Hydrogen and Methane Production from Styrofoam Waste Using an Atmospheric-pressure Microwave Plasma Reactor

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ABSTRACT

Polystyrene foam (PSF), which is widely used in oyster farming in Taiwan, generates approximately 120,000–200,000 pieces of floating waste annually. The issues related to processing this waste, however, include the financial cost, incinerator clogs, human exposure to carcinogenic and non-biodegradable components, and potential debris, which threatens the seashore. In this study, we obtained methane (CH₄) and hydrogen (H₂), two crucial gases in power generation, by treating PSF waste with an atmospheric-pressure microwave plasma reactor. Substituting argon with nitrogen as the carrier gas and increasing the microwave power (1200 W) produced a higher concentration of H₂ (4739 ppm) but a lower one of CH₄ (less than 300 ppm). Treating a larger quantity of waste (0.2 g) resulted in CH₄ and H₂ levels of 19,657 ppm and 440 ppm, respectively. SEM-EDX and XRD testing confirmed the transformation of the PSF structure and a reduction in carbon (C) content in the final residue. This research demonstrates how solid waste can be recycled into valuable gases by applying plasma technology.

Keywords: CH₄; H₂; Microwave power; Nitrogen; PSF.

INTRODUCTION

Plastic debris has a significant impact in various sectors of society, including beaches, biodiversity, tourism, ecosystems, and human health (Pomeroy and Guieb, 2006; Liang and Zhang, 2010; Allen *et al.*, 2013; Tanaka, 2013; UNEP, 2013; Hong *et al.*, 2014; Lee *et al.*, 2015; Lee *et al.*, 2017; Vince and Hardesty, 2018). Styrofoam, which is made from a polystyrene foam (PSF), is a type of plastic debris, and that is quite difficult to degrade naturally (Chen *et al.*, 2018). According to Tanaka *et al.* (2013), the transferring of chemical pollutants from marine environments to marine organisms occurs through the food chain, and is harmful to the ecosystem, and also to organism itself. Accumulation of plastic debris in animals, for examples, birds, occurs because of accidental ingestion, and was reported in 171 birds from 9 species by

Codina-Garcia *et al.* (2013). Provencher *et al.* (2010) and Holland *et al.* (2016) confirmed that plastic debris is ingested by diving seabirds in eastern Canadian Arctic and affects their health. Thereby, plastic waste is harmful to organisms and environments.

In several countries, PSF waste has become a serious environmental issue that should be managed properly because of the large amount that has contaminated the environment. Laglbauer *et al.* (2016) found that macro-debris in the ocean in Slovenia is comprised of as much as 64% plastics. Fujieda and Sasaki (2005) discovered that 99.5% of foamed plastic fragments can be found along approximately 48.6 km of Japan's coastline. A finding of Lee *et al.* (2015) stated that 1,800,000 buoys contaminate ocean annually in the South Korean sea. In Taiwan, between 3.7 million and 7.9 million approximately of plastic debris in the form of shopping bags, plastic bottle caps, tableware, fishing equipment, and plastic drinking straws, contaminated the coastline of Taiwan from 2004 to 2016 (Walther *et al.*, 2016). Chen *et al.* (2018) reported that in Taiwan, approximately 120,000–200,000 large floating pieces of Styrofoam used for oyster farming every year. Polystyrene foam has been used widely in oyster

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farming and has become a main issue because of their shorter lifetime of approximately three years, and it is difficult to recycle (Liu *et al.*, 2013; Chen *et al.*, 2018). Thus, contamination with plastic waste is a serious issue, and should be handled correctly to prevent environmental pollution.

Several technologies have been developed to deal with plastic waste, namely, incineration (Ganeshprasad, 2002; Choi *et al.*, 2008; Wang *et al.*, 2018, Yang *et al.*, 2019) and recycling (Xu *et al.*, 2013). Unfortunately, there are some drawbacks to both incineration and recycling. Unstable combustion, lack of air pollution control, high concentrations of dioxin, halogenated polycyclic hydrocarbons, and remaining pathogens are disadvantages of incineration (Nema and Ganeshprasad, 2002; Choi *et al.*, 2008; Wang *et al.*, 2018; Yang *et al.*, 2019), as well as limited energy recovery and heavy water consumption (European Commission, 2006). Xu *et al.* (2013) reported that the recycling areas are contaminated by tetrachlorodibenzo-*p*-dioxins (TCDDs) and octachlorodibenzo-*p*-dioxin (OCDD) from melting plastic of e-waste. The total concentrations of TCDDs to OCDD were 2816–17,738 pg g⁻¹ in soil. Thus, proper technology is required to tackle these issues.

Investigations of plasma technology in environmental application to treat waste have been performed by several authors (Heberlein and Murphy, 2008; Gomez *et al.*, 2009; Deng *et al.*, 2019; Sanito *et al.*, 2020). Transformation of electrical energy to thermal energy occurs because of the invention of an electrical arc between two electrodes; subsequently, ionization occurs, which leads to the conversion of gas to electrically conductive compounds for elimination of elements (Taylor and Pirzada, 1994; Chang, 2009). Heberlein and Murphy (2008) and Wang *et al.* (2010) stated that the benefits of plasma technology include start-up of the reactor and plants, variety of chemical processes, low gas flow rate, high electron density, straightforward operation procedure, and easier application of recycling products in manufacturing processes. Thereby, plasma technology is a prospective technology to treat waste.

Previous studies have stated that in term of plasma technology, hydrogen (H₂) and methane (CH₄) can be generated from biomass and plastic waste (Huang *et al.*, 2003; Chu *et al.*, 2006; Mazzoni and Janajreh, 2007; Dave and Joshi, 2010; Maczka, 2013; Tang *et al.*, 2013; Shie *et al.*, 2014; Materazzi *et al.*, 2015; Huang *et al.*, 2016; Sanlisoy and Carpinlioglu, 2017). Huang *et al.* (2013) found that the main components of the gaseous products from waste rubber were CO, C₂H₂, CH₄, C₂H₄ and H₂. Materazzi *et al.* (2015) reported that the final products, CO, H₂ and H₂S, can be obtained from tar under plasma gasification, which reduced complex organics by more than 96% v/v. In the treatment of paper mill waste, approximately 90% of CO and 99% of H₂ can be obtained with a 2 min reaction time in a Plasmatron reactor, and 1.2 tons of paper mill waste can be recovered per day (Byun *et al.*, 2011; Shie *et al.*, 2014). Therefore, plasma technology is a promising procedure for treatment of solid waste and gasification of materials.

Previous researchers have reported on how to handle the plastic waste and produces synthetic gas (“syngas”) through plasma pyrolysis (Ruj and Chang, 2003; Dave and Joshi,

2010; Maczka *et al.*, 2013; Zhou *et al.*, 2020). Tang *et al.* (2003) reported that H₂ gas can be produced from polypropylene in a nitrogen plasma reactor in a DC arc nitrogen plasma generator, with a maximum electric power input of 62.5 kVA in a 50 mm reaction chamber. Dave and Joshi (2010) found that the integration of thermo-chemical properties of plasma generates pyrolysis gas from polyethylene (PE), and polypropylene (PP) at temperatures ranging from 800–1000°C and can be considered on energy recovery with 78% propylene, and CO, H₂, and hydrocarbons can be successfully recovered. NO_x and H₂S, which are toxic gases, can be eliminated during plasma pyrolysis (Ruj and Chang, 2002). Maczka *et al.* (2013) discovered that plasma pyrolysis of waste plastics produces H₂, CH₄, and CO with values of 1.1%, 2%, and 0.3%, respectively. Zhou *et al.* (2020) found that industrial atmospheric dielectric-barrier-discharge plasma can be used to treat plastic bags using a mechanism that breaks the chemical bonds of the plastic bag. Therefore, plasma technology can be used to produce a syngas from plastic waste. However, the treatment of PSF waste in plasma technology for such applications has not been thoroughly investigated or successfully performed.

In this study, potential hydrogen (H₂) and methane (CH₄) production as a side product in an atmospheric-pressure microwave plasma reactor is investigated. Furthermore, the composition of organic compounds is analyzed. To the author’s knowledge, PSF waste has not yet been discussed in any scientific literature, especially in terms of treatment using an atmospheric-pressure microwave plasma reactor. This paper is a study of the use of atmospheric-pressure microwave plasma to produce gas as a side product derived from PSF waste. In this study, the effects of carrier gases and microwave power on the total concentration of H₂ and CH₄ are then presented to understand the gas production mechanism.

METHODS

Collection and Preparation of the Samples

PSF waste was collected from an oyster farm in Tainan, Taiwan. The PSF waste product measured 30 × 40 × 95 cm. The sample was cut into smaller pieces (1 cm) and was measured with a standard analytical balance (AUY-220; Shimadzu, Japan) before being used in the experiment.

Pyrolysis of PSF Waste

Fig. 1 describes the atmospheric-pressure microwave plasma reactor. In this experiment, an atmospheric-pressure microwave plasma reactor was used with a frequency ranging between 0.3 GHz and 10 GHz, and the slurry frequency was set at 2.45 GHz (wavelength: 12.2 cm). An MCw signal was generated by a magnetron through a waveguide. Pyrolysis of the PSF waste was performed in a 20 cm³ crucible, for which height and diameter were 4 cm and 2.5 cm, respectively. A 0.1-cm-thick quartz tube with a diameter of 3 cm and a length of 32 cm was positioned near the path of magnetron propagate where plasma jet discharged.

Fig. 2 illustrates the preparation of the sample and treatment in an atmospheric-pressure microwave plasma

Fig. 1. The system of an atmospheric-pressure microwave plasma reactor in this study.

a

b

Fig. 2. Setup of plasma treatment and preparation. (a). Schematic set up of plasma treatment. (b). PSF treatment in an atmospheric-pressure microwave plasma reactor.

reactor. Fig. 2(a) shows a schematic of the plasma treatment set-up. Approximately 0.1 g of PSF waste was used as the sample. Fig. 2(b) shows how the waste prepared and treated in atmospheric-pressure microwave plasma reactor. To generate a plasma jet, the microwave power was kept constant at 1000 W. Argon gas and nitrogen gas were used as the carrier gases to generate the plasma jet for 4 min with 0.1 g of PSF waste. The parameters of the experiment are explained in Table 1.

To investigate the effects of microwave power on the treatment, different amounts of power were utilized. The plasma power was maintained at 800 W and 1200 W, respectively. The plasma jet was discharged through a magnetron, and gases were collected via a 1 L gas bag (Tedlar gas bags) each 30 seconds. Plasma pyrolysis was performed at 4 min using nitrogen as the carrier gas (fast reaction and high metastable energy), while argon gas is used with 5 min of pyrolysis. The details of this process are shown in Table 2.

To assess the effects of the amount of PSF waste on production of H₂ and CH₄, 0.1 g, 0.2 g, and 0.3 g of PSF waste were used as the samples treated in the atmospheric-pressure microwave plasma reactor. The microwave power was maintained at 1000 W; nitrogen was used as the carrier gas, and pyrolysis was performed at 4 min. The experiment is displayed in Table 3. In this study, the liquid product and mass balance were not determined because of their small quantities in the final residue after treatment.

Gas Analysis

CH₄ and H₂ gases in the samples were analyzed via gas chromatography (GC-14A/B and GC-2014; Shimadzu, Japan). The lock syringe size of 1 mL (Taiwan) was used to inject the gas. A thermal conductivity detector (TCD) and flame ionization detector (FID) were used to detect the H₂ and CH₄, respectively. The columns were Porapak Q 80/100 mesh and a molecular sieve (5A Column). Standard carrier

gases (CH₄ and H₂) were purchased from the Ming Yang Company (Taiwan). The flow rate was set up at 30 mL min⁻¹ and maintained isothermally at 120°C. Concentrations of CH₄ gas standard were 100 ppm, 200 ppm, 400 ppm, and 800 ppm, and concentrations of H₂ gas were 100 ppm, 200 ppm, and 400 ppm. In this study, only analyses of H₂ and CH₄ were considered

Analysis of Sample Properties

Scanning electron microscopy (SEM-EDX; S-4800; Hitachi, Japan) was used to analyze the surface morphology of the PSF. The results of this analysis provided the surface and morphological structure of the residue.

To analyze the functional groups available in the PSF before and after treatment, Fourier transform infrared spectroscopy (FTIR; FT/IR-6000; Jasco, USA) was used with wavenumbers ranging from 400–4000 cm⁻¹. The PSF was pelleted with KBr, and samples were pressed using a manual hand press until samples were 1 mm in size. After that, the samples were placed in the FTIR instrument and scanned with infrared rays for 5 min. FTIR curves were determined using Origin software (version 9.1).

To analyze the characteristics and crystalline structures of the resin, X-ray diffraction (XRD; D8 Advance Eco; Bruker, Germany) was used. The scanning process was performed for 5 min using X-rays with 2θ scanning at a range 10–80°. The X-rays were performed using asymmetric diffraction from the modular components. The voltage was controlled at 40 kV, and the current was set up at 25 mA. The power was maintained at 1000 W, and 2θ peaks represented the PSF waste.

RESULTS AND DISCUSSION

Characterization Analysis of PSF

The surface morphology and elemental composition of the samples were determined using a scanning electron microscope

Table 1. Effect of sample weight on gas production rate of CH₄ and H₂.

No	Carrier Gas	Microwave Power (W)	Duration (min)	Weight of PSF (g)
1	Nitrogen	1000	4	0.1
2	Argon			

Table 2. Effect of sample weight on gas production rate of CH₄ and H₂.

No	Microwave Power (Watt)	Total Reaction Time (Min)	Carrier Gases	Capturing of the gas (Second)	Gas Flow (L min ⁻¹)
1	800	4	Nitrogen	30, 60, 90, 120,	6
2	1200			150, 180, 210,	
3	800	5	Argon	240, 270, 300	
4	1200				

Table 3. Effect of sample weight on gas production rate of CH₄ and H₂.

No	Parameters	Details Information
1	Microwave power	1000 W
2	Duration	4 Min
3	Weight of samples	0.1 g, 0.2 g, 0.3 g

with energy-dispersive X-ray spectroscopy (SEM-EDX; Hitachi S-4800, Japan). Fig. 3 provides information about the surface morphology of the PSF samples before treatment and after treatment. Fig. 3(a) explains the regular morphological structure of Styrofoam, which is comprised of a chain of hydrogen and carbon. Fig. 3(b) shows the breakage surface of the materials after treatment with an argon plasma, which was found to assume a typical shape after treatment. Fig. 3(c) displays the irregular, inhomogeneous surface of the materials after treatment using nitrogen plasma, indicating destruction of the materials. Farrelly and Shaw (2017) confirmed that Styrofoam consists of vinyl benzene. In this study, carbon in the form of vinyl benzene was detected in the PSF waste before treatment. Material transformation refers to the degradation of linkages between materials and elements in pyrolysis process (Benedikt, 2010) because of free electrons at high concentrations that establish electrical conductivity from the carrier gas (Safa and Soucy, 2014). Specifically, ionization from the gas creates the collision of atoms, and enthalpy from the plasma produce the gases (Mountouris *et al.*, 2006).

Fig. 4 explains the carbon composition before and after treatment. Fig. 4(a) gives an information about carbon in the PSF waste before treatment. Fig. 4(b) provides the carbon distribution after treatment in nitrogen plasma, and Fig. 4(c) depicts information about the PSF waste after treatment. All of this information shows that, based on the final residue after the plasma treatment, carbon was degraded better using

the treatment. Lower concentrations of carbon could be obtained after treatment with nitrogen plasma because the high thermal degradation of the material plasma pyrolysis broke carbon bonds (Yang and Shibasaki, 1998).

Fig. 5 illustrates the FTIR patterns of the PSF waste after treatment in an atmospheric-pressure microwave plasma reactor. A qualitative analysis of functional groups was carried out to determine characteristics in the residue ranging from 400–4000 cm^{-1} of wavenumbers (Table 4). The analysis shows that C–H and C–C stretching vibration could be detected at 1493 cm^{-1} and 1601 cm^{-1} , respectively. This finding was confirmed by Song *et al.* (2015), who stated that 721 cm^{-1} , 1378 cm^{-1} , 2825 cm^{-1} and 2923 cm^{-1} wavenumbers represent C–H groups. C–H aliphatic and C–H aromatic compounds, respectively, can be detected at wavenumbers ranging from 2910–2928 cm^{-1} and 3001–3082 cm^{-1} because of the presence of carbon. In the present, conversion of PSF waste to smaller components was due to the degradation of hydrocarbon and chemical bonds. There was a significant conversion of residue from the broadband peaks between 500 cm^{-1} and 1600 cm^{-1} .

PSF waste materials after treatment using an argon plasma jet were found at wavenumbers of 1601 cm^{-1} , 1493 cm^{-1} , 2910–2928 cm^{-1} and 3001–3082 cm^{-1} . However, the peaks became smaller at 3200 cm^{-1} . This indicates the transformation of these materials during the plasma treatment. A wavenumber at 3500 cm^{-1} was attributed to hydroxyl groups (–OH). This functional group relates to C=C double bonds,

Fig. 3. SEM images of materials surface of Styrofoam. (a) Materials of Styrofoam before treatment. (b) Surface material of Styrofoam after treatment with argon gas. (c) Surface material of Styrofoam after treatment with nitrogen gas.

Fig. 4. Composition of carbon in the Styrofoam before treatment and its distribution of sample after treatment based on the EDX data. (a) Composition of carbon before treatment of PSF waste. (b) Composition of carbon after treatment of PSF waste using nitrogen as the carrier gas. (c) Distribution of carbon after treatment of PSF waste with argon gas.

a peak at 1633 cm^{-1} . Interestingly, 1633 cm^{-1} and 3440 cm^{-1} wavenumbers were not detected during the analysis because of the elimination of chemical compounds after treatment using nitrogen plasma. Wavenumbers of $500\text{--}1600\text{ cm}^{-1}$ confirm C–H and C–C bonds (Singh *et al.*, 2015; Ismail *et al.*, 2017). In this study, peaks in the range $500\text{--}1600\text{ cm}^{-1}$ were detected in the final residue, which were C–H bonds and C–C bonds, confirming the transformation of carbon to H_2 and CH_4 .

Fig. 6 compares the XRD analysis of the PSF waste before treatment and after treatment with the different carrier gases. Before treatment, the analysis showed a peak in the sample of 2θ at 10° and 20° . The highest intensity peaks appeared in the final residue. Interestingly, the 2θ peak was not detected in the final residue after treatment using nitrogen plasma because of low intensity at 10° and 25° , thus confirming the transformation of PSF waste due to carbon degradation. Liu *et al.* (2010) confirmed that diffraction peaks of 2θ , ranging from $15\text{--}30^\circ$, explain amorphous carbon structures. In this study, the detection of peaks from 10° and 20° prior to treatment confirmed the amorphous carbon structure of the

PSF waste. Thus, gases can be possibly produced from the PSF waste because of the transformation of carbon.

Effects of Microwave Power and Carrier Gases on the Generation of CH_4 and H_2

Table 5 compares the results of H_2 and CH_4 after treatment with different microwave power settings and carrier gases in an atmospheric-pressure microwave plasma reactor. The highest concentrations were CH_4 and H_2 at 188 ppm and 4739 ppm, respectively, in 5 min, with 1200 W of microwave power and using nitrogen as the carrier gas. In this study, 1200 W of microwave power had a significant impact on greater generation of the gases. At 2 min, 2659 ppm of H_2 and 85 ppm of CH_4 were obtained with nitrogen plasma. This was a significant difference from plasma treatment with argon gas, for which the concentrations of CH_4 and H_2 were 7 ppm and 1114 ppm, respectively. The highest concentrations using argon plasma can be obtained at 188 ppm of CH_4 and 4739 ppm of H_2 .

Figs. 5(a) and 5(b) provide concentrations of H_2 and CH_4 in the final residue with different carrier gases and microwave

Fig. 5. Characterization of final residue (a) FTIR test of PSF waste before and after treatment. (b) XRD test of PSF waste before and after treatment.

Table 4. Spectrum analysis of PSF on the FTIR analysis.

Assignments	Wavenumbers (cm ⁻¹)	Vibration Types
C–H	3001–3082	Stretching
C–H	2910–2928	Stretching
C–C	1601	Stretching
C–H	1493	Stretching
C–H	1028	Bending

power settings. In the plasma treatment, the final concentrations of H₂ were 3500–5000 ppm. Furthermore, the final concentration of CH₄ was less than 500 ppm with treatment using the selected parameters (nitrogen gas, 800 W and 1200 W). With the use of argon as the carrier gas, the final concentrations of H₂ ranged from approximately 700 ppm to almost 1200 ppm, while the result for CH₄ were less than 100 ppm using the selected parameters (800 W and 1200 W).

From this analysis, it can be inferred that higher microwave power and nitrogen gas play an important role in generating gases due to high thermal plasma enthalpy (Mountouris *et al.*, 2006; An'shakov *et al.*, 2007). The conversion of carbon to gases during plasma pyrolysis occurs because of the reaction of molecules (Maczka *et al.*, 2013). During plasma treatment, a higher temperature plays an important role in degrading the components of the residue to simple molecules

Fig. 6. Total concentration of CH₄ and H₂ (a) treatment with nitrogen gas. (b) Treatment with argon gas.

Table 5. Analysis of hydrogen and methane on different microwave power.

Microwave power (watt)	Time (s)	Nitrogen Plasma		Argon Plasma	
		CH ₄ (ppm)	H ₂ (ppm)	CH ₄ (ppm)	H ₂ (ppm)
800 watt	0	0	0	0	0
	30	7	174	2	87
	60	5	179	0.4	54
	90	6	121	0.7	84
	120	6	274	1.2	64
	150	37	765	0.5	80
	180	85	1711	0.2	99
	210	101	338	0.2	42
	240	3	162	0.1	42
	270	-	-	1.8	72
	300	-	-	0.2	90
Total		250	3724	7	714
1200 watt	0	0	0	0	0
	30	15	103	3	149
	60	35	264	2.2	114
	90	25	929	0.6	136
	120	85	2659	1.2	91
	150	13	605	1	81
	180	7.4	90	2	106
	210	5	42	1.8	104
	240	3	47	2	101
	270	-	-	1.9	99
	300	-	-	1.6	133
Total		188	4739	17.3	1114

(Dave and Joshi, 2010). Specifically, the collision of molecules and reactive species occurs in the plasma, causing the degradation of complex molecules to simpler molecules. Furthermore, high ionization of atoms from energetic electrons colliding with the material rapidly decomposed the material into gaseous products that release radicals such as H, O, and N (Mackza *et al.*, 2013). Thus, CH₄ and H₂ gases can be formed directly in the plasma pyrolysis process, for which the mechanism described in Fig. 7, where it is

shown that electrons collide with atoms from the PSF waste, and then carbon is converted into gases. The final residues after treatment of PSF waste are both solid and liquid⁹. Approximately 0.002 g of solids were obtained. However, the amount of liquid was difficult to measure due to its limited amount. Fig. S1 shows the details for final PSF waste after treatment. The information of the mass balance was shown in Fig. S2. In this study, 0.1 g, 0.2 g and 0.3 g of PSF waste were the input amounts, respectively. Outputs were

Fig. 7. Mechanism of gas production during treatment in an atmospheric-pressure microwave plasma reactor.

hydrogen and methane gases, and black carbon residue. Dave and Joshi (2010) confirmed that plasma gasification generates 65% hydrogen. Maczka *et al.* (2013) stated that a common gasification reaction can be associated with the pattern:

According to Mountouris *et al.* (2005) the common gasification reaction known as an equilibrium reaction, that can be described by an ultimate analysis (CH_xO_y), as follows:

Mattox (2010) stated that electrons accelerate rapidly through an electric field from the plasma source, where ionizing collisions are responsible for the loss of atoms from the target, and the electrons from plasma bombarded the surface area of the sample, thus transforming the final residue. Furthermore, H and CH₄ gases are obtained as side products.

Effect of Different PSF Amounts to Generate CH₄ and H₂

Fig. 8 shows the different sample weights used for the CH₄ and H₂ production using nitrogen as the carrier gas. The highest H₂ gas concentration was 19,657 ppm obtained from 0.2 g sample (Table 6). More striking was the highest CH₄ concentration of 440 ppm with same amount of PSF waste (Table 6). The lowest concentrations of CH₄ and H₂ were 170 ppm and 5642 ppm, respectively, which were obtained with 0.1 g of sample material. When using higher amounts of PSF waste (0.3 g), a longer duration of pyrolysis should be used to obtain a better result. The higher microwave power improves the chemical reaction occurring during the plasma treatment, which results in higher H₂ concentrations

Fig. 8. Effect of sample weight on gas production rate of CH₄ and H₂.

due to the higher temperature (Dominguez *et al.*, 2007; Dave and Joshi, 2010). In this study, the rapid high-temperature plasma pyrolysis can be obtained on the higher set-up of microwave power. Dave and Joshi (2010) stated that a higher plasma temperature plays an auxiliary role in the transformation of a material into simpler molecules. In this study, lower concentrations of H₂ and CH₄ were achieved because of a slower reaction of the argon plasma jet at lower temperature corresponds to the microwave power. H₂ formation can be improved by increasing the pyrolysis temperature, causes dehydrogenation reaction of aromatic hydrocarbons and condensates associated with the pyrolysis temperature, dehydrogenation, and aromatic hydrocarbon (Zhao *et al.*, 2012; Dominguez *et al.*, 2017). A higher microwave power for plasma increases the temperature reaction, which was linked with the better results for H₂ and CH₄ found in this study. Thereby, higher concentrations of

Table 6. CH₄ and H₂ gases concentration after treatment in an atmospheric-pressure microwave plasma reactor using nitrogen as the carrier gas.

No	Time (s)	Hydrogen (ppm)			Methane (ppm)		
		0.1 g	0.2 g	0.3 g	0.1 g	0.2 g	0.3 g
1	0	0	0	0	0	0	0
2	30	105	510	633	6	21	39
3	60	338	209	610	9	8	92
4	90	710	514	511	16	6	3
5	120	2099	132	514	61	12	14
6	150	1926	3238	1009	64	89	27
7	180	213	2303	975	6	68	29
8	210	167	2666	1809	5	48	53
9	240	83	159	5800	3	30	135
10	270	-	534	569	-	50	12
11	300	-	4434	287	-	58	8
12	330	-	3100	81	-	35	11
13	360	-	1858	263	-	15	12
Total		5642	19,657	13,061	170	440	435

H₂ can be obtained when the microwave power is kept constant at a higher power. In this study, a 5 min plasma reaction increased the temperature from 600°C to 700°C.

Carbon and other volatile materials in PSF waste are converted to CO, H₂ and C_xH_y through chemical reactions (Ruj and Chang, 2012). Tang *et al.* (2003) stated that tar can be degraded effectively into CO and H₂ as the final products, thus confirming the significant production of H₂ because of the higher feed rate in a plasma system. This finding confirmed that PSF waste leads to good gas production results after 4 min of pyrolysis. Carbon decompose because of an oxidation process that generates CH₄ and H₂ (Fabry *et al.*, 2013; Maczka *et al.*, 2013). H₂ and CH₄ gases are the byproduct bond dissociation and endothermic reactions where the exothermic reaction releases energy from the heat at plasma jet discharge (Nema and Ganeshprasad, 2002). Thus, these gases can be generated from plasma pyrolysis.

In this investigation, H₂, the main product of plasma pyrolysis, was described as the main primary gas obtained during the plasma treatment. The pyrolysis of gas plays an important role in converting solid waste to syngas, namely, H₂ and CH₄, which can potentially be substituted for fossil fuels and as alternative sources of energy (Gomez *et al.*, 2009) and may be potentially used into the electricity application (Maczka *et al.*, 2013). H₂ and CH₄ can be obtained from the plasma pyrolysis of PSF waste, owing to carbon conversion in an atmospheric-pressure microwave plasma reactor. The pyrolysis of syngas depends on the parameters used in plasma treatment and amount of PSF waste. These results may be considered as preliminary information to give the information on the conversion of PSF waste to CH₄ and H₂.

CONCLUSION

Employing an atmospheric-pressure microwave plasma reactor, and argon and nitrogen as carrier gases, we produced syngas on a pilot scale by converting carbon into CH₄ and H₂ during the treatment of PSF waste. Using nitrogen instead of argon as the carrier gas and increasing the microwave

power proved to be the optimal method, achieving CH₄ and H₂ concentrations of 19,657 ppm and 440 ppm, respectively, for 0.2 g of PSF. The SEM-EDX and XRD results for the final residue confirmed the structural transformation of the PSF and a decrease in carbon content. Future research should focus on maximizing the concentration of the generated syngas, which depends partially on the quantity of the waste. Mixing the carrier gas with H₂O, increasing the duration of the pyrolysis, and performing a cost analysis are also potential steps. Furthermore, investigating the particulate matter (PM) and aerosols released by the atmospheric-pressure microwave plasma reactor will enable us to control pollutive emissions associated with this technology.

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DISCLAIMER

Authors declare no competing of financial interest in this research. Facts and opinions in articles are solely the primary results of authors.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <https://doi.org/10.4209/aaqr.2020.05.0252>

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