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Steam gasification as a viable solution for converting single-use medical items into chemical building blocks with high yields for the plastic industry

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ABSTRACT

This study explores the challenge of recycling single-use medical items due to their non-recyclable nature and associated environmental concerns. To align with the circular economy principles, we propose thermochemical recycling, specifically steam gasification, for carbon atoms recovery. Face masks, plastic syringes, non-woven gowns, and nitrile gloves were tested at different temperatures (700 °C, 750 °C, and 800 °C) in a lab-scale reactor. A significant portion of the carbon in the feedstock could be effectively recovered as valuable chemical building blocks (i.e., olefins, ethane, and BTXS species), enabling their direct application in the chemical industry and reducing reliance on fossil resources. At 700 °C, carbon recovery percentages were approximately 79 % for face masks, 82 % for plastic syringes, 38 % for nitrile gloves, and 76 % for non-woven gowns. Higher temperatures led to reduced recovery due to secondary cracking reactions. Overall, this study highlights the circularity potential of single-use medical waste contributing to sustainable waste management in healthcare.

1. Introduction

1.1. Background

Since the outbreak of COVID-19 the amount of plastic waste generated worldwide is estimated to be ca. 1.6 million tons/day (Benson et al., 2021). Even though the plastic recycling share is increasing, there are still many difficulties with some particular plastic wastes. An example of these difficult-to-manage wastes are infectious medical wastes (Bucătaru et al., 2021). The management of this kind of waste represents an important current challenge for our society due to the increased consumption of single-use items, which was emphasized during the COVID-19 pandemic (Patrício Silva et al., 2020). To illustrate the scale of this issue, it is estimated that worldwide, approximately 6600 million masks, weighing ca. 2641 tons, are used every day (Idrees et al., 2022). Furthermore, the manufacturing of single-use medical items presents a significant challenge when it comes to recycling (Lee et al., 2002). These products, designed for a one-time use, are typically composed of high-quality materials that offer essential functionalities and ensure the safety of medical procedures (Saini et al., 2022; Ivanović et al., 2022). However, their disposal poses a substantial environmental concern as they are mainly non-recyclable (Bucătaru et al., 2021), hindering the potential for the manufacturing companies to adopt circular economy principles (Guzzo et al., 2020). In circular economy policies, these infectious wastes are often overlooked due to the need for decontamination, concerns related to health risks, and the subsequent financial implications (Ibn-Mohammed et al., 2021). Thus, the management of this waste category has become a crucial and pressing societal challenge (Patrício Silva et al., 2020). If inadequate management of these waste products is followed, those plastic wastes are to be released into the environment (Benson et al., 2021).

To date, the technological knowledge available in literature to treat these infectious medical wastes is aimed at decreasing the volume and eliminating their hazardous characteristics. Incineration, autoclaving treatments, and chemical and microwave disinfection are the among the most used treatments (Voudrias, 2016). Nevertheless, recycling of these wastes is becoming a hot topic due to the implementation of circular economy policies. In this context, infectious medical wastes can be particularly interesting due to the different products that can be found in its composition. These can include typically contaminated personal protection gears such as gloves or gowns, single-use operational sheets, plastic tools for surgery, etc. These items are mostly made of synthetic polymers (i.e., polypropylene (PP), polyethylene (PE), polyvinylchloride (PVC), etc.) (Ivanović et al., 2022), which make them a suitable alternative for plastic recycling.

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List of abbreviations and symbols

BFB	Bubbling Fluidized Bed
BTXS	Benzene, Toluene, Xylene and Styrene
C_{He}	Concentration of Helium
C_i	Concentration of gaseous species
COVID-19	Coronavirus Disease
CO_x	Carbon Oxides
DSR	Direct Steam Reforming
GC	Gas Chromatography
GC-FID	Gas Chromatography with Flame Ionization Detection
L_N/min	Normal Litres per minute
M_{feed}	Mass of the feedstock
Mol/kg	Mols of product per kilogram of feedstock
N_i	Molar yield
PAHs	Polyaromatic compounds
PE	Polyethylene
PP	Polypropylene
PPE	Personal Protective Equipment
PS	Polyester
PVC	Polyvinylchloride
R	H_2/CO ratio for methanol synthesis
SMR	Steam Reforming of Methane
SPA	Solid-Phase Adsorption
TCD	Thermal Conductivity Detector
$V_{He\text{-}tracing}$	Volume of the tracer helium gas
V_m	Molar volume
%C	Carbon percentage
%H	Hydrogen percentage
%vol	Volumetric percentage
%wt.	Weight percentage

1.2. Overview of medical waste recycling

In the context of plastic-based waste, traditional recycling options primarily involve mechanical technologies, such as washing, sorting, and remelting (Vollmer et al., 2020). Mechanical recycling is largely limited to thermoplastics and is highly reliant on factors such as contamination level, material homogeneity, similarity, and color (Schyns and Shaver, 2021; Dertinger et al., 2020). In this sense, the complex nature of single-use medical items further complicates their recycling. This complex composition and the presence of various materials in single-use medical items, such as plastics, metals, and textiles, make traditional recycling methods inefficient and unprofitable (Schyns and Shaver, 2021). Furthermore, mechanical technologies cannot ensure the necessary decontamination for these infectious wastes (Joseph et al., 2021). Consequently, these products are often incinerated, leading to the release of harmful emissions, or they end up in landfills, contributing to the accumulation of waste (Wang et al., 2020; Kane et al., 2018). Additionally, the increased volume of medical waste resulting from the recent overcome pandemic has put significant strain on incineration facilities and storage areas (Thind et al., 2021), emphasizing the urgency for an effective solution.

Other recycling alternatives have been proposed for these kinds of waste aiming at energy and fuels production (Giakoumakis et al., 2021). For example, plasma gasification has been studied for converting medical waste into syngas, which can be further used to produce energy (Kaushal and Rohit, 2022; Erdogan and Yilmazoglu, 2021). However, the high energy consumption and the low service life are the main technical drawbacks of plasma technology (Erdogan and Yilmazoglu, 2021). Another recently developed treatment for medical waste valorization is hydrothermal carbonization, which works similar to an autoclaving technique (Sharma et al., 2020). The co-hydrothermal carbonization of non-contaminated plastic-rich medical waste with lignocellulosic biomass has been previously evaluated for solid fuel production (Shen et al., 2017). Nevertheless, if the European Waste Framework Directive is considered, waste management should target one step higher through moving from energy vectors production to material recovery (DIRECTIVE (EU), 2018). If plastic-based products are part of the waste stream, valuable materials or chemical building blocks may be recovered and recycled into the current chemical industries, thus replacing fossil-based feedstocks. Within this philosophy, a solution is needed for infectious medical waste to both recover chemical building blocks and provide the required conditions for decontamination in a single step.

In this line, chemical recycling is a potential alternative. Chemical recycling consists of the depolymerization of plastic materials to obtain secondary compounds of lower molecular weight that can be used for many purposes in different industries (Martínez Narro et al., 2019; Rahimi and Garciá, 2017). Among the treatments included within this category, solvolysis, pyrolysis and gasification are the most used (Jiang et al., 2022). These treatments present different disadvantages that limit their applicability. For example, solvolysis cannot be used for all polymers and it requires the use of other solvents and sometimes catalysts. In addition, long reactions times and high temperatures are needed (Jiang et al., 2022). Pyrolysis is a more versatile treatment with a higher tolerance. This process usually yields valuable energy vectors (i.e., syngas, char and liquid oil) (Dharmaraj et al., 2021). While catalysts are not mandatory for pyrolysis, they are often employed to facilitate the process and reduce the severity of the treatment required for an effective conversion. Catalysts can enhance the selectivity and efficiency of the pyrolysis reactions, enabling lower operating temperatures and shorter residence times. If catalysts are to be used, the poor recyclability and the rapid deactivation of these catalysts can entail an economic impact that needs to be solved before scaling up this technology (Li et al., 2020). Similarly, gasification is another well-known technology to convert plastic waste into high-calorific gases like H_2, CO and CH_4, which can be used as fuel (Janajreh et al., 2020; Lee et al., 2021). Still, problems like the formation of tars or the dilution effects lead to lower calorific values and difficulties in the gas separation, therefore reducing the overall performance of the process (Ciuffi et al., 2020). A similar process within the thermochemical recycling technologies is steam gasification, also known as steam cracking. This process has been traditionally used to get light olefins from hydrocarbons like naphtha or ethane (Ren et al., 2006). Light olefins such as ethylene or propylene are then used to produce plastics, fibers and other chemicals (Ren et al., 2006). Due to the similarities between the molecular structures of the typical fossil hydrocarbons used for this process and plastic materials like polyolefins (e.g., PE or PP), plastics have been considered as alternative feedstocks to obtain light olefins (Kaminsky, 2021; Abbas-Abadi et al., 2023). In this line, in previous works, our group has explored the possibility of thermochemical recycling for households and industrial plastic wastes using steam gasification, with promising results (Mandviwala et al., 2022; Thunman et al., 2019; Cañete Vela et al., 2024; González-Arias et al., 2023; Kiminaitė et al., 2023). In this context, infectious medical wastes can be particularly interesting for thermochemical recycling due to the different polymers that can be found in its composition as abovementioned. Furthermore, this technology not only can provide a decontamination process for infectious waste but also turn it into a resource for recovery of chemical building blocks to produce circular materials. Additionally, by recovering the chemical building blocks from this kind of waste, carbon is kept in the carbon cycle to produce new carbon-based materials (Cañete Vela et al., 2022). In this sense, our research team is devoted to achieving full circularity of plastics looking for the recovery of the chemical building blocks present in plastic wastes. Examples of chemical building blocks that can be recovered from this composition are propylene, ethylene or benzene (Kaminsky, 2021).

Thermochemical recycling of plastic materials to generate valuable chemicals has been previously studied, exploring also different reactor configurations and technologies (Kaminsky, 2021; Munir et al., 2018; Wilk and Hofbauer, 2013; Thunman et al., 2019). Among these, fluidized bed reactors have emerged as particularly suitable for thermochemical recycling of plastic waste due to their excellent heat transfer properties and capability to process heterogeneous feedstocks (Kaminsky, 2021; Wilk and Hofbauer, 2013; Thunman et al., 2019). As an example, Kaminsky et al. delved into the fluidized bed pyrolysis of mixed plastic waste to produce monomers for polymer synthesis, resulting in a product distribution abundant in light olefins and mono aromatics (Kaminsky, 2021). Similarly, Thunman et al. (2019) showcased that the product distribution from fluidized bed steam gasification of polyethylene closely resembles that obtained from a tubular naphtha cracker. Mandviwala et al. (2023) have explored the use of different bed materials in the steam gasification of high-density polyethylene aiming at obtaining valuable olefins to be reintroduced into the plastic industry. Other plastic wastes such as cable plastic waste, have also been studied using a fluidized bed reactor, obtaining high yields of valuable compounds (Cañete Vela et al., 2024). Beyond fluidized bed reactors, alternative configurations such as fixed bed and spouted bed reactors have also demonstrated effectiveness in the thermochemical conversion of plastic materials (Elordi et al., 2012; Al-Salem, 2019). This diversity in reactor setups highlights the ongoing exploration and optimization of various methods for enhancing the thermochemical recycling of plastic, offering promising avenues for sustainable chemical production.

1.3. Goal and scope

Within the current developments reported in the literature, we position our study aiming at investigating the feasibility of utilizing steam gasification as a sustainable recycling solution for single-use medical items. Through a comprehensive analysis of the product composition and product yields, we seek to provide valuable insights into the circularity potential of this waste stream. By assessing the advantages and challenges associated with steam gasification, we can contribute to the development of effective strategies that address the sustainability concerns posed by the disposal of single-use medical items. Furthermore, our position aims at providing a solution for the manufacturing companies to adopt circular economy strategies. As of today, the manufacturing companies of single-use items face a challenge when it comes to recycling, since the disposal of these items possess a substantial environmental concern as they are mainly non-recyclable (Guzzo et al., 2020; Bucătaru et al., 2021). As explained before and looking towards full circular policies, an efficient recycling of infectious waste is of key importance.

Fig. 1 provides a scheme which outlines the general concept of our approach. The main goal of this research was to experimentally investigate the potential for recovering chemical building blocks from infectious medical waste using steam gasification as a proof of concept before moving towards larger scales. The focus of our investigation lies on personal protective equipment (PPE), which represents the most commonly encountered single-use items within typical infectious medical waste streams from healthcare facilities. Consequently, we selected four representative materials frequently found in healthcare settings, namely face masks, gloves, plastic syringes, and non-woven gowns, for our experimental analysis. Our scope covers the experiments carried out to identify and quantify the potential chemical building blocks recovery from medical waste items. A potential mix of them was considered of great complexity due to potential variations in the composition and hence it is out of the scope of this first approach. This work is organized as follows: firstly, we present the composition of the different materials and outline the experimental procedures employed. Subsequently, we present and discuss the results obtained from our experiments, highlighting the potential for recovering chemical building blocks and evaluating the need of sorting some items within a typical medical waste stream. Finally, we summarize the main conclusions drawn from this study and provide recommendations for future research endeavors.

2. Materials and methods

2.1. Materials

The experimental analysis focused on four distinct single-use medical items that are typically classified as infectious waste upon disposal. These items, namely face masks, plastic syringes, nitrile gloves, and non-woven gowns, are widely utilized in healthcare facilities. For the purpose of this study, these materials were selected as representative reference medical wastes. To ensure safety during the experiments, unused materials were utilized instead of actual medical waste. This precautionary measure was taken to avoid potential contamination or health risks associated with handling infectious materials. By using unused materials, we were able to focus solely on the chemical composition and properties of the selected medical items, without

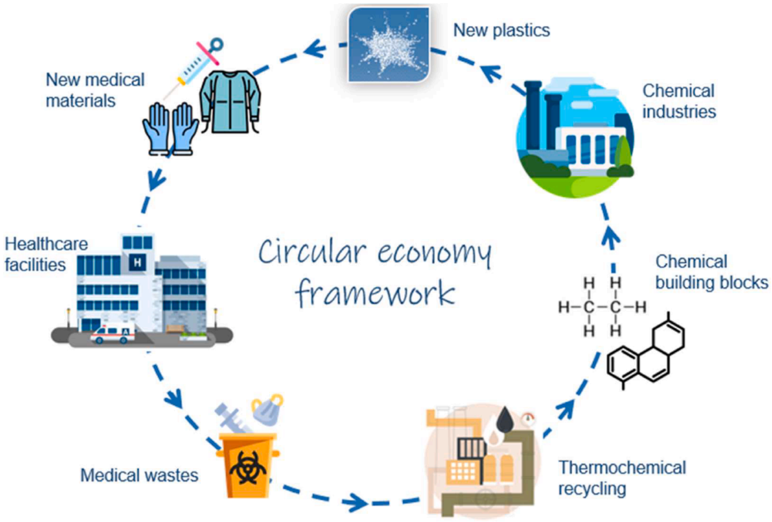

Fig. 1. Circular economy proposal scheme for the medical wastes to become new medical materials.

compromising the safety of the experimental setup or personnel involved. For the results presented here, the yields of thermal decomposition, a potential contribution of contaminations is negligible considering the amounts present. Table 1 provides the elemental analysis of the different products, offering insight into the composition of each material.

Based on the analysis shown in Table 1 and the information collected from published literature and commercial sites, the polymer composition of the different products can be drawn. In this sense, face masks are mainly composed of PP, PE, cellulose and aluminum; plastic syringes are mostly made of PP and PE; non-woven gowns are mainly composed of PP, with traces of polyester (PS) and PE; while nitrile gloves are mostly made of acrylonitrile and butadiene (Syringe PP/PE, 2023; Purnomo et al., 2021). This agrees with the elemental composition of the different materials assessed. While we are unable to provide specific compositional data due to limitations in our laboratory equipment, which might limit the reproducibility and transferability of our work, we believe that our work offers a valuable proof of concept for a technology that can address a wide range of polymeric waste materials. The heart of our proposed technology lies in its ability to process various polymeric waste streams, regardless of their specific composition. We believe that this adaptability is one of the key strengths of our approach.

In general, the moisture of the feedstock could have various impacts on the steam gasification process to obtain light olefins. Water presence could lead to the formation of undesirable by-products, such as coke or the generation of heavier compounds. This could affect the quality and quantity of the desired light olefins. Moisture could also influence the temperature and pressure required for the process, thereby affecting the kinetics of the cracking reactions.

Controlling and maintaining low moisture levels in the plastic sample is crucial to ensure an efficient process and achieve the desired results in steam gasification for light olefins production. In some cases, the differences in the moisture content may be minimal, while in others, especially in more porous or absorbent materials, the variation could be more significant. As we are aiming at thermally treating polymer-based materials, and one of their most characteristic features is that those materials are non-absorbent, we can neglect the moisture content in this case. In any case, different pretreatments such as pre-drying steps to reduce the moisture of the feedstock might be of interest in large scale facilities.

2.2. Experimental set-up and steam gasification procedure

The experiments were conducted on a laboratory scale using a bubbling fluidized bed (BFB) reactor made of stainless steel. The reactor had an internal diameter of 88.9 mm and a height of 1305 mm. The experiments were conducted in discrete batches, a specific quantity of the material is loaded into the reactor, and the reaction or treatment process is carried out for a predetermined duration. The experimental set-up, as illustrated in Fig. 2, involved introducing fluidization gases into the reactor from the bottom through a wind-box, where the gases were thoroughly mixed, and a distributor plate. The flow rate of the different fluidization gases was controlled using mass flow controllers. To facilitate temperature monitoring, the reactor was equipped with thermocouples placed along its height on the back side. The reactor was electrically heated, and the heating process commenced after loading the bed material from the top of the reactor.

Table 1
Elemental analysis of the different samples (% wt.).

	Carbon	Hydrogen	Oxygen	Nitrogen	Ash
Face masks	81.60	13.70	4.68	0.01	5.50
Syringes	84.24	14.34	0.01	0.18	0.18
Non-woven gowns	84.21	11.56	0.01	0.21	0.32
Nitrile gloves	76.02	8.26	9.41	6.34	5.78

During the experiments, approximately 2 gs of each material were used per batch and introduced into the reactor by dropping them from the top. To ensure proper feeding, the materials were first shredded and compacted using a hand-made pelletizer based on a small hydraulic press. The steam gasification reaction was conducted at three different temperatures: 700, 750, and 800 °C. These temperatures were selected based on previous experiences with pure polymers (Mandviwala et al., 2023; Milne et al., 1999). The temperature was measured using a thermocouple positioned at the height of the bed. To ensure the reliability of the results, each test was performed three times. The experimental procedure consisted of three main steps, which have been described in detail elsewhere (Mandviwala et al., 2022).

First, the inertization of the bed material was performed. The bed material in the fluidized reactor was exposed to an oxidizing atmosphere at the targeted reaction temperatures before introducing each batch of the different feedstocks. Oxidation was accomplished by introducing air into the reactor to create a fluidized state at a flow rate of 5 L_N/min. The inertization process was considered complete when the O_2 concentration, monitored by a continuous permanent gas analyzer, reached 20.9 %vol. Throughout each experimental batch, the bed material was completely oxidized to replicate the conditions in a dual fluidized bed (DFB) gasifier, where the bed material is introduced into the gasifier after undergoing full oxidation. Afterwards, the steam gasification step was carried out by switching the fluidization gas to nitrogen and steam (2 L_N/min and 3.9 L_N/min, respectively). Once this step was completed, the fluidization gases were switched back to air for the combustion of the remaining char after steam gasification. This step also allows for the complete oxidation of the bed material. Helium was added to the fluidization gases as a tracer, and its known volume (0.05 L_N/min) was used to determine the total gas volume produced. To control the total time of devolatilization and guarantee that no volatile gases were left after the sampling time, the concentrations of H_2, CO, CO_2 and CH_4 were continuously monitored from the sampled gas in a permanent gas analyzer. The residence time of the product gases from the steam gasification process can be calculated by dividing the volume of the reactor until the sampling point by the volumetric flow rate. As shown in Fig. 2, the sampling point is located at a specific height (i.e., 50 cm of which ca. 5 cm corresponds to the bed material. Thus, for the calculation 45 cm is considered). This corresponds to a volume of 0.002793 m^3 since the cross section of the reactor is 0.0062 m^2. To calculate the gas flow rate, the flows of N_2, steam ang He were considered along with the average flow of the product gas measured. This gives a residence time of approximately 25 and 26 s. This calculation corresponds to the residence time of the product gas before entering the sampling probe. Since the product gas is quenched down to 350 °C in the sampling probe, it is reasonable to neglect the residence time in the sampling probe.

2.3. Gas and tar analysis

During the steam gasification and combustion steps, the gas stream was divided into two parts for further analysis. One part underwent gas conditioning, which involved two steps: scrubbing and cooling with isopropanol, followed by drying with silica gel beads and glass wool. This treated gas, cold and dry, was continuously analyzed using a SICK GMS 820 permanent gas analyzer. The second part went through a solid-phase extraction amine and was collected in a 0.5 L Tedlar gas bag for further analysis. The sampling time during the devolatilization stage was 120 s, as measured with the permanent gas analyzer to ensure a complete conversion and to get all product gases. This gas bag was analyzed in an Agilent 490 micro-GC equipped with four different columns depending on the gas to measure, each of them coupled with a Thermal Conductivity Detector (TCD) detector. These columns are detailed below: (1) CP-Cox that allows to measure He, H_2, Air, CO and CH_4; (2) PoraPLOT U, to measure CO_2, C_2H_4, C_2H_6, C_2H_2 and C_3H_x; (3) CP-WAX 52 CB, to measure benzene and toluene; and (4) CP-Sil 5 CB, to measure C_4H_x hydrocarbons. Additionally, a Bruker GC-FID (Gas

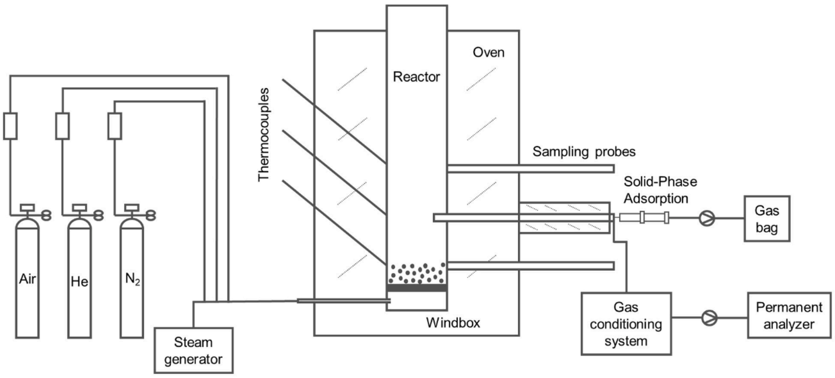

Fig. 2. Schematics of the experimental setup used in this work.

Chromatography with Flame Ionization Detection) equipment was utilized to quantify the condensable aromatic hydrocarbons, commonly referred to as tars. This was done using the solid-phase adsorption (SPA) method described elsewhere (Israelsson et al., 2013).

After the steam gasification stage, any unconverted char or carbon deposits that were formed, remain in the reactor along with the bed material. To determine the char yield, the fluidization gases used during the devolatilization phase (steam and nitrogen) were switched to air. This change in gas composition allowed for the combustion of the char, and the resulting CO and CO_2 gases produced in this step were measured. The combustion gases were sampled for a duration of 120 s and collected in a 0.5 L Tedlar gas bag. Subsequently, the gas samples were analyzed using the micro-GC system mentioned earlier.

To calculate the molar yield (mol/kg) of all the measured gaseous species analyzed, the He-tracing method was employed. According to Mandviwala et al. (2022) Eq. (1) was followed.

Table 2
Product distribution of the different feedstocks used at the selected temperatures presented in%carbon (by wt.).

	Face Masks			Plastic syringes			Nitrile gloves			Non-woven gowns		
Temp. (°C)	700	750	800	700	750	800	700	750	800	700	750	800
Olefins	65.64 ± 0.74	53.88 ± 0.47	38.78 ± 0.89	68.26 ± 0.86	56.02 ± 0.91	31.75 ± 1.02	22.44 ± 0.42	19.15 ± 0.31	14.35 ± 0.47	61.75 ± 0.42	51.52 ± 0.63	33.35 ± 0.75
C_2H_4	15.64 ± 0.64	19.83 ± 0.45	23.02 ± 0.17	21.50 ± 0.21	25.65 ± 1.24	20.14 ± 1.46	7.55 ± 0.36	8.02 ± 0.28	7.68 ± 0.68	12.88 ± 0.25	15.94 ± 0.53	17.12 ± 0.90
C_3H_x	28.19 ± 0.79	18.79 ± 0.49	7.95 ± 0.41	26.68 ± 0.43	18.16 ± 0.31	6.25 ± 0.62	6.14 ± 0.15	5.22 ± 0.16	2.94 ± 0.21	30.63 ± 0.71	22.63 ± 0.58	10.71 ± 0.16
C_4H_x	21.80 ± 0.97	15.27 ± 0.24	7.80 ± 1.56	20.08 ± 1.06	12.22 ± 1.50	5.36 ± 2.60	8.75 ± 0.39	5.91 ± 0.26	3.73 ± 0.33	18.24 ± 0.51	12.95 ± 0.46	5.52 ± 0.28
Paraffins	12.90 ± 0.46	16.11 ± 0.23	19.48 ± 0.18	12.81 ± 0.21	16.46 ± 0.47	14.60 ± 0.56	8.12 ± 0.09	8.75 ± 0.25	8.08 ± 0.36	12.23 ± 0.08	15.00 ± 0.24	15.92 ± 0.53
CH_4	8.90 ± 0.85	12.64 ± 0.14	17.00 ± 0.09	8.29 ± 0.19	12.39 ± 0.79	11.98 ± 0.90	5.53 ± 0.18	6.50 ± 0.37	6.70 ± 0.50	7.56 ± 0.11	10.91 ± 0.36	13.30 ± 0.80
C_2H_6	4.00 ± 0.05	3.47 ± 0.02	2.48 ± 0.04	4.52 ± 0.16	4.07 ± 0.07	2.62 ± 0.18	2.59 ± 0.07	2.25 ± 0.09	1.38 ± 0.08	4.67 ± 0.19	4.09 ± 0.07	2.62 ± 0.07
CO_x	4.24 ± 0.09	6.51 ± 0.11	11.84 ± 0.87	2.74 ± 0.10	5.59 ± 0.31	10.94 ± 0.28	4.85 ± 0.14	6.08 ± 0.32	7.70 ± 0.29	2.81 ± 0.10	3.40 ± 0.17	5.44 ± 0.26
CO	1.59 ± 0.07	3.15 ± 0.18	7.09 ± 0.63	0.82 ± 0.08	2.65 ± 0.22	6.70 ± 0.49	0.86 ± 0.02	1.18 ± 0.02	2.01 ± 0.25	0.87 ± 0.07	1.34 ± 0.13	2.79 ± 0.47
CO_2	2.65 ± 0.12	3.36 ± 0.11	4.75 ± 0.24	1.92 ± 0.08	2.94 ± 0.15	4.24 ± 0.13	3.99 ± 0.20	4.91 ± 0.30	5.69 ± 0.49	1.94 ± 0.04	2.07 ± 0.22	2.65 ± 0.16
Aromatics	15.54 ± 0.20	21.36 ± 0.63	25.55 ± 1.95	14.81 ± 0.08	20.48 ± 0.84	18.54 ± 2.30	40.35 ± 1.21	38.19 ± 2.01	32.41 ± 1.39	14.42 ± 0.69	22.45 ± 0.99	24.83 ± 1.34
Benzene	3.57 ± 0.87	7.05 ± 0.20	9.81 ± 0.58	3.49 ± 0.16	6.68 ± 1.19	7.87 ± 1.40	5.37 ± 0.11	6.25 ± 0.36	6.79 ± 0.38	3.75 ± 0.34	7.87 ± 0.13	10.22 ± 0.65
Toluene	4.30 ± 0.24	4.49 ± 0.24	4.18 ± 0.37	3.90 ± 0.16	4.55 ± 0.11	2.86 ± 0.37	4.53 ± 0.09	4.31 ± 0.23	3.35 ± 0.06	4.00 ± 0.10	5.49 ± 0.35	4.34 ± 0.22
Xylenes	1.34 ± 0.07	1.13 ± 0.09	0.58 ± 0.04	1.18 ± 0.05	0.87 ± 0.02	0.37 ± 0.07	1.20 ± 0.06	1.01 ± 0.06	0.60 ± 0.01	1.37 ± 0.09	1.43 ± 0.13	0.75 ± 0.05
Styrene	0.46 ± 0.03	1.04 ± 0.08	1.51 ± 0.15	0.54 ± 0.01	1.20 ± 0.08	1.17 ± 0.14	2.05 ± 0.09	1.91 ± 0.09	1.42 ± 0.04	0.38 ± 0.04	0.92 ± 0.03	1.31 ± 0.06
Naphthalene	0.35 ± 0.02	1.15 ± 0.07	2.47 ± 0.22	0.36 ± 0.01	1.32 ± 0.12	1.73 ± 0.19	0.99 ± 0.06	1.48 ± 0.06	1.90 ± 0.14	0.24 ± 0.02	0.90 ± 0.05	1.92 ± 0.12
Others known	1.15 ± 0.52	2.31 ± 0.36	3.18 ± 1.54	1.19 ± 0.06	2.50 ± 0.91	2.25 ± 2.05	4.10 ± 0.37	4.14 ± 1.14	3.92 ± 0.93	1.17 ± 0.67	2.25 ± 0.70	2.98 ± 1.18
Others unknown	4.36 ± 0.33	4.20 ± 0.28	3.81 ± 0.45	4.14 ± 0.14	3.37 ± 0.18	2.29 ± 0.46	22.11 ± 1.05	19.09 ± 0.86	14.44 ± 0.51	3.51 ± 0.09	3.59 ± 0.31	3.30 ± 0.22
Solid Char	1.49 ± 0.10	1.15 ± 0.16	0.84 ± 0.10	0.84 ± 0.14	0.56 ± 0.20	0.33 ± 0.12	2.98 ± 0.88	1.90 ± 0.36	1.04 ± 0.09	0.84 ± 0.17	0.81 ± 0.08	0.64 ± 0.19
Undetected	0.19 ± 0.02	0.99 ± 0.23	3.52 ± 0.74	0.54 ± 0.21	0.88 ± 0.08	23.84 ± 5.31	21.26 ± 6.83	25.93 ± 7.26	36.41 ± 8.94	7.94 ± 2.13	6.82 ± 1.89	19.82 ± 5.10
Hydrogen (% H)	5.27 ± 0.25	9.58 ± 0.46	18.12 ± 1.25	4.68 ± 0.24	10.00 ± 0.71	17.93 ± 0.63	5.06 ± 0.34	8.66 ± 0.15	13.11 ± 1.05	3.70 ± 0.13	6.47 ± 0.38	10.94 ± 1.06

$$n_i = \frac{c_i}{m_{feed}} \cdot \left(\frac{V_{He-tracing}}{C_{He}} \right) \cdot \frac{1}{V_m} \quad (1)$$

where n_i is the molar yield and c_i the concentration of gaseous species i; $V_{He\text{-}tracing}$ and C_{He} represent the volume and concentration of the tracer helium gas, respectively; m_{feed} is the mass of the feedstock for each batch, and V_m is the molar volume of an ideal gas at 0 °C. The molar yield of each species was then converted to carbon yield according to its molecular formula.

3. Results and discussion

3.1. Product distribution and carbon balance

Table 2 collects the product distribution obtained through the steam gasification of the selected materials at the evaluated temperatures. The yields of the measured species are presented in% carbon considering the initial carbon content of the different materials, allowing for an assessment of the carbon balance across the different experiments. The species shown here are grouped into olefins, paraffins, carbon oxides, aromatics and char (carbon deposits). Table 2 also presents the produced hydrogen in% hydrogen considering the initial hydrogen content of the different feedstocks. The "undetected fraction" represents the difference between the measured carbon in the products and the total carbon in the feedstocks. This difference may be attributed to undetected species that cannot be measured using the analytical methods employed in this study, along with potential errors in sampling and analysis and potential errors in the feedstock analysis.

Fig. 3 illustrates the main groups of species obtained from the feedstocks at the three evaluated temperatures (700, 750, and 800 °C) for the purpose of facilitating a comprehensive comparison at first sight.

As seen from the results shown in both Table 2 and Fig. 3, the products recovered from face masks (A), plastic syringes (B), and non-woven gowns (D) follow the same trend with the temperature. Olefins are the most generated species in these cases. The share of the different groups of species produced during the steam gasification reactions is similar in these three materials and follows the same trend when increasing the reaction temperature. On the contrary, for the nitrile gloves (C), the share of the different groups is quite different from the other medical items studied. In this case, the share of aromatics is the highest, followed by an increasing share of the undetected fraction with the reaction temperature. These results indicate that materials with a higher content of polyolefins, such as PE and PP, yield greater amounts of olefins. In this sense, plastic syringes and face masks, which consist mostly of PE and PP, as well as non-woven gowns mainly composed of PP, report the highest yields of olefins. On the other hand, nitrile gloves, which contain nitrogen-based compounds, yield fewer valuable compounds and generate heavier polyaromatic compounds that can potentially clog downstream equipment (Berdugo Vilches et al., 2018). Other than the difference observed due to the different composition of the evaluated items, the effect of the temperature is also clear on the distribution of products. If only considering the effect of the temperature, it is evident that at the lowest value tested (i.e., 700 °C), the yield of olefins is the highest among all the evaluated materials. This group comprises a significant portion of C2, C3, and C4 compounds, which are very valuable in the chemical industry. As the temperature increases, the yield of olefins decreases, albeit to varying extents depending on the specific feedstock. For example, in the case of face masks, there is an 18 % reduction in olefin yield from 700 to 750 °C, and a further 41 % reduction from 700 to 800 °C. This trend is similar for plastic syringes and non-woven gowns, fact that somehow was expected due to the similarities in their composition. Lower temperatures result in lower yields of carbon oxides (i.e., CO and CO_2) but higher yields of unconverted material (i.e., the char fraction). As an example, at 700 °C, the measured carbon content in face masks and plastic syringes was ca. 1.5 %C and 0.8 %C, respectively. These values decreased at 800 °C to ca. 0.8 %C and 0.3 %C, respectively. This reduction indicates that further char gasification occurs at higher temperatures, reducing the value of char but contributing to some extent to the increase in carbon oxides production (Zhou et al., 2014).

This temperature-dependent trend is consistent with previous observations made during steam gasification of polyolefins (Simon et al., 1996). Increasing the temperature of steam gasification results in a higher probability of chain scission, causing a shift in the distribution of species towards smaller chains. At higher severities, meaning in this case higher reaction temperatures, the C—C bonds in larger compounds are

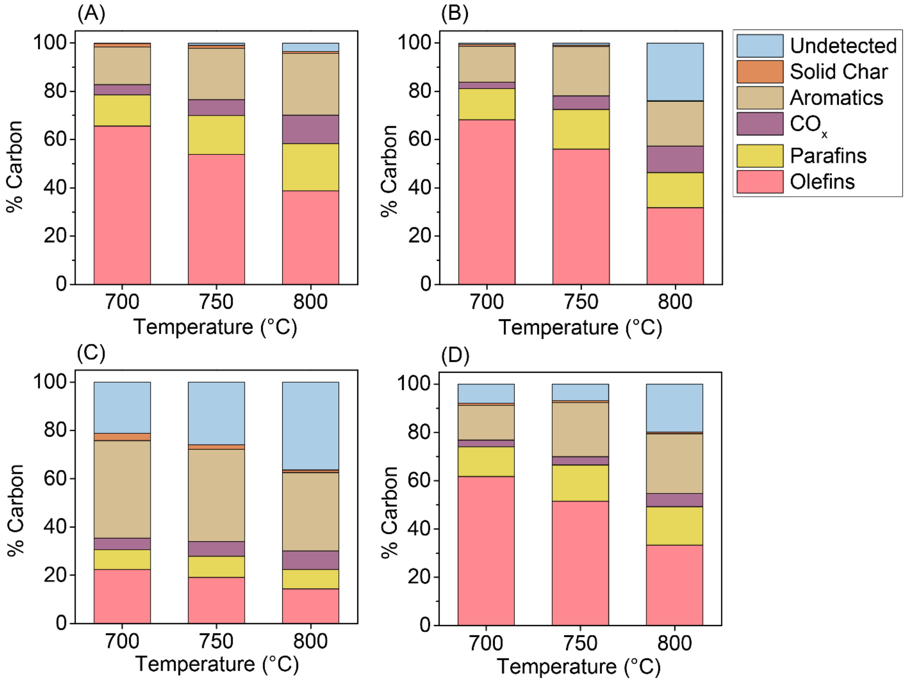

Fig. 3. Main groups of species represented in recovered% carbon of the feedstock. (A) Face masks, (B) Plastic syringes, (C) Nitrile gloves, (D) Non-woven gowns.

more easily broken, leading to a higher yield of smaller chain species at expenses of the longer ones (Mandviwala et al., 2022). For this reason, the yields of C2 species and CH_4 increase with rising temperature (Forero-Franco et al., 2023). In addition, there is a noticeable increase in aromatics at the expense of C3 and C4 species when the temperature increases. Dehydrogenation reactions are responsible for this fact. When polyolefin-based materials undergo steam gasification, primary reactions tend to form olefins and paraffins. These products undergo secondary reactions such as cyclization or dehydrogenation, forming more aromatic compounds. Hydrogen is also formed because of dehydrogenation and hydrogen transfer reactions (González-Arias et al., 2023). This effect is more pronounced at higher temperatures, as can be observed in Table 2 and Fig. 3. In the case of the nitrile gloves, we hypothesize that due to the initial low H/C ratio in nitrile rubber, and with the abovementioned tendency to hydrogen abstraction at elevated temperatures, polymerization reactions can lead to polyaromatic compounds (PAHs) that we cannot quantify (undetected fraction). This is an important consideration when mixed wastes are treated together, suggesting the need for a different recycling methodology for such products. This first approach, considered as a proof of concept, gives us an idea about materials to avoid when mixed wastes are to be treated together. In this sense, it is advisable to avoid using nitrile-based rubber products in steam gasification processes, since they lead to a higher PAHs production, which is not valuable for the chemical industry.

3.2. Aromatic fraction

Other aromatic compounds produced from the steam gasification of plastic-based waste are of interest to the chemical industry (Murray, 2022), specifically monoaromatics such as benzene, toluene, xylene and styrene, commonly referred to as BTXS compounds (Cherubini and Strømman, 2011). Fig. 4 displays the distribution of the aromatic fraction categorized by material.

As shown in Fig. 4, more than 60 % of the carbon in the total aromatic fraction corresponds to BTXS compounds in all the evaluated products except for the nitrile gloves. In this case, ca. 50 % of the produced aromatics are categorized as unknown PAHs species. For instance, considering the face masks samples, the %carbon of the aromatic fraction represents ca. 15, 21, and 25 %C of the total recovered products at the different reaction temperatures assessed (700, 750 and 800 °C, respectively). The BTXS fraction accounts for ca. 63 % of the total aromatics across all three temperatures, with benzene being the most generated product regardless of the reaction temperature. These observations agree with the trends observed in previous experimental tests with pure polyolefinic materials (Mandviwala et al., 2022). Plastic syringes and non-woven gowns exhibit a similar trend in the BTXS distribution. However, the aromatic distribution differs significantly in the case of nitrile gloves. More aromatic compounds are formed during the steam gasification of nitrile gloves, with nearly twice as much carbon being recovered as aromatic compounds compared to the other three materials. Regarding BTXS compounds, only approximately 35 % of the total aromatic fraction in the nitrile gloves corresponds to BTXS species. The majority of the measured species fall into the category of "Unknown PAHs", as they could not be identified with the available equipment. To calculate the carbon percentage of this fraction, the molecular weight and H/C ratio of the closest identified species in the GC analysis were considered.

3.3. Indirect carbon atoms recovery

In this section we show that the overall yield of recovered products can be enhanced if other valuable substances are obtained in an indirect way. Nowadays, the plastic industry usually employs fossil fuels cracking and reforming to get the desirable products. Nevertheless, with the steam gasification technology, these useful products can be obtained from waste, aiming at a 100 % circular use of the carbon atoms present in the waste fractions (Cañete Vela et al., 2022). According to the experimental results (recall previous sections), a significant percentage of the carbon present in the feedstock can be recovered directly as molecular building blocks suitable for direct utilization in the chemical industry (e.g., olefins, ethane, and monoaromatics). Nonetheless, if a 100 % recovery of the carbon atoms present in the feedstock is to be obtained, alternative indirect ways to produce these chemical building blocks are essential. The proposal of Thunman et al. (2019) suggests that indirect routes such as combustion, reforming and synthesis can be coupled with steam gasification of different wastes.

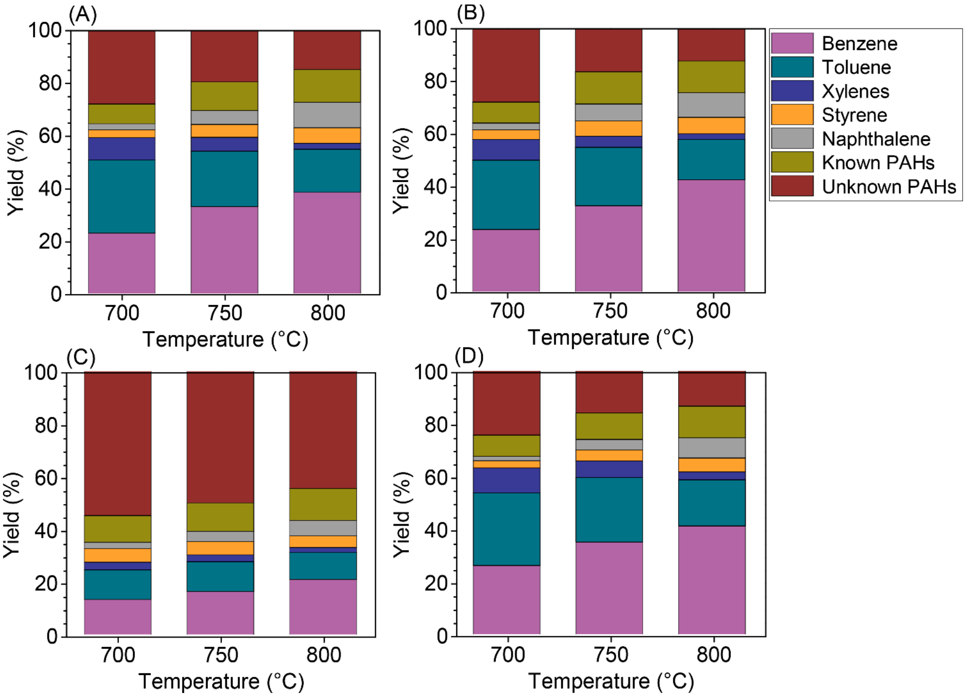

Fig. 4. Aromatics distribution: (A) Face masks; (B) Plastic syringes; (C) Nitrile gloves; and (D) Non-woven gowns.

Building upon Thunman and colleagues' proposal, steam reforming of methane (SMR) would provide a suitable stream for methanol synthesis. This produced methanol could then be further converted into olefins (Yang et al., 2019). To carry out this idea, the gas composition used as a basis for this analysis was derived from the measurements from Eq. (1). These values were used in our subsequent calculations, where we determined the potential yields of CO_2 and H_2 through the process of direct steam reforming (DSR) of methane, applied to the measured methane from steam gasification. We assume a complete conversion of the methane under the average temperature and pressure conditions used regularly for DSR. The produced flows of H_2 and CO_2 via direct SMR are further added to the flows of H_2 and CO+CO_2 produced from steam gasification. Later on, it is necessary to adjust the H_2/CO ratio to 2, to perform an optimal methanol synthesis. This ratio is defined as $R = (H_2 - CO_2) / (CO + CO_2)$. As H_2 is usually the limiting product when this process is carried out, the R ratio is the most common tool used to calculate the H_2 required (Giuliano et al., 2020). While the addition of H_2 in this process incurs a penalty, utilizing renewable sources for H_2 production could contribute to the sustainable production of chemical building blocks (Pareek et al., 2020). In order to know if further H_2 is needed to reach an optimal R ratio for methanol synthesis, the flows produced both in steam gasification and in SMR were calculated. In Fig. 5, these flows are represented in mol/kg of fuel used.

In Fig. 5, the symbols represent the R ratio calculated only with the H_2, CO and CO_2 generated from steam gasification of the different medical items, i.e., without any external addition of H_2, while the dashed line indicates the optimal R ratio. To reach this value, the corresponding required flow of H_2 is also displayed. As can be observed in Fig. 5, the required H_2 for an optimal CO/H_2 ratio for methanol synthesis significantly depends on the feedstock used and the reaction conditions selected. Only nitrile gloves require external H_2 addition, while for the rest of the materials evaluated, the H_2 produced during the thermochemical treatment and after SMR is sufficient to reach the optimal ratio for methanol production. Indeed, in all cases there is an excess of H_2 that can be further recovered.

Notably, our findings show a promising horizon for the practical integration of this technology alongside industrial gasifiers and crackers. This represents a landmark step towards the efficient and sustainable utilization of carbon resources. It is important to emphasize that while our study represents a pioneering endeavor, it serves as a crucial first attempt to showcase the feasibility of achieving 100 % carbon atom recovery from diverse feedstocks. This not only opens doors to addressing medical and plastic waste but also to broader applications, charting a course towards sustainable resource utilization.

4. Conclusions and future works

In this work, the potential of thermochemical recycling via steam gasification, as a means to recover high-value chemical building blocks from infectious medical waste was studied. The steam gasification experiments were conducted at three different temperatures: 700, 750, and 800 °C, using four representative medical waste materials: face masks, plastic syringes, nitrile gloves, and non-woven gowns. The potential of valuable chemical building blocks recovery was assessed through the product distribution and the carbon balance for the different materials. The main products obtained were olefins, particularly ethylene and propylene at the lowest temperature (values ranging from ca. 62 to ca. 68 %C). Nonetheless, other valuable products such as paraffins, carbon oxides and monoaromatics were also obtained. Generally, higher temperatures resulted in lower yields of paraffins and higher yields of carbon oxides and aromatics. Face masks, plastic syringes and non-woven gowns showed a similar behavior in terms of products distribution. Nevertheless, nitrile gloves presented a different trend. In this case, the main products obtained were aromatics (ca. 40 %C at 700 °C) with an important fraction of undetected species (ca. 21 %C at 700 °C). The share of olefins is quite low for this material, with values between 22 %C and 14 %C at the different temperatures. Overall, the experimental results support the use of steam gasification as a promising approach for the treatment of infectious medical waste. The findings highlight the potential for simultaneous decontamination and recovery of valuable chemical building blocks from high-risk waste streams. Even so, when mixed wastes are treated together, it is advisable to avoid rubber-based products in steam gasification processes, as they produce fewer valuable compounds and generate heavier polyaromatic compounds that can potentially clog the equipment. Thus, a different recycling approach for these products is needed.

Obtaining light olefins from medical waste with the aim to reintroduce these valuable chemicals into the plastic manufacturing industry through steam gasification is an innovative idea. For this reason, it needs further research in terms of development and industrial implementation

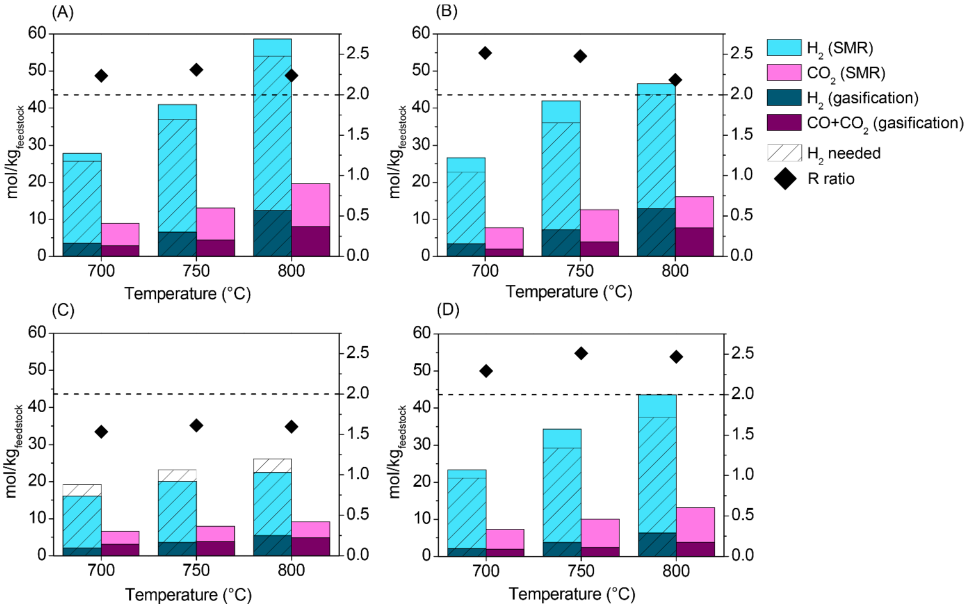

Fig. 5. CO, CO_2 and H_2 produced by steam gasification and SMR along with the R ratio in the different experiments: (A) Face masks, (B) Plastic syringes, (C) Nitrile gloves, (D) Non-woven gowns. The H_2 needed to reach an optimal ratio of 2 is also included.

considerations. Some of those are listed below: (1) Further research and development on the optimal reaction parameters for steam gasification to maximize the yield of light olefins from medical waste; (2) Implementation of an effective waste sorting and preprocessing techniques to ensure that only suitable medical waste materials are subjected to steam gasification. This may involve removing non-plastic contaminants and ensuring proper waste handling; (3) Conduct a comprehensive environmental impact assessment to evaluate the emissions, energy consumption, and overall sustainability of the process. This would require implementing any necessary modifications to minimize the environmental footprint; (4) The establishment of stringent quality control measures to ensure the purity of the obtained light olefins. High-quality feedstock is crucial for the plastic manufacturing industry; (5) Considerations on the cost-effectiveness and efficiency of large-scale implementation; (6) Exploration of opportunities for integrating the steam gasification process into existing waste treatment and plastic manufacturing infrastructures. This may require collaboration with waste management and plastic production facilities; (7) Ensuring that the process complies with local and international regulations governing waste management, emissions, and product quality, especially for materials intended for use in the plastics industry; (8) Performing a comprehensive economic analysis to determine the feasibility of the process. Considerations on factors like capital investment, operating costs, and potential revenue from selling light olefins to the plastic industry might be necessary; (9) Collaboration with research institutions, waste management companies, and plastic manufacturers to share knowledge and expertise, which can accelerate the development and implementation of the process; (10) Engagement in public awareness campaigns to address concerns related to medical waste treatment and the use of products derived from this process in plastic manufacturing. Building public acceptance is essential; and (11) Implementation of a robust monitoring and reporting system to track process performance, environmental impacts, and product quality. Regularly update stakeholders on progress and improvements.

CRediT authorship contribution statement

Judith González-Arias: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing. **Renesteban Forero-Franco:** Methodology, Investigation, Writing – review & editing. **Chahat Mandviwala:** Methodology, Visualization, Writing – review & editing. **Martin Seemann:** Conceptualization, Visualization, Writing – review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Abbas-Abadi, M.S., Ureel, Y., Eschenbacher, A., Vermeire, F.H., Varghese, R.J., Oenema, J., et al., 2023. Challenges and opportunities of light olefin production via thermal and catalytic pyrolysis of end-of-life polyolefins: towards full recyclability. Prog. Energy Combust. Sci. 96 https://doi.org/10.1016/j.pecs.2022.101046.

Al-Salem, S.M., 2019. Thermal pyrolysis of high density polyethylene (HDPE) in a novel fixed bed reactor system for the production of high value gasoline range hydrocarbons (HC). Process Saf. Environ. Prot. 127 https://doi.org/10.1016/j.psep.2019.05.008.

Benson, N.U., Bassey, D.E., Palanisami, T., 2021. COVID pollution: impact of COVID-19 pandemic on global plastic waste footprint. Heliyon 7. https://doi.org/10.1016/j.heliyon.2021.e06343.

Berdugo Vilches, T., Seemann, M., Thunman, H, 2018. Influence of in-bed catalysis by ash-coated olivine on tar formation in steam gasification of biomass. Energy Fuels 32. https://doi.org/10.1021/acs.energyfuels.8b02153.

Bucătaru, C., Săvescu, D., Repanovici, A., Blaga, L., Coman, E., Cocuz, M.E., 2021. The implications and effects of medical waste on development of sustainable society—a brief review of the literature. Sustainability 13. https://doi.org/10.3390/su13063300 (Switzerland).

Cañete Vela, I., Berdugo Vilches, T., Berndes, G., Johnsson, F., Thunman, H, 2022. Co-recycling of natural and synthetic carbon materials for a sustainable circular economy. J. Clean. Prod. 365, 132674 https://doi.org/10.1016/J.JCLEPRO.2022.132674.

Cañete Vela, I., Maric, J., González-Arias, J., Seemann, M, 2024. Feedstock recycling of cable plastic residue via steam cracking on an industrial-scale fluidized bed. Fuel 355, 129518. https://doi.org/10.1016/j.fuel.2023.129518.

Cherubini, F., Strømman, A.H., 2011. Chemicals from lignocellulosic biomass: opportunities, perspectives, and potential of biorefinery systems. Biofuels Bioprod. Biorefin. 5 https://doi.org/10.1002/bbb.297.

Ciuffi, B., Chiaramonti, D., Rizzo, A.M., Frediani, M., Rosi, L., 2020. A critical review of SCWG in the context of available gasification technologies for plastic waste. Appl. Sci. 10 https://doi.org/10.3390/APP10186307 (Switzerland).

Dertinger, S.C., Gallup, N., Tanikella, N.G., Grasso, M., Vahid, S., Foot, P.J.S., et al., 2020. Technical pathways for distributed recycling of polymer composites for distributed manufacturing: windshield wiper blades. Resour. Conserv. Recycl. 157 https://doi.org/10.1016/j.resconrec.2020.104810.

Dharmaraj, S., Ashokkumar, V., Pandiyan, R., Halimatul Munawaroh, H.S., Chew, K.W., Chen, W.H., et al., 2021. Pyrolysis: an effective technique for degradation of COVID-19 medical wastes. Chemosphere 275. https://doi.org/10.1016/j.chemosphere.2021.130092.

DIRECTIVE (EU) 2018/851 of the European parliament and of the council of 30 May 2018 amending Directive 2008/98/EC on waste (Text with EEA relevance) n.d.

Elordi, G., Olazar, M., Castaño, P., Artetxe, M., Bilbao, J., 2012. Polyethylene cracking on a spent FCC catalyst in a conical spouted bed. Ind. Eng. Chem. Res. 51 https://doi.org/10.1021/ie3018274.

Erdogan, A.A., Yilmazoglu, M.Z., 2021. Plasma gasification of the medical waste. Int. J. Hydrog. Energy 46. https://doi.org/10.1016/j.ijhydene.2020.12.069.

Forero-Franco, R., Cañete-Vela, I., Berdugo-Vilches, T., González-Arias, J., Maric, J., Thunman, H., et al., 2023. Correlations between product distribution and feedstock composition in thermal cracking processes for mixed plastic waste. Fuel 341. https://doi.org/10.1016/j.fuel.2023.127660.

Giakoumakis, G., Politi, D., Sidiras, D., 2021. Medical waste treatment technologies for energy, fuels, and materials production: a review. Energies 14, 8065. https://doi.org/10.3390/en14238065 (Basel).

Giuliano, A., Freda, C., Catizzone, E., 2020. Techno-economic assessment of bio-syngas production for methanol synthesis: a focus on the water–gas shift and carbon capture sections. Bioengineering 7. https://doi.org/10.3390/bioengineering7030070.

González-Arias, J., Berdugo-Vilches, T., Mandviwala, C., Cañete-Vela, I., Seemann, M., Thunman, H., 2023. Effect of biomass ash on preventing aromatization of olefinic cracking products in dual fluidized bed systems. Fuel 338. https://doi.org/10.1016/j.fuel.2022.127256.

Guzzo, D., Carvalho, M.M., Balkenende, R., Mascarenhas, J., 2020. Circular business models in the medical device industry: paths towards sustainable healthcare. Resour. Conserv. Recycl. 160 https://doi.org/10.1016/j.resconrec.2020.104904.

Ibn-Mohammed, T., Mustapha, K.B., Godsell, J., Adamu, Z., Babatunde, K.A., Akintade, D.D., et al., 2021. A critical analysis of the impacts of COVID-19 on the global economy and ecosystems and opportunities for circular economy strategies. Resour. Conserv. Recycl. 164, 105169 https://doi.org/10.1016/J.RESCONREC.2020.105169.

Idrees, M., Akbar, A., Mohamed, A.M., Fathi, D., Saeed, F., 2022. Recycling of waste facial masks as a construction material, a step towards sustainability. Materials 15. https://doi.org/10.3390/ma15051810 (Basel).

Israelsson, M., Seemann, M., Thunman, H., 2013. Assessment of the solid-phase adsorption method for sampling biomass-derived tar in industrial environments. Energy Fuels 27. https://doi.org/10.1021/ef401893j.

Ivanović, T., Meisel, H.J., Som, C., Nowack, B., 2022. Material flow analysis of single-use plastics in healthcare: a case study of a surgical hospital in Germany. Resour. Conserv. Recycl. 185 https://doi.org/10.1016/j.resconrec.2022.106425.

Janajreh, I., Adeyemi, I., Elagroudy, S., 2020. Gasification feasibility of polyethylene, polypropylene, polystyrene waste and their mixture: experimental studies and modeling. Sustain. Energy Technol. Assess. 39 https://doi.org/10.1016/j.seta.2020.100684.

Jiang, J., Shi, K., Zhang, X., Yu, K., Zhang, H., He, J., et al., 2022. From plastic waste to wealth using chemical recycling: a review. J. Environ. Chem. Eng. 10 https://doi.org/10.1016/j.jece.2021.106867.

Joseph, B., James, J., Kalarikkal, N., Thomas, S., 2021. Recycling of medical plastics. Adv. Ind. Eng. Polym. Res. 4, 199–208. https://doi.org/10.1016/J.AIEPR.2021.06.003.

Kaminsky, W., 2021. Chemical recycling of plastics by fluidized bed pyrolysis. Fuel Commun. 8 https://doi.org/10.1016/j.jfueco.2021.100023.

Kane, G.M., Bakker, C.A., Balkenende, A.R., 2018. Towards design strategies for circular medical products. Resour. Conserv. Recycl. 135 https://doi.org/10.1016/j.resconrec.2017.07.030.

Kaushal, R., Rohit, D.A.K., 2022. A comprehensive review of the application of plasma gasification technology in circumventing the medical waste in a post-COVID-19 scenario. Biomass Convers. Biorefin. https://doi.org/10.1007/s13399-022-02434-z.

Kiminaitė, I., González-Arias, J., Striūgas, N., Eimontas, J., Seemann, M., 2023. Syngas Production from Protective Face Masks through Pyrolysis/Steam Gasification. Energies 16. https://doi.org/10.3390/en16145417 (Basel).

Lee, B.K., Ellenbecker, M.J., Moure-Eraso, R., 2002. Analyses of the recycling potential of medical plastic wastes. Waste Manag. 22 https://doi.org/10.1016/S0956-053X(02)00006-5.

Lee, R.P., Seidl, L.G., Huang, Q.L., Meyer, B., 2021. An analysis of waste gasification and its contribution to China's transition towards carbon neutrality and zero waste cities. Ranliao Huaxue Xuebao J. Fuel Chem. Technol. 49 https://doi.org/10.1016/S1872-5813(21)60093-2.

Li, Q., Faramarzi, A., Zhang, S., Wang, Y., Hu, X., Gholizadeh, M., 2020. Progress in catalytic pyrolysis of municipal solid waste. Energy Convers. Manag. 226 https://doi.org/10.1016/j.enconman.2020.113525.

Mandviwala, C., Berdugo Vilches, T., Seemann, M., Faust, R., Thunman, H, 2022a. Thermochemical conversion of polyethylene in a fluidized bed: impact of transition metal-induced oxygen transport on product distribution. J. Anal. Appl. Pyrolysis 163, 105476. https://doi.org/10.1016/J.JAAP.2022.105476.

Mandviwala, C., González-Arias, J., Berdugo Vilches, T., Seemann, M., Thunman, H., 2023. Comparing bed materials for fluidized bed steam cracking of high-density polyethylene: olivine, bauxite, silica-sand, and feldspar. J. Anal. Appl. Pyrolysis 173. https://doi.org/10.1016/j.jaap.2023.106049.

Mandviwala, C., González-Arias, J., Seemann, Martin, Berdugo Vilches, T., Thunman, H., 2022b. Fluidized bed steam cracking of rapeseed oil: exploring the direct production of the molecular building blocks for the plastics industry. Biomass Convers. Biorefin. 1, 1–12. https://doi.org/10.1007/S13399-022-02925-Z, 2022.

Martínez Narro, G., Pozos Vázquez, C., Mercado González, M.O., 2019. Viscosity reduction of heavy crude oil by dilution with hydrocarbons obtained via chemical recycling of plastic wastes. Pet. Sci. Technol. 37 https://doi.org/10.1080/10916466.2019.1584634.

Milne, B.J., Behie, L.A., Berruti, F., 1999. Recycling of waste plastics by ultrapyrolysis using an internally circulating fluidized bed reactor. J. Anal. Appl. Pyrolysis. 51 https://doi.org/10.1016/S0165-2370(99)00014-5.

Munir, D., Irfan, M.F., Usman, M.R., 2018. Hydrocracking of virgin and waste plastics: a detailed review. Renew. Sustain. Energy Rev. 90 https://doi.org/10.1016/j.rser.2018.03.034.

Murray, C., 2022. Bewildering benzene. Nat. Chem. 14 https://doi.org/10.1038/s41557-022-00948-7, 2022 14:5584–584.

Pareek, A., Dom, R., Gupta, J., Chandran, J., Adepu, V., Borse, P.H., 2020. Insights into renewable hydrogen energy: recent advances and prospects. Mater. Sci. Energy Technol. 3 https://doi.org/10.1016/j.mset.2019.12.002.

Patrício Silva, A.L., Prata, J.C., Walker, T.R., Campos, D., Duarte, A.C., Soares, A.M.V.M., et al., 2020. Rethinking and optimising plastic waste management under COVID-19 pandemic: policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. Sci. Total Environ. 742 https://doi.org/10.1016/j.scitotenv.2020.140565.

Purnomo, C.W., Kurniawan, W., Aziz, M., 2021. Technological review on thermochemical conversion of COVID-19-related medical wastes. Resour. Conserv. Recycl. 167 https://doi.org/10.1016/j.resconrec.2021.105429.

Rahimi, A.R., Garciá, J.M., 2017. Chemical recycling of waste plastics for new materials production. Nat. Rev. Chem. 1 https://doi.org/10.1038/s41570-017-0046.

Ren, T., Patel, M., Blok, K., 2006. Olefins from conventional and heavy feedstocks: energy use in steam cracking and alternative processes. Energy 31. https://doi.org/10.1016/j.energy.2005.04.001.

Saini, G., Budhwar, V., Choudhary, M., 2022. Review on people's trust on home use medical devices during Covid-19 pandemic in India. Health Technol. 12 https://doi.org/10.1007/s12553-022-00645-y (Berl).

Schyns, Z.O.G., Shaver, M.P., 2021. Mechanical recycling of packaging plastics: a review. Macromol. Rapid Commun. 42 https://doi.org/10.1002/marc.202000415.

Sharma, H.B., Vanapalli, K.R., Cheela, V.S., Ranjan, V.P., Jaglan, A.K., Dubey, B., et al., 2020. Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. Resour. Conserv. Recycl. 162 https://doi.org/10.1016/j.resconrec.2020.105052.

Shen, Y., Yu, S., Ge, S., Chen, X., Ge, X., Chen, M., 2017. Hydrothermal carbonization of medical wastes and lignocellulosic biomass for solid fuel production from lab-scale to pilot-scale. Energy 118. https://doi.org/10.1016/j.energy.2016.12.047.

Simon, C.M., Kaminsky, W., Schlesselmann, B., 1996. Pyrolysis of polyolefins with steam to yield olefins. J. Anal. Appl. Pyrolysis 38. https://doi.org/10.1016/S0165-2370(96)00950-3.

Syringe PP/PE without needle - n.d. https://www.sigmaaldrich.com/ES/es/substance/syringepppewithoutneedle1234598765 (accessed September 12, 2023).AU: Please provide complete details in Ref. Syringe PP/PE (2023).

Thind, P.S., Sareen, A., Singh, D.D., Singh, S., John, S., 2021. Compromising situation of India's bio-medical waste incineration units during pandemic outbreak of COVID-19: associated environmental-health impacts and mitigation measures. Environ. Pollut. 276 https://doi.org/10.1016/j.envpol.2021.116621.

Thunman, H., Berdugo Vilches, T., Seemann, M., Maric, J., Vela, I.C., Pissot, S., et al., 2019. Circular use of plastics-transformation of existing petrochemical clusters into thermochemical recycling plants with 100% plastics recovery. Sustain. Mater. Technol. 22 https://doi.org/10.1016/j.susmat.2019.e00124.

Vollmer, I., Jenks, M.J.F., Roelands, M.C.P., White, R.J., van Harmelen, T., de Wild, P., et al., 2020. Beyond mechanical recycling: giving new life to plastic waste. Angew. Chem. Int. Ed. 59 https://doi.org/10.1002/anie.201915651.

Voudrias, E.A., 2016. Technology selection for infectious medical waste treatment using the analytic hierarchy process. J. Air Waste Manag. Assoc. 66 https://doi.org/10.1080/10962247.2016.1162226.

Wang, J., Shen, J., Ye, D., Yan, X., Zhang, Y., Yang, W., et al., 2020. Disinfection technology of hospital wastes and wastewater: suggestions for disinfection strategy during coronavirus disease 2019 (COVID-19) pandemic in China. Environ. Pollut. 262 https://doi.org/10.1016/j.envpol.2020.114665.

Wilk, V., Hofbauer, H., 2013. Conversion of mixed plastic wastes in a dual fluidized bed steam gasifier. Fuel 107. https://doi.org/10.1016/j.fuel.2013.01.068.

Yang, M., Fan, D., Wei, Y., Tian, P., Liu, Z., 2019. Recent progress in methanol-to-olefins (MTO) catalysts. Adv. Mater. 31 https://doi.org/10.1002/adma.201902181.

Zhou, C., Stuermer, T., Gunarathne, R., Yang, W., Blasiak, W., 2014. Effect of calcium oxide on high-temperature steam gasification of municipal solid waste. Fuel 122. https://doi.org/10.1016/j.fuel.2014.01.029.