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Influence of the microwave absorbent and moisture content on the microwave pyrolysis of an organic municipal solid waste

D. Beneroso, J.M. Bermúdez, A. Arenillas, J.A. Menéndez*

Instituto Nacional del Carbón, CSIC, Apartado 73, 33080 Oviedo, Spain

* Corresponding author. Tel.: +34 985 118972; Fax: +34 985 297672

E-mail address: angelmd@incar.csic.es

Abstract

Microwave pyrolysis is presented in this study as a recycling approach for municipal solid waste treatment. The process is based on the conversion of solid waste to syngas ($CO + H_2$) by means of a microwave absorbent. Experiments to characterise the syngas produced were performed using the char obtained from the pyrolysis of a municipal solid waste as microwave absorbent in the microwave power range of 150 - 450 W and in an absorbent-to-waste ratio range of 0.2:1 – 1:1 (wt.% : wt.%). A rich-syngas fraction with a high H_2 content (c.a. 50 - 55 vol.%) was obtained and analysed by means of Response Surface Methodology through the interaction between the microwave power and absorbent-to-waste ratio. Moreover, a positive effect of the moisture content on gas production is attained since gasification of the char occurs. Thus, the simple use of a cheap waste-derived char leads to a reduction in the microwave power and economic cost of the process.

Keywords

Microwave Absorbent, Pyrolysis, Municipal Solid Waste, Syngas, Waste Valorisation

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1. Introduction

Municipal solid waste (MSW) consists mainly of waste from households (60-90%), though similar wastes from other sources such as commerce or public institutions are also included. According to Eurostat, which is the statistical body of the EU, MSW generation in Europe has remained stable at about 260 Mt per year since 2002 [1]. Various management alternatives are available for the treatment of MSW such as landfilling, incineration, recycling or composting. In recent years, recycling has increased, although landfilling still remains the most widely used method of disposal, in spite of its several drawbacks, such as the leaching of dangerous chemicals into the soil and the release of methane to the air. However, this gap has narrowed in the last few years. In the EU the landfill/recycling MSW weight ratio was 56/17 in 2001 compared to 37/25 in 2011 [2].

Pyrolysis technology has emerged not only as a very effective way of MSW disposal but also as an attractive technology for valorising these residues by producing fuels or precursors of valuable chemicals, such as syngas ($CO + H_2$). As an example, the SYNPOL project [3] aims to produce new biopolymers via the fermentation of syngas from waste materials.

Several studies have been carried out on MSW pyrolysis [4-7]. In general, the syngas content of the gas fraction produced in pyrolysis processes is not very high, since it is mixed with large amounts of CO_2, CH_4 and light hydrocarbons. As a way to improve the syngas concentration and, especially, the H_2 content, several researchers have proposed catalytic pyrolysis. In such cases, the role of the catalyst, such as dolomite [4], is to crack the heavy compounds in order to obtain lighter gases. However, the same effect can be achieved by means of microwave irradiation, without the need to add a

catalyst to the system, as demonstrated in previous studies [8-10]. Microwaves are able to generate microplasmas, which promote heterogeneous catalytic reactions, but not all materials can be heated by means of microwave irradiation, since some materials are transparent to microwaves. To solve this problem, the addition of carbon-rich materials has been proposed to absorb microwaves [11-14]. The material to be pyrolysed is then heated by conduction. Use of the char obtained from MSW pyrolysis process as microwave absorbent is an attractive solution since it avoids the addition of materials that might increase the cost of the process.

The microwave pyrolysis of MSW has been performed previously by Gedam and Regupathi [15], but it is still at an early stage of development. In the study of Gedam and Regupathi, both the microwave power and irradiation time were varied. Although a minimum value of power was required to carry out the pyrolysis of MSW, the addition of different carbon materials that served as microwave absorbents allowed the pyrolysis to proceed at a lower microwave power. Surprisingly, no hydrogen was produced other than trace concentrations, providing a gas rich in CO, CO_2 and CH_4. So far the effect of the amount of microwave absorbent on MSW pyrolysis has not received much attention. However, this parameter has been studied in relation to other materials. The microwave induced pyrolysis (MIP) of microalgae with various microwave absorbents, such as activated carbon, CaO, SiC or microalgae char has been carried out by Hu *et al.* [16]. These authors found that there was a specific proportion of absorbent-to-microalga at which the liquid fraction was maximised, depending on the absorbent used. Oil palm shell biomass was recently subjected to MIP in a study by Salema and Ani [17], which showed the importance of the quantity of microwave absorbent added to the oil palm shell as a method of controlling the pyrolysis temperature in an overhead stirrer reactor. The authors reported that an increase in microwave absorbent led to a decrease in the

pyrolysis temperature and in turn in to higher solid fraction yields. All of these studies were focused on maximising the liquid fraction yield. However, to the best of our knowledge, no studies have been aimed at maximising the gas fraction yield.

Herein, we report for the first time on a statistical model based on Response Surface Methodology (RSM) designed to assess the combined effect of microwave power and ratio of microwave absorbent-to-waste upon the amount and characteristics of the syngas generated from MIP. In addition, the effect of moisture content of the MSW is evaluated.

2. Materials and Methods

2.1. Materials

The sample selected for this study was an organic fraction from a municipal solid waste, supplied by BEFESA *Gestión de Residuos Industriales* S. L. (Seville, Spain) in two forms: wet (with a moisture content of c.a. 45 wt.%) and dry (with a moisture content of c.a. 1.5 wt.%). The dry and wet fractions will be labelled as D and W respectively. Proximate and ultimate analyses were performed to characterise the composition of the feedstock samples. The moisture, ash content and volatile matter data (from a LECO TGA-601) are summarised in Table 1 together with the ultimate analysis results (a LECO-CHNS-932 micro-analyser and LECO-TF-900 furnace were used). Metallic content of the ashes from the organic MSW was determined by means of atomic absorption spectroscopy.

The gases were analysed in a Varian-CP3800 gas-chromatograph equipped with a TCD detector and two columns connected in series. The first column was 80/100 Hayesep Q (2 m x 1/8 in. x 2mm) and the second column was a 80/100 Molesieve 13X (1.5 m x 1/8

in. x 2 mm). The second column was bypassed by a six-port valve for the analysis of CO_2 and hydrocarbons. The TCD was calibrated with a standard gas mixture.

Table 1. Proximate and ultimate analyses of the organic fraction from MSW and metal content of the ashes.

Proximate Analysis (wt.%)			Ultimate Analysis (wt.%)[a]					
Moisture	Ash[a]	Volatile matter[a]	C	H	N	S	Cl	O[c]
1.5[b]	30.3	61.1	39.4	5.2	1.5	0.4	0.9	22.3

Metal content of ashes (mg_{metal} / kg_{MSW})						
Fe	Zn	Mn	Cr	Cu	Pb	Ni
8896	183	83	59	45	31	18

[a] Dry basis

[b] Moisture content of D. In the case of W, moisture content is 45 wt.%

[c] Calculated by difference

2.2 Microwave induced pyrolysis

The pyrolysis of D and W was carried out in a microwave oven which consisted basically of a microwave magnetron with a maximum output power of 2 kW operating at 2450 MHz and a single mode cavity where the sample was irradiated using powers ranging from 150 to 450 W. The single mode cavity allows a well-defined electric field in a relatively small volume due to the superposition of incident and reflected waves, and causes the microwave field to focus on a given location [18]. The reflected power is regulated until it is reduced to zero by means of stub tuners. About 3 g of sample (on a dry basis) was placed on an inert bed inside a quartz reactor. The reactor was purged with N_2 for 30 minutes at a flow rate of 50 mL_{STP} min^{-1}. The N_2 flow rate was then set to 10 mL_{STP} min^{-1} for the pyrolysis experiments in order to ensure an oxygen-free atmosphere.

As mentioned in previous studies on microwave induced pyrolysis of biomass, it is also necessary to mix the MSW fraction with an appropriate microwave absorbent to achieve the high temperatures required for pyrolysis [11-14]. The char obtained from the prior pyrolysis of D and W at 800 °C in an electrical furnace was used as microwave absorbent in different absorbent-to-waste ratios (0.2:1, 0.4:1 and 1:1), in order to evaluate the influence of this parameter on the characteristics of the syngas. Preliminary experiments showed that lower values of absorbent-to-waste ratio prevented the pyrolysis of the MSW fraction.

The experiments lasted 1 hour, but the time chosen for the calculation of the parameters was 40 minutes, since by this time all the MIP experiments would have reached 90% of total syngas production.

The volatiles released from the pyrolysis of both organic fractions were passed through a condensing system cooled by a cryogenic solution of water and NaCl. The liquid fraction was recovered from the condensing system by dissolving it in CH_2Cl_2. It was then subjected to further evaporation to remove the solvent at 40 °C. The non-condensable gases were collected at intervals of 10 minutes in Tedlar sample bags and then analysed by gas chromatography. The composition of the gaseous fraction was determined from the composition of each bag and the N_2 flow rate.

2.3 Statistical model

RSM is a widely used technique for the optimisation of a set of parameters. This methodology assesses the combined effect of a set of independent variables on response variables by means of three-dimensional surface plots. The experimental response variables are fitted to a mathematical model by multiple regression analysis, which is then subjected to statistical evaluation by means of the analysis of variance (ANOVA)

in order to determine whether the model and model parameters are significant on the basis of the *p*-value to within a certain level of confidence, e.g. at 95%. In the field of MIP, only a few studies employ RSM [19,20], but none of them are focused on the influence of the microwave power or on the effect of the microwave absorbent on the syngas produced.

As mentioned at the end of Section 1, three factors were selected as the independent variables used to model the characteristics of the gas obtained from the MIP of the organic fraction of municipal solid waste: the microwave power (*P*, expressed in watts), the absorbent-to-waste ratio (*A*, wt.% : wt.%) and the moisture content (*M*, wt.%). The values of *P* ranged from 150 W to 450 W and those of *A* from 0.2:1 to 1:1. Additional experiments were performed on the W fraction (45 wt.% of moisture) to evaluate the influence of the water content on the pyrolysis process.

In order to model the gas fraction evolved during the MIP, the following response variables were characterised: the syngas concentration, i.e. CO + H_2 concentration in the pyrolysis gases (S, vol.%); the syngas production (SP, $L_{STP}\ g_{MSW}^{-1}$) and the H_2, CO, CO_2 and CH_4 concentrations in the gas fraction (vol.%). The experimental design is shown in Table 2.

The experimental results for D and W were fitted using a polynomial quadratic equation (Eq. (2.1)) by means of Design Expert® software to correlate the response variables *R(P,A)* to the independent variables *P* and *A* within the model parameters: the offset term (α), the linear effects (β, γ) the squared effects (δ, ε) and the interaction term (ζ):

$$R(P,A) = \alpha + \beta P + \gamma A + \delta P^2 + \varepsilon A^2 + \zeta PA \qquad (2.1)`$$

Table 2. Experimental design for the MIP of organic MSW.

Experiment	*P* (W)	*A* (wt.% absorbent : wt.% residue)	*M* (wt.%)
1	150	0.2:1	1.5
2	150	0.4:1	1.5
3	150	1:1	1.5
4	250	0.2:1	1.5
5	250	0.4:1	1.5
6	250	1:1	1.5
7	350	0.2:1	1.5
8	350	0.4:1	1.5
9	350	1:1	1.5
10	450	0.2:1	1.5
11	450	0.4:1	1.5
12	450	1:1	1.5
13	150	0.2:1	45
14	150	1:1	45
15	450	0.2:1	45
16	450	1:1	45

3. Results and Discussion

3.1 Syngas production models

The main objective of this study is to characterise the syngas generated by the microwave induced pyrolysis of municipal solid waste and determine its composition and production. The relationships between the factors *P* and *A* and the responses S and SP are illustrated Fig. 1(a)-(b). Qualitatively, an increase in the microwave power directed at the sample leads to a higher syngas concentration and production. Factor *A* seems to have only a slight effect on the responses studied. The regression models calculated to predict S (vol.%) and SP ($L_{STP}\ g_{MSW}^{-1}$) are expressed as follows:

$$S = 75.247 + 0.087P - 0.787A + 0.024PA - 1.171 \cdot 10^{-4}P^2 - 7.885A^2 \quad (3.1)$$

$$SP = 0.039 + 1.765P - 0.393A + 3.395 \cdot 10^{-5}PA - 1.870 \cdot 10^{-6}P^2 + 0.253A^2 \quad (3.2)$$

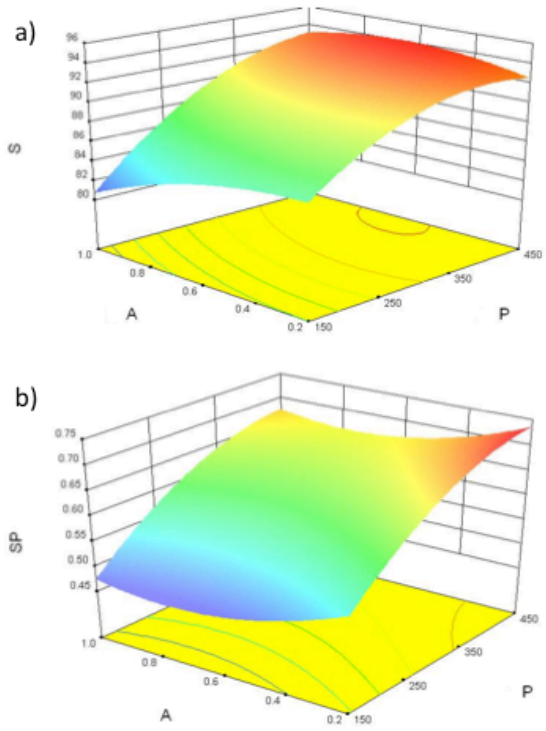

Figure 1. Response surface plots based on syngas concentration (S, vol.%) (a), and syngas production (SP, $L_{STP}\ g_{MSW}^{-1}$) (b), as a function of microwave power (P) and absorbent-to-waste ratio (A).

To statistically quantify the influences of the P and A factors, ANOVA tests were performed. In Table 3, the model *p*-values << 0.05 suggest that both models are significant to within a 95% confidence level. In the case of the syngas concentration model (Eq. 3.1), the linear term for microwave power (*P*) has the greatest effect on the H_2 + CO content due to the extremely low *p*-value (<0.0001). In contrast, the influence of the microwave absorbent quantity, although significant, is not as great. The term for the absorbent-to-waste ratio (*A*) has a significant effect on S with a *p*-value of 0.0012. In the case of the syngas production model, the terms *P* and *A* were found to be significant factors too.

Table 3. ANOVA for the syngas models (*S* and *SP*).

Source	Sum of squares	Degree of freedom	Mean Square	*F* value	*p*-value	Significance (to within a 95% confidence level)	R^2 $Adj\text{-}R^2$
Response: Syngas composition (S, vol.%)							
Model	179.697	5	35.939	109.125	<0.0001	Significant	
P	145.264	1	145.264	441.072	<0.0001	Significant	
A	10.904	1	10.904	33.109	0.0012	Significant	0.989
PA	10.359	1	10.349	31.423	0.0014	Significant	0.980
P^2	16.450	1	16.450	49.948	0.0004	Significant	
A^2	2.204	1	2.204	6.692	0.0414	Significant	
Response: Syngas production (SP, $L_{STP}\ g_{MSW}^{-1}$)							
Model	0.068	5	0.014	52.400	0.0010	Significant	
P	0.062	1	0.062	235.94	<0.0001	Significant	
A	0.005	1	0.005	17.78	0.014	Significant	0.985
PA	$1.932 \cdot 10^{-5}$	1	$1.932 \cdot 10^{-5}$	0.074	0.799	Not significant	0.966
P^2	0.003	1	0.003	10.770	0.031	Significant	
A^2	0.001	1	0.001	5.700	0.075	Not significant	

From the surface plots of the regression models (Fig. 1(a)-(b)), it is possible to determine the effect exerted by *P* and *A* on the response variables in the experimental space studied. At a low microwave power (150, 250 and 350 W), a high *A* leads to a decrease in both the syngas concentration and production, although at 450 W the trend of S seems to change, since a maximum appears at A = 0.4:1. Anyway, the concentration of syngas in the gas fraction obtained over the entire range of experimental conditions studied is considerable (>80 vol.% in all the cases). In short, the MIP of MSW is very selective towards syngas.

To investigate the fit of the model, the *R*-squared and Adjusted *R*-squared values were evaluated. As can be observed in Table 3, the S model has an R^2 value of 0.989, indicating that the model variation of 98.9% for the syngas concentration is attributable to the independent variables and only 1.1% of the total variation could not be explained by the model. The value of $Adj\text{-}R^2$ is also very high, lending further support to the high significance of the model proposed. In the case of the SP model, similar conclusions can be drawn.

Of the two factors (i.e. microwave power and the absorbent-to-waste ratio), microwave power plays the more important role in MIP. Nevertheless, it is important to emphasize that without the presence of a microwave absorbent, it would be impossible to carry out the MIP experiments and that its presence allows the microwave power to be reduced, as mentioned by Gedam and Regupathi [15]. These authors found that with a single mode cavity, the MIP of MSW was not possible without the addition of a microwave absorbent, unless the microwave power was higher than 450 W. However, the addition of carbonaceous absorbents such as charcoal with an *A* value of 0.5:1 allowed MSW to be pyrolysed even at 100 W. In a more recent study by Hu *et al.* [16], the authors performed the MIP of microalgae without any absorbents but at powers higher than 750 W. They also found that the addition of small amounts of solid residue obtained from the microalgae promoted gas production.

3.2 Gas component models

The response surface models corresponding to the major components of the gas fraction (i.e. H_2, CO, CO_2 and CH_4) are shown in Fig. 2(a)-(d). From the trends of these models, it can be seen that the concentrations of the most valuable components (H_2 and CO) were favoured by the power irradiated at the sample. As observed by Hu *et al.* [16], the higher the microwave power is, the higher the temperature reached inside the bulk, since both the microwave density and the microwave energy absorbed by the bulk increase. As a consequence, the endothermic reactions leading to the formation of syngas are favoured [9]. On the other hand, the addition of absorbent to MSW seems to have little effect on the gas concentrations. To assess the effects of both factors more effectively, the following regression models for H_2, CO, CO_2 and CH_4 (vol.%) were obtained:

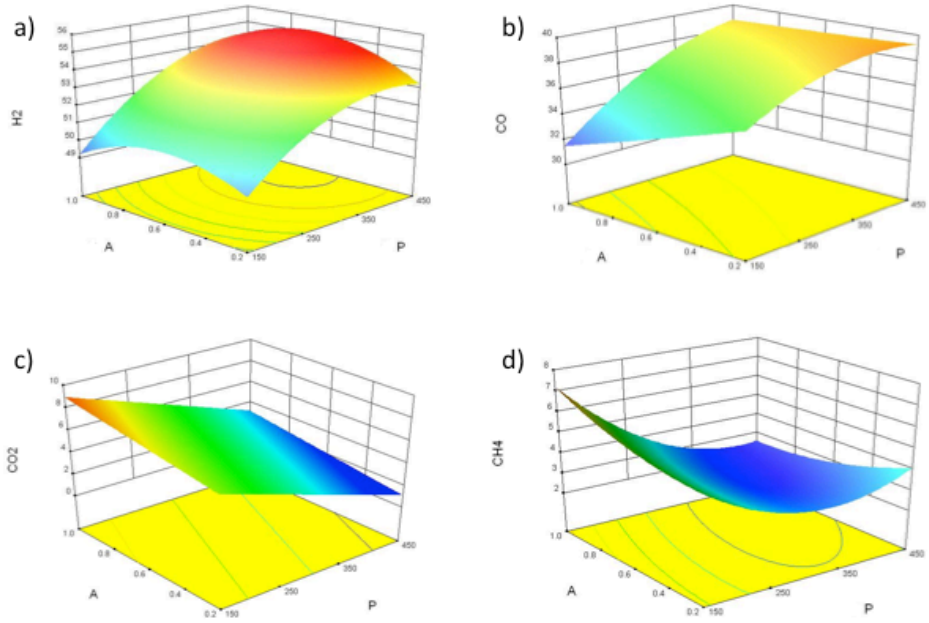

Figure 2. Response surface plots based on H_2 (a), CO (b), CO_2 (c) and CH_4 (d) concentrations (vol.%) in the gas fraction as a function of microwave power (P) and absorbent-to-waste ratio (A).

$$H_2 = 42.367 + 0.048P + 8.242A + 6.475 \cdot 10^{-3}PA - 6.183 \cdot 10^{-5}P^2 - 8.162A^2 \quad (3.3)$$

$$CO = 32.870 + 0.039P - 9.013A + 0.018PA - 5.533 \cdot 10^{-5}P^2 + 0.271A^2 \quad (3.4)$$

$$CO_2 = 9.114 - 0.019P + 2.693A \quad (3.5)$$

$$CH_4 = 9.768 - 0.039P + 1.524A - 0.015PA + 6.508 \cdot 10^{-5}P^2 + 2.667A^2 \quad (3.6)$$

ANOVA tests were carried out as in Section 3.2. The model *p*-values << 0.05 (Table 4) imply that all the models are significant to within a confidence level of 95%. In the case of the hydrogen concentration model (Eq. 3.3), the only significant term is the microwave power linear term (*P*) since its *p*-value is 0.0029. No significance was found for the other terms. In the case of the CO model (Eq. 3.4), both the *P* and the *A* terms

have significance, their *p*-values 0.0028 and 0.0310 being respectively. For CO_2, a linear model was found to be the most accurate (Eq. 3.5). Both linear terms were found to be significant for the CO_2 model. However, the trend of the CO_2 model was the opposite to that of the CO model. This is because CO and CO_2 are related by *Boudouard*'s equilibrium (Eq. 3.7):

$$C + CO_2 \leftrightarrow 2\,CO\ ,\ \Delta H^0 = 173\ kJ\ mol^{-1} \qquad (3.7)$$

Table 4. ANOVA for the gas fraction component models.

Source	Sum of squares	Degree of freedom	Mean Square	*F* value	*p*-value	Significance (to within a 95% confidence level)	R^2 $Adj\text{-}R^2$
Response: Hydrogen concentration (H_2, vol.%)							
Model	37.809	5	7.562	5.726	0.0277	Significant	
P	30.811	1	30.811	23.330	0.0029	Significant	
A	0.195	1	0.195	0.148	0.7138	Not significant	0.827
PA	0.727	1	0.727	0.550	0.4862	Not significant	0.682
P^2	4.588	1	4.588	3.474	0.1116	Not significant	
A^2	2.361	1	2.361	1.788	0.2297	Not significant	
Response: Carbon monoxide concentration (CO, vol.%)							
Model	62.265	5	12.453	6.967	0.0175	Significant	
P	42.210	1	42.210	23.615	0.0028	Significant	
A	14.045	1	14.045	7.857	0.0310	Significant	0.853
PA	5.566	1	5.566	3.114	0.1281	Not significant	0.731
P^2	3.674	1	3.674	2.055	0.2016	Not significant	
A^2	0.003	1	0.003	0.002	0.9708	Not significant	
Response: Carbon dioxide concentration (CO_2, vol.%)							
Model	63.830	2	31.910	50.230	<0.0001	Significant	0.918
P	53.770	1	53.770	84.640	<0.0001	Significant	0.899
A	10.050	1	10.050	15.830	0.0032	Significant	
Response: Methane concentration (CH_4, vol.%)							
Model	20.628	5	4.126	6.032	0.0246	Significant	
P	13.455	1	13.455	19.672	0.0044	Significant	
A	0.146	1	0.146	0.213	0.6606	Not significant	0.834
PA	3.706	1	3.706	5.419	0.0588	Not significant	0.695
P^2	5.083	1	5.083	7.431	0.0344	Significant	
A^2	0.252	1	0.252	0.369	0.5661	Not significant	

From Fig. 2(b)-(c) it can be observed that the maximum CO_2 concentration corresponds to the conditions at which the CO concentration is minimised (low power and a high

quantity of microwave absorbent) and vice versa. This behaviour could be due to the fact that, as *A* increases, the bulk temperature decreases as stated in another study by Salema and Ani [17] and that the lower power leads to lower temperatures, shifting Eq. 3.7 to the side of reactants since it has an endothermic enthalpy (173 kJ mol^{-1}).

Finally, in the CH_4 model (Eq. 3.6), *P* is the only significant factor since it has *p*-value of 0.0044, and its trend is similar to that of the CO_2 model. Endothermic reforming reaction of methane (Eq. 3.8) is favoured at high power and so CO and H_2 production from these reactions is greater.

$$CH_4 + CO_2 \leftrightarrow 2\,H_2 + 2\,CO, \Delta H^0 = 247\ kJ\ mol^{-1} \quad (3.8)$$

From the mathematical models presented above (Eqs. 3.3-3.6), it can be seen that the microwave power has a positive effect on H_2 and CO production, but a negative effect on the production of CO_2 and CH_4. Moreover, the addition of larger quantities of absorbent to MSW inhibits the production of CO but favours the production of CO_2. Table 4 shows that factor *A* has no significance for the H_2 and CH_4 response variables in the experimental set-up employed in this study. Anyway, it would seem that the hydrogen model would not represent the physical process very well since the absorbent would modify the pyrolysis temperature and, hence, affect the production of hydrogen. As scale-effects may be masking this point, larger scale experiments are being carried out by our research group.

An interesting point in relation to the quality of the syngas produced is the H_2/CO ratio, especially in regard to its future use. For example, in the case of methanol synthesis from syngas, a H_2/CO ratio of around 2 would be the ideal [21]. In this work, it was found that from the microwave pyrolysis of MSW, this parameter does not vary

290 appreciably. H_2/CO ratios between 1.3-1.5 were obtained over the entire experimental
291 space analysed.
292

293 3.3 Effect of the moisture content of the MSW

294 Since the wet fraction has a large moisture content (*M)*, H_2O might be expected to play
295 an important role in the pyrolysis process via the gasification reactions of the char (Eq.
296 3.9-3.10) and the reforming reactions (Eq. 3.11-3.12), leading to an enrichment in H_2,
297 CO or CO_2 depending on the experimental conditions.

298 $$C + H_2O \leftrightarrow H_2 + CO \ , \Delta H^0 = 131 \ kJ \ mol^{-1} \quad (3.9)$$

299 $$C + 2\ H_2O \leftrightarrow 2\ H_2 + CO_2 \ , \Delta H^0 = 90 \ kJ \ mol^{-1} \quad (3.10)$$

300 $$CH_4 + H_2O \leftrightarrow 3\ H_2 + CO, \Delta H^0 = 205 \ kJ \ mol^{-1} \quad (3.11)$$

301 $$C_nH_m + nH_2O \leftrightarrow (n + m/2)\ H_2 + nCO \quad (3.12)$$

302 The MIP experiments on W were conducted at both low and high power (150 W and
303 450 W). In addition, the quantity of microwave absorbent was evaluated along with *M*,
304 using *A* ratios of 0.2:1 and 1:1, as shown in Table 2. The results of the analysis of the
305 gas fraction for these cases are reported in Table 5. As might be expected from Eq. 3.10,
306 the H_2 and CO_2 concentrations obtained from the wet fraction at 150 W are greater than
307 those obtained from the dry fraction. In fact, water condenses at the top of the reactor,
308 which is at a much lower temperature than the sample. In other words, there is a water
309 reflux effect which favours a vapour-rich atmosphere and the gasification of the char.
310 However, when the power is increased to 450 W, there are no appreciable differences in
311 the gas composition of W and D. Therefore, Eq. 3.9 might be taking place to a much
312 greater extent than Eq. 3.10, since the endothermic character of Eq. 3.9 is favoured by

313 the higher temperatures. Moreover, *M* also affects the CH_4 concentration in the gas
314 fraction by reducing its content. This may be due to the steam reforming reaction of
315 methane (Eq. 3.11). At 450 W the higher temperature would favour the thermal
316 cracking and the steam reforming reaction of CH_4 much more than at 150 W. Finally, it
317 could be remarkable that the percentage of syngas within the gas fractions seems to be
318 similar regardless the moisture content. However, this behaviour might not be
319 generalised yet.

320 **Table 5.** Comparison of the gas fraction from the MIP of the dry fraction (D) and the
321 wet fraction (W) with different *A* ratios (0.2:1 and 1:1) at 150 W and 450 W.

P = 150 W				
	A = 0.2:1		**A = 1:1**	
	D	**W**	**D**	**W**
H_2 (vol.%)	49.37	53.40	48.94	57.03
CO (vol.%)	36.89	33.72	31.46	23.45
CO_2 (vol.%)	6.52	7.62	9.59	15.33
CH_4 (vol.%)	5.43	3.99	7.70	3.05
S (vol.%)	86.26	87.12	80.40	80.48
Gas production (L_{STP}/g_{MSW})*	**0.64**	**0.92**	**0.58**	**1.06**
*SP (L_{STP}/g_{MSW})**	0.55	0.73	0.47	0.85
P = 450 W				
	A = 0.2:1		**A = 1:1**	
	D	**W**	**D**	**W**
H_2 (vol.%)	53.54	53.10	54.30	53.61
CO (vol.%)	38.60	37.42	38.66	41.13
CO_2 (vol.%)	2.17	5.17	3.50	3.77
CH_4 (vol.%)	4.22	2.50	2.50	1.01
S (vol.%)	92.14	90.52	92.96	94.74
Gas production (L_{STP}/g_{MSW})*	**0.79**	**0.94**	**0.73**	**1.10**
*SP (L_{STP}/g_{MSW})**	0.73	0.85	0.68	1.05

322

323 * Calculated on a dry basis

324

325 Also important is the effect of moisture on syngas production. At 450 W, the W fraction
326 produces 35% more syngas than the D fraction when a ratio 1:1 is employed, but their
327 values converge at a ratio of 0.2:1, there being a difference in this case of around 15%.
328 There is also a marked difference between these values at 150 W, since the W fraction

produces much more syngas than fraction D (45% higher) when a 1:1 ratio is employed. Once more, these values converge at a ratio of 0.2:1, the wet fraction producing 25% more syngas than the dry fraction. This suggests that moisture content favours the production of a greater amount of gas, an impression that is confirmed by the results in Table 5. This is an interesting point since it implies that the drying and pyrolysis processes of MSW could be integrated in the MIP process to increase the production of gas.

Both the quantity of absorbent and the moisture content influence the gas composition. However, in the case of the wet fraction the amount of absorbent added has a much greater influence. Hence gasification of the char from the wet fraction is bound to occur. At 150 W, a greater increase in H_2 and CO_2 is observed at a ratio of 1:1 than at 0.2:1. However, at 450 W the CO_2 concentration decreases as CO is produced due to the increase in the quantity of absorbent. Thus, it may be assumed that the *Boudouard* equilibrium (Eq. 3.7) is controlling the process in these conditions. In contrast, the syngas production results reported in the above paragraph suggest that the addition of more microwave absorbent to the wet fraction improves the production of syngas, which is not the case with the dry fraction. Once more, this evidences the importance of the char gasification reactions.

4. Conclusions

This study has demonstrated the possibility of recycling the char obtained from municipal solid wastes for use as microwave absorbent in the microwave pyrolysis process. Although microwave power is the most important factor for controlling the pyrolysis, since higher power allows better conversion to syngas and syngas production, the presence of the char in the material subjected to microwave pyrolysis is of

overwhelming importance. This allows a rich syngas ($CO + H_2$) fraction (c.a. 80-94 vol.% of the gas fraction) to be obtained with a low microwave power. A minimum *A* ratio of 0.2:1 was found to be necessary to induce the microwave pyrolysis process. In addition, low ratios seem to be more suitable for obtaining a higher concentration and production of syngas. Moisture also plays an important role, as it favours H_2 and CO_2 production, especially at low power, in addition to improving the syngas production process.

List of abbreviations

A: absorbent-to-waste ratio (kg:kg)

ANOVA: Analysis of variance

D: Dry fraction from organic municipal solid waste

MIP: Microwave induced pyrolysis

MSW: Municipal solid waste

P: Microwave power (watts)

RSM: Response surface methodology

S: Syngas concentration (vol.%)

SP: Syngas production ($L_{STP}\ g_{MSW}^{-1}$)

W: Wet fraction from organic municipal solid waste

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