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Identifying the Characteristics After Microwave Inactivation for Recovering Materials to Make Plastic Wood

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Abstract

In hospitals in Colombia, inactivation processes of sanitary wastes are usually carried out by external managers, which are taken directly to the landfill to close the cycle after removing the biological load, which leads to the generation of high CO_2 emissions not only for the process implemented, but also for the transport that this implies. This work shows the main results of the inactivation process with a commercial microwave technology, for which it was necessary to run 10 samples of sanitary waste from different areas (surgery, pediatric emergencies, hospitalization, etc.), and evaluate the effectiveness of inactivation by measuring the presence of microorganisms, the inactivated by-products were characterized and analyzed thoroughly to identify their potential as raw material for plastic wood. The carbon footprint associated with the avoided transport to common sites outs/ide the cities to inactivate high volumes of waste and the subsequent emissions associated with the final landfill were also determined. In this sense, it was shown that the inactivation process is efficient and allows compliance with Colombian regulations, since there is no evidence of the presence of microorganisms. In addition, the characterization process identified that the waste contains mainly plastic and textile waste, which makes it a good alternative for obtaining plastic wood and closing the cycle of such waste. Finally, it was evidenced that scenario 1, in which the Sterilwave was used, is undoubtedly the alternative that generates the least emissions in tons of CO_2e.

Keywords: Healthcare Waste; Microwave; Circular Economy; Environment; Valorization; Carbon Footprint; Hospital; Plastic; Textile; Waste Management.

Identificación de las Características de Tras la Inactivación por Microondas Destinada a Recuperar Materiales Para Producir Madera Plástica

Resumen

En los hospitales en Colombia por lo general se realizan procesos de inactivación de los residuos sanitarios por gestores externos, los cuales son llevados directamente al relleno sanitario para cerrar el ciclo luego de retirar la carga biológica, lo cual con lleva a la generación de altas emisiones de CO_2 no sólo por el proceso que se implementa, sino también por el transporte que esto implica. Es así como, en este trabajo se muestran los principales resultados del proceso de inactivación con una tecnología comercial de microondas, para la cual fue necesario correr 10 muestras de residuos sanitarios de diferentes áreas (cirugía, urgencias pediátricas, unidades de cuidados intensivos, hospitalización, etc), y evaluar la efectividad de la inactivación midiendo la presencia de microorganismos, los subproductos inactivados fueron caracterizados y analizados exhaustivamente para identificar su potencial como materia prima para madera plástica. También se determinó la huella de carbono asociada al transporte evitado a los lugares comunes fuera de las ciudades para inactivar altos volúmenes de residuos y a las emisiones posteriores acompañadas del vertedero final. En este sentido, se logró evidenciar que el proceso de inactivación es eficiente y permite el cumplimiento de la normatividad colombiana, ya que no se evidencia la presencia de microorganismos, además que en el proceso de caracterización se identificaron que los residuos contienen principalmente residuos plásticos y textiles lo que les permiten ser una buena alternativa para la obtención de madera plástica y el cierre de ciclo de dichos residuos. Finalmente, se logró evidenciar que el escenario 1 en el que se utilizó el Sterilwave, siendo sin duda la alternativa que menos emisiones genera en toneladas de CO_2e.

Palabras claves: Residuos Sanitarios; Microondas; Economía Circular; Medio Ambiente; Valorización; Huella de Carbono; Hospital, Plásticos, Textiles, Tratamiento de Residuos.

1. Introduction

Medical waste covers a wide range of by-products derived from health-care facilities such as hospitals, laboratories and mortuary and autopsy centers among others. All these wastes are frequently contaminated by blood, body fluids, or human cell; and hence, represent a high risk for potential infectious. Although all hospital waste is not necessarily health-care waste, most of them are sometimes hard to be separated once are disposed; and therefore, fall in the category of hazardous. According to World Health Organization (WHO), 1 in 3 healthcare facilities globally do not safely manage healthcare waste (WHO, 2022). The generation of these waste have been increasing worldwide due to different health affectations, including COVID-19 pandemic. In this regard, it is worth mentioning those waste generated from single-use plastics, such as personal protective equipment (PPE), COVID-19 testing and vaccinations. For instance, the average waste generation rate ranges from 0.3–8.4 kg of health-care waste per hospital bed per day (Singh et al., 2021). However, the pandemic demands for medical resources could be a potential cause for a rapid global increment in hospital waste generation (Singh et al., 2020; Singh et al., 2021). Roughly speaking, high-income countries generate on average up to 0.5 kg of health-care waste per hospital bed per day; while low-income countries generate on average 0.2 kg (WHO, 2018). According to the latest published report by the United Nations Environment Programme (UNEP), the rise in healthcare waste from COVID-19-associated healthcare facilities was reported to be 3.4 kg per person per day worldwide, and approximately 2.5 kg per bed per day of COVID-19 healthcare waste was produced in developing countries (UNEP, 2020).

In addition, the safe management of these waste are lacking, especially in developing economies. Poor waste management may affect healthcare workers through needlestick injuries, burns and exposure to pathogenic microorganisms. Also, it has the potential to affect communities living in proximity to poorly managed landfills and waste disposal sites, because of contaminated air, poor water quality or disease-carrying pests (WHO, 2022). Although COVID-19 pandemic has shrunken economic activity, and it did not slow the relentless advance of climate change, the generation of waste plastic grew more than 10% globally during 2019 and 2021 (Adyel, 2020). Indeed, as oil prices plummeted, the manufacture of virgin plastics from it was less expensive than recycling (Kimani, 2020). As a result, these issues have increased the pressure on waste management practices, and have triggered to inappropriate strategies, including mobile incineration, direct landfills, and local burnings (Silva et al., 2020). Likewise, pandemic-associate plastic waste seems to lead to marine life, as many of them reached the ocean. It is estimated that more than 8 million tons of these waste have been generated globally, and more than 25,000 tons have entered to the global ocean (Peng et al., 2021).

Thus, the search for economically and environmentally viable alternatives through processes such as upcycling is practically mandatory not only for a proper disposal of these waste but also for recovering valued-added products that can be reincorporated in practical processes. Health-care waste have commonly treated by incineration without no recovering of products and both high costs and risks for environment and public health (Takata et al., 2013). Non-incineration technologies, such as steam sterilization and microwaves, are the preferred treatment methods mainly due to the fact that they appear to emit fewer pollutants and generate non-hazardous residues (Dursun et al., 2011). These technologies are commonly small in size; and therefore, present an important advantage since allow the treatment waste in the same center, i.e. practically *in-situ*. For these reasons, risks due to spills, leaks, or accidents, as well as the CO_2 emissions from transport to other sites are avoided.

Among these technologies, inactivation by microwaves is recently gaining important attention given the high efficiency, low operating costs, drastic reduction volume, safety and no by-products generation (water or liquid effluents) while the health-care waste are sterilized. This technology is being implemented more and more in the world since its capability to inactivate all pathogen and bacterial endospores (*B. stearothermophilus* or *B. subtilis*) to Level III (reduction of 6. Log10 for vegetative cells or 4.Log10 for *Bacillus* spores) (STAATT, 1998; Oliveira et al. 2010; WHO, 2014). In this process, the common temperature and residence time used ensure that the hazardousness of the waste was eliminated. In addition, the scientific literature has demonstrated how microwaving leads to the inactivation of vegetative *Escherichia coli* and spores of *Bacillus subtilis* (Glodblith & Wang, 1997), *Streptococcus faecalis* and *Saccharomyces cerevisiae* (Lechowich et al., 1969), among others. According to the waste's manual in Colombia, a proper inactivation process must be guarantees that the resulting product does not contain *Bacillus sterothermophilus* (MSPS & MADS, 2020, p. 46.).

Inactivation by microwaving has been thoroughly studied in literature, and many works were found showing the performance and influence of governing variables using several waste including health-c/are ones (Oliveira et al., 2010; Zimmermann, 2017; Kollu et al., 2022), and on the assessment given the presence of some microorganisms (Lechowich et al., 1969; Glodblith & Wang, 1997; Oliveira et al., 2010). However, no works were found on detailing not only the inactivation performance of commercial equipment using medical waste generated *in-situ*, but also on the identification and characterization of the inactivated product aimed at being used in the industrial sector as raw material.

In Colombia, around 640,000 tons of hazardous wastes were generated in 2019 (IDEAM, 2019). The economic activities leading to this waste are: i) mixtures of waste oil and water or hydrocarbons and waters (52.5%), ii) industrial operations (10.8%), iii) health-care facilities (6.6%), iv) mineral oils (6.0%), v) lead compounds (5.5%), vi) production or processing of petroleum coke and asphalt (4.2%), vii) production, preparation and use of dyes and pigments (1.6%), viii) acidic or basic solutions (1.4%), ix) industrial pollution control (1.3%), x) chemical product (0.8%) and xi) others (9.5%) (IDEAM, 2019). In the country, it has different types of health-care waste treatments such as biological (anaerobic digesters, bioremediation, etc), physicochemical (neutralization, evaporation, disinfection, etc) and thermal (incineration, high efficiency inactivation, pyrolysis, and gasification) (IDEAM, 2019). Although microwaving treatments offer an attractive alternative for dealing with waste generated in clinics, hospitals and health centers, this technology was rather scarce in Colombia, and autoclave inactivation was more widely used. Colombia is the third country from Latin American to join the OECD, following Chile and Mexico (OEDC, 2020). Among other commitments, this country must leverage policies and practices engaged with waste management and circular economy (OEDC, 2021). In this sense, the increasing demand of resources, and the continued need for safeguarding nature, should lead to society both develop and implement highly efficient technologies capable not only to deal with waste generation but also to produce secondary raw materials from them.

The aims in this work were the inactivation process of health-care waste generated in a major Hospital in Medellín (Colombia) was tested *in-situ* using a commercial microwave technology. In addition to running 10 health-care waste samples from different areas (surgery, emergency pediatrics, intensive care units, hospitalization, etc), and assessing the inactivation effectiveness by measuring the presence of microorganisms, the inactivated by-products were thoroughly characterized and analyzed to identify their potential as raw material for plastic wood. The carbon footprint associated with avoided transport to the common sites out of the cities to inactivate high volumes of waste and to the later accompanied emissions of the final landfill is also shown. This work intends to provide an important impetus to recovering materials from health-care waste aimed at being used in other industrial processes. Thus, the outcomes found herein are expected to contribute with the circularity of materials involved in a complex sector as the health one in a developing country as Colombia.

2. Materials and methods

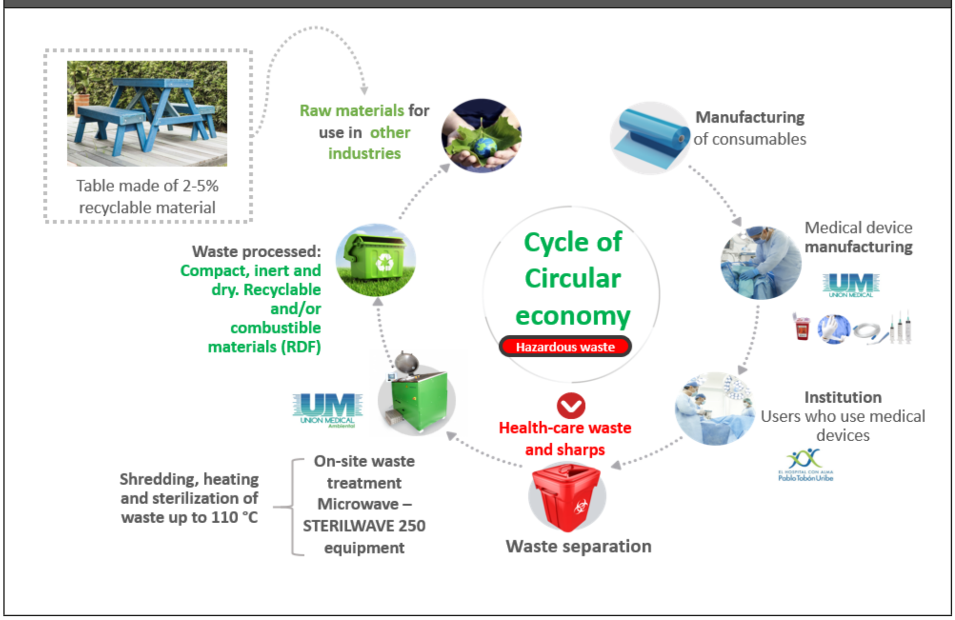
2.1. Inactivation equipment

The facility used to inactivate the hospital waste is electric technology capable of both shredding and sterilizing by microwaves in one single vessel. Sterilwave 250 was a single reactor where a simple and fully automatic cycle which shreds and sterilizes any type of health-care waste. The waste inactivation time was between 30 and 40 min. The process produces waste with a low percentage of moisture, with reduced particle size and a heterogeneous composition, which could be further easily managed.

Figure 1 shows the process diagram of cycle of circular economy, which must of STERILWAVE 250 equipment has a capacity of 20-25 kg for a 40-minute cycle. To start operation, the weights of the waste to be processed were recorded and loaded manually. Then, the safety door was closed, and the operator starts the process automatically. The residues were finally ground by rotating blades at up to 1500 rpm, taking between 5 and 7 minutes. The temperature increases to 70° C with the friction of the blades and its was obtained reduction in waste volume of up to 85%.

Subsequently, the waste was exposed to a temperature above 100° C by means of an HF (microwave) generator and kept at this temperature for 20 minutes for sterilization. At the end of the process, the sterilized waste was automatically discharged into a metal container located at the bottom of the equipment. The trap door of the container opens, and the treated waste was automatically transferred.

Figure 1. *Cycle of circular economy diagram of health-care waste*



2.2. Health-care waste samples

Based on the dictionary of supplies available at the hospital, a study was made of the materials present in the health-care waste generated in the surgery area, diagnostic aids (DA), and other areas such as hospitalization, with the purpose of knowing their approximate composition, and thus supporting the results obtained from the characterization of the inactivated waste. Likewise, this stage allows us to obtainer significant preliminary information in order to propose possible alternatives for use and recovery.

This made it possible to identify 91 products that end up as health-care waste, including probes, used disposable clothing, bandages, and surgical gloves, among others. Subsequently, a search of the materials present in these products was carried out, recognizing the different types of plastics, metals, and textile fibers.

Of all the materials identified in the health-care waste, the most frequent by product units, i.e., those found most frequently in the 91 products, were polyvinyl chloride (PVC) (30 units), polypropylene (PP) (25 units), silicone (21 units), cotton (12 units), cellulose (12 units), polyurethane (11 units), low-density polyethylene (LDPE) (10 units), stainless steel (8 units), latex (7 units) and polyester (7 units). Thus, there was a high probability that the health-care waste generated in the hospital was mainly composed of these materials, so that, by analyzing their properties, an approximation of the mixing characteristics of these products would be obtained. In addition, these wastes include, to a lesser extent, materials such as steel, silver, aluminum, high-density polyethylene (HDPE), acrylonitrile butadiene (ABS), polycarbonate, and nylon, among others.

The samples used and inactivated in this work were: Surgery (S1); surgery (S2); X-ray, surgery, pediatric emergency, and hospitalization waste (S3); private emergency room, pediatric intensive care unit, adult emergency room, adult intensive care unit and pediatric hospitalization (S4); surgery, diagnostic aids and pediatrics (S5); surgery, hospitalization and intensive care units (S6); surgery, diagnostic aids and adult emergencies (S7), element surgery, diagnostic aids and X-rays (S8); exclusive surgery and adult emergency room (S9); and emergency pediatrics, surgery, elements and cancerology (S10).

2.3. Sampling of inactivated health-care waste

Figure 2 shows the bags with health-care waste when they enter the inactivation equipment and how the waste remains after the inactivation process was carried out, showing that there was a reduction in volume of more than 80% and a reduction in weight of approximately 25%. In addition, the residues at the end of the process were characterized by being dry and with a very fine particle size almost unrecognizable to what was initially present and could be stored for a long period of time because the odors of such residues were reduced.

Figure 2. *Health-care waste before and after inactivation process and sampling of the sterilized health-care waste (Carried out with an Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM)-accredited laboratory).*

After the inactivation process in the microwave to carried out the characterization, a representative sampling was performed portion for laboratory analysis. The sampling methodology selected to obtain the samples was SYSTEMATIC PROBABILISTIC SAMPLING IN SPACE ON INDEPENDENT OR SEPARATE UNITS. In order to obtain a representative sample portion, five (5) points were defined on the storage unit (container) for the collection of aliquots in a sampling pattern type X, from each of the five (5) points. Four (4) aliquots were taken from each of them using previously sterilized tweezers in the 0 - 15 cm transect. The collected samples were placed in a new and clean plastic bag (**Figure 2**). The samples were then delivered to the accredited laboratories for the analyses described below.

2.4. Analysis for the presence of microorganisms

For the characterization of the samples, the provisions of Resolution 1164 of 2002 and the methodologies of the AOAC (Association of Official Analytical Chemists), SM 9230C and SM 9213E, were considered.

In this process, the following microbiological tests were performed at the request of the contracting company: *Bacillus stearothermophilus*, *Bacillus subtilis*, *Enterococcus faecalis*, *proliferating moniliform fungi*, *Pseudomona aeruginosa* and *Staphylococcus aureus*, in accordance with Section 7.2.4.2 of Resolution 1164 of 2002, which adopts the Procedures Manual for the Integral Management of hospital and similar waste.

According to Resolution 1164 of 2002, the procedures for inactivation and treatment of hospital and similar waste must generate a type of waste that complies with the following standards or maximum limits of microbiological agents, as a requirement for disposal in sanitary landfills (**Table 1**).

Microorganisms	Maximum limit	Method
Proliferating moniliform fungi	ND	-
Bacillus subtilis	ND	AOAC 980.31 Ed 19
Bacillus stearothermophilus	ND	AOAC 972.45 Ed 19
Enterococcus faecalis	ND	Standard methods 9230C Ed 2012
Mycobacterium tuberculosis hominia	ND	DIN 58943
Herpesvirus	ND	-
Poliovirus	ND	-
Staphilococcus aureus	ND	AOAC 995.12 Ed- 19
Pseudomona aeruginosa	ND	Standard methods for the examination of wastewater 9213E 23nd Ed 2017

Table 1. *Maximum standards for microorganisms*

ND: Not detected

2.5. Samples for elemental, proximate analysis and heating value analyses

Elemental, proximate and heating value analyses were conducted on the ten samples. Elemental analysis was performed using a Thermo Scientific Flash 2000 device. Proximate analysis was carried out according to the Spanish UNE-CEN/TS 14774-3 ex and UNE-CEN/TS14775 ex standards for determining moisture and ash content, respectively, while volatile matter was measured according to the oven drying method specified by the ISO 5623:1974 standard. Fixed carbon was determined by difference. Finally, the higher heating value (HHV) was determined by applying the ASTM 240-09 standard using an IKA C2000 oxygen bomb calorimeter.

2.6. Thermogravimetric analysis

TGA was performed under inert atmospheric pressure using a METTLER TOLEDO at one heating rates of 10 °C/min. In all cases, the sample weight was fixed at 10± 0.5 mg, while the particle size and the N_2 flow rate were 177–250 µm and 150 mL/min, respectively. The thermobalance was starting the heating programmed from room temperature to 800 °C. The temperature range for studies was taken as 25–800 °C. The experimental conversion (X_{exp}) was calculated from Eq. (1).

$$X_{\text{exp}} = \frac{m_i - m}{m_i - m_f} \quad (1)$$

Where m_i is the initial mass of sample (mg); m is the sample mass at time t (mg); and m_f is the sample mass (mg) at 800 °C.

2.7. Carbon footprint measurement

In this article we present a summary of the methodology applied to calculate the carbon footprint, which will be published in detail in a future publication. In which, it was borne in mind that the transport of hospital waste from the place of generation to the treatment or disposal site generates critical impacts on the population and the environment due to the distances to be covered.

The Carbon Footprint was determined based on the GHG Protocol methodology developed by the World Resources Institute and the World Business Council for Sustainable Development. This methodology makes it possible to identify and quantify greenhouse gas (GHG) emissions, expressed in tons of CO_2 equivalent, according to the dynamics of the organization, its processes and operations. The GHG Protocol defines three different scopes to help identify the sources of direct and indirect emissions, thus improving transparency, providing benefits for different types of organizations, developing climate change policies and setting corporate targets.

Thus, in the development of this research project, three different scenarios were considered to identify the scenario that provides the greatest reduction in greenhouse gas emissions. The scenarios were as follows: (i) ***First scenario***, on-site inactivation at the hospital and transport to landfill; (ii) s***econd scenario - current process at the hospital***, health-care waste taken to an external manager for inactivation in autoclave from Medellín to Manizales (202 km) and disposal in landfill near the inactivation site and finally, (iii) ***third scenario - Future alternative proposed by the operator***, the waste is collected and transported to an area 4 km from Medellín for inactivation by autoclave and final disposal.

3. Results and discussions

3.1. Presence of microorganisms

The definition of the term “sterilization” is the complete destruction of all living microorganisms. In this sense, **Table 3** shows the microorganisms that, according to Colombian regulations, must be evaluated in sterilized health-care waste to verify if the process was efficient. The ten samples evaluated show that the sterilization process with the Sterilwave 250 equipment is a good alternative, since the different microorganisms evaluated have a negative presence because of the characterization and at the same time it allows to demonstrate compliance with numeral 7.2.4.2 of Resolution 1164 of 2002 (**Table 1**).

In addition, the STAAT II (State and Territorial Association on Alternative Treatment Technologies) recommends at least identifying that the presence of *Mycobacterium s.p.*, *Bacillus stearothermophilus* and *Bacillus subtilis* is reduced at the time of submitting biosanitary waste samples to disinfection processes (STAATT, 1998). It can be verified that the samples reported in **Table 2** comply with the non-presence of these three microorganisms. In addition, STAAT II mentions that countries may include other biological indicators such as bacteria, fungi and viruses that were recommended by regulations to be sufficient for disinfection tests to be efficient, which shows that the results comply with international and national indicators.

Table 2. *Microbiological characterization results*

Sample / Microorganisms	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Proliferating moniliform fungi	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
Bacillus subtilis	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
Bacillus stearothermophilus	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
Enterococcus faecalis	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
Staphilococcus aureus	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
Pseudomona aeruginosa	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT
Mycobacterium tuberculosis	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT

NT: Negative

3.2. Elemental, proximate and heating value analyses

Table 3 shows the elemental, proximate and heating value analyses of the ten samples considered in this work. According to the origin of the materials that were part of the sample, they show a high carbon content (58.96-78.00 wt%), moreover oxygen and hydrogen content was relatively similar (14.09-25-79 wt% and 7.74-11.58 wt%, respectively), with no major differences between them. Nitrogen and Sulphur content was very low (<3.46 wt% and <0.16 wt%, respectively). In general terms, all these elements come from the main constituent of raw materials such as plastics, textiles, among others (Na et al., 2008; Cho et al., 2010; Hall et al., 2009) related to the raw materials with the greatest presence in the supplies used in the hospital areas that later become health-care waste (**Figure 3**).

On the other hand, the volatile matter content for all samples is high (84.72-97.19 wt%), which gives it potential as a raw material for the production of alternative fuels and other raw materials for the chemical industry (Kara, 2012; Karmakar, 2020). Moreover, the ash and fixed carbon content were low (2.28 – 5.80 %wt and 0.53-5.02 %wt, respectively), except for the case fixed carbon of S2, which was high (11.58 %wt), this may be attributed to the fact that this sample may have a high content of cellulose attributed to the textiles present in the residues, since this material presents a fixed carbon value of approximately 9.90 %wt (dry basis), as reported by Heikkinen et al. (2004) (Heikkinen et al., 2004). On the other hand, Zannikos et al. (2012) in their study of mixtures of biomass (cellulose contents) with plastics reports fixed carbon values of 11.62 wt% for the 50%HDPE+50%straw mixture (Zannikos et al., 2012).

The HHV for the samples were between 24.39 and 38.38 MJ/kg, which were similar to those obtained by Dianda et al. (2018), who obtained refuse derived fuels (RDF) from municipal solid waste with a calorific value between 17-36 MJ/kg with a content of approximately 40% of organic waste, indicating that they could be used to replace part of the coal in the main burning and calcination processes of the cement industry (Dianda et al., 2018). From this, it can be mentioned that as the wastes of this project have similar calorific values, they have the same potential.

***Table 3**. Proximate, elemental and heating value analyses*

Samples	Elemental analysis d.b. (wt.%)					Proximate analysis d.b. (wt.%)			HHV (MJ/kg)
	C	H	O	N	S	A	MV	FC	
S1	67.04	10.20	17.88	1.16	0.11	3.87	94.42	1.71	34.15
S2	78.00	11.58	14.09	0.90	<0.10	2.28	97.19	0.53	38.38
S3	70.65	10.42	15.57	2.56	0.11	3.19	93.09	3.72	33.17
S4	58.96	9.21	25.23	0.71	<0.10	5.76	89.22	5.02	24.39
S5	65.78	7.55	17.40	2.17	<0.10	3.29	84.72	11.98	27.29
S6	76.70	11.44	12.65	3.46	0.16	2.81	96.52	0.67	37.52
S7	63.14	7.74	22.12	1.80	0.10	4.39	91.69	3.92	31.12
S8	63.30	9.76	18.72	2.76	<0.10	3.69	93.81	2.50	27.12
S9	63.27	9.89	21.28	0.50	<0.10	4.78	91.51	3.71	32.10
S10	60.99	9.50	25.79	0.47	<0.10	5.80	90.40	3.79	29.78

M: Moisture; VM: Volatile Material; FC: Fixed Carbon; C: Carbon, H: Hydrogen, O: Oxygen, N: Nitrogen; S: Sulphur, d.b.: dry basis, HHV: higher heating value

3.3. Thermogravimetric analysis

The thermogravimetric analysis performed on the samples in **Table 2** allowed the behavior of the different materials present in the samples to be reviewed. Graphs of the degree of conversion (X) and the rate of weight loss (dX/dt) versus temperature were plotted (**Figure 3** and **Figure 4**). These figures show important thermochemical parameters such as initial temperature (T_i), final temperature (T_{final}) and maximum temperature (T_{max}) of degradation, as well as the qualitative and semi-quantitative identification of the possible materials present in the mixtures of inactivated health-care waste, in order to identify the components and define the best potential for utilization while avoiding landfill disposal. Also, **Figure 4** shows that the T_i for all samples was approximately 250 °C, and T_{final} at around 800 °C. It is important to mention that the behavior of these materials was very heterogeneous, given the presence of different slopes throughout the temperature range studied.

Figure 3. *Weight loss as a function of temperature.*

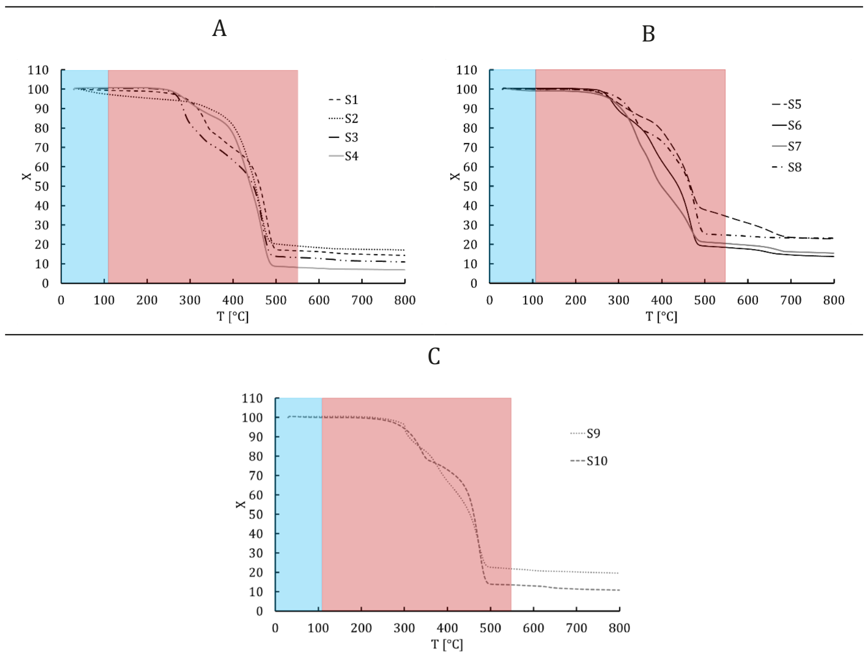


Figure 4 shows the deconvolution of the peaks identified in each of the samples, making it possible to identify and semi-quantify the presence of materials susceptible to recovery by recycling techniques. The analysis of each of the peaks present in the samples of the inactivated health-care waste suggests the presence of LDPE and PP in each of the samples, since these materials were characterized by having a mass loss in a temperature range between 311 - 500 °C, starting their decomposition at 327 and 380 °C, respectively (Shin Park et al., 2012). In the case of polyester, latex and polyurethane, mass loss can be generated between 250-475 °C (Chen et al.,

2015; Hall et al., 2009; Font et al., 2001). On the other hand, the deconvolution of the *dX/dT* plots also suggests the presence of PVC given of two degradation zones characteristic of this material: between 200 and 380 °C (attributed to the release of HCl and minor hydrocarbons), and between 400 and 550 °C (attributed to the degradation of the remaining organic materials) (Shin Park et al., 2012; Torres et al., 2020). These peaks were evident in most of the samples of the inactivated health-care waste, which was related to the presence of these materials, in sync with the results shown in numeral 2.2.

That the presence of different plastics usually results in different degradation zones, depending on the similarity of the structures that make up the plastic material. For example, Chhabra et al. reported two important zones, the first between 283 and 416 °C, and the second between 416 to 480 °C, in a mixture of HPDE, LDPE, PP, PS and PET, an important interaction effect between the plastic samples present in the mixture (Chhabra et al., 2019). On the other hand, textile materials commonly decompose between 300 and 385 °C, since they were mostly composed of cellulose as mentioned above and have a peak T_{max} *of* around 360 °C (Anca-Couce, 2016).

Figure 4. *Deconvolution of the thermograms for each of the samples.*

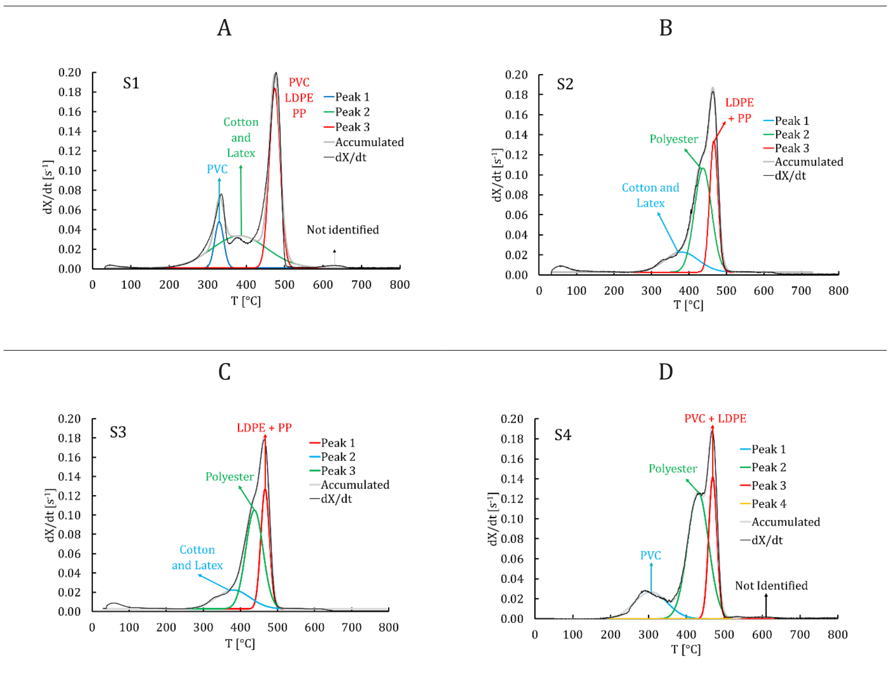
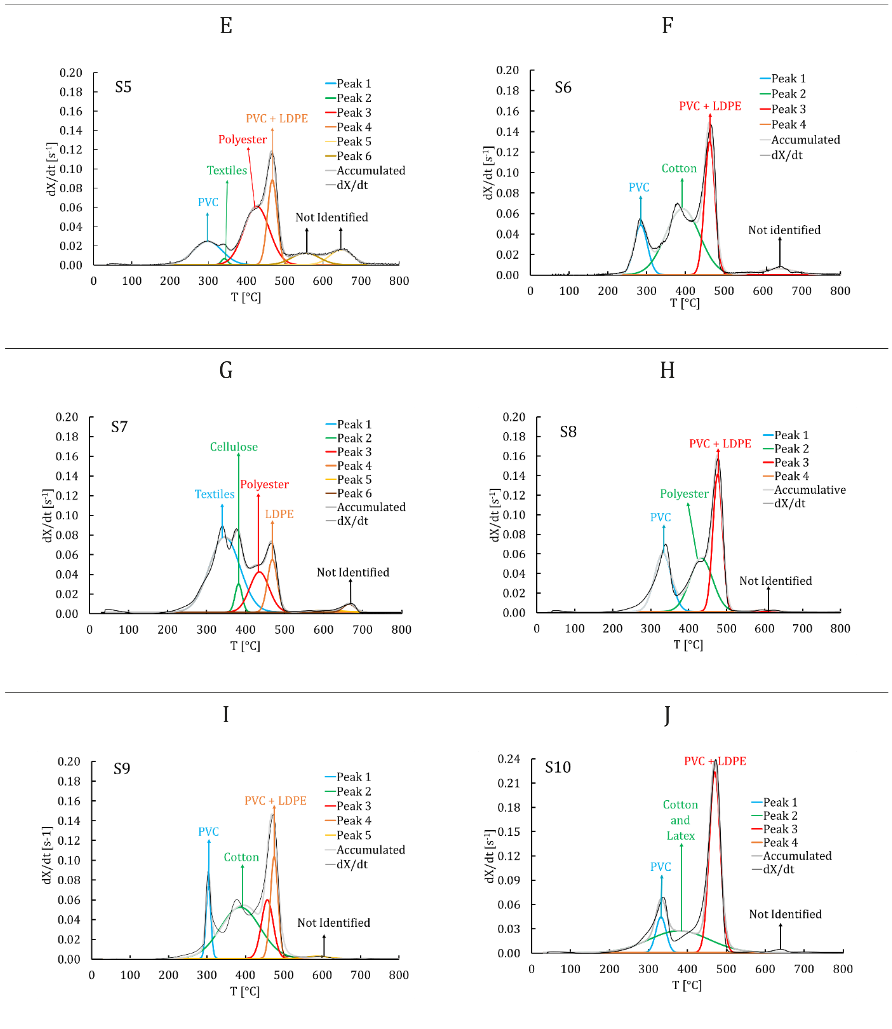


***Figure 4.** Deconvolution of the thermograms for each of the samples.*



From the areas under the curve and the association of the compounds to the deconvoluted peaks (**Figure 4**), the percentage identification of the possible materials that were present in the analyzed bio-sanitary waste samples was performed. Thus, identifying that PVC, Polyester and LDPE were present, since in most of the sample representative contents higher than 10% by mass were present and the sum between the polymers (PVC, PP, LDPE and polyester) was in a range between 25-99% by mass. In the case of textiles, which as mentioned were characterized by their high cellulose content, there were contents higher than 6% and the sum the varieties of textiles, cotton and cellulose was between 6-63% in mass, these variations could be attributed largely to the origin of the waste generated in the different areas of the hospital.

3.4. Circular economy strategy: plastic wood from inactivated health-care waste

With the previously obtained and analyzed results of thermogravimetry, elemental and proximate analysis and calorific value, the waste presents important conditions to be used as raw material in energy recovery processes as an alternative fuel due to its high calorific value (numeral 3.2). In addition, the aim was to add value by converting ordinary waste into recyclable waste, i.e. by marketing or offering waste to companies that transform it into raw material for the production of new products such as plastic wood for the manufacture of chairs, pallets for the storage of producers, among others. In this case, samples S1, S4, S8 and S10 were used to obtain the plastic wood (**Figure 1**).

The sample was prepared via extruding molding, where once the mixture was uniformly mixed, its final shape was given by extrusion molding to different sizes. These composites were prepared by mixing 2-5% of the sampling of inactivated health-care with 98-95% of a polymer matrix (polyethylene and polypropylene) and additives. The extrusion process was carried out at 150-200 °C with a motor 60 HP.

The properties of the sample measured were the flexural tests carried out by according to ASTM D 648-2016, the deterioration of weathered plastic using an artificial chamber by ASTM D4329-13 and the water absorption test conducted as per NTC 4917-2001. The water absorption was one of the most important characteristics of plastic wood exposed to environmental conditions that determine their ultimate applications (Li et al., 2014).

3.5. Carbon footprint measurement

The transportation of bio-sanitary waste for inactivation and disposal generates greenhouse gas emissions that have a negative environmental impact on the air and human health. This is currently the case because the waste generated in the hospital was transported approximately 202 km away to be inactivated and disposed of in the landfill in the city of Manizales. With on-site microwave technology, the distance was significantly reduced for the inactivation and disposal process, thus contributing to the reduction of CO_2 emissions generated by the hospital.

The differences between each of the scenarios proposed for the inactivation process of the health-care waste generated in the hospital surgery area (numeral 2.8). Scenario 1 generated 104.50 tCO2e/year, which were attributed to direct emissions from the use of refrigerants and energy consumption, and indirect emissions from the generation and transport of health-care waste. In the case of scenario 2 and scenario 3 there were 223.73 and 214.64 tCO_2e/year, respectively, which were associated with indirect emissions from the consumption of natural gas in the inactivation process, generation, and transport (before and after inactivation).

It is important to highlight these alternatives has a value proposition, it was evidenced by the carbon footprint results of scenario 1 in which the Sterilwave 250 equipment was used, being undoubtedly the alternative that generates the least emissions in tones of CO_2e and its implementation would excellent alternative for the management of health-care waste, as it contributes to its environmental commitment and compliance with SDGs 3, 4, 8, 11, 12 and 17.

A view to circular economy strategies for obtaining plastic wood and the contribution to the reduction of CO_2 emissions by reducing the volume of waste by more than 70% and avoiding transporting waste from the hospital to an inactivation site and finally disposing of it in the landfill.

The traditional Colombian processes of inactivation are done by external managers (carried out by companies external to the health centers) thus involving the transport of waste in general to places outside the urban areas where the hospital is located.

4. Conclusions

This study involved the effective treatment of public healthcare waste with Sterilwave 250 equipment. The inactivation of the microorganisms was according to Colombian regulations. These wastes have the potential to be a raw material for plastic wood production by analyzing their physicochemical characteristics. Therefore, the carbon footprint results of scenario 1 in which the Sterilwave was used, being undoubtedly the alternative that generates the least emissions in tones of CO_2e. The analysis of a Circular Economy strategy framed in the use of hospital waste and similar generated and deactivated by microwaves In Situ. Which focuses on supporting innovation and the use of technologies considered low in carbon to carry out the in-situ deactivation process of health-care waste.

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