Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company’s public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Plasma gasification of the medical waste

Altug Alp Erdogan a, Mustafa Zeki Yılmazoğlu b,∗

a Anadolu Plasma Technology Center, Gazi University, Golbasi Campus, Teknoplaza, Block C, 23, Ankara, 06830, Turkey
b Gazi University, Faculty of Engineering, Department of Mechanical Engineering, Ankara, Turkey

HIGHLIGHTS

• Plasma gasification of medical waste is numerically investigated.
• Due to Covid-19 pandemic the increased amount of medical waste must be disposed.
• Three different medical waste samples are investigated with different ER values.
• The results are obtained for the different operating conditions.
• Plasma gasification of MW increases the sustainable operation and safe disposal.

ABSTRACT

In terms of infection control in hospitals, especially the Covid-19 pandemic that we are living in, it has revealed the necessity of proper disposal of medical waste. The increasing amount of medical waste with the pandemic is straining the capacity of incineration facilities or storage areas. Converting this waste to energy with gasification technologies instead of incineration is also important for sustainability. This study investigates the gasification characteristics of the medical waste in a novel updraft plasma gasifier with numerical simulations in the presence of the plasma reactions. Three different medical waste samples, chosen according to the carbon content and five different equivalence ratios (ER) ranging from 0.1 to 0.5 are considered in the simulations to compare the effects of different chemical compositions and waste feeding rates on hydrogen (H₂) content and syngas production. The outlet properties of a 10 kW microwave air plasma generator are used to define the plasma inlet in the numerical model and the air flow rate is held constant for all cases. Results showed that the maximum H₂ production can be obtained with ER = 0.1 for all waste samples.

© 2020 Hydrogen Energy Publications LLC. Published by Elsevier Ltd. All rights reserved.

Introduction

With the increase in the number of healthcare facilities and the occurrence of the COVID-19 pandemic, medical waste (MW) has become an important issue concerning health risks, environmental pollution, and sustainability. By the reports of the World Health Organization (WHO), International Committee of the Red Cross (ICRC), and European Council (EC), these wastes are classified as hazardous wastes, which mainly include infectious, sharps, pathological, chemical, pharmaceutical, cytotoxic, heavy-metal containing and radioactive
wastes [1–3]. The main sources of the MW production are hospitals, whereas other sources can be stated as medical schools or research centers, veterinary clinics, blood banks, mortuaries, autopsy centers, and biotechnology laboratories [4]. Hazardous MWs are assumed to form 15% of the total waste production in a hospital and that value can also be as high as 35%, depending on the waste production characteristics [5–7]. According to the literature, production rates of MW in hospitals has increased by up to 280 tons/day during the COVID-19 outbreak [8–11]. These wastes require cold and ventilated storage in a separate area from hospitals until transported to incineration facilities by MW municipal trucks, high disposal costs for hospitals, strict emissions control for municipalities, and incineration facilities, and detailed considerations for health risks [12–17]. During the treatment of MW via conventional incineration processes, high contents of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/PCDF), which are stated as cancerogenic, polluting the air and landfills, and reducing the soil quality [18–22], are emitted to the environment by their exhaust gas (77–894 ng N/m³) and residual ashes (69–4915 μg/m³), which are not acceptable by the requirements of European Council 2000/76/EC [23]. Especially in the case of the COVID-19 outbreak, it should be considered that the viral activity on surfaces can endure up to 72 h [1]. WHO recommends on-site high-temperature treatment before disposal of these wastes to reduce the risks of infection during transportation and storage, which brings extra risks of infection and treatment costs [24]. On the other hand, MW physically contains up to 54% paper, 20% textile, 26% organic, 50% plastic, 10% metal-containing, and 15% glass-containing wastes, while they consist of up to 35% carbon (C), 15% hydrogen (H), 16% nitrogen (N), 26% oxygen (O), 1% sulphur (S) and 3% chlorine (Cl) by ultimate analyses, with a maximum calorific value of 8820 kcal/kg [25–27]. Therefore, the fuel characteristics of MW show many similarities with municipal solid waste (MSW), which can be used for energy production. Besides these wastes could be used as refuse-derived fuels if more eco-friendly, healthy, and sustainable disposal options are developed.

Plasma gasification is one of the most promising techniques for waste treatment due to its high-temperature characteristics and lower hazardous emissions. Plasma is defined as the fourth state of matter which consists of radicals, free electrons, charged particles, and ions. During the transformation of a substance into the plasma phase, there are various chemical reactions, comprised of ionization, dissociation, and reassociation chains occurred in the fluid medium, which causes thermal dissociation of a substance. Through these features, thermal plasma generators are widely used in the energy industry for thermal processes, requiring high temperatures such as burning and pyrolysis [28,29]. Plasma generators commonly used in plasma gasifiers can be indicated as microwave plasma torches (magnetrons, klystrons, etc), and transferred/non-transferred arc plasma torches [30–33]. With the continuous supply of electricity and working fluid into these torches, high-temperature plasma jets up to 10,000 K can be achieved in the gasifier, which causes pyrolysis of feeding materials such as fuels and wastes [34–36]. In many cases, the plasma medium is air, water, steam, nitrogen, carbon dioxide, or their mixtures [37–40].

During the pyrolysis of the feedstock, syngas that contains considerable amounts of hydrogen (H₂) and carbon monoxide (CO) is produced, which can be later used for electricity production with the usage of reciprocating engines or fuel cells. According to the literature, plasma gasification of MSW can yield electrical, thermal, and cold gas efficiencies up to 32%, 80%, and 95%, respectively, depending on moisture, plasma temperature, plasma working fluid, and so on [41–43]. Moreover, valuable materials such as metallic substances (containing iron (Fe), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), etc.), or high-carbon-containing materials like graphite are captured in the residual slag, which can be collected as molten slag during the gasification process. The emissions emitted during the plasma gasification of MSW are stated as 18 ppm NOx, 6 ppm SOx, 5 ppm CO, 0.38 ppm HCl, and 0.43 mg/m³ dust, which are considerably lower than the limits of European Standards (159 ppm NOx, 19 ppm SOx, 10 mg/m³ CO, 7 ppm HCl, 10 mg/m³ dust) [44,45]. Besides, the total PCDD/PCDFs generation by the plasma gasification of hospital solid wastes are found to be lower than 0.01 ng toxic equivalent (TEQ), which should not exceed 0.1 ng TEQ/m³ according to the limits of European Commission Directive 2000/76/EC [2], and the detailed PCDD/PCDFs emissions for the plasma gasification are given in Table 1. These benefits show that plasma gasification can be a sustainable and eco-friendly alternative for on-site treatment of MW, whereas H₂-rich syngas can also be obtained during the process.

Although its overwhelming advantages compared to conventional methods, high specific energy consumption and low

| Chemical Structure | PCDD/PCDFs Generation via Plasma Gasification (ng TEQ/Nm³) |
|--------------------|-------------------------------------------------------------|
| PCDDs              |                                                             |
| 1,2,3,4,6,7,8-HxCDD| <0.000024                                                   |
| 1,2,3,4,7,8-HxCDD  | <0.00024                                                   |
| 1,2,3,7,8,9-HxCDD  | <0.0024                                                    |
| 1,2,3,7,8-PeCDD    | <0.0024                                                    |
| 2,3,7,8-TCDD       | <0.0005                                                    |
| 1,2,3,6,7,8-HxCDD  | <0.0024                                                    |
| OCDD               | <0.000015                                                   |
| PCDFs              |                                                             |
| 2,3,4,7,8-PeCDF    | <0.00072                                                   |
| 1,2,3,4,6,7,8-HpCDF| <0.000024                                                  |
| 1,2,3,4,7,8-HpCDF  | <0.000024                                                  |
| 1,2,3,4,7,8-HxCDF  | <0.00024                                                   |
| 1,2,3,6,7,8-HxCDF  | <0.0024                                                    |
| 1,2,3,7,8-PeCDF    | <0.000072                                                  |
| 2,3,4,6,7,8-HxCDF  | <0.00024                                                   |
| OCDF               | <0.000015                                                   |
service life are the main technical drawbacks of plasma generators [47]. Therefore, detailed design and optimization procedures should be evaluated in order to design a plasma gasifier. However, a plasma gasifier could not be designed or optimized easily because of its complexity. Since the characteristics of plasma could not have been fully understood yet, series of experiments and theoretical studies should be performed to design and optimize a plasma gasifier, which brings high additional costs. Hence, small-scale applications are not feasible yet, and the technology requires further studies to become a commercially widespread [48]. There are various experimental and numerical studies in the literature about the treatment of MSW via plasma gasification process and H2 production, while there are limited studies on MW. However, the studies about MW can also give an insight into the treatment of MW due to the similarities of their fuel characteristics. Nicholas Agon [49] performed a study on the plasma gasification of MSW, has a lower heating value (LHV) of 22.37 MJ/kg with using a one-stage plasma gasifier, having a waste gasification capacity of 56.7 kg/h as a maximum. The gasifier was operated with a plasma torch having a capacity of 120 kW by feeding the system with argon gas to form plasma having a flow rate of 6 SL/min. The tar formation is found to be lower than 10 mg/Nm³ the produced syngas can be obtained with a LHV up to 11 MJ/Nm³ and with a CO and H2 volumetric content of 40.6% and 49.5%, respectively. Tavares et al. [50] performed an analysis on plasma gasification of MSW by Aspen Plus and the results showed that up to 64% H2 and 58% CO content can be achieved in the syngas, which can yield a LHV up to 13 MJ/Nm³ when ER = 1 with a gasifier temperature of 1500 °C. Indrawan et al. [51] investigated the effects of the usage of a low-temperature plasma gasifier for MSW. The study presented that up to 49.6% gasification efficiency can be obtained by the application of plasma with air, forming a syngas LHV up to 6.02 MJ/Nm³ and 29.1% H2 content with an energy input range of 2.4—3.2 kW and a temperature range of 1500—2500 °C. Khuriati et al. [52] investigated the effects of the plasma working fluid type on process efficiencies and H2 production for the plasma gasification of MSW. The results show that the usage of 100% air as the plasma medium yields 32.64% H2 production and 45% process efficiency, while it is stated that the usage of 60% steam-40% air mixture as the plasma medium increases the H2 percentage (by 5.87% with 60% steam-40% air mixture) and decreases the CO percentage (by 7.9%). Messerle et al. [53] performed a study on the plasma gasification of toxic MW-containing carbonaceous waste with air-plasma and steam-plasma mediums. According to the results, 50.7% and 60.9% H2 concentrations can be achievable with air-plasma and steam-plasma, while the calorific values of the syngas were found to be 3410 kcal/kg and 4640 kcal/kg, respectively, with an optimum temperature of 1600 K. Furthermore, the chemical composition of the slag is found to be 63% iron carbide (Fe3C), 21% calcium silicate (CaSiO3), 13% silica (SiO2), and 3% iron (Fe), while no harmful impurities
were detected in the produced gas. Another study [54] showed the plasma gasification of MSW with a temperature range of 300–3000 K. By using TERRA commercial code for the calculations, it was found that the maximum syngas production can be achieved at 1600 K, where H2 concentration was 44.6% and 50.7% according to experimental and numerical results, respectively, with 16% error as a maximum. Hartati et al. [55] investigated the results of the possible utilization of plasma gasification technology for various waste types and it was found that plasma treatment can reduce the amount of wastes by greater than 50%, while the H2 production can be as high as 56.9% for MSW. Bin et al. [56] developed a dual-torch plasma arc furnace for MW treatment with the usage of argon (Ar) as the plasma working fluid, and the temperature at the center of the furnace is found to be 11,000 K. Sikandar Mashayak [57] performed a numerical study for the plasma gasification of MW in PTDR-100 model plasma gasifier and 39% H2 composition is obtained in syngas, which is validated by experimental results. Fiedler et al. [58] performed a numerical study to understand the limitations of plasma gasification of MW properly, and the results showed that inlet velocity and direction of oxygen supply are highly effective on the process efficiency. Mazzoni and Janajreh [59] thermodynamically analyzed the performance of plasma co-gasification processing of MSW and plastic solid waste (PSW) mixtures with different compositions in Aspen Plus environment. The study showed that higher overall performances can be obtained with higher oxygen or steam ratios, and higher H2 production with lower plasma power consumptions can be achieved by 50% MSW and 50% PSW. Carpinoglu and Sanlisoy [60] presented a methodology for the performance analyses of plasma gasification of solid waste, which is based on first and second laws of thermodynamics, and introduced practical scale parameters for such as capacity, power or hydrogen production. Ismail et al. [61] studied the benefits of using Euler-Euler multiphase model for plasma gasification of solid waste inside a fixed bed reactor. The deviation between experimental and numerical results was not found to be greater than 10% and ER = 0.3 yielded the most suitable conditions for H2 production, as well as tar formation.

The major limitation for plasma gasification alternatives is the difficulty of gasifier design because there are a wide variety of MW compositions and operational parameters, requiring series of experiments for each specific gasifier design. Also, further numerical simulations are needed to understand the benefits of the plasma gasification process, properly. In this study, the gasification characteristics of two different MW compositions in an updraft plasma gasifier are compared according to the numerical simulations and hydrogen production capacities are investigated. In each case, the effects of five ER values ranging between 0.1 and 0.5 were also compared. Chemical compositions of each MW sample were defined as calculated in reference studies [62–64], which are chosen to represent the minimum, average, and maximum carbon and hydrogen contents. The boundary conditions for the plasma inlet are obtained from the outlet of a 10 kW microwave plasma torch and held constant for all cases. ANSYS FLUENT code used in the simulations and kinetic parameters of the plasma reaction mechanism is obtained from TERRA commercial code [65].

### Materials and methods

#### Model geometry

Detailed design geometry of the updraft plasma gasifier is given in Fig. 1. The gasifier capacity is considered to be approximately 2 tons/day for PSW, which is close to the daily MW load of Gazi University Hospital (Ankara, Turkey) during the COVID-19 pandemic. There are two microwave plasma torches having 10 kW input power each. The exhaust pipe is movable along the vertical axis to control the gasification region, and the distance between the exhaust pipe and the base of the gasifier is 525 mm and held constant for all cases. The gasifier is insulated with a fire brick layer from the inside of the gasifier and the insulation thickness is 72.5 mm. To simplify the numerical model, only the inside domain of the gasifier is used in simulations as shown in Fig. 2.

#### Mathematical modeling

Navier-Stokes equations are solved for the fluid phase modeling for time-averaged steady-state conditions. Accordingly, governing equations including conservation of mass, conservation of momentum, and conservation of energy can be written as:

**Continuity:**

\[
\frac{\partial}{\partial t} (\rho \rho_q) + \nabla \cdot (\rho \rho_q \vec{V}_q) = \sum_{p=1}^{n} (m_p - m_{wp}) + S_q
\]

(1)

**Momentum:**

\[
\frac{\partial}{\partial t} \left( \rho \rho_q \vec{V}_q \right) + \nabla \cdot (\rho \rho_q \vec{V}_q \vec{V}_q) = -\alpha \nabla p + \nabla \tau_q \]

\[
+ \sum_{p=1}^{n} \left( \frac{\rho_{mp}}{C_{18}} \nabla \rho_{mp} - m_{wp} \vec{V}_{wp} \right) + \left( \overrightarrow{F}_q + \overrightarrow{F}_{mpq} + \overrightarrow{F}_{wnq} \right)
\]

(2)

**Energy:**

\[
\frac{\partial}{\partial t} \left( \rho \rho_q \rho_{h_q} \right) + \nabla \cdot (\rho \rho_q \rho_{h_q} \vec{V}_q) = -\frac{\partial \rho_{q \rho_{h_q}}}{\partial t} - \tau_q 
\]

\[
+ \nabla \vec{v}_q \vec{V}_q + S_q + \sum_{p=1}^{n} \left( \frac{\rho_{mp}}{C_{19}} \nabla \rho_{mp} - m_{wp} \rho_{hwp} - m_{wp} \rho_{hwp} \right)
\]

(3)

The standard k-ε model is used to implement the effects of turbulence under the assumption that the flow is fully turbulent. Hence, the effects of viscosity are neglected. As a result, the turbulent kinetic energy (k) and its dissipation rate (ε) are obtained from:

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + G_k + G_o - \rho \varepsilon - Y_M + S_k
\]

(4)

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right] + C_{21} \frac{\varepsilon}{k} (G_k + C_{3} \rho_{h_k} - C_{22} \rho_{h} \varepsilon) - C_{21} \frac{\varepsilon^2}{k} + S_\varepsilon
\]

(5)

where G_q is the turbulent kinetic energy generation due to mean velocity gradients, G_o is the generation due to buoyancy, $Y_M$ is the contribution of the fluctuating dilatation in a
Table 2 – Homogeneous and heterogeneous reactions and kinetic parameters.

| Reactions | \(A_i\) | \(E_i\) (J/kgmol) | \(a\) | \(b\) |
|-----------|---------|-------------------|------|------|
| 1         | \(1.127\)CO + 0.021H\(_2\)S + 0.236CH\(_4\) + 0.125H\(_2\)O + 0.018N\(_2\) | \(10^{10}\) | 100  | –    | 0.2  |
| 2         | C\(_6\) + H\(_2\)O → CO + H\(_2\) | \(4.18 \times 10^3\) | 1.751 \times 10^6 | – | 1 |
| 3         | C\(_6\) + CO\(_2\) → 2CO | \(6.27 \times 10^5\) | 2.83 \times 10^8 | – | 1 |
| 4         | C\(_6\) + O\(_2\) → CO\(_2\) | \(1.233 \times 10^3\) | 1.59 \times 10^8 | – | 1 |
| 5         | C\(_6\) + 0.5O\(_2\) → CO | \(8.71 \times 10^4\) | 1.49 \times 10^8 | – | 0.5 |
| 6         | C\(_6\) + H\(_2\)S → CS + H\(_2\) | \(1.0966 \times 10^5\) | 1.34 \times 10^8 | – | – |
| 7         | C\(_6\) + H\(_2\) → CH\(_4\) | 1.2 | 1.49 \times 10^8 | – | 2 |
| 8         | CH\(_4\) + H → CH\(_3\) + H\(_2\) | \(6.6171 \times 10^4\) | 4.97 \times 10^7 | – | – |
| 9         | CH\(_4\) + OH → CH\(_3\) + H\(_2\)O | 1.72 | 8.36 \times 10^6 | – | – |
| 10        | CH\(_4\) + O → CH\(_2\) + OH | \(2.6903 \times 10^4\) | 3.85 \times 10^7 | – | – |
| 11        | CH\(_3\) + H\(_2\)O → CH\(_4\) + OH | \(1.877 \times 10^5\) | 1.04 \times 10^8 | – | – |
| 12        | CH\(_2\) + H → CH\(_2\) + H | \(1.56 \times 10^4\) | 4.77 \times 10^7 | – | – |
| 13        | CH\(_3\) + O → CH\(_2\) + O | \(4.35 \times 10^4\) | 1.21 \times 10^8 | – | – |
| 14        | CH\(_4\) + OH → CH\(_2\)O + H\(_2\) | \(1.48 \times 10^4\) | 0 | – | – |
| 15        | CH\(_3\) + O → CH\(_2\)O + H | \(6.68 \times 10^4\) | 8.36 \times 10^6 | – | – |
| 16        | H + O\(_2\) → O + OH | \(7.843 \times 10^4\) | 7.02 | – | – |
| 17        | H + H\(_2\)O → H\(_2\) + OH | \(5.8689 \times 10^4\) | 8.49 \times 10^7 | – | – |
| 18        | H\(_2\) + O → H + OH | \(1.42 \times 10^5\) | 3.72 \times 10^7 | – | – |
| 19        | H\(_2\)O + O → OH + OH | \(3.74 \times 10^4\) | 7.65 \times 10^7 | – | – |
| 20        | CO + OH → CO\(_2\) + H | 60.95 | 3.22 \times 10^6 | – | – |
| 21        | CO + O → CO\(_2\) + O | \(9.87 \times 10^4\) | 1.57 \times 10^8 | – | – |
| 22        | CO\(_2\) + H → CO + OH | 468.72 | 9.03 \times 10^7 | – | – |
| 23        | C\(_2\)H\(_2\) + H → C\(_2\)H + H\(_2\) | \(8.08 \times 10^4\) | 7.94 \times 10^7 | – | – |
| 24        | C\(_2\)H\(_2\) + OH → C\(_2\)H + CO | \(8.96 \times 10^4\) | 2.09 \times 10^6 | – | – |
| 25        | OH + OH → H\(_2\)O + O | \(1.34 \times 10^4\) | 4.6 \times 10^6 | – | – |
| 26        | H + OH → H\(_2\) + O | \(1.877 \times 10^4\) | 2.94 \times 10^7 | – | – |
| 27        | H\(_2\) + OH → H\(_2\)O + H | \(8.93 \times 10^4\) | 4.18 \times 10^7 | – | – |
| 28        | CO + H\(_2\)O → CO\(_2\) + H\(_2\) | \(2.34 \times 10^{10}\) | 2.883 \times 10^8 | 0.5 | 1 |
| 29        | CO + 0.5O\(_2\) → CO\(_2\) | \(2.239 \times 10^{12}\) | 1.674 \times 10^8 | 1 | 0.25 |
| 30        | H\(_2\) + 0.5O\(_2\) → H\(_2\)O | \(9.87 \times 10^4\) | 3.1 \times 10^7 | 0.25 | 1.5 |
| 31        | CH\(_4\) + H\(_2\) → CO + H\(_2\)O | 22 | 1.9 \times 10^8 | 1 | 0.5 |
| 32        | CH\(_4\) + 2O\(_2\) → CO\(_2\) + 2H\(_2\)O | \(2.119 \times 10^{11}\) | 2.0525 \times 10^8 | 0.2 | 1.3 |
| 33        | CH\(_4\) + H\(_2\)O → CO + 3H\(_2\) | \(8 \times 10^7\) | 2.51 \times 10^8 | 0.5 | 1 |
| 34        | H\(_2\)O + H → 0.5O\(_2\) | \(2.5 \times 10^{10}\) | 3.5 \times 10^6 | 1 | 0 |
| 35        | H\(_2\) + CO\(_2\) → CO + H\(_2\)O | \(2.2 \times 10^{12}\) | 1.9 \times 10^6 | 0.5 | 1 |
| 36        | CH\(_4\) + 0.5O\(_2\) → CO + 2H\(_2\) | \(4.4 \times 10^{11}\) | 1.25 \times 10^8 | 0.5 | 1.25 |
| 37        | CO + 3H\(_2\) → CH\(_4\) + H\(_2\)O | \(5.12 \times 10^{14}\) | 2.73 \times 10^8 | 1 | 1 |

To integrate the pressure-velocity coupling scheme, SIMPLE algorithm is used in each iteration step. The pressure-based solver is used in the simulations.

The discrete ordinates (DO) radiation model used is to model radiation heat transfer through the walls of the gasifier. The model consists of a radiative transfer equation that is solved for discrete solid angles associated with positions \(\vec{r}\) and vector directions \(\vec{s}\) as:

\[
\frac{dI(\vec{r}, \vec{s})}{ds} + (\alpha + \sigma_t)I(\vec{r}, \vec{s}) = \alpha n^2 \frac{A_i}{\pi} + \sigma_t \int_{0}^{4\pi} I(\vec{r}, \vec{s}) \phi(\vec{s}, \vec{s'}) d\Omega'
\]

(7)

For the direction \(\vec{s'}\) as a field equation, the radiative transfer equation becomes:

\[
\nabla . I(\vec{r}, \vec{s'}) + (\alpha + \sigma_t)I(\vec{r}, \vec{s'}) = \alpha n^2 \frac{A_i}{\pi} + \sigma_t \int_{0}^{4\pi} I(\vec{r}, \vec{s'}) \phi(\vec{s}, \vec{s'}) d\Omega'
\]

(8)

The Weighted-sum-of-gray-gases model (WSGGM) is used.
addition of any user-defined sources. Similarly, species diffusion in the turbulence flow domain is calculated by;
\[ J_i = \left( \rho D_i, m + \mu_i \frac{\partial}{\partial x_i} \right) \nabla Y_i \]  
(11)

Finite-rate and eddy-dissipation models are used together for the calculation of the reaction rate of ith species (R_i). The finite-rate model uses Arrhenius expressions for the computation of chemical source terms, while the effects of turbulence fluctuations are neglected. The molar rate of creation/ destruction for ith species in rth reaction is computed from;
\[ \dot{R}_i = \Gamma \left( \bar{u}_{i_r} - \bar{u}_{i} \right) \left( k_f, r \prod_{j=1}^{n} \left[ C_{i,j}^0 \right]^{Y_j} - k_b, r \prod_{j=1}^{n} \left[ C_{i,j}^0 \right]^{Y_j} \right) \]  
(12)

where k_f, r and k_b, r are forward and backward rate constants, respectively, for rth reaction. k_f, r is calculated from the Arrhenius expression as in Eq. (13), while k_b, r is calculated with k_f, r as in Eq. (14).
\[ k_f, r = A_r e^{-\frac{E_r}{RT}} \]  
(13)
\[ k_b, r = \frac{E_r}{k_r} \]  
(14)

where A_r is the pre-exponential factor, \( \beta_r \) is temperature exponent, E_r is the activation energy for the reaction (J/kgmol), K_r is the equilibrium constant and R is the universal gas constant (J/kgmolK).

Net production rates of the chemical species are calculated by Eqs. (15) and Eq. (16) as
\[ R_i = \bar{u}_{i_r} M_{i, a} A_p \min \left( \frac{Y_i}{\bar{u}_{i_r} M_{i, a}}, \rho \right) \]  
(15)
\[ R_i = \bar{u}_{i_r} M_{i, a} A_p \rho \frac{\sum_{j=1}^{n} Y_j}{\sum_{j=1}^{n} \bar{u}_{j_r} M_{j, a}} \]  
(16)

where \( Y_i \) represents the mass fraction of produced species, \( Y_r \) is the mass fraction of reactants, and A and B are empirical constants that equal to 4.0 and 0.5, respectively.

Finite-rate/eddy-dissipation model is used for the calculations of Arrhenius and chemical reaction rates in control of the large-eddy mixing time scale, \( k/e \). Chemical reactions and the related kinetic parameters are obtained from the TERRA commercial code, which is commonly used for the 0-D simulation of plasma-chemical processes. Reaction mechanisms and the kinetic parameters are given in Table 2 [65]. Since the major effects of the plasma phase on gasification are caused by the plasma-related chemical reactions, the plasma jet is modeled as hot gas entering into the gasifier, and only the chemical effects of the plasma phase are considered in simulations. Chemical reactions for the conventional gasification phase are listed in 1–6, 28–30, and 32.

Waste feed into the gasifier and the gasifier domain are modeled as discrete and gas phases. Interactions between these phases are solved according to the Eulerian-Lagrangian approach.

Since the study mainly focuses on the investigation of gasification characteristics and hydrogen production

| Table 3 – Proximate and ultimate analyses of the MW samples. |
|-------------------|-------------------|-------------------|
| **Proximate Analysis** | **Sample 1 [62]** | **Sample 2 [63]** | **Sample 3 [64]** |
| Moisture | 0.32% | 0.29% | 7.04% |
| Ash | 0.00% | 2.30% | 1.89% |
| Volatiles | 99.13% | 78.52% | 82.37% |
| Fixed Carbon | 0.55% | 18.89% | 8.70% |
| **Ultimate Analysis** | | | |
| C | 81.81% | 65.92% | 48.99% |
| H | 12.17% | 10.03% | 7.2% |
| O | 5.76% | 23.09% | 43.52% |
| N | 0.15% | 0.22% | 0.08% |
| S | 0.11% | 0.22% | 0.08% |
| LHV | 42.65 MJ/kg | 29.12 MJ/kg | 15.57 MJ/kg |

| Table 4 – Operational parameters. |
|-------------------|-------------------|-------------------|
| **MW Sample No** | **Case No** | **Air Feeding Rate (kg/s)** | **Waste Feeding Rate (kg/s)** | **ER (–)** |
| 1 | 1–1 | 0.1 | 0.07 | 0.10 |
| | 1–2 | 0.1 | 0.035 | 0.20 |
| | 1–3 | 0.1 | 0.024 | 0.30 |
| | 1–4 | 0.1 | 0.0175 | 0.40 |
| | 1–5 | 0.1 | 0.0141 | 0.50 |
| | 2–1 | 0.1 | 0.09 | 0.10 |
| | 2–2 | 0.1 | 0.047 | 0.20 |
| | 2–3 | 0.1 | 0.031 | 0.30 |
| | 2–4 | 0.1 | 0.0235 | 0.40 |
| | 2–5 | 0.1 | 0.0188 | 0.50 |
| | 3–1 | 0.1 | 0.15 | 0.10 |
| | 3–2 | 0.1 | 0.075 | 0.20 |
| | 3–3 | 0.1 | 0.05 | 0.30 |
| | 3–4 | 0.1 | 0.0375 | 0.40 |
| | 3–5 | 0.1 | 0.03 | 0.50 |
capabilities, the formation of tar and other harmful substances are not included in the numerical model.

**Model suitability for MW gasification**

To evaluate the suitability of the numerical model for MW gasification, two approaches are followed. Firstly, the reactor geometry of a previous numerical study carried out by Ibrahimoglu and Yilmazoglu [66] is simulated for the MW feeding case. Then the results are compared with the results of the reference study for plasma gasification of lignite coal to observe the differences between MW gasification and coal gasification. In the second step, the results are verified by other reference studies related to the gasification of hazardous waste, MSW, and MW.

Simulated geometry for the comparison is shown in Fig. 3. This geometry is the inside domain of a downdraft plasma gasifier having two additional steam inlets, which increases hydrogen production during the process.

**Boundary conditions**

The proximate and ultimate analysis results of the MW samples are given in Table 3. Those wastes are chosen according to the C content, where Sample 1 and 3 represent the maximum and the minimum amounts, respectively. The waste feed is modeled as dispersed spherical particles having a uniform diameter of 100 μm and held constant for all cases, including the coal gasification scheme. Therefore, the effects of different particle sizes are not investigated in this study.

To evaluate the best conditions for the operation, simulations are performed for each MW sample with five different ER values, ranging between 0.1 and 0.5, with an increment of 0.1. ER is defined as the ratio of the real and stoichiometric ratios between mass flow rates of oxidizer and fuel feeds. That ratio is calculated from Eq. (17) as;

$$ER = \frac{m_{oxidizer}/m_{fuel}}{m_{oxidizer}/m_{fuel}}_{stoic}$$  \hspace{1cm} (17)

where $m_{oxidizer}$ is the mass flow rate of the oxidizing agent, and $m_{fuel}$ is the mass flow rate of fuel input. Since the air supplied...
to the plasma torch is the only oxidizer and MW is the fuel input, ER represents the ratio between air feeding and waste feeding rates. The air feeding rate is held constant for all cases. Accordingly, operational parameters and other boundary conditions for each case are summarized in Tables 4 and 5, respectively. Inlet boundary conditions for the plasma jet are obtained from a 10 kW AC microwave plasma generator. Insulation is modeled as a shell conduction layer, which allows only 1-D heat transfer between the reactor and the environment. The ambient temperature is set to 20 °C.

The compared reference study focused on the gasification of lignite coal, of which properties are listed in Table 6. The operational parameters and other boundary conditions are summarized in Tables 7 and 8 for the compared geometry presented in Fig. 3, respectively. The compared gasifier model in the reference study is supplied by two steam inlets with 0.1 steam to fuel ratio (SFR) and the study has investigated the effects of steam addition on hydrogen production. Therefore, the same amount of steam is supplied into the gasifier for the MW gasification scheme to acquire the comparison according to the same conditions.

**Process efficiency**

To evaluate the benefits of the gasification process, LHV of produced syngas, carbon conversion rate (CCR) and cold gas efficiency (CGE) are calculated after the simulations. In order to calculate the LHV of syngas, the produced gas has been considered as a cold and combustible ideal gas mixture. Therefore, LHV is calculated with the standard LHV values of H₂, CO and CH₄, which are given in Table 9, as follows;

\[
\text{(LHV)}_{\text{syngas}} = v_{\text{H}_2}\text{LHV}_{\text{H}_2} + v_{\text{CO}}\text{LHV}_{\text{CO}} + v_{\text{CH}_4}\text{LHV}_{\text{CH}_4}
\]  

(18)

where \(v_{\text{H}_2}\), \(v_{\text{CO}}\) and \(v_{\text{CH}_4}\) represents the mole fractions of H₂, CO and CH₄, respectively.

CCR is the ratio between the amounts of carbon mass in syngas and in the feedstock, which is calculated as given in Eq. (19).

\[
\text{CCR} = \frac{\dot{m}_{\text{out}} \sum_i f_i (\frac{w_i}{\rho_i})}{\dot{m}_{\text{in}} + \text{recycled chars}}
\]  

(19)

where \(i\) represents each species, \(\dot{m}_{\text{out}}\) and \(\dot{m}_{\text{in}}\) are the mass flow rates of the gas output and the feedstock, and \(f_i\) and \(w_i\) are the carbon mass fractions in each species and the feedstock, respectively.

On the other hand, CGE is the ratio of the syngas heating value to the feedstock heating value for dry and ash-free (DAF) conditions, which denotes the amount of produced energy with the consumed energy of feeding fuel. CGE is calculated as;

\[
\text{CGE} = \frac{\dot{m}_{\text{out}} \sum_i f_i (\text{LHV}_{\text{DAF}})_{\text{i}}}{\dot{m}_{\text{in}} (\text{LHV}_{\text{DAF}})_{\text{feedstock}}}
\]  

(20)

where \(\text{LHV}_{\text{DAF}}\) represents the LHV of each species as MJ per kg within the produced syngas.

**Results and discussion**

**Verification of numerical model**

In the reference study, the effects of three different mesh numbers were compared and in the simulations, a mesh

---

**Table 10 – Results for the comparison of MW and coal gasification schemes.**

| Parameter     | MW Sample 1 | Lignite Coal [66] |
|---------------|-------------|-------------------|
| Outlet Temperature | 1990 °C | 1560 °C (1833 K) |
| H₂            | 27.96% | 10.16% | |
| CO            | 20.77% | 16.76% | |
| CO₂           | 9.04%  | 6.34%  | |
| CH₄           | 0.00%  | 3.22%  | |
| H₂O           | 0.00%  | 4.63%  | |
| N₂            | 42.22% | 48.98% | |
| O₂            | 0.00%  | 9.64%  | |
| LHV           | 5.640 MJ/m³ | 4.694 MJ/m³ | |
| CCR           | 49.92% | 67.80% | |
| CGE           | 34.42% | 47.31% | |
structure with 720,000 nodes, which had an orthogonal quality of 0.85 was used. In the current study, the suitable mesh configuration is obtained for 1,400,000 mesh with 0.82 average orthogonal quality. An outline view of the mesh structure is given in Fig. 4.

Since the purpose of that comparison is to check the main differences between MW and coal gasification processes, syngas compositions, carbon conversion rates and cold gas efficiencies are compared. The compared gasification results of MW gasification and coal gasification schemes are presented in Table 10. The MW gasification yields higher exhaust temperature than the coal gasification due to its greater LHV and surplus amounts of volatile matter. Although the higher production of H₂, CO and the greater LHV of gasification the MW Sample 1, CCR and CGE values are lower than the coal gasification case. Following the results, plasma gasification of the coal scheme yields greater CCR and CGE values and lower exhaust temperatures than MW gasification according to the literature [65,67,68]. Hence, it can be said that results are meaningful compared to coal gasification.

The comparison of the same results with the results of other reference studies for different waste characteristics are presented in Table 11. According to the results, plasma gasification of MSW can yield a LHV range of 4–9 MJ/Nm³ under conditions of air and steam supply. Also, compositions of

| Results | MW | Indrawan et al. [51] | Khuriati et al. [52] | Messerle et al. [54] | Zhang et al. [69] | Arena et al. [70] |
|---------|----|---------------------|----------------------|---------------------|------------------|------------------|
| H₂ (%)  | 27.96 | 24.4–33.8           | 32.64–38.51          | 44.6                | 19.23–26.87      | 33.32            |
| CO (%)  | 20.77 | 22.0–30.9           | 23.85–31.25          | 26.5                | 12.50–15.74      | 27.47            |
| H₂/CO (−) | 1.35 | 1.09–1.11          | 1.04–1.61            | 1.68                | 1.24–1.70        | 1.21             |
| LHV (MJ/Nm³) | 5.640 | 5.41–7.56         | 4.95–5.32           | 8.16                | 8.23–8.70        | 4–7              |

![Fig. 5 — Sampling line for the velocity profile.](image)

![Fig. 6 — Velocity profile along the centerline for different mesh configurations.](image)
produced syngas from MSW contain up to 28.3% H₂ and 18.8% CO content, in which H₂/CO ratios can vary between 1.16 and 2.00 [51,52,54,69,70]. Hence, it is clear that the numerical model can be used for evaluating the results of MW gasification.

**Mesh independency**

For the current geometry, meshing is performed with the tetrahedral mesh structure. Mesh study is carried out with seven different mesh structures, having mesh quantities varying between 360 k to 1359 k, and mesh configurations are generated according to average values of orthogonal quality, skewness, and aspect ratio. The obtained mesh qualities of each case are listed in Table 12. In this table, the percentage denotes the percent mesh having the worst quality throughout the whole mesh structure.

To examine the effects of mesh quantity, velocity distribution results inside the gasifier are compared for the results of cold phase simulations. Results are plotted along the centerline of the gasifier, which is marked in Fig. 5 with a red line. 350 sampling points are used for the sampling of velocity values through the centerline.

Accordingly, centerline velocity profiles for each mesh configuration are plotted against the distance from the base surface of the gasifier. As can be seen in Fig. 6, the velocity profile along the centerline is not affected considerably. Since there are not any significant changes between the results, 360 k mesh configuration is selected to reduce computational time during the simulations. The selected mesh structure is presented in Fig. 7.

**Temperature distribution**

Since geometric parameters of the model geometry are not changed and the effects of the geometric configurations are not investigated in this study, temperature contour plots for each MW sample are obtained only for ER = 0.1, whereas temperature profiles along the centerline of the gasifier are obtained for all ER values.

Fig. 8 presents the temperature contours of each MW sample for ER = 0.1. Temperature profiles show that some portion of gasification occurs at the bottom region of the...
Fig. 9 – Temperature profiles for all cases. These results represent the temperature distributions of (a) Sample 1, (b) Sample 2, and (c) Sample 3 for all ER values.

Fig. 10 – H₂ distribution inside the gasifier for ER values. (a) Sample 1, (b) Sample 2, and (c) Sample 3.
Fig. 11 – CO distribution inside the gasifier for ER values. (a) Sample 1, (b) Sample 2, and (c) Sample 3.
exhaust pipe. Also, the height of the gasification layer decreases slightly as LHV of the MW feedstock decreases. That shows the position of the temperature transition region is affected by the fuel characteristics of MW and the position of the exhaust pipe. On the other hand, temperatures along the exhaust pipe tend to decrease with the decrement of LHV.

Temperature profiles along the centerline are plotted against the distance from the bottom of the gasifier as presented in Fig. 9. Temperature distribution behavior after the region above 0.4 m shows variances, and there are no correlations found between ER values and temperatures. It can be concluded that the gasification process takes place after the height of 0.4 m, which is near to the exhaust pipe height. Except for the Case 2–5, temperatures tend to decrease after the distance of 0.8 m. Maximum temperatures are obtained with \( \text{ER} = 0.2 \) for Sample 1 and 2, whereas those are obtained with \( \text{ER} = 0.3 \) and \( \text{ER} = 0.4 \) for Sample 3. Especially for Case 3-1, the temperature profile tends to decrease down to 2200 \(^\circ\)C,

**Fig. 12** – \( \text{CH}_4 \) distribution inside the gasifier for ER values. (a) Sample 1, (b) Sample 2, and (c) Sample 3.

**Fig. 13** – \( \text{CO}_2 \) distribution inside the gasifier for ER values. (a) Sample 1, (b) Sample 2, and (c) Sample 3.
which can be affected by the higher moisture content of Sample 3.

**Species distribution**

The distribution characteristics of species are found to have parallels with the temperature distribution, whereas the variances in each species can be examined along the centerline. Therefore, the results are plotted for the centerline as similar to the temperature distribution for the sake of simplicity.

Distributions of H$_2$ mole fractions along the centerline are given in Fig. 10. Similar to the characteristics of temperature distribution, H$_2$ content tends to increase after 0.4 m. With the increase of ER, the mole fractions of H$_2$ generated along the centerline decrease for all MW samples, whereas the tendency of H$_2$ generation profiles shows differences for each case. After the height of 0.8 m, H$_2$ generation profiles show an upward tendency for Case 1-2, 2-3, 2-5, 3-1, 3-3, 3-4, and 3-5, which indicates that H$_2$ production capabilities can be controlled by adjusting the height for some cases. Although Sample 1 has the maximum H content, maximum H$_2$ mole fractions are achieved by the gasification of Sample 3 having 7.04% moisture. That denotes the benefits of moisture content for H$_2$ production during the plasma gasification of MW.

CO distribution profiles along the centerline for all cases are given in Fig. 11. Except for ER $= 0.1$ cases and Case 3-2 (ER = 0.2), peak values of the CO mole fractions are obtained at the height of 0.6 m, approximately. Also, generated CO species cannot reach the output of the gasifier for these cases, which shows the importance of the gasifier height as for the results of H$_2$. Similar to the H$_2$ mole fractions, the CO mole fractions tend to decrease with the increment of ER. Despite its lowest C percentage, maximum CO mole fractions are obtained from the gasification of Sample 3 for all ER values.

Although methane (CH$_4$) production values from MW gasification are found to be substantially lower than gasification of fuels, CH$_4$ mole fractions should also be considered in the gasifier design because of their higher LHV (35.8 MJ/kg). Therefore, CH$_4$ generation profiles are plotted against the distance for all cases, which are presented in Fig. 12. As expected, there are no CH$_4$ outputs from the system, except for Case 3-1, and the mole fractions of generated CH$_4$ can be neglected. However, the maximum CH$_4$ mole fraction between 0.6 m and 0.8 m is found to be 2.0% for Sample 3, approximately, which is close to the CH$_4$ production from the gasification of lignite (3.32%) as given in Table 9. Hence, there is a possibility to increase the production of CH$_4$ by controlling the distance between the output and the gasification region.

The distribution of CO$_2$ inside the gasifier is given in Fig. 13. Although the carbon contents are different for each MW sample, CO$_2$ generation does not decrease with the decrement of carbon percentage in the feedstock. On the other hand, there are correlations found between the temperature distribution and CO$_2$ mole fractions for Sample 1 and 3, whereas such correlation for Sample 2 is found for up to ER = 0.3. It can be concluded that CO$_2$ mole fractions can be affected by the temperature distribution inside the gasifier more than its carbon content.

H$_2$S mole fractions along the centerline are given in Fig. 14. Unlike the previous results, there are no significant variances found in the H$_2$S profiles after the gasification region. The H$_2$S mole fraction decreases with the increment of ER values. The
maximum H2S generation is found to be 0.6% through all cases.

**Syngas properties**

Differences in syngas temperatures with the variance of ER values are given in Fig. 15 for each sample. Minimum syngas temperatures are found for ER = 0.1 for all MW samples. The maximum syngas temperatures are found to be 3260 °C for Sample 1 and 3220 °C for Sample 2 with ER = 0.2, whereas that of Sample 3 is 3150 °C for ER = 0.3.

Mole fractions of syngas output are presented in Fig. 16. Despite its lowest carbon and hydrogen contents, maximum mole fractions of H2 and CO are obtained by the gasification of Sample 3, which is mainly affected by its higher moisture content. The maximum H2 mole fractions are found to be 24.43%, 25.48%, and 32.79% for Sample 1, 2, and 3, respectively. Similarly, maximum syngas heating values are obtained by ER = 0.1. The minimum CO2 mole fractions are found to be 10.78% and 12.45% for Sample 1 and 2 for ER = 0.5, whereas that of Sample 3 is found 11.75% with ER = 0.1. The mole fractions of H2S by ER = 0.1 for all cases, which has a maximum value of 0.6% and can be neglected. Hence, the results showed that the best syngas properties for all cases are obtained for ER = 0.1.

**Process efficiency**

The differences between CCR and CGE are plotted against ER values as given in Fig. 17. The results show that CCR values are slightly affected by ER, which is negligible. The maximum CCR is obtained with the gasification of Sample 3, which is

---

**Fig. 15** — Syngas temperatures against ER values for each sample.

**Fig. 16** — Syngas compositions against ER values for each sample. Those represent (a) H2, (b) CO, (c) CO2 and (d) H2S contents, and (e) LHV.
approximately 71%. On the other hand, maximum CGE values are obtained by $ER = 0.1$ for all cases, and the highest efficiencies are obtained in Sample 3, in which the maximum CGE is found to be 78.61%. Consequently, $ER = 0.1$ yields the best results for the gasification of MW compared to other ER values.

**Conclusions**

Especially after the COVID-19 pandemic, MW production rates of all hospitals are increased drastically, and strict management strategies should be followed. Due to their high amounts of toxic and hazardous emissions, high energy consumption rates, and constant loss of valuable materials, traditional methods for the disposal of MW are not sustainable. Compared to conventional systems, plasma gasification yields promising results for the future.

This study investigates the plasma gasification characteristics and $H_2$ production capabilities of MW samples having different carbon and hydrogen contents by performing numerical simulations. ANSYS FLUENT code is used for the simulations and the reaction mechanisms of plasma with its related kinetic parameters are obtained from TERRA code. Results showed that;

- $ER = 0.1$ provides the best results for the gasification of MW, which yields up to 32.78% $H_2$ production, 25.37% CO and 78.61% CGE.
- Compared to the effects of C and H in the MW feedstock, the moisture content is found to be more effective on the gasification characteristics and $H_2$ production capabilities.
- A correlation is evaluated between temperature distribution and $CO_2$ distribution.
- There is a possibility of controlling the gasification characteristics of MW by the distance between the gasification region and the syngas output for this gasifier.
- The maximum $H_2S$ mole fraction is found to be 0.6%.

As can be seen from the results, there is a possibility to use the plasma gasification technology for both the treatment of MW and the production of $H_2$. The gasification characteristics can be enhanced by controlling the position of syngas output, increasing the moisture content, and lowering the ER values. Hence, the exhaust pipe height of the gasifier should be optimized for its utilization in MW gasification more efficiently. Although the formation of harmful substances is generally found below the limits of many standards and codes according to the literature. Therefore, further studies are required to evaluate the harmful substance formations inside the gasifier. Also, the effects of moisture content and ER values lower than 0.1 should be analyzed.

**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.

**Acknowledgements**

We sincerely thank Prof. Beycan Ibrahimoglu and Anadolu Plasma Technology Energy Center for their support.

**REFERENCES**

[1] Twinch E. Medical waste management. Geneva, Switzerland: International committee of the Red Cross (ICRC); 2011.
[2] Consultation, W. H. O.. Assessment of the health risk of dioxins: re-evaluation of the Tolerable Daily Intake (TDI). 1998. p. 25–9. May, Geneva, Switzerland.
[3] Directive EU. Directive 2000/76/EC of the European parliament and of the Council of 4 december 2000 on the incineration of waste. Off J Eur Communities - Legis 2000;332:91–111.
[4] Mathur P, Patan S, Shobhawat AS. Need of Biomedical Waste Management system in hospitals-an emerging issue-a review. Curr World Environ 2012;7(1):117–24.
[5] Taghipour H, Mosaferi M. Characterization of medical waste from hospitals in Tabriz, Iran. Sci Total Environ 2009;407(5):1527–35. https://doi.org/10.1016/j.scitotenv.2008.11.032.
[6] Deng N, Cui WQ, Wang WW, Zhang Q, Zhang YF, Ma HT. Experimental study on co-pyrolysis characteristics of typical medical waste compositions. J Cent S Univ 2014;21(12):4613–22. https://doi.org/10.1007/s11771-014-2468-4.
[7] Shareefdeen ZM. Medical waste management and control. J Environ Prot 2012;3(12):1625–8. https://doi.org/10.4236/jepr.2012.312179.

[8] You S, Sonne C, Ok YA. COVID-19’s unsustainable waste management. Science (New York, NY) 2020;368(6648):1438. https://doi.org/10.1126/science.abc7778.

[9] Ranjan MR, Tripathi A, Sharma G. Medical waste generation during COVID-19 (SARS-CoV-2) pandemic and its management: an Indian perspective. Asian J Environ & Ecol 2020:10–5. https://doi.org/10.11734/ajeell1313017.

[10] Klemes JJ, Fan YV, Tan RR, Jiang P. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. Renew Sustain Energy Rev 2020;127(C). https://doi.org/10.1016/j.rser.2020.109883.

[11] Kalina M, Tilley E. “This is our next problem”- cleaning up from the COVID-19 response. Waste Manag 2020;108:202–5. https://doi.org/10.1016/j.wasman.2020.05.006.

[12] Lee BK, Elenbecker MJ, Moure-Ersaso R. Alternatives for treatment and disposal cost reduction of regulated medical wastes. Waste Manag 2004;24(2):143–51. https://doi.org/10.1016/j.wasman.2003.10.006.

[13] Diaz LF, Eggerth LL, Enkhtsetseg SH, Savage GM. Waste management: an Indian perspective. Asian J Environ Protect 2012;3(12):1625. https://doi.org/10.1126/science.abc7778.

[14] McGain F, Hendel SA, Story DA. An audit of potentially hazardous medical wastes. Waste Manag 2004;24(2):143–51. https://doi.org/10.1016/j.wasman.2003.10.008.

[15] Rutala WA, Mayhall CG. Medical waste. Infect Contr Hosp Ecol 2008;28(7):1219–26. https://doi.org/10.1016/j.jwhse.2007.04.010.

[16] McCain F, Hendel SA, Story DA. An audit of potentially recyclable waste from anaesthetic practice. Anaesth Intensive Care 2009;37(5):820–3. https://doi.org/10.11177/0310057X0903700521.

[17] Windfeld ES, Brooks MS. Medical waste management—a review. J Environ Manag 2015;163:98–108. https://doi.org/10.1016/j.jenvman.2015.08.013.

[18] Rutala WA, Mayhall CG. Medical waste. Infect Contr Hosp Epidemiol 1992;13(1):38–48.

[19] Kuo HW, Shu SL, Wu CC, Lai JS. Characteristics of medical waste in Taiwan. Water Air Soil Pollut 1999;114(3):413–21. https://doi.org/10.1023/A:1005169032759.

[20] Goncuoglu M, Ayaz ND, Cengiz G, Onaran B, Çufalo glu G. Emerging details about COVID-19 and chronology of the pandemic in Turkey. Ankara Univ Vet Fak Derg 2020;67(3):323–32. https://doi.org/10.33988/avufd.730560.

[21] Kilçıraslan MA, Şenel FC, Ozcan M. Assessment of dental care during the COVID-19 pandemic in Turkey and future projections. Brazil Dental Sci 2020;23(2):7. https://doi.org/10.14295/bds.2020.v23i2.2260.

[22] Gupta N, Desalegn H, Ocamar P, Lacombe K, Njoum R, Afhiene M, Cunha L, Spearman CW, Sonderup MW, Vierendeels J. Plasma gasification of refuse derived fuel in a single-stage system using different gasifying agents. Waste Manag 2016;47:246–55. https://doi.org/10.1016/j.wasman.2015.07.014.

[23] Singh S, Prakash V. Toxic environmental releases from medical waste incineration: a review. Environ Monit Assess 2007;132(1–3):67–81. https://doi.org/10.1007/s10661-006-9503-3.

[24] World Health Organization. Management of solid health-care waste at primary health-care centres: a decision-making guide. Immunization, Vaccines and Biologicals (IVB) Protection of the human environment. Water. Sanitation and Health (WSH); 2005.

[25] Li CS, Jenq FT. Physical and chemical composition of hospital waste. Infect Contr Hosp Epidemiol 1993;14(3):145–50. https://doi.org/10.1086/646700.

[26] Deng N, Zhang YF, Wang Y. Thermogravimetric analysis and kinetic study on pyrolysis of representative medical waste composition. Waste Manag 2008;28(9):1572–80. https://doi.org/10.1016/j.wasman.2007.05.024.

[27] Komilis D, Katsafaros N, Vassiopoules P. Hazardous medical waste generation in Greece: case studies from medical facilities in Attica and from a small insular hospital. Waste Manag Res 2011;29(8):807–14. https://doi.org/10.1177/0734242X10388684.

[28] Smith MD. Plasma technology. Kirk-Othmer Encyclop ChemTechnol 2000. https://doi.org/10.1002/1435640661.Books on Books on Plasma Technology.p.63.

[29] Li H, Li T, Wei X. Main performance analysis of kitchen waste gasification in a small-power horizontal plasma jet reactor. J Environ Manag 2006;74(4):1331–7. https://doi.org/10.1016/j.jenman.2006.08.013.

[30] Li H, Li T, Wei X. Main performance analysis of kitchen waste gasification in a small-power horizontal plasma jet reactor. J Environ Manag 2006;74(4):1331–7. https://doi.org/10.1016/j.jenman.2006.08.013.

[31] Surov AV, Popov SD, Popov VE, Subbotin DI, Serba EO, Spodobin VA, Nakonechny GV, Pavlov AV. Multi-gas AC plasma torches for gasification of organic substances. Fuel 2017;203:1007–14. https://doi.org/10.1016/j.fuel.2017.02.104.

[32] Agon N, Hrabovský M, Chumák O, Hlina M, Kopecky V, Maslani A, Bosmans A, Helsen L, Skolija S, Van Oost G. Synthesis of refined fuel for use as a hydrogen source in a single-stage system using different gasifying agents. Waste Manag 2016;47:246–55. https://doi.org/10.1016/j.wasman.2015.07.014.

[33] Tripathi N, Jawney K. Experimental analysis of thermochemical properties for domestic waste using microwave induced plasma gasification. Doctoral dissertation. Lovely Professional University, 2017.

[34] Hee J, Min B, Kim JH, Park BS, Kim JG, Kim YS, Kim JH, Kim CS. Environmental performances and energy efficiency for MSW gasification treatment. Waste Biomass Valor 2015;6(1):123–35. https://doi.org/10.1007/s12649-014-9322-7.

[35] Ismail TM, Monteiro E, Ramos A, Abd El-Salam M, Roubou A. An Eulerian model for forest residues gasification in a
plasma gasifier. Energy 2019;182:1069–83. https://doi.org/10.1016/j.energy.2019.06.070.

[44] Kaur RR. Plasma gasification: an alternative solution for municipal solid waste disposal. Crime Mapp: A GIS Based Spatial Opt Approach 1 Toledo 2016:87–92. Ohio, USA, September.

[45] Directive EU. Directive on the reduction of air pollution from existing municipal waste-incineration plants, 89/429/EEC. Off J Europ Communities 1989:50–4. 21 June.

[46] Byun Y, Namkung W, Cho M, Chung JW, Kim YS, Lee JH, Lee CR, Hwang SM. Demonstration of thermal plasma gasification/vitrification for municipal solid waste treatment. Environ Sci Technol 2010;44(17):6680–4. https://doi.org/10.1021/es101244u.

[47] Sharina IA, Perepechko LN, Domarov PV. June). Development and study of different numerical plasma jet models and experimental study of plasma gasification of waste. Doctoral dissertation. Ghent University, 2015.

[48] Tavares R, Ramos A, Rouboa A. A theoretical study on municipal solid waste plasma gasification. Waste Manag 2019;90:37–45. https://doi.org/10.1016/j.wasman.2019.03.051.

[49] Indrawan N, Mohammad S, Kumar A, Huhnke RL. Municipal solid waste disposal. Crime Mapp: A GIS Based Spatial Opt Approach 1 Toledo 2016:87–92. Ohio, USA, September.

[50] Indrawan N, Mohammad S, Kumar A, Huhnke RL. Modeling low temperature plasma gasification of municipal solid waste. Environ Technol & Innov 2019;15:100412. https://doi.org/10.1016/j.eti.2019.100412.

[51] Khuriati A, Purwanto P, Huboyo HS, Suryono S, Putro AB. Plasma fixed bed gasification using an Eulerian model. Int J Hydrogen Energy 2018;43(25):5136–43. https://doi.org/10.1016/j.jhydene.2017.08.147.

[52] Agon N. Development and study of different numerical plasma jet models and experimental study of plasma gasification of waste. Doctoral dissertation. Ghent University, 2015.

[53] Messerle VE, Mosse AL, Ustimenko AB. Plasma gasification of carbonaceous wastes: thermodynamic analysis and experiment. Thermophys Aeromechanics 2016;23(4):613–20. https://doi.org/10.1149/088984316040144.

[54] Messerle VE, Mosse AL, Ustimenko AB. Municipal solid waste plasma processing: thermodynamic computation and experiment. IEEE Trans Plasma Sci 2016;44(12):3017–22. https://doi.org/10.1109/TPS.2016.2601107.

[55] Hartati A, Widiputri D, Dimyati A. Municipal solid waste treatment using plasma gasification with the potential production of synthesis gas (syngas). Proceed Int Conf Innov, Entrepreneur Technol 2018;2(1):8–12.

[56] Bin L, Kikuchi M, Heping L, Iwao T, Inaba T. Dual torch plasma arc furnace for medical waste treatment. Plasma Sci Technol 2007;9(6):709–12. https://doi.org/10.1007/989/6616.

[57] Mashayak SY. CFD modeling of plasma thermal reactor for waste treatment. Master of Science, Mechanical Engineering. West Lafayette, Indiana: Purdue University; 2009.

[58] Fiedler J, Lietz E, Bendix D, Hebecker D. Experimental and numerical investigations of a plasma reactor for the thermal destruction of medical waste using a model substance. J Phys Appl Phys 2004;37(7):1031–40. https://doi.org/10.1088/0022-3727/37/7/013.

[59] Mazzoni L, Janajreh I. Plasma gasification of municipal solid waste with variable content of plastic solid waste for enhanced energy recovery. Int J Hydrogen Energy 2017;42(30):1946–57. https://doi.org/10.1016/j.jhydene.2017.06.069.

[60] Carpiniloglu MO, Sanlisoy A. Performance assessment of plasma gasification for waste to energy conversion: a methodology for thermodynamic analysis. Int J Hydrogen Energy 2018;43(25):5136–43. https://doi.org/10.1016/j.jhydene.2017.08.147.

[61] Ismail TM, Ramos A, Abd El-Salam M, Monteiro E, Roubao A. Plasma fixed bed gasification using an Eulerian model. Int J Hydrogen Energy 2019;44(54):28668–84. https://doi.org/10.1016/j.jhydene.2019.08.035.

[62] Qin L, Han J, Zhao B, Chen W, Xing F. The kinetics of typical medical waste pyrolysis based on gaseous evolution behaviour in a micro-fluidised bed reactor. Waste Manag Res 2018;36(11):1073–82. https://doi.org/10.1177/0734242X18790357.

[63] Gerasimova K, Khakshachikhkh V, Kornilievac V, Tarasov C. Study of pyrolysis of components and mixture of medical waste. Chem Eng 2019;76:1423–8. https://doi.org/10.3303/CET197628.

[64] Zhu HM, Yan JH, Jiang XG, Lai YE, Cen KF. Study on pyrolysis of typical medical waste materials by using TG-FTIR analysis. J Hazard Mater 2008;153(1–2):670–6. https://doi.org/10.1016/j.jhazmat.2007.09.011.

[65] Messerle VE, Ustimenko AB, Lavrishchev OA. Comparative study of coal plasma gasification: simulation and experiment. Fuel 2016;164:172–9. https://doi.org/10.1016/j.fuel.2015.09.095.

[66] Ibrahimoglu B, Yilmazoglu MZ. Numerical modeling of a downdraft plasma coal gasifier with plasma reactions. Int J Hydrogen Energy 2020;45(5):3532–48. https://doi.org/10.1016/j.jhydene.2018.12.198.

[67] Matveev IB, Messerle VE, Ustimenko AB. Plasma gasification of coal in different oxidants. IEEE Trans Plasma Sci 2008;36(6):2947–54. https://doi.org/10.1109/TPS.2008.207643.

[68] Yoon SJ, Goo Lee J. Syngas production from coal through microwave plasma gasification: influence of oxygen, steam, and coal particle size. Energy & Fuels 2012;26(1):524–9. https://doi.org/10.1021/ef2013584.

[69] Zhang Q, Dor L, Zhang L, Yang W, Blasiak W. Performance analysis of municipal solid waste gasification with steam in a Plasma Gasification Melting reactor. Appl Energy 2012;98:219–29. https://doi.org/10.1016/j.apenergy.2012.03.028.

[70] Arena U. Process and technological aspects of municipal solid waste gasification. A Review. Waste Manag 2012;32(4):625–39. https://doi.org/10.1016/j.wasman.2011.09.025.

[71] Waldheim L, Nilsson T. Heating value of gases from biomass gasification. Task: Report prepared for: IEA bioenergy agreement; 2001. p. 20.