Journal of Theoretical and Applied Physics (JTAP), Vol.16, No. 4, 162241 (1-6), 2022
Received 22 August 2022 ; Accepted 30 September 2022 ; [http://dx.doi.org/10.30495/jtap.162241]

Chemical and pharmaceutical waste disposal with thermal plasma pyrolysis-melting

Shahrooz Saviz *, Davoud Dorranian, Amir Hossein Sari

Abstract
Thermal plasma treatment is considered as a suitable alternative for treatment of highly-hazardous wastes such as industrial, radioactive and medical wastes. Therefore, a Plasma-Gasification-Melting (PGM) system for treatment of Chemical and Pharmaceutical Wastes (CPW) with a capacity of 1 ton/day is developed using a melting and gasification furnace equipped with two non-transferred thermal plasma torches. In this article, the whole method of chemical and pharmaceutical waste disposal is presented along with exhaust gas analysis, and slag and energy balance approach for improving the relevant technology process. It is successfully demonstrated that the thermal plasma process converts chemical and pharmaceutical wastes into harmless slag. Also, the associated emission level of air pollutants is shown to be very low. The produced synthetic gas can be used as a source of energy. (11.7 Nm^3 / hr for CO and 16.4 Nm^3 / hr for H_2). The total power consumption of the system is 120 kW including 90 kW for thermal plasma torch and 30 kW for utilities with natural gas flow rate of 1.3 Nm^3/hr.

Keywords
Plasma torch, Gasification, Slag, Plasma Reactor, Covid-19 wastes.

Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
***Corresponding author**: shahrooz.saviz@srbiau.ac.ir

1. Introduction

Hazardous wastes such as pathology, chemical and pharmaceutical and radioactive wastes pose many hazards to human health and living organisms [1–6]. There is currently no balance between the production of hazardous waste and the methods of its disposal [7, 8]. The diversity of hazardous wastes is increasing though no specific methods have yet been proposed for their disposal. The most recent example is the Covid-19 virus. The horrific number of patients infected with the virus and the daily increase in the number of hospitalized patients have led to a dramatic increase in hazardous waste. Any medications, equipment, vaccines etc. that are relevant to patients with Covid-19 can be a potential source of hazardous waste contaminated with the covid-19 virus. In the third world countries, due to the lack of separation of corona patients' waste from other hazardous wastes, it is more likely for all wastes to be infected with this virus. One type of hazardous waste that is difficult to dispose of, are chemical and pharmaceutical wastes. These wastes cannot be decontaminated by convenient methods such as autoclaving. Therefore, one of the possible methods to eliminate them is the application of thermal methods. The presence of chemicals, outdated drugs, and a variety of attenuated viruses and large volumes of minerals in vial containers require high temperature systems. Fossil fuels are not able to create adequately high temperature for melting minerals, thus large amounts of ash remain and many chemicals are left unchanged inside the ash. The new method of using thermal plasma solves the temperature problem [9–13]. Plasma torches [14] can produce temperatures of up to 15,000 °C. In this method, plasma furnaces reach a temperature of about 1800 °C. Therefore, all minerals are removed from the furnace in the form of melt. The volume of waste is significantly reduced and the remaining melt is completely safe. On the other hand, organic matter is released as a synthetic gas from the top of the furnace and can be used to generate energy.

2. Experimental Section

2.1 Process overview and plasma reactor configuration

The process of design and construction of the disposal plant for thermal-plasma-based and chemical and pharmaceutical wastes was implemented in three six-month periods. In the first six months, the whole plant was designed by professional consulate teams led by PPRC specialists. Second period was dedicated to technical works on construction of the plant and the third period was devoted to tests and optimizations. During the optimization period, attempts were made to improve the operation process of the plant. Some of the main activities performed during this period include normal operation of the plant, decreasing the amount of pollutants in the exhaust gas, reducing the operational cost and upgrading of the feeding system. The schematic setup of the constructed thermal plasma-based medical waste disposal plant is presented in Fig. 1.

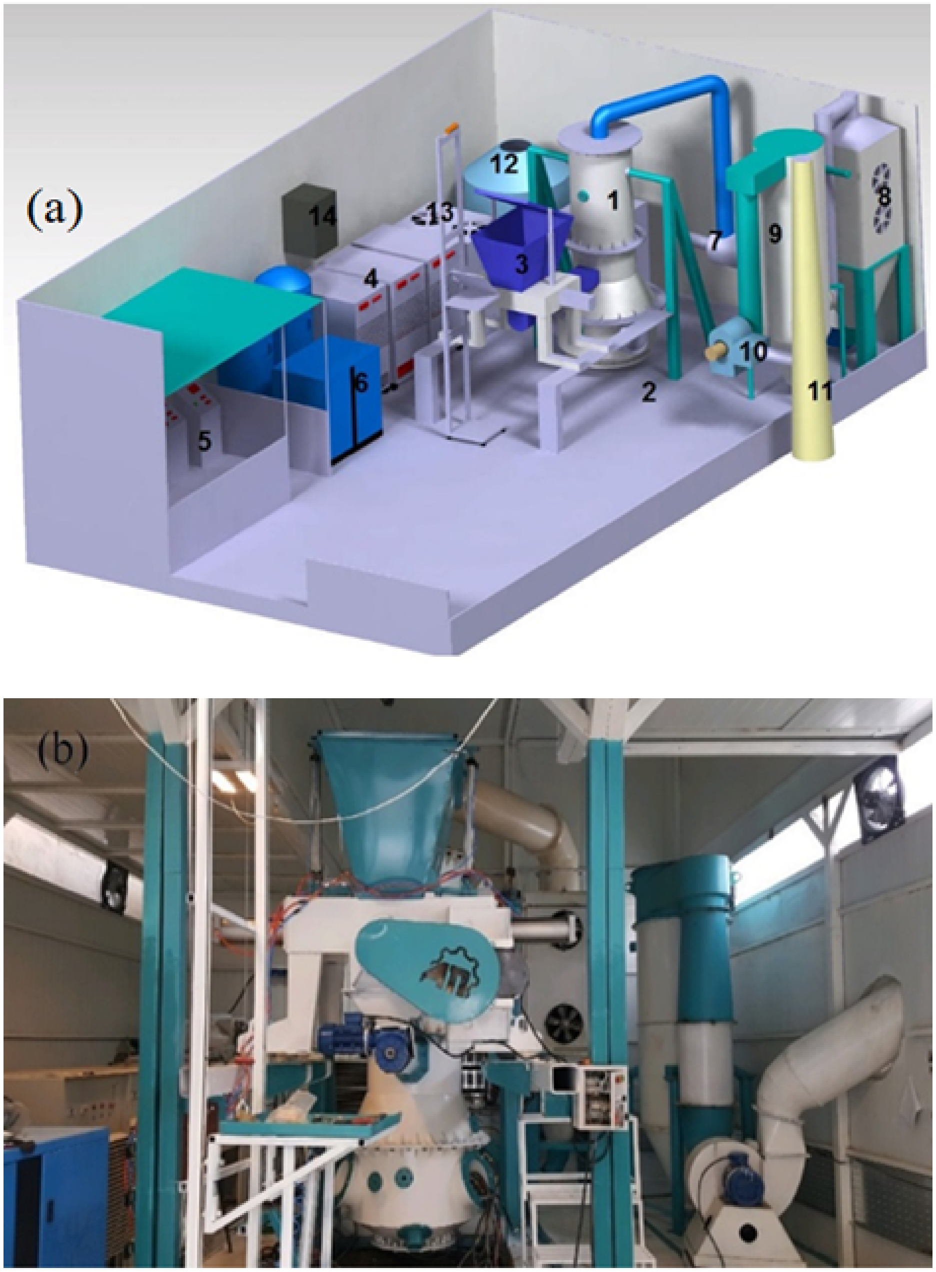

Figure 1. (a), (b) System setup: 1- main shaft furnace, 2- plasma torch, 3- feeding system, 4- power supplies, 5- control room, 6- air compressor, 7- after-burner, 8- water quench, 9- wet scrubber, 10- jet fan, 11- stack, 12- water reserve, 13- chiller, 14- Air purification system.

The components of the plasma disposal system are shown in Figure 1. The system consists of three main sections for PGM process on CPW: 1- Waste feeding system 2- Long shaft furnace with two non-transfer plasma torches 3- Exhaust gas purification system including afterburner system and water scrubber.

2.2 Specification of CPW

The CPWs are taken from Farhikhtegan Hospital, Tehran, Iran. The physical properties of CPW in terms of weight percentage of different compounds are given in Table 1.

One of the important parameters in examining the mass and energy balance of a reactor is Lower Heating Value (LHV) of the wastes. Equation 1 presence the method of calculation of LHV.

$$\mathrm{LHV} = X_C A - X_W B - X_G C - X_M D - X_O E \qquad (1)$$

The definitions and mean values of the coefficients in Equation 1. are as follows:
A(kJ/kg): Heating value of the combustible materials=18400,
B(kJ/kg): Heat loss due to water in the waste=2636,
C(kJ/kg): Heat loss due to glass in the waste=628,

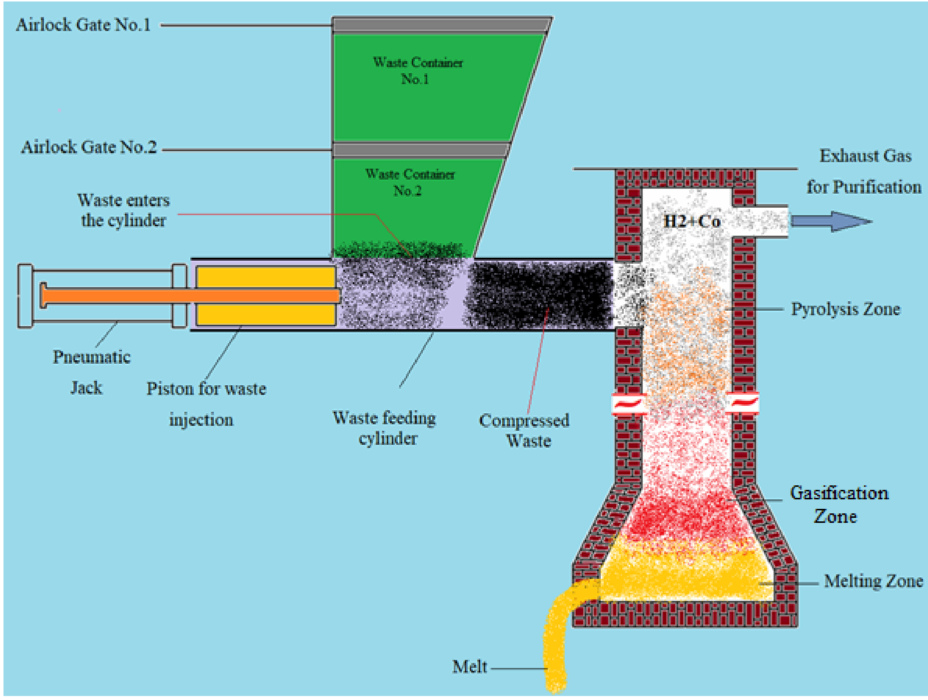

Figure 2. CPW feeding system.

D(kJ/kg): Heat loss due to metals in the waste=544,
E(kJ/kg): Average heat loss due to other inorganic materials in the waste=450,
X_C (wt%): Weight percentage of combustible materials,
X_w (wt%): Water weight percentage,
X_G (wt%): Glass weight percentage,
X_M (wt%): Metals weight percentage,
X_O (wt%): Weight percentage of other inorganic materials.
The percentages of combustible and non-combustible materials are given in Table 2. Using Eq. 1 and the given weight percentages of combustible and non-combustible materials as well as the coefficients A, B, C, D and E, the LHVs of the wastes are calculated for five samples as given in Table 2.

2.3 CPW feeding system

Considering the hazardous nature of CPW, it is necessary to inject it into the furnace without opening the bags. A special injection system must be designed and built for each type of waste. Therefore, after testing several methods, the special system is designed for CPW (Fig. 2). This mechanism consists of several pneumatic jacks that are used to transfer waste through a cylinder into the furnace. The steps of injecting chemical and pharmaceutical waste into the furnace are as follows:

1- Airlock Gate No.1, opened by the pneumatic jack, 2- Waste is thrown into waste container No.1, 3- Airlock Gate No. 1 closes, 4- Airlock Gate No. 2 is opened by the pneumatic jack, and the CPW first enters the waste container No. 2 and then gradually enters the waste injection cylinder, 5- The piston is moved inside the cylinder by a pneumatic jack and pushes the waste into the furnace.

2.4 Long shaft furnace with two plasma torches

The reactor is the heart of the CPW disposal plant. The reactor is a vertical cylinder of 4 m height. The diameter of the upper part is 1 m while the diameter of the lower part is 1.5 m. The lateral surface of the reactor consists of three layers. The

Table 1. Percentage of the physical composition of the CPW.

Material	Test 1	Test 2	Test 3	Test 4	Test 5
Vial(glass)	49.3	42.2	50.2	39.7	43.2
Plastic	28.4	32.6	26.1	30.4	28.7
Paper	2.2	1.9	2.9	1.7	2.1
Metal	1.1	1.3	0.4	0.6	0.8
Drug powders	9.2	8.8	5.1	11.2	10.8
Drug solutions	8.4	7.9	10.2	12.2	10.3
Others	1.4	5.3	5.1	4.2	4.1

Table 2. The weight percentage (wt%) and LHV of the CPW for five tests.

Test	X_C	X_W	X_G	X_M	X_O	**LHV** (kJ/kg)
1	30.6	8.4	49.3	1.1	10.6	5045.7
2	34.5	7.9	42.2	1.3	1.41	5804.2
3	29	10.2	50.2	0.4	10.2	4703.8
4	32.1	12.2	39.7	0.6	15.4	5262.9
5	30.8	10.3	43.2	0.8	14.9	5053.0
Average	31.4	9.8	44.92	0.84	10.5	5173.9

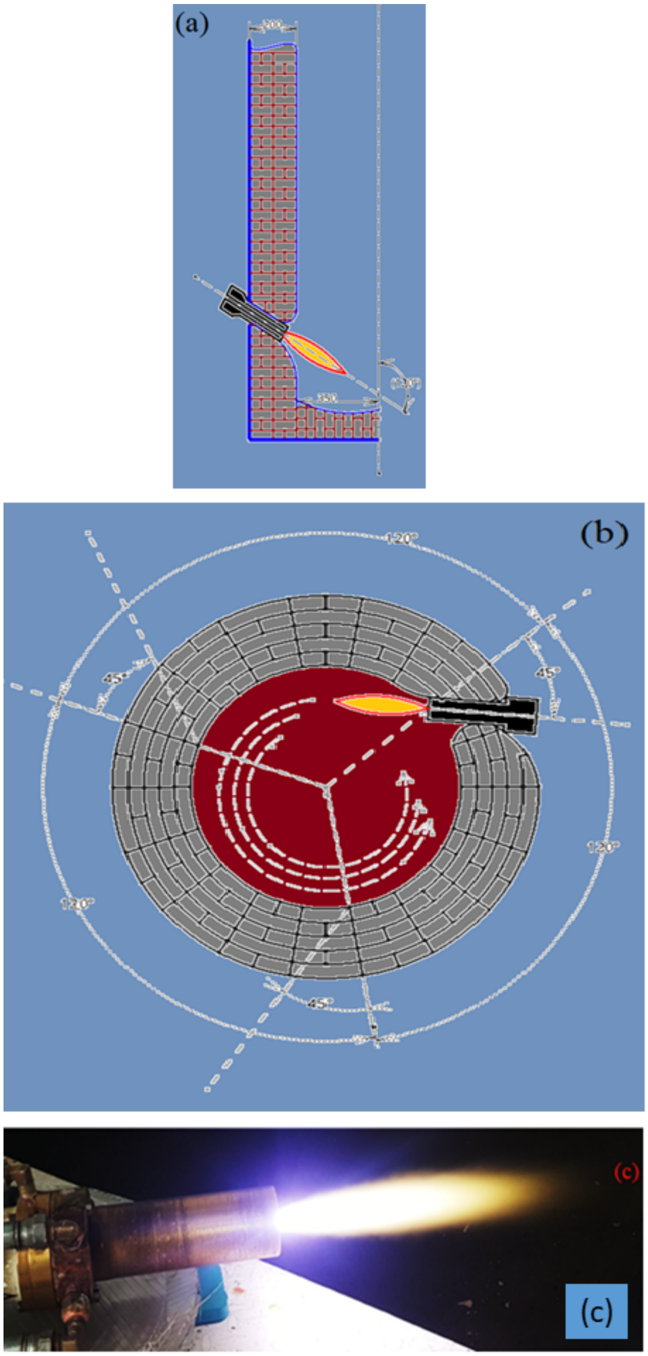

Figure 3. (a) Position of the plasma torches respect to furnace axis, (b) Position of the plasma torches respect to furnace circumference, (c) Plasma torch in operation.

inner layer is made of refractory bricks covered by thermal insulation bricks with 20 cm thickness as the thermal insulator. The outer surface is made of steel plate with a thickness of 5 cm. The reactor is equipped with two 70 kW thermal plasma torches in its bottom part. They are installed symmetrically around the cylinder at a height of 0.3 m from the base of the reactor (Fig.3). As shown in Figure 3a, the angle of the plasma torches with the furnace axis is 120 degrees. Figure 3b shows that, the plasma torches are placed tangentially in the furnace circumference. This causes: 1- the heat of the plasma torches circulates inside the furnace environment, 2- the retention time of the heat of the plasma torches inside the furnace is maximized, 3- the furnace reaches faster the desired temperature, and 4- the efficiency of the system increases.
Two of the three torches are on duty and one of them is standby. To drain the slag, a gate is installed at the base of reactor. Two gates at the top of the reactor serve as the feeding gate and exhaust. The waste pyrolysis and gasification process is performed in the furnace shaft and melting is done in the bottom of the furnace (Fig. 2 and Fig.4). This design is based on the fact that minerals make up a large portion of the waste composition. In the melt chamber, the temperature reaches 1800 °C. As high temperatures pass through the waste in the furnace shaft, organic matter is converted to synthetic gas and minerals flow to the melt chamber. Waste is continuously fed into the furnace shaft and the melt is removed from the bottom of the furnace. The furnace shaft and the furnace melt chamber can be separated. This design is very applicable due to the fact that the molten part needs to be repaired in some cases as a result of the high temperature. An air sheath between the plasma torch and the furnace is used to protect the plasma torches from the impacts of furnace temperature. Thermal plasma torches (Fig. 3) are non-transferred DC torches with a maximum current of 200 A and voltage of 350 V. They are water-cooled with copper electrodes and use pressured air as the carrier gas. For each thermal plasma torch, a pressure of 10 bars is provided by high-pressure air compressor. Through the use of the two torches, the temperature in the bottom of the reactor reaches to 1800 °C. These plasma torches were designed and manufactured by us in the plasma physics research center of the university. Their cathode consists of a rod electrode and the anode is a hollow copper electrode. The cathode life is 100 hours and the anode life is 400 hours.

2.5 Effluent gas purification system

The exhaust system which is actually a gas cleaning system, consists of an afterburner (Fig.4) and water scrubber which are installed in series. The fly ashes are collected and removed in the afterburner. The natural gas burner is employed to complete the combustion of H_2 and CO and fly ash molecules. Furthermore, caustic soda solvent is fed into the scrubber to remove acidic gases. The water quencher and scrubber are located at the outlet of the afterburner. The role of the water quencher is to quickly cool the gas to 60 °C. It also partially removes the remaining acidic gases but the total removal of all acidic gases is achieved in the scrubber using NaOH solution. The scrubbing solution with controlled pH is constantly recirculated. Finally, the output gas of the afterburner is sent to stack through a gas cooler system. The temperature of the gas flowing in the stack is 60 °C.

Figure 4. Molten material leaking from the furnace bottom.

3. Results and discussion

In the process of CPW disposal, solid, liquid and gaseous by-products are produced. The solid by-product comes out of the bottom of the furnace in the form of a slag. The liquid byproducts are generated in the scrubber waste water treatment system and the gaseous byproducts are due to the gasification of CPW.

3.1 Slag byproducts

The results of the slag composition analysis are shown in Table 3. The highest percentage belongs to silicon dioxide. There were other elements that were not included in the Table due to their very low percentage. The weight percentage (wt%) of slag produced in proportion to the total injected CPW is measured in five steps. As shown in Table 4, the average weight percentage (wt %) of slag is 59.4%. The density of the destroyed CPW was about 283 kg/m^3 which is higher than the municipal solid waste (MSW) density of about 100 kg/m^3. This high density is attributed to the high content of minerals in chemical and pharmaceutical wastes. The measured density of the slag is about 2400 kg/m^3. Therefore, the reduction in CPW volume is about 89%. Further, Toxicity Characteristic Leaching Procedure (TCLP) is performed on the five slag samples. The results show that there is no heavy metal detected in slag

Table 3. Percentage of the physical composition of the CPW slag.

Material	Test 1	Test 2	Test 3	Test 4	Test 5
SiO_2	57.6	58.3	54.1	55.4	59.2
Al_2O_3	8.26	9.2	9.8	8.4	9.5
Na_2O	6.56	10.4	6.9	6.4	5.7
MgO	0.64	0.52	0.72	0.51	0.65
CaO	4.85	4.2	3.9	5.1	4.8
TiO_2	0.35	0.21	0.45	0.12	0.24
MnO	0.12	0.08	0.21	0.17	0.3
Fe_2O_3	0.38	0.31	0.28	0.14	0.25

Table 4. Percentage of the ratio of the weight of remaining slag to the injected CPW (wt%).

Test 1	Test 2	Test 3	Test 4	Test 5
58.5	61.4	59.4	57.3	60.4

Given that the slag is not toxic and does not contain hazardous substances, it can be used in various industries including road infrastructure, construction industries etc.

3.2 Liquid Byproducts

The water scrubber is located after the combustion system. Treatment is necessary for the water used for rapid gas cooling and de-acidification

3.3 Gaseous Byproducts

The most important requirement for a hazardous waste disposal system is the standard amount of exhaust gases. For this purpose, the concentration of air pollutants before the afterburner (Table 5) and in the stack (Table 6) is measured. The gas flow rate before afterburner and in the stack is about 43 Nm^3/hr and 95 Nm^3/hr, respectively. This flux difference is due to the presence of the afterburner system. Gas chromatography results of the CPW plasma-pyrolysis before afterburner (Table 5) indicate that the produced gases are rich in hydrogen and carbon monoxide and also contain some other compounds. The total quantity of H_2 and CO in the gaseous mixture is above 66% so we expect the afterburner temperature to rise. Possible reactions which take place during the pyrolysis of CPW include:

$C_6 H_10 O_5$+heat $\rightarrow$ CH_4+2CO+3H_2O+3C   for cellulose

[-CH_2-CH_2-]$_n$+H_2O+heat $\rightarrow$ xCH_4+yH_2+zCO   for plastic

As shown in Table 1, a significant constituent of organic matter in chemical and pharmaceutical wastes is plastic. Therefore, the percentage of hydrogen is expected to be higher than carbon monoxide. This prediction can be clearly observed in Table 5. The concentrations of O_2 before afterburner is 0.3 which is very small and shows that oxygen starvation has taken place inside the furnace.

Table 5. Composition of the exhaust gas before afterburner (%).

CO	H_2	CO_2	N_2	CH_4	H_2O	HCL	H_2S	O_2
27.2	38.9	13.94	6.6	4.8	8.2	0.04	0.02	0.3

Table 6. Composition of the exhaust gas at the stack.

Gas composition	Molar distribution (ppm)
SO_x	0.1±0.1
NO_x	9.8±2.2
CO	7.9±2.8
Cl_2	0.03±0.02
NH_3	1.3±0.5
HCl	0.3±0
F	0.9±0.3
H_2S	0.02±0.01

In this system, our goal is not to produce energy from synthetic gas. Synthetic gas is burned in the afterburner system. Results of exhaust gas analysis after the afterburner system is given in Table 6. Amount of dust in the exhaust gas is about 11.1±1.3 mg/Nm^3. The results are indicative of the standard amounts of hazardous pollutants.

4. Conclusions

Thermal plasma technology is a trustable method for disposing of chemical and pharmaceutical wastes. In this method, both organic and inorganic wastes are paralyzed, gasified and melted to ensure their complete elimination and the least environmental pollution. The exhaust gas from the furnace is full of energy and can be recycled to increase the energy efficiency of the system. Also, with the provision of the combustion system, the amounts of dangerous exhaust gases are within the standard range.

Conflict of interest statement:
The authors declare that they have no conflict of interest.

References

[1] A. Prüss, E. Giroult, and P. Rushbrook. *Safe management of wastes from health-care activities: a practical guide*. Nonserial Publications, WHO Press, Geneva, 2th edition, 2014.

[2] D. P. Komilis. *Waste Manag*, **48**:1, 2016.

[3] E. Y. Choueiri. *Physics of Plasmas*, **8**:1411, 2001.

[4] Y. Xie and J. Zhu. *Journal of Material Cycles and Waste Management*, **15**:440, 2013.

[5] Z. Homayouni and M. S. Pishvaee. *Journal of Material Cycles and Waste Management*, **22**:1965, 2020.

[6] U. Barua and D. Hossain. *Journal of Material Cycles and Waste Management*, **23**:2057, 2021.

[7] E. S. Windfeld and M. S.-L Brooks. *Journal of Environment Managment*, **163**:98, 2015.

[8] S. Fang, L. Jiang, P. Li, J. Bai, and C. Chang. *Energy*, **195**:116969, 2020.

[9] S. K. Nema and K. S. Ganeshprasad. *Curr. Sci.*, **83**:271, 2020.

[10] J. Fiedler, E. Lietz, D. Bendix, and D. Hebecker. *J. Phys. D: Appl. Phys.*, **37**:1031, 2004.

[11] Y. Byun, M. Cho, S. M. Hwang, and J. Chung. *Thermal plasma gasification of municipal solid waste (MSW)*. InTech, London, 1th edition, 2012.

[12] J. Huang, W. Guo, and P. Xu. *Plasma Sci. Technol.*, **7**:3148, 2005.

[13] C. Xiaowei and D. Changming. *Plasma Chemistry and Plasma Processing*, **41**:1, 2021.

[14] M. F. Zhukov and I. M. Zasypkina. *Thermal plasma torches: design, characteristics, application*. Cambridge International Science Publishing, Cambridge, 1th edition, 2007.