafe manner. Waste treatment using the combustion method is still an effective way to deal with medical waste, such as in China, Indonesia, and Italy [10,11]. One of the impacts of combustion is the ash produced. The quantity of ash produced increases with the increase in medical waste.

The ash produced by the combustion process of medical waste is used to minimize ash piles [12]. Ash is one of the negative impacts produced, in addition to emissions, during the waste incineration process, which has an impact on the environment and public health [13]. The Regulation of the Minister of Environment and Forestry of the Republic of Indonesia concerning Procedures and Requirements for Hazardous and Toxic Waste Management (No. 6 of 2021) states that it can be utilized as a substitute for raw materials. Using the solidification method, paving blocks are made by adding ash as a mixture of raw materials. Solidification is a waste treatment technique that compacts ash or residue making its chemical and physical qualities more stable and preventing leaching [14].

An environmental impact assessment is carried out to assess the environmental impact generated by an activity. The activity of utilizing ash from burning medical waste into block paving is carried out to estimate the environmental impact so that it can produce environmentally friendly products. The ash resulting from the incineration of medical waste is used to make a paving block mixture to function as a substitute for sand. Ash's mineral content could serve as a pozzolan material for cement mixtures [15,16].

Currently, various methods and technologies are used to determine the environmental impact of medical waste. Life cycle assessment (LCA) is the most appropriate and reliable tool for evaluating the environmental impact of products and processes over their entire life cycle [17]. LCA-plus life cycle costing (LCC), a systematic and practical approach to measuring the environmental and economic impacts of a targeted process, activity, or product over its life cycle, is widely applied in eco-design, product improvement, decision-making, and policy formulation. However, LCA studies are relatively rare in medical waste management and disposal despite their importance for quantifying the ecological footprint and associated health risks.

Environmental impact forecasts use the LCA method. The LCA approach was used in this research to holistically analyze the environmental impact of utilizing medical waste ash in paving blocks. LCA has also been used to compare biomass and coal fuels as energy for methanol production, with biomass having potentially less impact than coal [18]. LCA analysis of utilizing solid plastic waste in paving blocks shows that it can reduce negative impacts, especially global warming and photochemical oxidants [19]. The use of ash in paving blocks has the potential to pollute the environment since the ash composition contains heavy metal compounds derived from burned medical waste [20,21]. The heavy metals found in the combustion residue include polycyclic aromatic hydrocarbons (PAHs), Ag, As, Ba, Bi, Cu, Cd, Cr, Ni, Ti, Sb, Sn, Pb, and Zn [22]. Water quality can suffer because paving block soak water derived from combustion ash contains heavy metal compounds such as Pb, Ni, Cu, and Cd [23]. The impact of heavy metal compounds on the environment is a complex problem that occurs continuously [24].

Good waste management in healthcare settings has a positive impact on preventing the spread of disease and environmental pollution [25]. External and operational costs are important to consider in waste management [26]. Using human health parameters for estimating the environmental impacts and costs of utilizing ash as raw materials in paving blocks can advocate for government policies on sustainable and environmentally friendly waste management. Although many studies have been conducted on environmental cost analysis, this study is unique in that it uses cost and benefit analysis techniques to explore the possibility of converting medical waste containing heavy metals into paving blocks that already have heavy metal content below environmental quality standards.

2. Materials and methods

2.1. Materials

This study used ash from the combustion of medical waste, namely bottom ash. The ash was collected from a medical waste processing plant in Central Java, Indonesia. The feasibility of utilizing ash from the incineration of medical waste from health facilities as raw material for ecologically friendly paving blocks is first analyzed by subjecting to a TCLP test to determine the leaching potential and then using the LCA method based on gate-to-gate. Gate-to-gate was used to determine the environmental impact caused by the stages of the product life cycle, starting from the preparation of raw materials to be utilized and ending with the production of a paving block product. Figure 1 shows the research flow diagram.

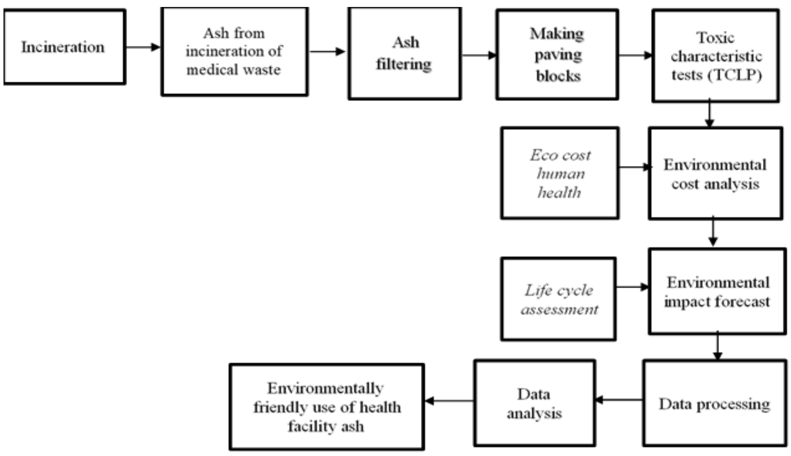

Figure 1. Research flow diagram.

2.2. Data collection

Data collection used observation and interviews. Participatory observation was carried out by directly observing the process of utilizing ash from medical waste incineration into paving blocks so that researchers could know the field conditions and correctly identify the utilization process. Interviews were conducted with entrepreneurs and workers who made paving blocks from ash from medical waste incineration. Data on electrical energy use, fuel use, and emissions released from the utilization process can be determined with guidelines Intergovernmental Panel on Climate Change (IPCC), 2006 [27]. Figure 2 presents a flowchart on the use of medical waste for paving blocks.

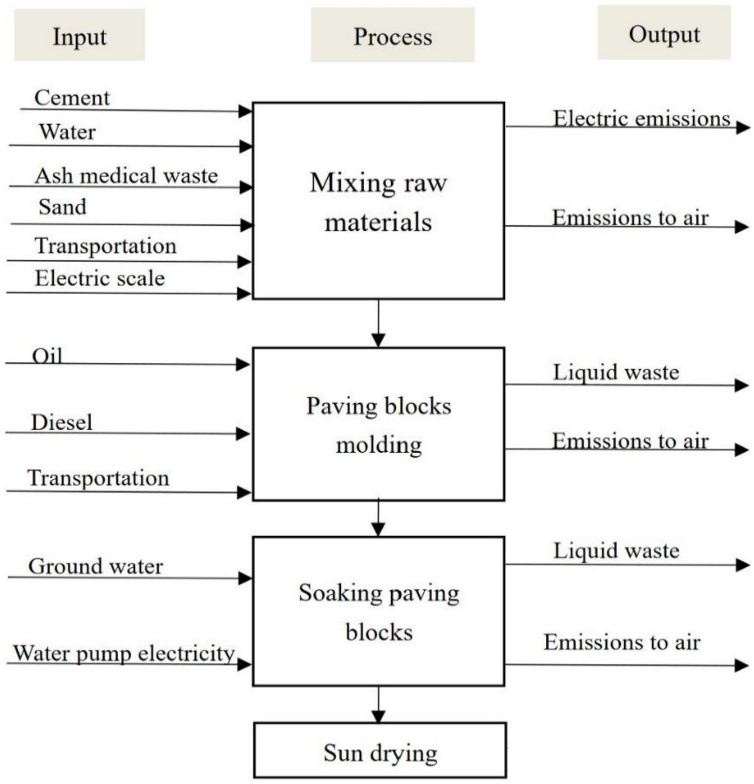

Figure 2. Flowchart on the use of medical waste for paving blocks.

2.3. Life cycle assessment of ash utilization process

The purpose and scope of this study are to investigate the environmental impact of mixing raw materials, molding, soaking, and drying paving blocks. The approach in this research uses the LCA method with SimaPro 9.5 software. Data input adapts to data available in SimaPro 9.5 database software, such as EcoInvent 3, Agri-footprint-economic, Industry Data 2.0, and USLCI. The functional unit calculated in this research is a paving block with a strength of 13.28 MPa. The life cycle inventory (LCI) is completed by defining the inputs and outputs of each process. In this study, the LCI collects data on the amount of input and output utilizing ash from medical waste incineration. The life cycle impact assessment (LCIA) stage involves identifying the environmental impacts of employing ash from medical waste incineration process. At this stage, the ReCiPe midpoint (H) method is applied.

Assessment using an LCA approach has several environmental impact categories, as described in ISO 14040, both midpoint and endpoint. The impact categories included in the endpoint (environmental damage–oriented approach) are depletion of natural resources, ecosystem health, and human health. Regarding the impact categories included in the midpoint (problem-oriented approach), each environmental impact category has its category indicator; for example, the category indicator for the potential impact of global warming is CO_2-equivalent [28]. The potential environmental impact categories (endpoint impact) include impacts on human health, ecosystem quality, and availability of natural resources. The endpoint impact category shows an approach oriented toward environmental damage so that environmental management and protection are required. The assessment requires interpretation in order to provide alternatives in the form of waste utilization innovation that can improve environmental performance and be environmentally friendly. Figure 3 presents system boundaries and functional units in this research.

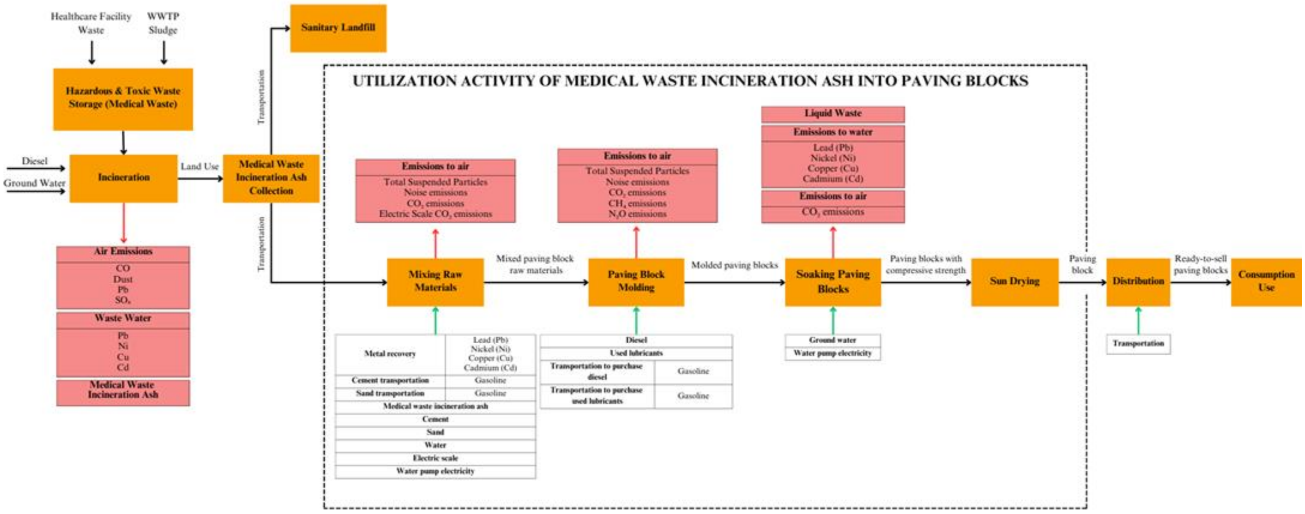

Figure 3. The system boundaries.

2.4. Environmental costs

This type of eco-cost prevention cost is used to calculate the environmental impact on human health parameters of utilizing bottom ash resulting from the incineration of medical waste as a mixture for paving blocks. The calculation uses LCA with software SimaPro 9.5; then, the damage assessment value, which includes human health, is calculated in disability-adjusted life years (DALY) or QALY. DALY is a measure of the impact a person receives, expressed as the number of healthy years lost due to health problems, disability, or death. The LCA calculation results are evaluated for their eco-cost value by converting them to euro units and then to rupiah (IDR) units. Table 1 shows the amount of unit conversion. The exchange rate for euro to rupiah, based on December 2023, is IDR 16,764.20.

Tabel 1. Damage assessment unit conversion.

Category damage assessment	Unit	Description
Human health	*Euro*	1 QALYs*74,000

*Note: Source : (Peruzzini, Germani, and Marilungo 2013) [54].

2.5. TCLP and solidification tests

This research stage aims to determine the content of the heavy metal compounds Pb, Ni, Cu, and Cd using ash from medical waste incineration activities. The TCLP test identifies the leaching of hazardous and toxic compounds in a waste. The TCLP test is carried out by identifying the hazardous and toxic waste as listed in Appendix XI of Government Regulation No. 22 of 2021. The test uses the SNI 8808 method of 2019 on Toxicity Characteristic Leaching Procedure (TCLP), an extraction procedure using a rotary agitator tool. The results of this extraction are then analyzed using inductively couple plasma (ICP) to determine the total amount of Ni, Cd, Cu, and Pb metals. Testing is required to ensure that the solidification process is effective. Tests are conducted to ensure the strength of the solidification product and the leaching ability of the pollutants contained in the product. The movement rate of waste pollutants can be slowed down by stabilization and solidification. Rainwater seeping into the stabilized effluent can allow the transfer of liquid effluent pollutants to the surrounding environment. Leaching is the process of contaminant migration from the stabilized matrix into the liquid. Hazardous waste containing organic and inorganic pollutants can be tested using the toxicity characteristic leaching procedure (TCLP) test.

3. Results

The ash from burning medical waste is included in the list of hazardous and toxic waste with a general specific source category, including the type of activity of health care facilities from incinerator facility waste sources. Waste utilization, especially in the hazardous and toxic waste category, must be carried out by the organization or activity that releases the waste or be submitted to agencies or third parties with permission to utilize it. The mandatory criteria for utilizing hazardous and toxic waste in paving blocks is a total metal oxide content for SiO_2+Al_2O_3+Fe_2O_3+CaO higher than 50% (Minister of Environment Regulation No. 6 of 2021). Figure 4 shows the ash from medical waste incineration that falls to the bottom during the incineration treatment; Figure 5 shows the result of filtering the ash from medical waste incineration.

Figure 4. Medical waste incineration ash.

Figure 5. Medical waste incineration ash after screening.

Paving block products with a mixture of ash from medical waste combustion were created based on the maximum condition of mortar determined with a composition of 50% ash (0.47 kg) and 50% sand (0.47 kg), cement, and water. Cement and water are used in making paving blocks, and both materials are included in the controlled variables. Compressive strength is determined based on SNI 03-0691-1996 concerning concrete bricks (paving blocks). Paving block materials are mixed in accordance with the mix design and carried out in accordance with SNI 03-6825-2002 concerning testing methods for compressive strength of Portland cement mortar for civil works. The required composition of mortar cubes is bottom ash (419.9 kg/m^3), sand (419.9 kg/m^3), cement (600 kg/m^3), and water (300 kg/m^3). The resulting optimum compressive strength is 13.28 MPa, so it is included in the D-quality paving block category, which is intended for parks and walking users. Figure 6 shows a paving block product that uses the maximum condition composition and is soaked for 28 days.

Figure 6. Paving blocks from incinerator medical waste.

The TCLP test uses the Indonesian National Standard (SNI) 8808:2019 concerning the toxic characteristic leaching procedure to determine the content of heavy metal compounds in ash and paving blocks. Table 2 shows that the ash content resulting from the incineration of medical waste contains the heavy metal compounds Pb, Ni, Cu, and Cd. The type of burning medical waste determines the content of heavy metal compounds. Pb compounds exceed the quality standards set by Indonesia in the Minister of Environment and Forestry Regulation No. 6 of 2021. Ni, Cu, and Cd compounds are within the Indonesian Government's safe limits for quality standards. The measurement results show that heavy metal paving blocks have decreased in Pb, Ni, Cu, and Cd compounds. The solidification technique is quite effective in stabilizing heavy metals in ash resulting from medical waste incineration.

Table 2. Heavy metal content in medical waste incinerator paving blocks.

Heavy metal compound parameters	TCLP test content of heavy metal compounds in ash (mg/kg) (before solidification technique)	TCLP test content of heavy metal compounds in ash (mg/kg) (after solidification technique)	Environmental quality standards PermenLHK number 6 of 2021
Pb	3.34	0.78	3
Ni	0.64	0.4	21
Cu	14.8	2.33	60
Cd	2.39	0.09	0.9

Figure 7 illustrates the concentration of the metal compounds Pb, Ni, Cu, and Cd in the ash that arises from the burning of soaked paving blocks. We soak the paving blocks for 7, 14, 21, and 28 days to assess their leaching potential in the field. The concentration in heavy metals significantly decreased, but the Cd parameter increased during the 28-day soaking period. Therefore, we recommend soaking for up to 21 days, given that the 21st day produced a compressive strength of 13.7 MPa, still in line with the D-quality paving block classification, which requires a minimum compressive strength of 8.5 MPa.

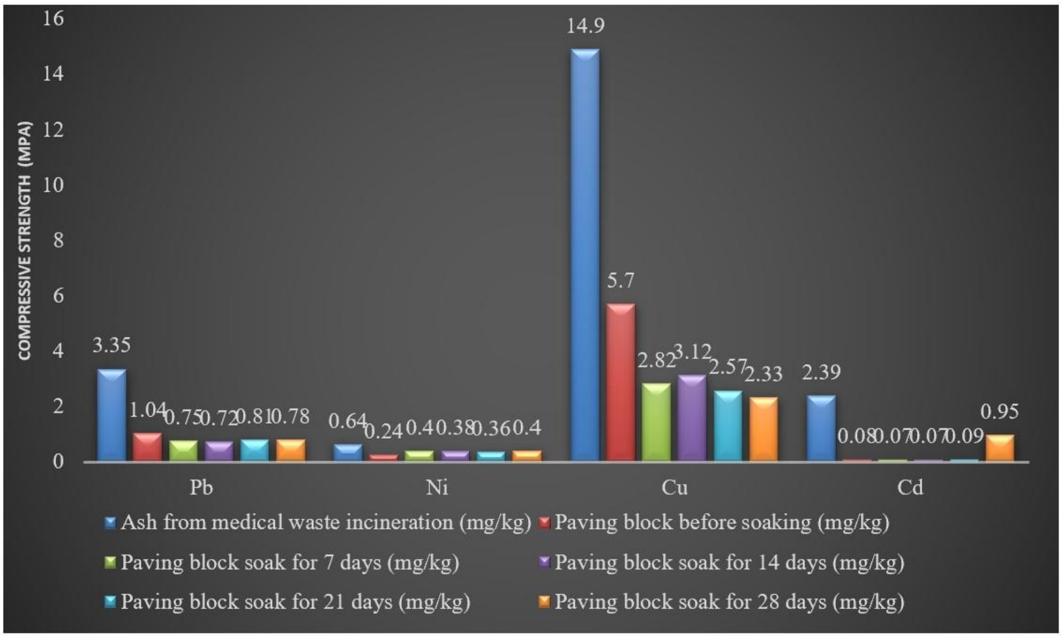

Figure 7. Reduction of heavy metal compounds in paving blocks.

3.1. Mixing of raw materials

Mixing raw materials is done by weighing the raw materials in the form of 21.25 kg of sand, 23.8 kg of cement, and 8.5 kg of incineration ash. Weighing is carried out using an electric scale with a capacity of 0.016 kWh. Workers do the mixing manually, adding 0.5 L of water to create a mixture of raw materials that will be molded into 53.25 kg of paving blocks. The water used is taken from groundwater using a water pump. This process produces waste in the form of TSP dust, so workers wear personal protective equipment such as gloves and masks during this process.

3.2. Molding of paving blocks

Sand and incinerator medical waste ash are mixed in the tub and then stirred until evenly distributed. The cement is then added to the mixture and stirred until evenly distributed, and water is poured gradually while stirring until the mixture clumps. The mixture of ready-to-print raw materials is molded using a press machine to produce paving blocks. The press machine uses diesel fuel. Used oil is used for lubrication during the molding of paving blocks. The dough is put into the mold, which is then shaken/hit with a rubber mallet so that the dough can spread in the mold (going down to the bottom to fill all the cavities). The mortar is removed from the mold and soaked in water for several days, according to the soaking period, to maintain the mixture's strength. Noise and TSP dust are generated during the molding process. The noise generated by the diesel engine is muffled using a room cover. The TSP dust generated by the molding process is due to the tiny particulate size of the ash and cement, which poses a risk to workers' lung function.

3.3. Paving block immersion

The immersion is carried out on the paving block after a 7-day printing period aimed at helping the hydration process between cement and ash from the incineration waste activities in healthcare facilities. The groundwater water is taken using a water pump of 105 L. The waste produced in this process is the diving water paving block, as no further treatment is thrown into the water pipes.

3.4. Drying with sunlight

Drying is done on the paving block using sunlight. The paving block is placed in an area vulnerable to sunlight, so it accelerates the drying process and is ready for sale by consumers.

3.5. Life cycle assessment of ash utilization in paving blocks

The results of the environmental impact assessment show the value that emerges from the impact category on the ashtray process unit, resulting from the engineering of medical waste into the paving block in each unit, as shown in Table 3.

Table 3 shows that utilizing ash from the incineration of medical waste in paving blocks has the three highest potential environmental impacts, namely global warming, terrestrial ecotoxicity, and human non-carcinogenic toxicity.

Table 3. Total impact category results for entire process units with ReCiPe midpoint characterization model (H).

Impact category	Unit	Total
Global warming	kg CO_2 eq	453.60727
Terrestrial ecotoxicity	kg 1.4-DCB	100.83346
Human non-carcinogenic toxicity	kg 1.4-DCB	29.396636

3.6. Life cycle assessment of ash utilization in paving blocks

Eco-costs refer to the expenses incurred to mitigate environmental effects stemming from the production process. Impact determination can be done by calculating the results of the life cycle assessment in the form of damage assessment using SimaPro 9.5 software with the ReCiPe Endpoint (H) method, which is presented in Table 4.

Table 4. Assessment of the environmental damage of utilization activities in paving blocks with life cycle analysis.

Total environmental costs (*Eco-cost*)		
Damage category	Unit	Utilization activities into paving blocks
Human health	DALY	0.00048

In the human health category, the total value of environmental damage is 0.00048 DALY, which means that the number of years of healthy life lost by a person due to disability or premature death is 0.00048 per year. The results of calculating the cost on human health are as follows:

1 DALYs = 1 QALYs

Human health = 1 QALYs*74,000*convert euro to IDR

= 0.00048611717*74,000*16,684.36

= IDR 600,180.9

The disability-adjusted life years (DALY) unit shows the years of healthy life lost due to disability or death. Table 5 reveals that the total environmental costs associated with the human health category amount to IDR 600,180.9

Table 5. Environmental costs of utilization activities in paving blocks.

Total environmental costs (*Eco-cost*)		
Damage category	Unit	Utilization activities into paving blocks
Human health	DALY	IDR 600,180.9

4. Discussion

Health service facilities like hospitals, health centers, and clinics must manage the medical waste they generate, which includes reducing, sorting, containing, storing, transporting, and processing. Health service facilities can conduct processing activities both internally and externally. Health service facilities, with permits according to government regulations, can independently carry out internal health services such as autoclaving, burials, microwaves, encapsulation, and inertia. Health facilities that use incinerators to process medical waste must meet specific requirements, including a capacity proportionate to the burnt waste volume, two combustion chambers, a chimney measuring at least 14 meters, and air pollution control equipment (Permenkes 02 of 2023). If health facilities are unable to process the produced medical waste, the region or regional government can also facilitate internal processing (Minister of Health Regulation Number 18 of 2020). The government issues a medical waste processing permit to third parties who carry out the processing externally.

According to quality standards for toxic characteristic tests like the TCLP and LD50 tests (PermenLHK 6 of 2021), products produced as a result of waste utilization must have SNI and contain total oxides higher than 50%. Utilization of ash as raw material for paving blocks can be carried out as a manifestation of waste recycling activities and as a solution to reduce the amount of ash produced from incineration activities using incinerators. Health facilities or third parties that process medical waste using incinerators can utilize ash as a raw material for paving blocks by submitting a utilization permit to the government. Economic calculations indicate that using ash from incineration as a raw material for paving blocks is both feasible and effective in reducing the content of heavy metal compounds in the ash. Ash utilization activities are an embodiment of the waste reduction program, as it reduces the amount of waste and controls the use of natural resources. According to PP 22 of 2021, the ash from incineration serves as a replacement for sand in the production of paving blocks.

The type of burning of medical waste determines the content of heavy metal compounds in the ash. Pb compounds exceed Indonesia's quality standards set in Minister of Environment and Forestry Regulation No. 6 of 2021. Medical waste processing companies burn a variety of waste types, including medical equipment, contaminated waste, infectious waste, IPAL sludge, expired pharmaceutical products, pharmaceutical packaging, and chemical packaging. Pb compounds are indicated to originate from types of medical equipment [29,30]. The increase in Cd parameters in paving blocks with a soaking period of 28 days is due to the water used for soaking being contaminated with Cd metal compounds, so there is potential for heavy metal adsorption in the water toward the paving blocks. Adsorption is the stage where compound components move from one phase to another by crossing several boundaries or moving substances from the solvent to the absorber [31]. The contact period is one of the factors in the success of the adsorption process: the longer the exposure period, the better the adsorption process [32].

Global warming can occur as a result of heat wave radiation from the sun being trapped on Earth by greenhouse gases (GHGs) present in the atmosphere [28]. The greenhouse gases that contribute to global warming include carbon dioxide (CO_2), methane (CH_4), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), perfluorocarbons (CFCs) and nitrogen oxide (N_2O) [32]. The impact category is measured in kg CO_2-equivalent, meaning that when the atmosphere absorbs more greenhouse gases, a retention layer forms, reflecting heat waves back to Earth and increasing the temperature. Exploiting incineration ashes for paving blocks emits emissions that contribute to global warming. Additionally, using electricity, solar fuel, and fuel for transporting, purchasing, and acquiring raw materials and additives generates emissions. CO_2 from fossil fuel emissions will enter the atmosphere if the increase in the gas exceeds the adsorption capacity of vegetation and the sea [33]. The global warming potential indicates the impact of CO_2 emissions in comparison to other greenhouse gases, such as CH_4, which is 21 times more potent, and N_2O, which is 300 times more powerful than CO_2 in contributing to GHGs [34].

Terrestrial ecotoxicity refers to the impact on terrestrial ecosystems caused by the emission of toxic substances into air, water, and soil. A paving block constructed using ash made from medical waste incineration may contain heavy metals. The type of waste burned influences the heavy metal composition in the residues. The incineration results of this study show heavy metal compounds in concentrations such as 3.34 mg/L (Pb), 0.64 mg/L (Ni), 14.8 mg/L (Cu), and 2.39 mg/L (Cd). Ash also contains CaO compounds; Ca compounds are the largest contributor to bottom ash because the waste mostly comes from health equipment such as protective clothing, face masks, and glasses made from polypropylene (PP) [35]. Metal compounds play a significant role in terrestrial ecotoxicity [36].

The terrestrial eco-toxicity caused by metals depends on the location due to the influence of soil characteristics and climate conditions [37]. Heavy metals enter waters and cause ecotoxicity to aquatic organisms in freshwater through the gills or organs, absorption in the body through the digestive tract, and absorption through the animal subcutaneous tissue [38]. Moisture, organic matter, microbial activity, rainfall, microorganic activity, and soil erosion are soil variables that influence the impact of eco-toxicity on metals, making them susceptible to climate change [32, 39–41].

Non-cancerous effects on human health can include respiration disorders, metabolism, skin, or symptoms of other diseases. When using ash in paving blocks, the mixing and printing process of raw materials produces dust in the form of total suspended particulate (TSP). The immersion process produces liquid waste from diving water containing heavy metal compounds such as Pb, Ni, Cu, and Cd. The dust can physically affect the human respiratory system. The impact starts from dust accumulation in the respiratory tract, which causes coughing and sneezing. The size of the dust particles and the pollutant compounds they contain significantly impact health. The dust will reach the lower respiratory tract or alveoli as the diameter becomes smaller [42–44]. Potential non-carcinogenic health effects of TSP dust are worsening respiratory conditions and pneumoconiosis. This is a disease caused by dust particles entering and settling the lungs [45]. Particulate dust accumulates in the lungs in three ways: inhalation (through the respiratory system), ingestion (through the digestive system), and skin penetration (through the pores of the skin) [46]. Copper (Cu), one of the heavy metals, can penetrate all layers of the environment, including soil, water, and the atmosphere (air) [47]. Radical metals can enter directly or indirectly into the human body [48,49]. Exposure to Cd potentially results in non-maximum kidney activity, thus disturbing the body balance [47,48], in addition to causing damage to the kidneys, lungs, blood, heart, reproductive glands, sense of smell, and fragility of bones [50]. This result is in line with previous research showing that toxicity to humans has the highest impact; this is because the materials used, transportation of raw materials, and energy used during the production process provide emissions and impacts on the environment [51].

Environmental impact estimates using the LCA method can provide information on the most significant impact contributions from raw materials to activity processes [52]. Efforts to prevent predicted impacts include using personal protective equipment such as safety glasses, safety shoes, and mandatory respirator masks. Exposure to dust affects the respiratory tract, causing symptoms like coughing, shortness of breath, and impaired mucociliary transport [53]. Work rotation and regulation of working hours are carried out to reduce exposure to potential hazards from utilizing medical waste ash in paving block products.

Environmental impact prevention is often referred to as environmental cost (eco-cost). “Eco” relates to the environment, while “cost” refers to the expenses incurred. Impact determination can be done by calculating the life cycle assessment results, which is the damage assessment using SimaPro 9.5 software with the ReCiPe Endpoint (H) method for activities involving the use of ash in paving blocks. To create paving blocks products from ashes of medical waste incineration, a variety of raw materials are required. The use of these materials, primarily derived from incinerated medical waste, produces waste and emissions that can affect human health. Preventing such environmental impacts leads to costs that can reduce the profit margin from the sale of paving blocks. Eco-cost refers to the cost required to mitigate the environmental impact of the production process.

The total environmental damage value for the human health category is 0.00048 DALY, meaning the loss of 0.00048 years of healthy life due to disability or premature death. Disability-adjusted life years (DALY) units indicate healthy life years lost to invalidity/death. Table 4 shows that the total environmental cost for the human health category is IDR 600,180.9. The environmental impact value is derived from the damage assessment converted into monetary terms. The conversion value of the human health damage category to euros is 74,000 [54]. Significant environmental costs can be prevented by reducing the environmental impact, making the production process more material-efficient, or substituting raw materials with more environmentally friendly alternatives. Determining environmental costs can help businesses consider setting the sale price of paving blocks to achieve greater profits while covering production and environmental costs. Environmental costs can also be used to estimate a building's economic and environmental impacts by including several costs, such as maintenance costs [55]. Selecting the right scenario significantly influences the reduction of environmental costs [56, 57].

5. Conclusions

Utilizing ash from the incineration of medical waste into raw materials for paving blocks is predicted to have the highest environmental impact in terms of global warming, terrestrial ecotoxicity, and non-carcinogenic toxicity to humans. In one cycle, the cost of environmental damage caused by ash utilization activities in the human health category is IDR 600,180.9. The process of converting ash from the incineration of medical waste into raw material for paving blocks is quite effective, especially when combined with environmentally friendly fuel, which reduces the impact of global warming. The management of wastewater resulting from immersion activities involves the construction of wastewater treatment plants, with the aim of reducing the emissions released into the air, water, and soil, thereby preventing impacts on land ecosystems. Personal protective equipment, such as KN95 masks, can prevent non-carcinogenic toxicity to humans during utilization activities by reducing potential exposure to ash hazards. The Minister of Environment and Forestry Regulation No. 6 of 2021, which outlines the requirements for hazardous and toxic waste, permits the use of ash from medical waste incineration in paving block products. This program effectively contributes to the government's waste reduction efforts by minimizing waste and managing resource usage.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

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