Environmental Impact of Medical Waste Treatment

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Abstract

The significant increase in the generation of medical waste in recent years has raised many concerns worldwide. This work aims to determine the environmental impacts produced by the different technologies used for the recovery of medical waste as part of waste management (incineration and pyrolysis), thermal treatments considered effective for the decontamination and sterilization of infectious medical waste. The Leopold Matrix was applied to evaluate in quantitative terms the environmental impacts of each of the processes. For this purpose, the interactions of the physical, biological, and socioeconomic elements were established with each of the stages of the waste management treatment processes, which were evaluated using the results of a literature review. In the physical aspect, the negative impact of soil, air and water contamination was considered; in the biological aspect, the damage caused to flora and fauna; and in the socioeconomic aspect, the risk of spreading diseases; despite the generation of employment and contribution to the economy. The results showed that both waste management treatments are polluting; however, pyrolysis scored higher, reflecting that this treatment generates fewer negative impacts than incineration. This research is a starting point for further research into new methods of medical waste management that are environmentally friendly and efficient.

Keywords
Medical Waste, Environmental Impact, Leopold Matrix, Incineration and Pyrolysis.

1. Introduction
Medical waste (MW) management is often downplayed, yet since the coronavirus outbreak, a significant increase has emerged that has changed the dynamics of waste generation worldwide (Singh et al. 2022). Thirty percent of health facilities (60 percent in less developed countries) are not equipped to handle existing waste loads, let alone the additional burden generated by the pandemic. This potentially exposes health care workers to a variety of pathogenic microorganisms and at the same time affects communities living near poorly managed landfills and waste disposal sites (WHO 2022).

With the COVID-19 pandemic, the use of various medical items such as masks and gloves has become widespread. However, the control of disposal of these wastes has lagged the growing demand. For example, in South Korea, the demand for these products increased by 816% and 2551% respectively from 2019 to 2020 (Lee 2022). In Indonesia, around 12,740 tons of medical waste has been generated every two months. The threat of medical waste that is not managed properly is that it causes diseases as it is a point of transmission and therefore at least 5.2 million people die every year worldwide (Chowdhury 2022).

According to existing literature, mishandling of hospital waste by healthcare workers can lead to diseases such as AIDS, hepatitis B, hepatitis C and tuberculosis. This exposure is mainly due to the mixing of hospital and municipal waste in low- and middle-income countries, resulting in staff being inadequately trained to handle these items (Khalid et al. 2021). According to one survey, more than 49% of people use the same container to dispose household and COVID waste, which can increase infection (Shammi et al. 2021). Similarly, another article found that this type of waste has pathogenic organisms that can enter the body through punctures, breaks in the skin and mucous membranes such as the mouth and nose. Also, personnel who cut or prick themselves with sharp waste can become infected with HIV/AIDS, hepatitis B and C viruses and become infected with commonly identified bacterial pathogens such as Pseudomonas spp, Corynebacterium diphtheriae, Escherichia coli, Staphylococcus spp. that cause respiratory tract infections and other diseases (Egbenyah 2021).

However, despite the studies in Europe and Asia presented above, there are few articles in Latin America that address this problem and possible solutions (Chisholm 2021). It is, therefore, necessary to have a better understanding of the existing solutions for medical waste management and their environmental impact, as they are not yet being applied in many countries.

Thermal treatment is considered essential to decontaminate and sterilize infectious medical waste. Among the possible thermal conversion technologies to treat and recover medical waste, there are several technologies, including incineration (combustion), carbonization (torrefaction), pyrolysis (liquefaction) and gasification (Purnomo et al. 2021). The purpose of the research is to quantitatively identify which waste management treatment has the least harmful impact on the environment in physical, biological, and socio-economic aspects, the use of which should be promoted.

2. Literature Review

2.1. Incineration Treatment

Incineration of medical waste is a universal disposal method that is suitable for all types of infectious waste. For this reason, it has been the preferred method for many years and was the only method used until 2005 for medical waste treatment. (Yoon 2022).

Currently, in the western sphere, 50% of hospital waste is incinerated. It employs a high-temperature combustion range (800 - 1200 °C), which completely eradicates pathogens. In addition, the deep oxidation of the waste under the high-temperature flame results in the drying and incineration of the substances and their conversion into a waste mass that can be treated as harmless material and gas. Therefore, the application of this method is effective, as the waste consists mainly of hydrocarbons with a high calorific value that can be easily destroyed during incineration (Giakoumakis et al. 2021).

The incineration procedure occurs through a grate system, which burns the unrefined and raw waste (Cudjoe et al. 2022). It consists of the main combustion chamber which is the space for the incineration of waste at 600-800 °C. It is a separate chamber surrounded by a furnace wall, a grate and an arch, which is the central part of the incinerator. The second combustion chamber is located behind the main combustion chamber to deeply burn organic matter such as dioxin at 900-1200 °C (Miao et al. 2022).

2.2. Impacts of Incineration

Although incineration is one of the most widely used methods worldwide, it also has disadvantages, as it has a negative impact on air quality. This is because incineration of medical waste contains many plastics that generates toxic air emissions such as dioxins and furans, which if not properly administered or managed, can cause serious health consequences (Yoon 2022). Other studies also agree that residues, such as ashes, contribute to the formation of dioxins and furans during incineration. Therefore, it is essential to equip incineration facilities with air pollution control devices to mitigate environmental pollution (Cudjoe et al. 2022). (Table 1)

Therefore, comprehensive exhaust gas purification systems are required due to the generation of compounds such as polychlorinated biphenyls, polycyclic aromatic hydrocarbons, toxic substances, or noxious gases such as hydrogen fluoride, hydrogen chloride and sulfur dioxide (Xu et al. 2020).

Dioxins caused by incineration were also found to be carcinogenic and associated with reproductive harm (Joob 2019). The impact of atmospheric emissions of mercury (Hg) is serious for public health and the environment, as Hg can accumulate in fatty tissues when inhaled. In addition, they cause damage to the nervous, reproductive, and excretory systems (Polat 2022).

On the other hand, the main substances as air pollutants are carbon monoxide (CO), sulfur dioxide (SO2), nitrogen oxides (NOx), particulate matter (PM) and volatile organic compounds (VOC). Also, according to existing literature, when MRI is incinerated, ashes are released into the atmosphere, which contains a large amount of highly toxic metallic substances such as cadmium, chromium, lead, mercury, zinc, and copper (Nabavi-Pelesaraei 2022). Similarly, another study conducted agrees that the ashes released into the atmosphere contain a large amount of highly toxic metallic substances and substances such as dioxin which causes water, soil, and air pollution as well as acid rain (Ahmad et al. 2019).

Finally, incineration waste such as bottom ash is sent to landfills for burial. In addition, it is important to mention the carbon footprint generated by transport from collection points to incineration plants or from the incineration plant to landfills. From 5 to 125 kg CO2/t of waste is generated, the range is large as it depends on the distance traveled, the weight transported, and the type of vehicle used (Rizan et al. 2021).

Table 1. Summary of Incineration Impacts

Incineration	Area of impact	Impact	Autor
COLLECTION	Socioeconomic	If workers do not collect MW with proper PPE, they could suffer from various diseases or be infected by viruses.	(Khalid et al. 2021; Egbenyah, 2021; Ahmed et al. 2021)
TREATMENT	Physical	- Release of ashes into the atmosphere containing metallic substances. - Release of highly toxic substances such as dioxins leading to the water, soil, and air pollution, as well as acid rain. - Release of greenhouse gases.	(Abouzid et al. 2022; El-Ramady et al. 2021; Riaz et al. 2019; Ashkan et al. 2022; Xu et al. 2020; Nabavi-Pelesaraei et al. 2022; Ye et al. 2022; Thind, P. S. et al. 2021)
	Biological	Alteration of terrestrial ecosystems.	(Polat, 2022)
	Socioeconomic	Health impact, Dioxins are carcinogenic and are also associated with reproductive harm in humans.	(Giakoumakis et al. 2021; Joob 2019; Polat 2022)
FINAL DISPOSAL	Physical	Organic compounds that break down easily and produce noxious gases, oxidize completely.	(Nabavi-Pelesaraei et al. 2022)
	Biological	Destruction of habitat by landfill contamination All pathogens that were a health hazard are burned when incinerated.	(Rizan et al. 2021)
	Socioeconomic	The collection and treatment of this waste generate many jobs as it is the most used method.	(Yoon 2022)

2.3. Pyrolysis Treatment

More advanced technology for the treatment of medical waste is pyrolysis operating at 540-830°C, including plasma/laser/oxidation-based pyrolysis and induction-based pyrolysis. It is one of the thermochemical processes in which the organic compounds (solid and liquid waste) present are disintegrated at high temperatures under anaerobic conditions or in the absence of oxygen (Dharmaraj et a., 2021).

The essence of the process is the thermochemical decomposition of organic matter at high temperatures in the absence of oxygen, due to which it breaks its chemical bonds, so that high molecular weight organic compounds are transformed into a liquid and combustible gases. Pyrolysis gas contains H2, CH4, CO, CO2 and other hydrocarbons and volatile organic substances. Pyrolysis temperature and time are substantial while moisture and particle size have a significant impact on the efficiency of the procedure (Giakoumakis et al., 2021).

The solid or liquid products formed after pyrolysis have high commercial value and can also act as an alternative energy substitute for existing fossil fuels, which are nowadays depleting (Dharmaraj et al., 2021). They can also be used in many applications related to chemicals, pharmaceuticals, and energy, among others. Therefore, pyrolysis treatment can be considered a promising strategy to dispose of wastes and convert them into energy products, especially at high temperatures (Yousef et al., 2021).

2.4. Impacts of Pyrolysis

Pyrolysis compared to other treatments is environmentally friendly due to its cleanliness and safety features. (Table 2). However, the process is slow and consumes a good amount of energy, hence the costs it generates are also high (Ye, 2022). However, it is important to mention that during the pyrolysis process 3 components can be obtained that can also help to reduce costs, the first one is a gas that can be used for the same process. Then you have a liquid substance that can serve as fuel or can be used for the manufacture of inert chemicals and finally you get a solid residue also known as Char that can also be used as fuel (Martin-Lara, 2021).

A pyrolysis reactor, by using its own products as an energy source, generates fewer costs for the company, has a lower environmental tax and produces less SO2 and NOx emissions than an incineration plant (Skrzyniarz et al., 2022). Also, compared to incineration, pyrolysis uses a lower process temperature, has lower particulate entrainment and although it also produces dioxins like the former process it generates lower emissions of air pollutants, leading to a lower impact on the environment (Gerasimov et al., 2019).

In addition, it has low carbon emissions due to lower generation of carbon monoxide (0.8-3.9 % by volume) and carbon dioxide (1.0-9.1 % by volume) compared to incineration, making it an environmentally friendly process. Finally, one study showed that investment in the pyrolysis process as a waste management system could generate an internal rate of return of up to 43 %, supporting its economic viability (Purnomo et al., 2021).

On the other hand, waste such as cotton and medical respirators were found to release the following gases during the pyrolysis treatment; H2O, CO2, CO, benzaldehyde, 2-butane, formic acid, hydrocarbons, and acetic acid. Likewise, plastic bottles containing medicines, produce substances such as toluene, benzene, styrene, and a small amount of C1-C4 aliphatic hydrocarbons during the pyrolysis treatment (Ding et al., 2021).

Table 2. Summary of Pyrolysis Impacts

Incineration	Area of impact	Impact	Autor
COLLECTION	Socioeconomic	Workers can be infected by viruses or suffer from diseases if they don't collect MW with proper PPE.	(Khalid et al. 2021; Egbenyah 2021; Ahmed et al. 2021)
TREATMENT	Physical	- Poor waste management leads to soil contamination. - Emission of NO, CO, HF, HCI, PM, CO2 and dioxins into the atmosphere. Contribution to the carbon footprint, due to the transport of RM. - Use of water in the process. Water contamination is possible if there is poor management.	(Ahmad et al. 2019; Skrzyniarz 2022; Rizan et al. 2021)
	Socioeconomic	- Emission of harmful gases impacts people's health. - Employment generation in pyrolysis plants.	(Ahmad et al. 2019)

FINAL DISPOSAL	Physical	- Pyrolysis is environmentally friendly due to its cleanliness and safety features. - The waste produced by pyrolysis is transported to landfills, which generate land contamination because the waste remains in the environment for a long time. -Landfills cause contact risk in nearby communities.	(Martín-Lara et al. 2021; Chisholm et al., 2021)
	Socioeconomic	- Internal rate of return of up to 43%. Work. - The final product is petroleum that is transportable and can be converted by catalysis into fuels and valuable products.	(Purnomo et al. 2021; Giwa 2019)

3. Methods

To assess the environmental impact, the Leopold matrix will be used to quantitatively measure the impact based on different environmental factors. A systematic literature review was conducted, taking into consideration articles between the years 2017-2021, as a basis for completing the matrix.

In the cause-effect matrix, the environmental element is placed in the rows and the actions in the columns. If there is a crossover between an element and an action, the box is divided into two. Magnitude is listed at the top with a rating of 1-10, with a positive sign if it is beneficial or a negative sign if it is a harmful effect. Importance appears in the lower part of the box also with a rating of 1-10 but always with a positive sign (Cotán-Pinto 2007).

The environmental elements consider 3 areas:

1. Physical elements: This considers the soil, air and water environments.
2. Biological elements: Focuses on flora and fauna.
3. Socio-economic elements: It considers impacts such as employment generation or contribution to the economy.

The actions correspond to the processes in the treatment of medical waste, which are divided into 3 main areas:

1. Collection: Considers the procedure from collection to transport to incineration or pyrolysis plants.
2. Treatment: The use of the system and waste generation.
3. Disposal: Identifies the impact whether landfill is used or whether recycling is used to manage the waste.

4. Results and Discussion

In the following, 2 Leopold matrices are presented based on the incineration and pyrolysis treatments, considering the elements and actions already mentioned. (Table 3)

4.1. Numerical Results

As can be seen in the matrix, the result is -523 with a total of 25 interactions between elements and actions. The element that stands out the most is the physical element with a score of -257, where air pollution (release of toxic substances) and soil pollution caused by the incineration of medical waste have the greatest influence. This element does not have any positive interaction to counteract the negative impacts. (Table 3).

The next element with the highest score is the biological element with -190, with the most damaging impacts being the incineration process and the emission of waste such as ashes, as these pollute the water, leading to damage to marine species. There is no positive impact on this element.

Finally, we have the socio-economic element with a score of -76, which is due to the risks of the generation of diseases due to the transport of toxic medical waste and the gases generated by incineration. The positive impact is highlighted in terms of the generation of jobs in the collection, transport, and incineration plants.

Table 3. Leopold matrix (Incineration Process)

INCINERATION PROCESS			EXTRACTION		TREATMENT		FINAL TREATMENT		POSITIVE AVERAGES	NEGATIVE AVERAGES	ARITHMETIC AVERAGES	IMPACT OF SUBCOMPONENT	IMPACT OF COMPONENT	IMPACT OF THE PROJECT
ELEMENTS AND ACTIONS			Waste collection	Transport to incineration plants	Use of the incinerator	Incineration residues	Landfills	Waste recycling						
ENVIRONMENTAL FACTORS		ENVIRONMENTAL IMPACTS	Resultados											
Physical	Soil	Soil pollution			-6/3	-6/3	-2/2			3	-40	-40	-257	-523
	Atmosphere	Contribution to climate change		-3/3	-5/5	-3/5				3	-49	-168		
		Air pollution			-10/7	-7/7				2	-119			
	Water	Water pollution			-7/7					1	-49	-49		
Biological	Flora	Ecosystem Alteration			-5/7	-5/3	-3/5			3	-65	-130	-190	
		Habitat Alteration			-5/7	-5/3	-3/5			3	-65			
	Fauna	Alteration of animal species			-5/7	-5/5				2	-60	-60		
Socioeconomic	Health	Decease generation	-5/7		-7/7	-5/5	3/1		1	3	-106	-106	-76	
	Economy	Contribution to the economy			-3/5					1	-15	-15		
	Employment	Employment generation	3/5	3/5	3/5				3	0	45	45		
POSITIVE AVERAGES			1	1	1	0	1	0	4				-523	
NEGATIVE AVERAGES			1	1	9	7	3	0		21				
ARITHMETIC AVERAGE			-20	6	-316	-162	-31	0			-523			

Table 4. Leopold matrix (Pyrolysis Process)

PYROLISIS PROCESS			EXTRACTION		TREATMENT		FINAL TREATMENT		POSITIVE AVERAGES	NEGATIVE AVERAGES	ARITHMETIC AVERAGES	IMPACT OF SUBCOMPONENT	IMPACT OF COMPONENT	IMPACT OF THE PROJECT
ELEMENTS AND ACTIONS			Waste collection	Transport to pyrolisis plants	Use of the pyrolisis reactor	Pyrolisis products	Landfills	Waste recycling						
ENVIRONMENTAL FACTORS		ENVIRONMENTAL IMPACTS	Resultados											
Physical	Soil	Soil pollution	-6/7		-2/3		-5/5			3	-73	-73	-140	-57
	Atmosphere	Contribution to climate change		-3/3	-2/3	-3/5		5/1	1	3	-25	-55		
		Air pollution			-5/3	-5/3				2	-30			
	Water	Water pollution			-2/3	-2/3				2	-12	-12		
Biological	Flora	Ecosystem Alteration								0	0	0	0	
		Habitat Alteration								0	0			
	Fauna	Alteration of animal species								0	0	0		
Socioeconomic	Health	Decease generation	-5/7			-3/3				2	-44	-44	83	
	Economy	Contribution to the economy			6/7			5/5	2	0	67	67		
	Employment	Employment generation	3/5	3/5	3/5			3/5	3	1	60	60		
POSITIVE AVERAGES			1	1	2	0	0	3	7				-57	
NEGATIVE AVERAGES			2	1	4	4	1	0		13				
ARITHMETIC AVERAGE			-62	6	24	-45	-25	45			-57			

In the case of the pyrolysis process, a score of -57 was obtained with a total of 19 interactions. (Table 4). The most relevant element, in this case, is also the physical element with a score of -140, mainly due to the emission of harmful gases into the atmosphere (air pollution) and due to the pollution generated by the waste when it is taken to landfills (soil pollution).

In the case of the socio-economic element, there was a positive impact with a value of 83. The collection, treatment and disposal processes contribute to employment generation and the economy in various ways. For example, one study claims that investing in this technology would have a rate of return of up to 43%. Negative effects include damage to health that can occur in the collection and treatment areas.

After the quantitative evaluation of both treatments, incineration, and pyrolysis, through the Leopold matrix, it can be concluded that both processes generate environmental pollution, especially in the physical factor.

The results obtained in the study are like those of Nabavi-Pelesaraei (2020) and Ye (2022) where it is mentioned that the production of toxic substances such as ash and dioxin cause air, soil and water pollution, as well as acid rain. Similarly, the results of the present study show that the incineration of medical waste leads to increased air pollution. Authors Xu (2020), Yoon (2022) and Abouzid (2022) agree that it generates major air pollution, as it easily produces dioxins as well as polycyclic aromatic compounds, polychlorinated biphenyls and other highly toxic substances and noxious gases, since most medical waste is made of plastic. This is supported by author Rizan (2021) as within his discussion it is mentioned that incineration generates the largest carbon footprint.

4.2. Selected Treatment

Therefore, authors Gerasimov (2019) and Skrzyniarz (2022) considered that the pyrolysis treatment is a better alternative to dispose of medical waste because it generates less waste and emits a lower amount of air pollutant emissions, such as SO2 and NOx which leads to a lower impact on the environment. Furthermore, Purnomo (2021), Chisholm (2021) and Siwal (2021) point out that gaseous and liquid products can be obtained during the process, which can be used as a source of chemicals and fuels. On the other hand, Martin-Lara (2021) also mentions that a solid product is obtained that functions as an adsorbent for lead present in aqueous media.

5. Conclusions

After the quantitative evaluation of the environmental impact caused by the management and final disposal of medical waste by incineration and pyrolysis using the Leopold matrix, it can be concluded that both methods are polluting and harmful to the environment because both obtained a negative value. In the case of incineration, a value of -523 was obtained and the pyrolysis method a value of -51.

Although the accuracy of the analyses in this study is inevitably subjective, this research is a starting point for further research into new, more eco-friendly, and effective methods of medical waste management and disposal. Although treatment and disposal options such as incineration and pyrolysis have been effective in the management of medical waste (including COVID-19 waste), new and improved technologies have recently been introduced. Some of the most recent include irradiation (UV, Cobalt 60, electron beam), thermal (quartz infrared dry heat or plasma pyrolysis) and other inactivation mechanisms (including electrothermal inactivation and gasification) (Andeobu et al. 2022).

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