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1 **Oil production from waste polypropylene and polystyrene co-** 2 **pyrolysis: Interactions of temperature and carrier gas flow rate**

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10 **Abstract:** This study investigated the co-pyrolysis of waste polyethylene (WPE) and
11 polystyrene (WPS) for oil production under different operating conditions (temperature and
12 carrier gas flow rate). The ratio of the real-life WPE and WPS is different in different regions.
13 Therefore, the interactions of operating conditions were investigated under different
14 WPE/WPS mixture compositions. A hybrid model of artificial neural network-genetic
15 algorithm (ANN-GA) was adopted to predict and optimize the co-pyrolysis oil yield due to
16 the complex interactions of the WPE/WPS mixture composition and operating conditions.
17 Consequently, the highest oil yield was 82.33wt% under 525°C, 10wt% PS, and a non-
18 sweeping atmosphere (0mL/min). The results indicated that high temperature, low PS mass
19 fraction, and low carrier gas flow rate led to a higher oil yield. The WPE/WPS co-pyrolysis
20 oils were composed of alkanes, alkenes, and aromatics. Meanwhile, styrene accounted for the
21 highest proportion of aromatics in oils. ANN-GA was also adopted to predict and optimize the

22 oil components and fractions. The results revealed that low temperature, high PS mass
23 fraction, and low carrier gas flow rate were conducive to a light WPE/WPS co-pyrolysis oil
24 production. The findings could guide the industrial process of waste plastic pyrolysis in
25 different regions. Moreover, ANN-GA coupled with central-composite design can be used to
26 regulate different target products under more complex conditions due to its good robustness.

27

28 **Keywords:** *Waste Plastic; Co-pyrolysis; Oil Production; Artificial neural network; Genetic*
29 *algorithm.*

30

31 **1. Introduction**

32 The production of plastic has grown promptly from 1.5 million tons in 1950 to 368
33 million tons in 2019 [1]. The European plastic production was up to 57.9 million tons in 2019
34 [1], and almost half of the produced plastic became waste [2]. Moreover, nearly 25% of waste
35 plastic winds up in landfills [3]. Consequently, waste plastic accumulates rapidly due to the
36 low environmental degradability [4]. Plastic pollution destroys ecosystems [5] and causes
37 harm to living creatures [6]. Pyrolysis is considered a promising alternative to landfill
38 disposal of waste plastic, which can simultaneously produce liquid oil similar to commercial
39 fuels (gasoline and diesel) [7-10]. Polyethylene (PE) and polystyrene (PS) are the first and
40 third-most components in waste plastic due to their wide range of uses [11-12]. Therefore,
41 many studies have investigated waste polyethylene (WPE) and polystyrene (WPS) pyrolysis
42 for oil production. Park et al. [13] studied the pyrolysis of WPE at 653–736°C and recovered

43 15–38wt% oil in a tandem two-stage reactor. Al-Salem et al. [7,14] conducted the low-density
44 PE pyrolysis experiments at 500–800°C. They found that the maximum wax yield was
45 64.5wt% at 500°C [14], and the highest oil yield was 29wt% at 600°C [7]. The WPS pyrolysis
46 oil has been reported to have a higher yield than the WPE pyrolysis oil. Nisar et al. [15]
47 recovered 44.9–86.1wt% oil from the pyrolysis of WPS at 340–420°C. Quesada et al. [11]
48 also obtained a high yield of 80wt% WPS thermal pyrolysis oil at 500°C in a fixed bed reactor.
49 It can be concluded that temperature is a critical parameter determining pyrolysis oil
50 production.

51 WPE and WPS in waste plastic have different contents in different regions [3]. Therefore,
52 the effect of WPE/WPS mixture composition on oil production has also been studied by
53 researchers. Quesada et al. [11] investigated the WPE/WPS mixture (25wt% PS) co-pyrolysis
54 at 500°C and obtained ~70wt% of oil yield. Siddiqui and Redhwi [16] investigated the high-
55 density-PE/PS (50–75wt% PS) co-pyrolysis at 440°C in a batch reactor. It was found that as
56 the PS mass fraction increased, the oil yield decreased from 72.8wt% (under 50wt% PS) to
57 25.6wt% (under 66.7wt% PS), while it increased to 56.1wt% when the PS mass fraction
58 continuously increased to 75wt% PS. Williams and Williams [17] obtained 67.3wt% oil from
59 PE/PS mixture (50wt% PS) co-pyrolysis at 700°C. While the predicted oil yield, calculated by
60 the PE and PS sole pyrolysis oil yields, was 81.7wt%. They concluded that an interaction
61 between PE and PS led to a lower-than-expected oil yield. Klaimy et al. found that the co-
62 pyrolysis of plastic mixtures promoted the production of lightweight components (C6 and C7)
63 in the oil [18]. Saad et al. [19] suggested that PE and PS could be fully decomposed before

64 500°C with a heating rate of 10°C/min. However, the plastic compositions affected the
65 activation energies of mixed plastics. Moreover, co-pyrolysis of other types of plastics [20]
66 and co-pyrolysis of plastics with biomass [21] also found the complex interactive effects of
67 the mixture compositions.

68 On the other hand, the carrier gas flow rate is a significant parameter during the pyrolysis
69 of plastic [22-23]. Muhammad et al. [23] investigated the effect of carrier gas flow rate on the
70 pyrolysis of linear low-density PE. They found that increasing the flow rate from 0mL/min to
71 1mL/min could dramatically enhance the oil yield from 54.0wt% to 61.5wt%. In contrast, the
72 oil yield decreased to 45.0wt% under the flow rate of 60mL/min. Pan et al. [22] concluded
73 that the WPE pyrolysis oil yield would decrease from 82.43wt% to 65.32wt% when the flow
74 rate increased from 20mL/min to 100mL/min.

75 It can be concluded that the temperature and the carrier gas flow rate are two vital
76 parameters during plastic pyrolysis. The WPE/WPS mixture composition also has a non-linear
77 effect on the co-pyrolysis oil yield. The artificial neural network (ANN) is a promising
78 method to formulate the dependent variable in terms of independent variables with complex
79 interactions [24]. Neshat et al. [25-26] adopted ANN to predict wind speed and wind turbine
80 power output. The findings revealed that ANN could accurately establish the expressions of
81 the dependent variables. ANN can also be competent for detection works, e.g., plate's
82 structural damage [27] and COVID-19 [28]. An optimization algorithm is required to
83 determine the extrema of complex mathematical expressions established by the ANN. Genetic
84 algorithm (GA), inspired by the evolution theory, is a widely used optimization algorithm [29].

85 Furthermore, GA has been proven to be qualified to determine the extrema of ANN-
86 established expression [30].

87 The primary aim of this study is to investigate the interactions of operating conditions
88 (temperature and flow rate of carrier gas) on the WPE/WPS (with different mixture
89 compositions) co-pyrolysis oil yield. A hybrid model of the artificial neural network coupled
90 with a genetic algorithm (ANN-GA) is adopted to quantitatively describe the complex
91 interactions of operating conditions and WPE/WPS mixture composition on the product yields
92 based on the experimental results. The oil samples are analyzed by gas chromatography/mass
93 spectrometry (GC/MS) to determine the specific components. The ANN-GA is also adopted to
94 predict and optimize the oil components and fractions under different operating conditions
95 and WPE/WPS mixture compositions. The findings can guide the regional industrialization of
96 waste plastic pyrolysis.

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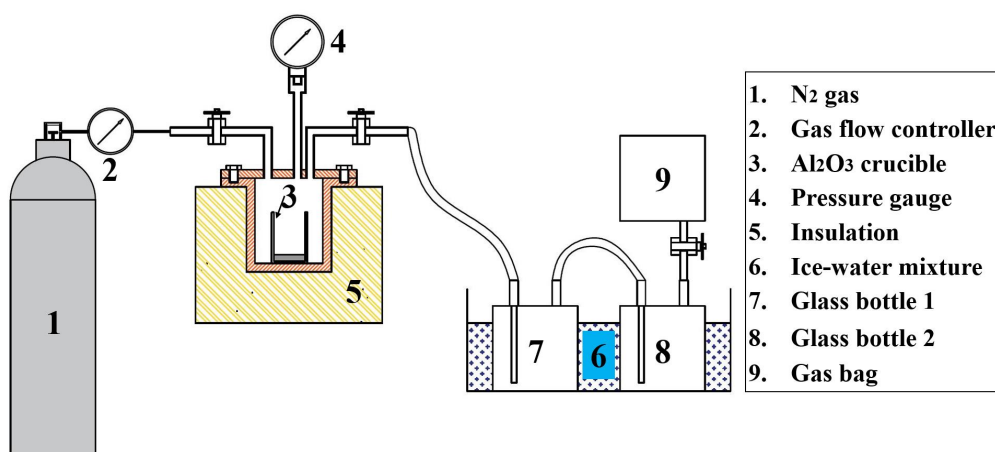
98 **2. Experiments and method**

99 *2.1. Pyrolysis experiments*

100 WPE and WPS were recycled from municipal solid waste (MSW) and provided by
101 Zhoushan Jinke Renewable Resources Co., China. The waste plastics were first collected and
102 sorted, then washed and dried, and finally made into pellets of about 3mm. The total mass of
103 the WPE/WPS mixture used in each pyrolysis experiment was ~5g. As shown in Fig. 1, the
104 WPE/WPS co-pyrolysis experiments were carried out in a 200mL semi-batch reactor. The
105 WPE/WPS samples were mixed well and placed in the Al₂O₃ crucible. The reactor was

106 purged with nitrogen (under 100mL/min) for 30min to ensure an inert atmosphere. The
107 reactor was heated to the target temperature at 6°C/min and stayed at the target temperature
108 for 20min. Two in-tandem glass bottles collected the WPE/WPS pyrolysis oil in a mixture of
109 ice and water. A gas bag collected the pyrolysis gas. The char remained in the Al₂O₃ crucible
110 and was collected after cooling the reactor to 20°C.

111 The temperature, PS mass fraction, and flow rate of carrier gas were studied in the ranges
112 of 425–525°C [19,22,31], 10–30wt% PS [3], and 0–60mL/min [23] based on the plastic
113 pyrolysis characteristics, regional WPE/WPS composition, and reactor size. The WPE/WPS
114 co-pyrolysis experiments were designed according to the central-composite design [32] and
115 tabulated in Table A.1. 17 sets of experiments (R1–R17) were conducted to obtain the training
116 set data of ANN-GA. 5 sets of experiments (R18–R22) were carried out to get the testing set
117 data of ANN-GA. Moreover, the WPE/WPS co-pyrolysis oil samples were characterized by
118 GC/MS to determine the specific composition of the oil.



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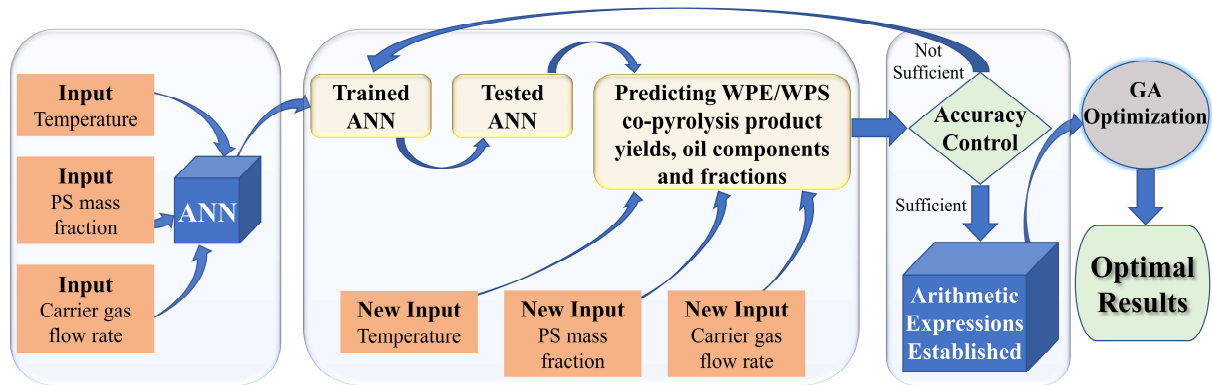
120

Fig. 1. The WPE/WPS co-pyrolysis experimental setup.

121

122 2.2. Method

123 A hybrid artificial neural network model coupled with a genetic algorithm (ANN-GA)
 124 was adopted to predict and optimize the WPE/WPS co-pyrolysis product yields, oil
 125 components, and fractions. The simulation platform of the ANN-GA is Matlab R2016a. Fig. 2
 126 demonstrates the flow chart of ANN-GA. The mathematical expressions of ANN-GA have
 127 been detailed described in the previous study [30]. The arithmetic expressions between the
 128 independent (temperature, PS mass fraction, and flow rate of carrier gas) and dependent
 129 variables (co-pyrolysis product yields, oil components, and fractions) were established by
 130 ANN based on the experimental results [33]. Subsequently, GA was used to optimize the
 131 objective functions built by ANN. Consequently, the conditions (temperature, PS mass
 132 fraction, and carrier gas flow rate) for the highest oil yield and the lightest oil production
 133 could be determined by ANN-GA.



134
 135 **Fig. 2.** The flow chart of ANN-GA.

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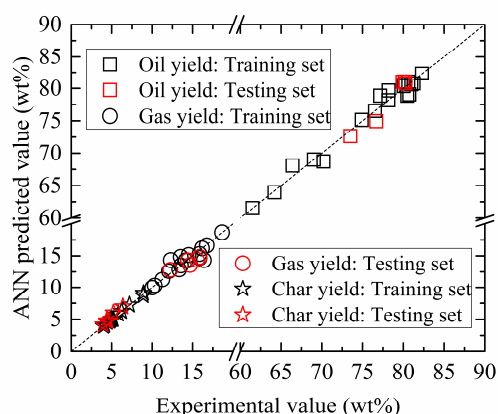
137 3. Results and discussion

138 3.1. Accuracy of ANN predicted co-pyrolysis product yields

139 Fig. 3 shows the experimental and ANN predicted WPE/WPS co-pyrolysis oil, gas, and
 140 char yields. It can be seen that the experimental oil yield varied from 61.51wt% (Sample R4)

141 to 82.28wt% (Sample R13), the experimental gas yield fluctuated from 10.01wt% (Sample R1)
142 to 18.65wt% (Sample R17), and the experimental char yield oscillated from 3.93wt% (Sample
143 R21) to 8.92wt% (Sample R5). It was reported that the WPE thermal pyrolysis oil and gas
144 yields were 65.32–83.50wt% and 11.50–18.75wt% in the temperature range of 425–525°C
145 [22]. The PS thermal pyrolysis oil yields were 80wt% under 450°C [34] and 71wt% under
146 500°C [35]. Moreover, the WPS pyrolysis gas and char yields were ~16wt% and ~4wt% under
147 500°C, respectively [11]. The WPE/WPS co-pyrolysis product yields obtained in the present
148 work were within the ranges of individual WPE and WPS pyrolysis ones. Quesada et al. [11]
149 studied the WPE/WPS co-pyrolysis under 500°C and 25wt% PS, obtaining ~70wt% of oil
150 yield, ~22wt% of gas yield, and ~8wt% of char yield, values highly close to that obtained in
151 the present work. Williams and Williams [17] obtained 64.0–67.3wt% oil yield and 1.2–
152 2.2wt% char yield from PE/PS co-pyrolysis, which were also very close to the results in the
153 present work.

154 On the other hand, Table 1 lists the root mean square error (RMSE), mean relative error
155 (MRE), mean absolute error (MAE), standard deviation (SD), and coefficient of
156 determination (R^2) values between the experimental and ANN predicted co-pyrolysis product
157 yields in the training and testing sets. The high R^2 values and low RMSE, MRE, MAE, and
158 SD values [36] exhibited the high accuracy of the ANN predicted WPE/WPS co-pyrolysis
159 product yields.



160

161

Fig. 3. Experimental and ANN predicted co-pyrolysis product yields.

162

163

Table 1. Errors in the ANN predicted co-pyrolysis product yields.

	RMSE`	MRE	MAE	SD	R2
Training set	0.76%	-0.14%	2.06%	3.23%	0.9994
Testing set	0.87%	-1.60%	5.07%	4.03%	0.9993

164

165 *3.2. Interactions of temperature, PS mass fraction, and carrier gas flow rate on product*
 166 *yields*

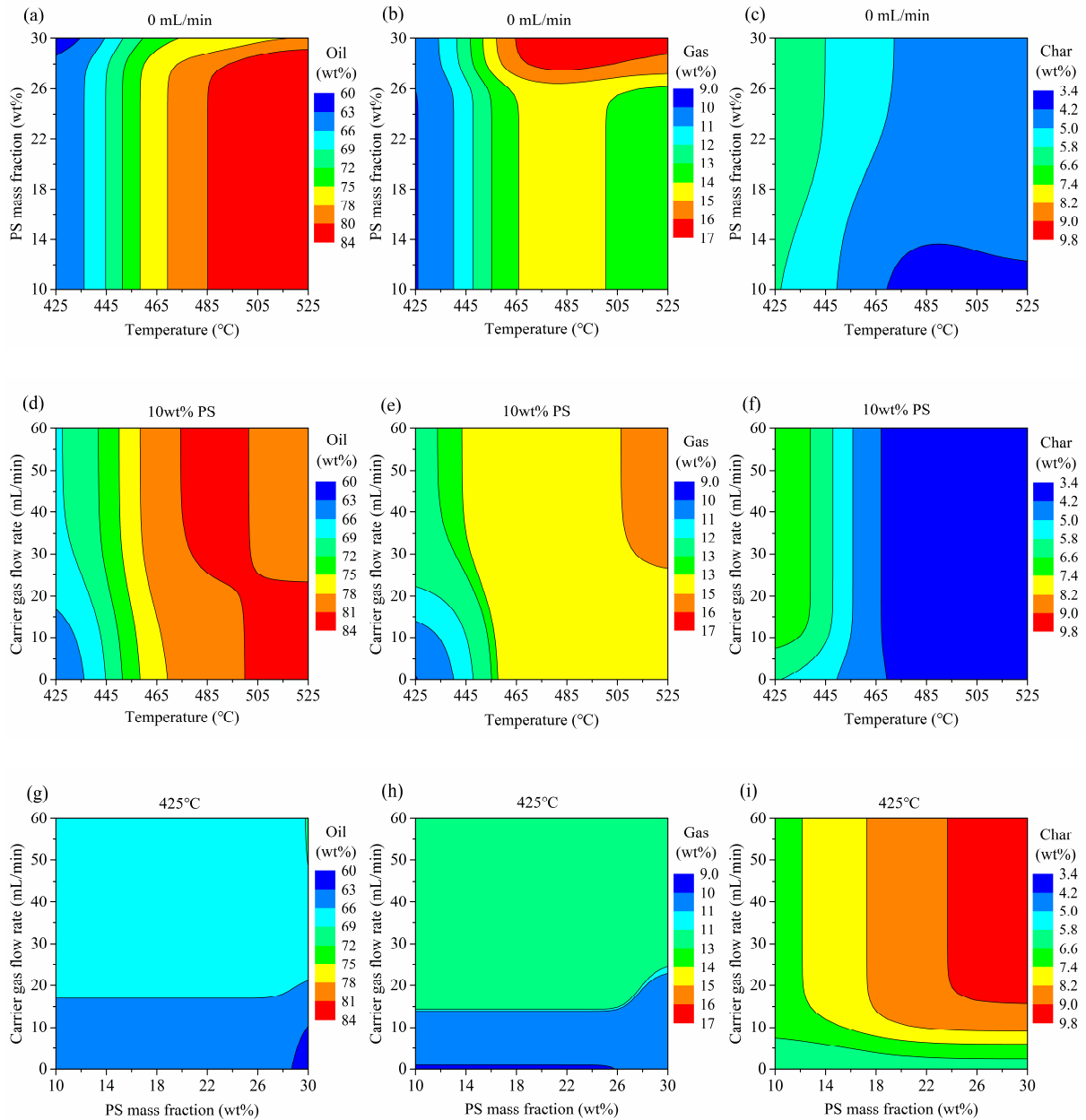
167 Fig. 4 demonstrates the interactions of temperature, PS mass fraction, and carrier gas flow
 168 rate on the distributions of oil, gas, and char productions under 0mL/min, 10wt% PS, and
 169 425°C. It is worth noting that due to the pressure difference generated during the pyrolysis of
 170 plastics, oil and gas can flow out of the reactor spontaneously under 0mL/min. Moreover, Figs.
 171 A.1–3 illustrate the ANN predicted oil, gas, and char yields under 30mL/min and 60mL/min,
 172 20wt% PS and 30wt% PS, and 475°C and 525°C, respectively. It could be seen that the
 173 temperature had a more significant impact on the oil yield than the PS mass fraction under all
 174 flow rates of carrier gas (Fig. 4a, Fig. A.1a, and Fig. A.1d). Quesada et al. [11] also reported

175 that the WPE/WPS co-pyrolysis oil yield only hovered in a narrow range of ~70–73wt%
176 within the range of 25–75wt% PS. As the temperature increased, the oil yields were
177 significantly enhanced by 18.35wt% (under 10wt% PS) and 16.65wt% (under 30wt% PS)
178 under the non-sweeping atmosphere (0mL/min, Fig. 4a). Higher temperatures could deepen
179 the random scissions of WPE/WPS long chains [37] and the secondary cracking of char [38-
180 39], thereby enhancing oil and gas yields and reducing char yield. Increasing the temperature
181 further would cause the secondary reactions of oil cracking [15,40], and gas recondensation
182 and repolymerization [17]. Therefore, when the temperature exceeded 480°C and continued to
183 rise, the decrease in gas yield under 0mL/min (Fig. 4b) could be ascribed to the gas
184 recondensation and repolymerization (gas consumption) were more intense than the oil
185 cracking (gas generation). However, as the temperature increased from 488°C, the decrease in
186 oil yield under 30mL/min (Fig. A.1a) and 60mL/min (Fig. A.1d) might be attributed to the oil
187 cracking (oil consumption) was more violent than the gas recondensation and
188 repolymerization (oil formation) [14].

189 Improving the flow rate of carrier gas under low temperatures would enhance the oil and
190 gas yields, regardless of the variation of PS mass fraction. For instance, the oil and gas yields
191 were enhanced by 4.76wt% and 2.90wt% under 425°C and 10wt% PS (Fig. 4d). However,
192 increasing the carrier gas flow rate decreased the oil yield by ~2wt% under the highest
193 temperature (525°C). The reduction of the oil yield might be ascribed to the shorter residence
194 time of volatile products in the reaction zone under higher flow rates of carrier gas, thereby
195 inhibiting the Diels-Alder reactions of gaseous olefin for oil formation [41]. Simultaneously,

196 the gas yield was enhanced by 1.80wt% (13.50wt%–15.30wt%) as the flow rate of carrier gas
197 increased under 525°C (Fig. 4e). On the other hand, the carrier gas flow rate's increase led to a
198 decrease in char yield under high temperatures. As the flow rate of carrier gas increased, the
199 char yields reduced by 0.09wt%, 0.15wt%, and 0.17wt% under 10wt% PS (Fig. 4f), 20wt%
200 PS (Fig. A.2c), and 30wt% PS (Fig. A.2f), respectively. The decrease in char yield could be
201 ascribed to the inhabitation of secondary reactions of the co-pyrolysis volatiles for char
202 generation [42]. However, enhancing the carrier gas flow rate increased the char yield under
203 lower temperatures. The flow rate change would affect the heat transfer efficiency in the
204 reaction zone [43], which might enhance the char yield.

205 Enhancing the PS mass fraction in WPE/WPS led to a decrease in oil yield and an
206 increase in gas and char yields under the non-sweeping atmosphere (0mL/min). For instance,
207 the enhancement of PS mass fraction led to a reduction of 2.46wt% in oil yield (Fig. 4g), an
208 enhancement of 0.35wt% in gas yield (Fig. 4h), and an enhancement of 0.40wt% in char yield
209 (Fig. 4i) under 425°C and 0mL/min. Similar trends were reported by Quesada et al. [11]: a
210 decrease of ~3.5wt% in oil yield, an increase of ~1.5wt% in gas yield, and an increase of
211 ~2wt% in char yield were observed when the PS mass fraction increased from 50wt% to
212 75wt% in WPE/WPS. The increase in char yield might be ascribed to the abundant aromatics
213 presented in the PS pyrolysis oil, which could further generate char [15].



214

215

216

217 **Fig. 4.** Interactive effects of temperature, PS mass fraction, and carrier gas flow rate on the distributions of

218 WPE/WPS co-pyrolysis products: (a) Oil yield under 0mL/min; (b) Gas yield under 0mL/min; (c) Char

219 yield under 0mL/min; (d) Oil yield under 10wt% PS; (e) Gas yield under 10wt% PS; (f) Char yield under

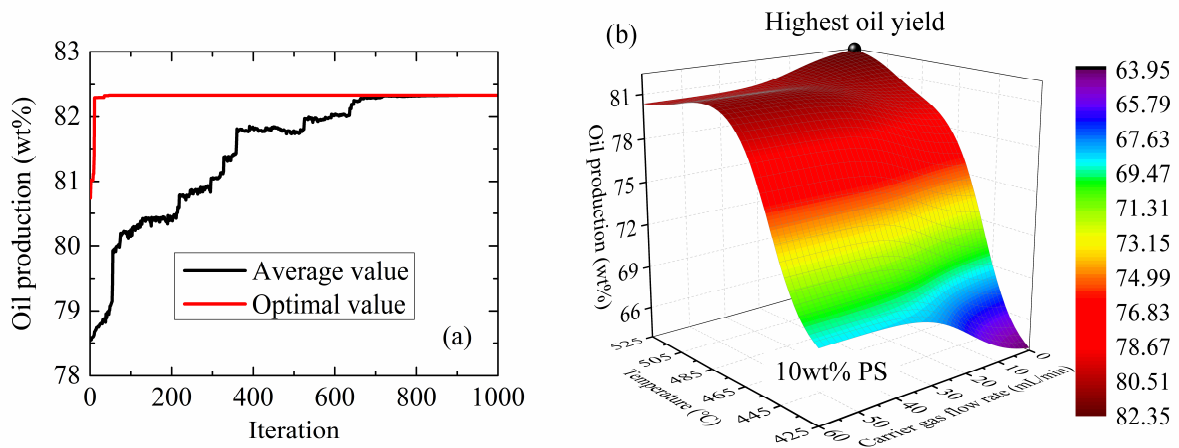
220 10wt% PS; (g) Oil yield under 425°C; (h) Gas yield under 425°C; (i) Char yield under 425°C.

221

222 3.3. Optimization of oil yield by ANN-GA

223 Fig. 5a shows the optimal and average values of the ANN-GA objective function (oil
 224 yield). The ANN-GA predicted the highest oil yield was 82.33wt% under 525°C, 10wt% PS,
 225 and 0mL/min (Fig. 5b). Meanwhile, the experimental oil yield under the ANN-GA optimized
 226 conditions was 82.28wt%. The relative error between the experimental and ANN-GA
 227 predicted oil yields was merely 0.06%, revealing the ANN-GA optimized value's high
 228 accuracy.

229 It is also noteworthy that the highest oil yield under 60mL/min was obtained at 485°C.
 230 The optimal temperature of 485°C was close to the optimal WPE pyrolysis temperatures
 231 reported by Quesada et al. [31] (500°C) and Pan et al. [22] (488°C). Carrier gas could
 232 accelerate the purging of the pyrolysis volatiles and carry heavier volatile molecules out of the
 233 reactor. The heavy pyrolysis oil components remained in the reactor under the non-sweeping
 234 atmosphere (0mL/min). Higher temperatures were required for the thermal cracking of oil's
 235 heavy components into shorter-chain hydrocarbons, which then could volatilize and
 236 spontaneously leave the reactor [44]. Therefore, WPE/WPS co-pyrolysis oil yield optimized
 237 temperature exceeded 500°C, generally considered the optimal temperature for the pyrolysis
 238 of waste plastics with carrier gas [45].



239

240 **Fig. 5.** Optimization of oil yield by ANN-GA: (a) Representation of optimization process; (b) Highest oil
241 yield.

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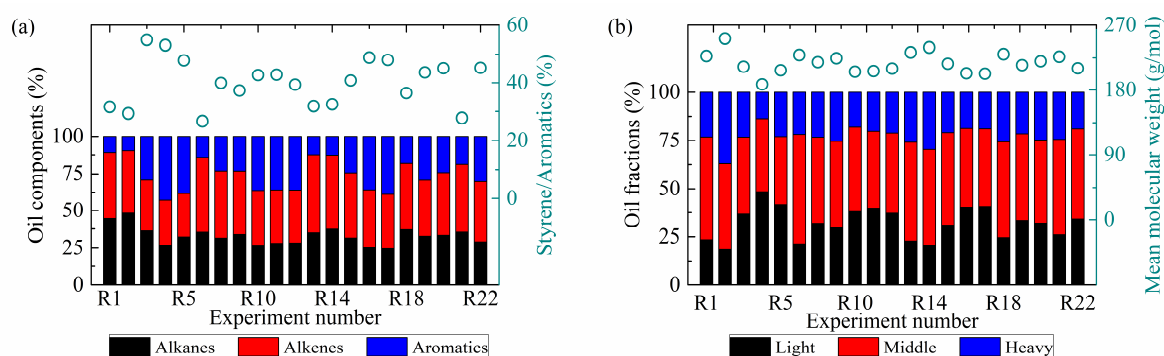
243 3.4. GC/MS analysis

244 The components of WPE/WPS co-pyrolysis oil samples (R1–R22) were analyzed by
245 GC/MS. Moreover, the WPE/WPS co-pyrolysis oils were divided into light (C7–C11), middle
246 (C12–C20), and heavy fractions (>C20) based on the carbon numbers [22]. Fig. 6a indicates
247 that the oils were composed of alkanes (24.55–48.25%), alkenes (29.38–52.57%), and
248 aromatics (9.68–42.89%) [11]. Meanwhile, styrene accounted for the highest proportion of
249 aromatics in oils, which varied from 26.73% to 54.87%. High styrene proportion might be
250 ascribed to aromatic hydrocarbons that take up the main component of WPS thermal pyrolysis
251 oil, of which styrene occupies 33–40% [46].

252 Fig. 6b shows that the light, middle, and heavy oil fractions fluctuated from 18.49–
253 48.49%, 35.32–56.78%, and 13.64–37.05%, respectively. The WPE/WPS co-pyrolysis oils
254 had more light and middle fractions than WPE pyrolysis oils [22]. Moreover, the mean
255 molecular weight of the WPE/WPS co-pyrolysis oil oscillated from 187.73g/mol to
256 251.01g/mol, which was between the mean molecular weights of individual PS (176g/mol)
257 and PE (306g/mol) thermal pyrolysis oils [17].

258 The operating conditions of temperature and carrier gas flow rate had complex
259 interactions on the WPE/WPS co-pyrolysis oil components and fractions [47]. Moreover, the
260 styrene/aromatics ratio and the mean molecular weight of WPE/WPS co-pyrolysis oil did not

261 linearly change as the PS mass fraction increased [16]. The non-linear relationship indicated
 262 that the reaction species of WPE and WPS had undetermined interactions on the distributions
 263 of co-pyrolysis oil components and fractions [17]. Therefore, ANN-GA was adopted to
 264 investigate the interactions of temperature, PS mass fraction, and carrier gas flow rate on the
 265 oil components and fractions; and determine the optimal conditions for each component and
 266 fraction.

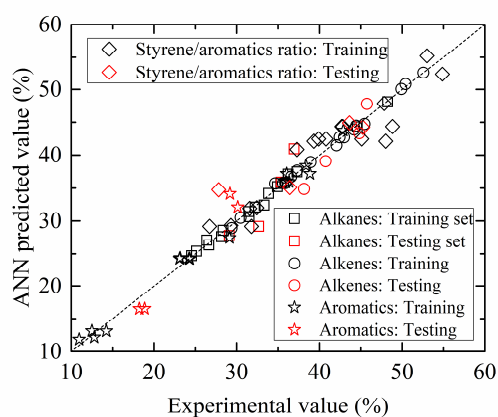


267
 268 **Fig. 6.** WPE/WPS co-pyrolysis oil components and fractions: (a) Distributions of alkanes, alkenes, and
 269 aromatics in oils, and the styrene/aromatics ratio variations; (b) Distributions of light, middle, and heavy
 270 fractions in oils, and the mean molecular weight variations.

271
 272 **3.5. WPE/WPS co-pyrolysis oil components**

273 **3.5.1. Interactions of temperature, PS mass fraction, and carrier gas flow rate**

274 Fig. 7 demonstrates the experimental and ANN predicted oil components in the training
 275 and testing sets. Besides, Table 2 tabulates the RMSE, MRE, MAE, SD, and R2 values
 276 between the experimental and ANN predicted oil components. The high R2 values and low
 277 RMSE, MRE, MAE, and SD values verified the accuracy of predicted results.



278

279

Fig. 7. Experimental and ANN predicted oil components.

280

281

Table 2. Errors in the ANN predicted oil components.

	RMSE`	MRE	MAE	SD	R2
Training set	1.44%	-0.16%	2.60%	3.38%	0.9798
Testing set	2.96%	-0.53%	7.97%	3.39%	0.8762

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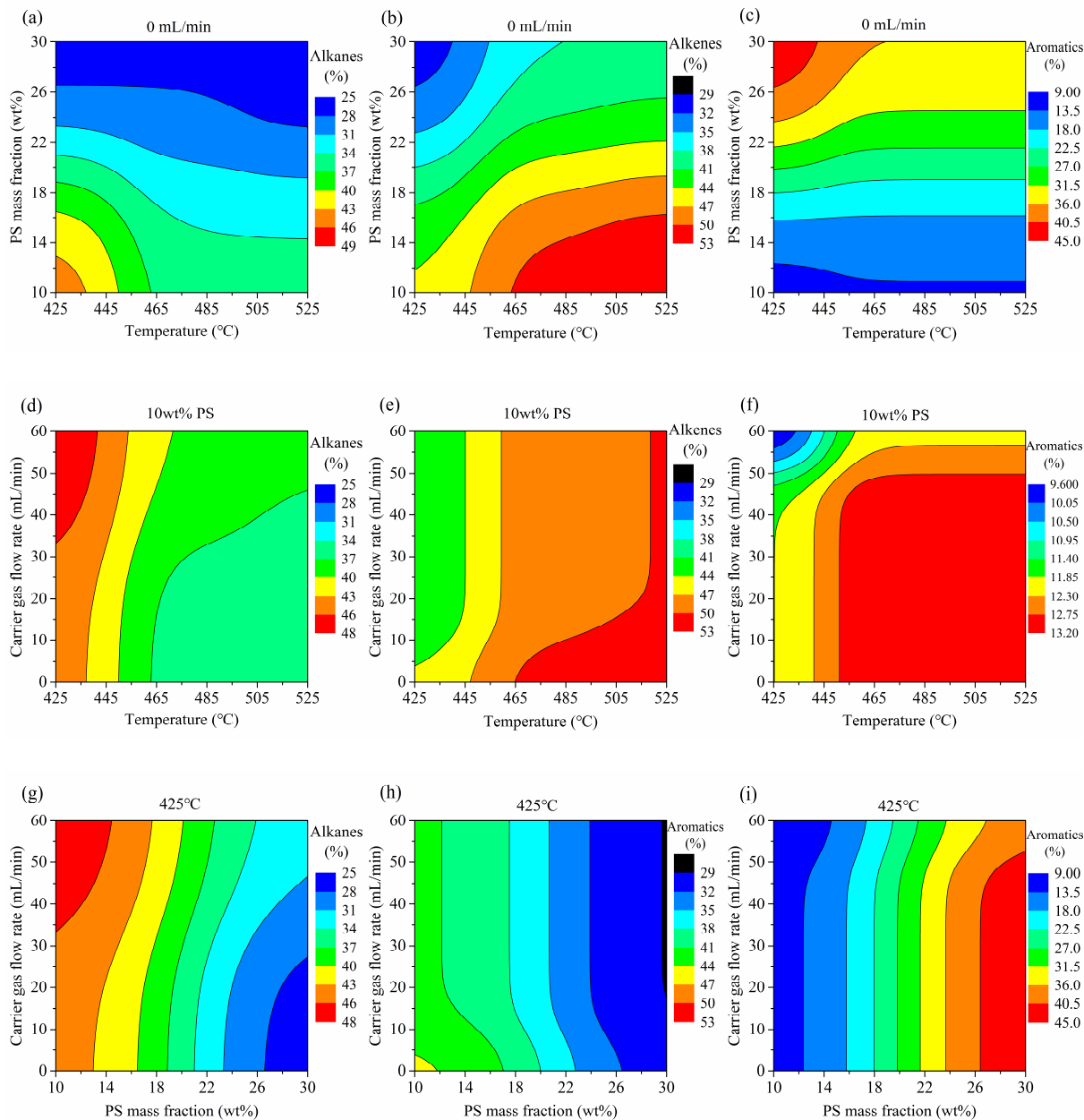
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Fig. 8 shows the interactions of temperature, PS mass fraction, and carrier gas flow rate on the distributions of oil components under 0mL/min, 10wt% PS, and 425°C. The interactions of triple conditions under 30mL/min, 20wt% PS, and 475°C (Fig. A.5); and 60mL/min, 30wt% PS, and 525°C (Fig. A.7) are similar to the conditions under 0mL/min, 10wt% PS, and 425°C. It could be observed that the temperature had a more significant influence on the alkanes proportion under lower PS mass fractions (Fig. 8a). As the temperature increased under 10wt% PS, the alkanes proportion reduced by 9.10% (44.31%–35.21%, Fig. 8a), while the alkanes proportion enhanced by 8.12% (44.45%–52.57%, Fig. 8b). Increasing temperature contributed to a decrease of 7.87% (43.73%–35.86%) in aromatics proportion under 30wt% PS (Fig. 8c). Aromatics were mainly generated from the thermal

293 decomposition of PS in WPE/WPS. The polycyclic PS could be decomposed under a lower
294 temperature than PE [48], thereby a high aromatics proportion of 43.73% was obtained under
295 425°C, 30wt% PS, and 0mL/min (Fig. 8c). Enhancing the temperature aggravates the
296 secondary cracking reactions of alkanes and aromatics for the generation of alkenes, leading
297 to a decrease in alkanes and aromatics proportions and an increase in alkenes proportion [49].

298 Figs. 8d–f demonstrate the interactions of carrier gas flow rate and temperature on the
299 proportions of alkanes, alkenes, and aromatics under 10wt% PS, respectively. It could be seen
300 that improving the flow rate of carrier gas would enhance the alkanes proportion and reduce
301 the alkenes and aromatics proportions under all temperatures. For instance, as the flow rate of
302 carrier gas increased under 525°C and 10wt% PS, the alkanes proportion increased by 2.25%
303 (35.21%–37.46%), while the alkenes and aromatics proportions decreased by 2.51%
304 (52.57%–50.06%) and 0.94% (13.11%–12.17%), respectively. Higher carrier gas flow rates
305 could purge the co-pyrolysis volatiles out of the reaction zone faster [50], thereby suppressing
306 the secondary cracking of alkanes for alkenes formation and the Diels-Alder reactions of
307 alkenes for aromatics formation [41].

308 On the other hand, as the PS mass fraction increased, the alkanes and alkenes proportions
309 reduced by ~16–18% (Fig. 8g) and ~12.6–14% (Fig. 8h), while the aromatics proportion
310 significantly enhanced by ~29–32% (Fig. 8i) under 425°C. The principal components of PS
311 pyrolysis oil were aromatics [51], thereby enhancing the PS mass fraction led to an increase in
312 aromatics proportion and a decrease in alkanes and alkenes proportions.



313

314

315

316 **Fig. 8.** Interactive effects of temperature, PS mass fraction, and carrier gas flow rate on the distributions of

317 WPE/WPS co-pyrolysis oil components: (a) Alkanes proportion under 0mL/min; (b) Alkenes proportion

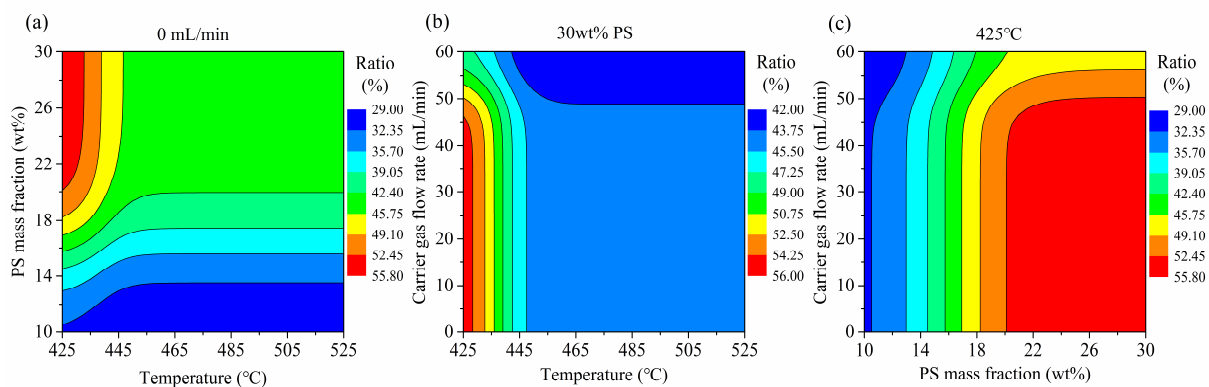
318 under 0mL/min; (c) Aromatics proportion under 0mL/min; (d) Alkanes proportion under 10wt% PS; (e)

319 Alkenes proportion under 10wt% PS; (f) Aromatics proportion under 10wt% PS; (g) Alkanes proportion

320 under 425°C; (h) Alkenes proportion under 425°C; (i) Aromatics proportion under 425°C.

321

322 Styrene was the dominant component in the WPE/WPS co-pyrolysis oil's aromatics
323 proportion, which could be ascribed to the primary product of styrene in the PS pyrolysis oil
324 [16,46]. Fig. 9 depicts the interactions of temperature, PS mass fraction, and carrier gas flow
325 rate on the styrene/aromatics ratio under 0mL/min, 30wt% PS, and 425°C. Moreover, Fig. A.6
326 and Fig. A.8 demonstrate the interactions of triple conditions under 30mL/min, 20wt% PS,
327 and 475°C; and 60mL/min, 10wt% PS, and 525°C, respectively. The enhancement of PS mass
328 fraction contributed to the increases of ~26%, ~26%, and ~19% in styrene/aromatics ratio
329 under 0mL/min (Fig. 9a), 30mL/min (Fig. A.6a), and 60mL/min (Fig. A.8a), respectively. The
330 temperature had a more significant impact on the styrene/aromatics ratio under 20wt% (Fig.
331 A.6b) and 30wt% (Fig. 9b) PS mass fractions compared to the one under 10wt% PS mass
332 fraction (Fig. A.8b). Besides, the increase in temperature under 20wt% and 30wt% PS mass
333 fractions resulted in a reduction of styrene/aromatics ratio, which might be ascribed to the
334 secondary cracking of styrene under higher temperatures [52]. On the other hand, improving
335 the flow rate of carrier gas led to a decrease in styrene/aromatics ratio under 425°C (Fig. 9c),
336 regardless of the variation of PS mass fraction. Higher carrier gas flow rates would shorten
337 the volatiles residence time in the reaction zone, thereby resulting in the incomplete pyrolysis
338 of PS for styrene formation.



339

340

Fig. 9. Interactive effects of temperature, PS mass fraction, and carrier gas flow rate on the

341

styrene/aromatics ratio: (a) Under 0mL/min; (b) Under 30wt% PS; (c) Under 425°C.

342

343 3.5.2. ANN-GA optimization

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Fig. 10a shows that the highest alkanes proportion was 48.09% under 425°C, 10wt% PS,

345

and 60mL/min, which indicated that low temperature and high carrier gas flow rate could

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suppress the secondary cracking of alkanes in oil [53-56]. On the other hand, the highest

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alkenes proportion was 52.57% under 525°C, 10wt% PS, and the non-sweeping atmosphere

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(0mL/min). High temperature and low carrier gas flow rate resulted in the over-cracking of

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the oil, which might be conducive to the formation of alkene.

350

The highest aromatics proportion of 43.73% was obtained under 425°C, 30wt% PS, and

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0mL/min. Increasing temperature can affect the aromatics proportion in three aspects: i)

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promoting the alkanes' dehydro-aromatization [57] for aromatics formation, ii) facilitating the

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alkenes' Diels-Alder reactions [41] for aromatics formation, and iii) exacerbating the over-

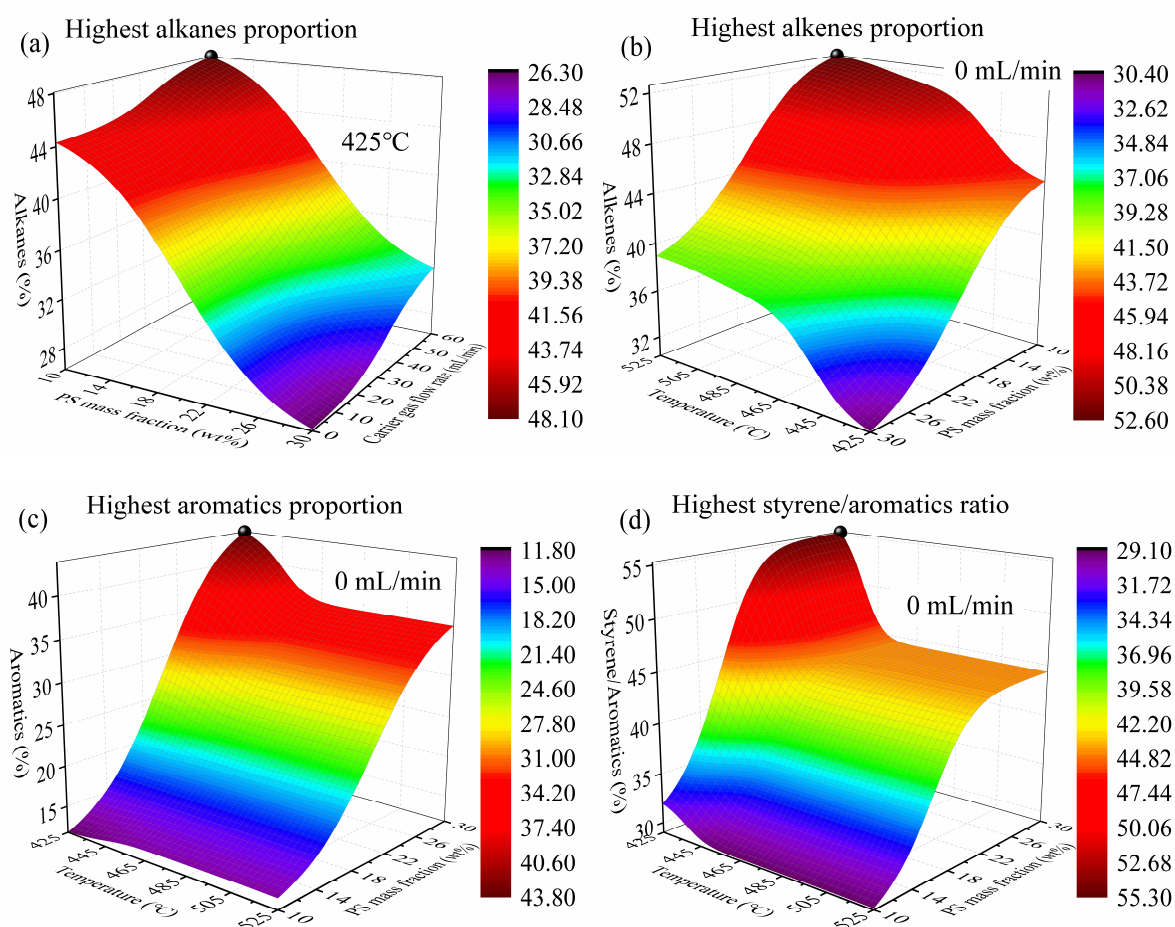
354

cracking for aromatics consumption [49]. The highest aromatics proportion achieved under

355

low temperature indicated that the inhibition of aromatics over-cracking dominated the

356 aromatics formation. High PS mass fraction in the WPE/WPS mixture could enhance the
 357 proportion of the aromatics; thereby, the highest aromatics proportion was gained under
 358 30wt% PS. Meanwhile, the highest styrene/aromatics ratio was 55.22% under the same
 359 conditions (425°C, 30wt% PS, and 0mL/min). This was because styrene was the dominant
 360 component in the PS pyrolysis oil.



361

362

363 **Fig. 10.** ANN-GA optimized proportions of the oil components and styrene/aromatics ratio: (a) Highest

364 alkanes proportion; (b) Highest alkenes proportion; (c) Highest aromatics proportion; (d) Highest

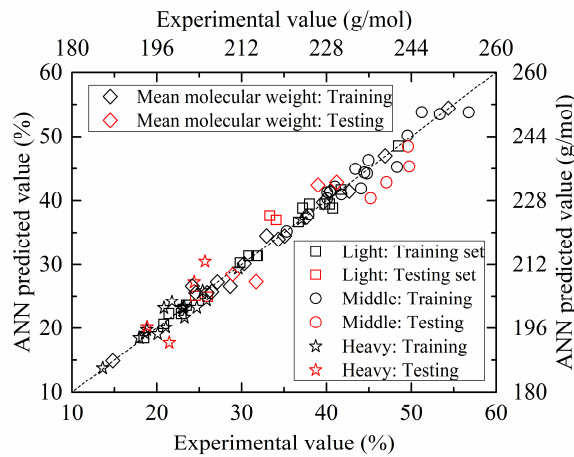
365 styrene/aromatics ratio.

366

367 3.6. WPE/WPS co-pyrolysis oil fractions

368 3.6.1. Interactions of temperature, PS mass fraction, and carrier gas flow rate

369 Fig. 11 shows the experimental and ANN predicted oil fractions in the training and testing
 370 sets. Moreover, Table 3 lists the RMSE, MRE, MAE, SD, and R2 values between the
 371 experimental and ANN predicted oil fractions. The high R2 values and low RMSE, MRE,
 372 MAE, and SD values exhibited high accuracy of the predicted results.



373
 374 **Fig. 11.** Experimental and ANN predicted oil fractions.

375
 376 **Table 3.** Errors in the ANN predicted oil fractions.

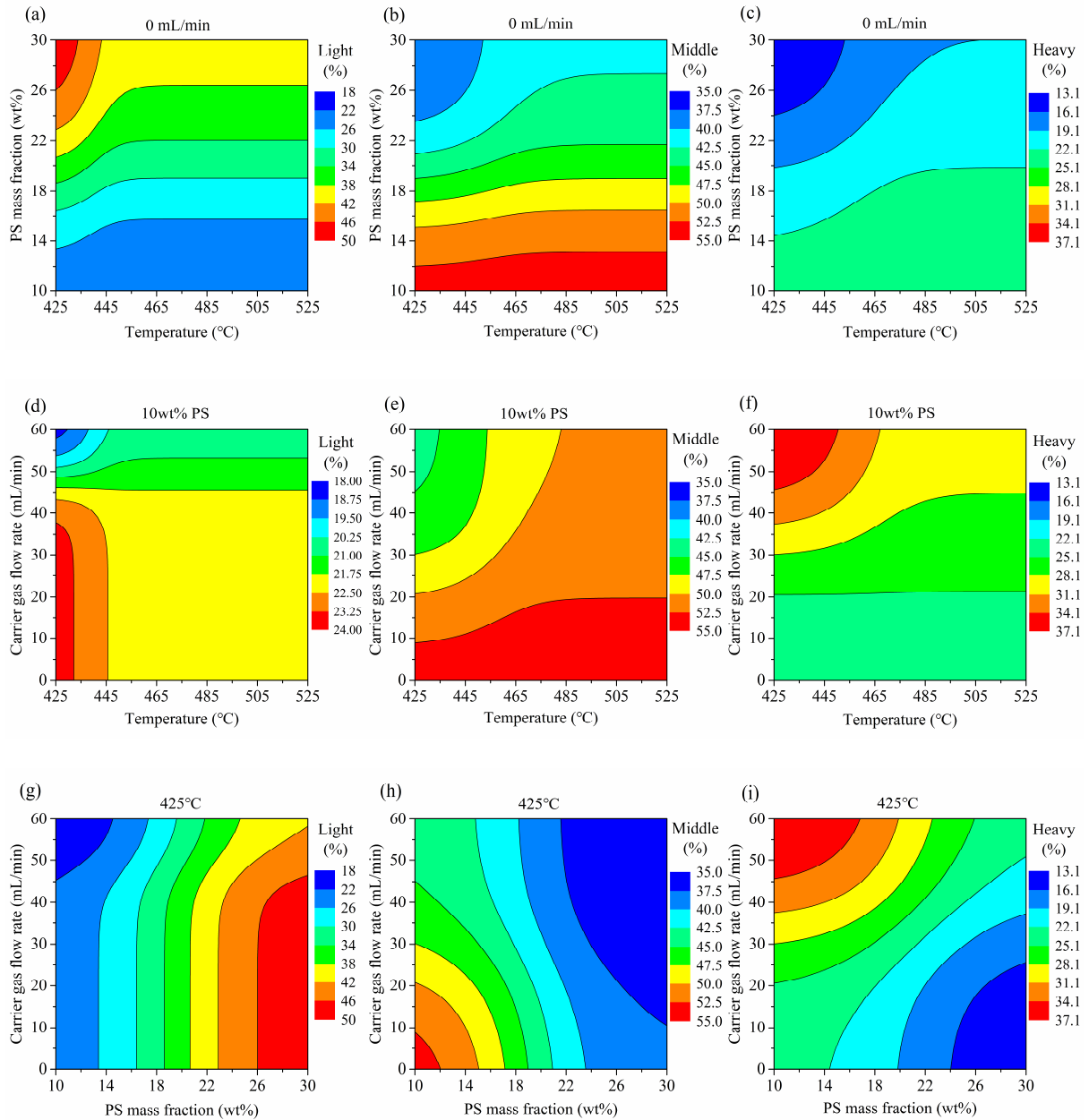
	RMSE`	MRE	MAE	SD	R2
Training set	1.38%	-0.09%	2.00%	2.91%	0.9995
Testing set	3.38%	-1.77%	6.88%	3.22%	0.9970

377
 378 Fig. 12 depicts the interactions of temperature, PS mass fraction, and carrier gas flow rate
 379 on the distributions of oil fractions under 0mL/min, 10wt% PS, and 425°C. The interactions of
 380 triple conditions under 30mL/min, 20wt% PS, and 475°C (Fig. A.11); and 60mL/min, 30wt%
 381 PS, and 525°C (Fig. A.13) are similar to the conditions under 0mL/min, 10wt% PS, and 425°C.
 382 Figs. 12a–c demonstrate that the temperature significantly impacted the oil fractions under

383 higher PS mass fractions. As the temperature increased under 10wt% PS, the light fraction
384 decreased by 1.24%, and the middle and heavy fractions increased by 0.31% and 1.30%,
385 respectively. However, the light fraction significantly reduced by 9.03%, and the middle and
386 heavy fractions enhanced by 4.32% and 5.35% when the temperature increased under 30wt%
387 PS. Higher temperatures could aggravate the secondary cracking of light fraction in oil,
388 thereby reducing the light fraction and enhancing the middle and heavy fractions [58].

389 It is noteworthy that the light and middle fractions would decrease, and the heavy fraction
390 would increase as the flow rate of carrier gas increased, regardless of the variations of
391 temperature and PS mass fraction (Figs. 12d–f). For instance, the carrier gas flow rate's
392 increase reduced the light (by 5.02%) and middle (by 9.10%) fractions, and enhanced the
393 heavy fraction (by 14.05%) under 425°C and 10wt% PS, respectively. It might be ascribed to
394 the suppression of gas recondensation and repolymerization for generating the light and
395 middle fractions in oil under higher carrier gas flow rates.

396 On the other hand, enhancing the PS mass fraction could considerably increase the light
397 fraction and decrease the middle and heavy fractions in oil. For example, as the PS mass
398 fraction enhanced under 425°C and non-sweeping atmosphere (0mL/min), the light fraction
399 increased by 24.99% (23.51%–48.50%), whereas the middle and heavy fractions decreased by
400 15.62% (53.48%–37.86%) and 9.23% (22.99%–13.76%), respectively. It might be ascribed to
401 the high proportion of styrene in the PS pyrolysis oil [11], which belonged to the light fraction.
402 Consequently, a higher PS mass fraction could contribute to an increase in the light fraction.



403

404

405

406 **Fig. 12.** Interactive effects of temperature, PS mass fraction, and carrier gas flow rate on the distributions of

407 oil fractions: (a) Light fraction under 0mL/min; (b) Middle fraction under 0mL/min; (c) Heavy fraction

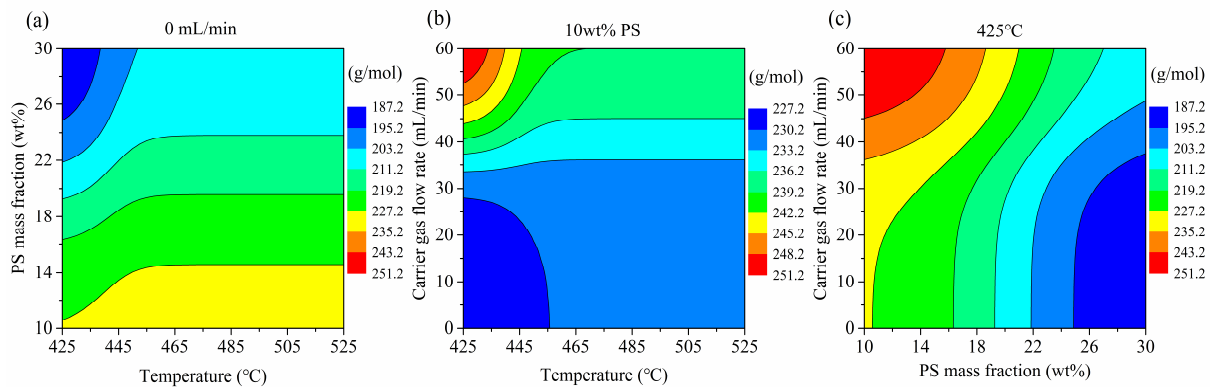
408 under 0mL/min; (d) Light fraction under 10wt% PS; (e) Middle fraction under 10wt% PS; (f) Heavy

409 fraction under 10wt% PS; (g) Light fraction under 425°C; (h) Middle fraction under 425°C; (i) Heavy

410 fraction under 425°C.

411

412 Fig. 13 depicts the interactions of temperature, PS mass fraction, and carrier gas flow rate
 413 on the oil's mean molecular weight under 0mL/min, 10wt% PS, and 425°C. Moreover, Fig.
 414 A.12 and Fig. A.14 demonstrate the interactions of triple conditions under 30mL/min, 20wt%
 415 PS, and 475°C; and 60mL/min, 30wt% PS, and 525°C, respectively. Fig. 13a shows that the
 416 oil's mean molecular weight increased with the increasing temperature under all PS mass
 417 fractions. Moreover, the temperature significantly impacted the oil's mean molecular weight
 418 under higher PS mass fractions. For instance, as the temperature increased under 0mL/min,
 419 the oil's mean molecular weight was enhanced by 2.77g/mol and 16.98g/mol under 10wt% PS
 420 and 30wt% PS, respectively. The enhancement might be due to the more intense over-
 421 cracking reaction of the oil's light fraction [59], producing a heavier oil with a higher mean
 422 molecular weight. A higher carrier gas flow rate increased the oil's mean molecular weight
 423 under all temperatures (Fig. 13b). The increase was because the light and middle fractions
 424 decreased, whereas the heavy fraction increased with the increasing flow rate of carrier gas
 425 (Figs. 12d–f). Besides, the increase in PS mass fraction contributed to a significant decrease
 426 of ~40g/mol in the oil's mean molecular weight under 425°C (Fig. 13c).



427
 428 **Fig. 13.** Interactive effects of temperature, PS mass fraction, and carrier gas flow rate on the oil's mean

429 molecular weight: (a) Under 0mL/min; (b) Under 10wt% PS; (c) Under 425°C.

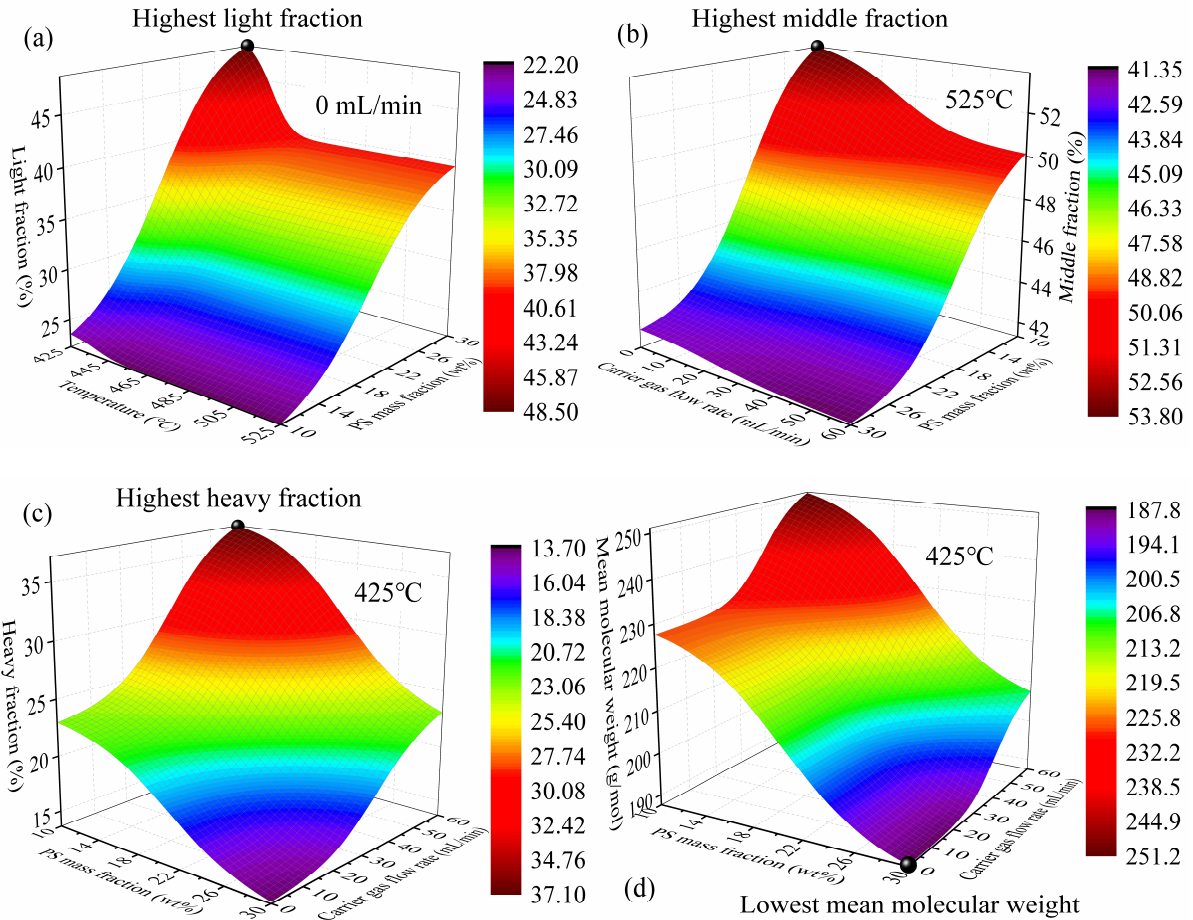
430

431 3.6.2. ANN-GA optimization

432 As discussed in Section 3.6.1, the temperature, PS mass fraction, and carrier gas flow rate
433 had complex interactions on the distributions of WPE/WPS co-pyrolysis oil fractions and the
434 oil's mean molecular weight. Therefore, the ANN-GA was adopted to determine the highest
435 oil fractions and the lightest co-pyrolysis oil with the lowest mean molecular weight.

436 Fig. 14a shows that the highest light fraction was 48.50% under 425°C, 30wt% PS, and
437 0mL/min. Low temperature and non-sweeping atmosphere could suppress the secondary
438 cracking of light fraction and promote gas recondensation for light fraction formation. The
439 highest middle fraction of 53.79% was obtained under 525°C, 10wt% PS, and 0mL/min (Fig.
440 14b). Higher temperatures might be conducive to the secondary cracking of heavy fraction for
441 middle fraction generation. On the other hand, the highest heavy fraction was 37.04% under
442 425°C, 10wt% PS, and 60mL/min (Fig. 14c).

443 The lightest WPE/WPS co-pyrolysis oil with the lowest mean molecular weight of
444 187.85g/mol was obtained under 425°C, 30wt% PS, and 0mL/min (Fig. 14d). It could be
445 concluded that low temperature, high PS mass fraction, and non-sweeping atmosphere were
446 conducive to the light WPE/WPS co-pyrolysis oil production.



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452 4. Conclusions

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Fig. 14. ANN-GA optimized oil fractions and mean molecular weight: (a) Highest light fraction; (b) Highest middle fraction; (c) Highest heavy fraction; (d) Lowest mean molecular weight.

This study investigated the co-pyrolysis of WPE/WPS for oil production under different temperatures and carrier gas flow rates. The ratio of the real-life WPE and WPS is different in different regions. Therefore, the effect of WPE/WPS mixture composition on oil production was also studied. It was found that the WPE/WPS mixture composition and operating conditions had complex interactions on the co-pyrolysis oil yield. Therefore, a hybrid model of ANN-GA was adopted to optimize the conditions for oil production based on the central-

459 composite design. It is noteworthy that the optimized conditions in this study have limitations
460 because the experiments were performed in a bench-scale reactor. Nevertheless, the findings
461 could provide qualitative guidance for the regional industrialization of waste plastic pyrolysis.
462 ANN-GA can also be used to regulate different target products under more complicated
463 conditions due to its good robustness. This study's principal conclusions are outlined as
464 follows.

- 465 ● The highest oil yield was 82.33wt% under 525°C, 10wt% PS, and 0mL/min. The findings
466 revealed that high temperature, low PS mass fraction, and low carrier gas flow rate were
467 conducive to a higher oil yield.
- 468 ● The highest alkanes, alkenes, and aromatics proportions were 48.09%, 52.57%, and
469 43.73%, respectively. Additionally, the highest styrene/aromatics ratio was 55.22% under
470 the same conditions as the highest aromatics proportion (425°C, 30wt% PS, and 0mL/min).
- 471 ● The lightest WPE/WPS co-pyrolysis oil with the lowest mean molecular weight of
472 187.85g/mol was obtained under 425°C, 30wt% PS, and 0mL/min. It could be concluded
473 that low temperature, high PS mass fraction, and low carrier gas flow rate were conducive
474 to the light WPE/WPS co-pyrolysis oil production.

475

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478 **Competing Interest**

479 The authors declare no competing financial interest.

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References

485 [1] Plastics - the Facts 2020. PlasticsEurope (2020),
486 <https://www.plasticseurope.org/en/resources/market-data>.

487 [2] S. Karayılan, Ö. Yılmaz, Ç. Uysal, S. Naneci. Prospective evaluation of circular economy
488 practices within plastic packaging value chain through optimization of life cycle impacts
489 and circularity. *Resour Conserv Recycl*, 173 (2021), p. 105691,
490 <https://doi.org/10.1016/j.resconrec.2021.105691>.

491 [3] Z. Dobó, G. Kecsmár, G. Nagy, T. Koós, G. Muránszky, M. Ayari. Characterization of
492 gasoline-like transportation fuels obtained by distillation of pyrolysis oils from plastic
493 waste mixtures. *Energ Fuel*, 35 (3) (2021), pp. 2347-2356,
494 <https://doi.org/10.1021/acs.energyfuels.0c04022>.

495 [4] M. MacLeod, H.P.H. Arp, M.B. Tekman, A. Jahnke. The global threat from plastic
496 pollution. *Science*, 373 (2021), pp. 61-65, <https://doi.org/10.1126/science.abg5433>.

497 [5] S.Y. Zhao, C. Wang, B. Bai, H. Jin, W.W. Wei. Study on the polystyrene plastic
498 degradation in supercritical water/CO₂ mixed environment and carbon fixation of
499 polystyrene plastic in CO₂ environment. *J Hazard Mater* (2021), p. 126763,
500 <https://doi.org/10.1016/j.jhazmat.2021.126763>.

501 [6] L.D. Ellis, N.A. Rorrer, K.P. Sullivan, M. Otto, J.E. McGeehan, Y. Román-Leshkov, N.
502 Wierckx, G.T. Beckham. Chemical and biological catalysis for plastics recycling and
503 upcycling. *Nat Catal*, 4 (2021), pp. 539-556, <https://doi.org/10.1038/s41929-021-00648-4>.

504 [7] S.M. Al-Salem, S.R. Chandrasekaran, A. Dutta, B.K. Sharma. Study of the fuel properties

505 of extracted oils obtained from low and linear low density polyethylene pyrolysis. *Fuel*,
506 304 (2021), p. 121396, <https://doi.org/10.1016/j.fuel.2021.121396>.

507 [8] L.L. Dai, N. Zhou, Y.C. Lv, K. Cobb, Y.L. Cheng, Y.P. Wang, Y.H. Liu, P. Chen, R.G. Zou,
508 H.W. Lei, R. Ruan. Pyrolysis-catalysis for waste polyolefin conversion into low aromatic
509 naphtha. *Energy Convers Manag*, 245 (2021), p. 114578,
510 <https://doi.org/10.1016/j.enconman.2021.114578>.

511 [9] S. Mazloum, Y. Aboumsallem, S. Awad, N. Allam, K. Loubar. Modelling pyrolysis
512 process for PP and HDPE inside thermogravimetric analyzer coupled with differential
513 scanning calorimeter. *Int J Heat Mass Transfer*, 176 (2021), p. 121468,
514 <https://doi.org/10.1016/j.ijheatmasstransfer.2021.121468>.

515 [10] Y.M. Wen, I.N. Zaini, S.L. Wang, W.Z. Mu, P.G. Jönsson, W.H. Yang. Synergistic effect
516 of the co-pyrolysis of cardboard and polyethylene: A kinetic and thermodynamic study.
517 *Energy*, 229 (2021), p. 120693, <https://doi.org/10.1016/j.energy.2021.120693>.

518 [11] L. Quesada, M. Calero, M.A. Martin-Lara, A. Perez, G. Blazquez. Production of an
519 alternative fuel by pyrolysis of plastic wastes mixtures. *Energ Fuel*, 34 (2020), pp. 1781-
520 1790, <https://doi.org/10.1021/acs.energyfuels.9b03350>.

521 [12] W. Luo, Z.Y. Fan, J. Wan, Q. Hu, H. Dong, X.J. Zhang, Z. Zhou. Study on the reusability
522 of kaolin as catalysts for catalytic pyrolysis of low-density polyethylene. *Fuel*, 302 (2021),
523 p. 121164, <https://doi.org/10.1016/j.fuel.2021.121164>.

524 [13] K.B. Park, Y.S. Jeong, B. Guzelciftci, J.S. Kim. Characteristics of a new type continuous
525 two-stage pyrolysis of waste polyethylene. *Energy*, 166 (2019), pp. 343-351,

- 526 <https://doi.org/10.1016/j.energy.2018.10.078>.
- 527 [14]S.M. Al-Salem, A. Dutta. Wax recovery from the pyrolysis of virgin and waste plastics.
528 Ind Eng Chem Res, 60 (22) (2021), pp. 8301-8309,
529 <https://doi.org/10.1021/acs.iecr.1c01176>.
- 530 [15]J. Nisar, G. Ali, A. Shah, M. Iqbal, R.A. Khan, Sirajuddin, F. Anwar, R. Ullah, M.S.
531 Akhter. Fuel production from waste polystyrene via pyrolysis: Kinetics and products
532 distribution. Waste Manage, 88 (2019), pp. 236-247,
533 <https://doi.org/10.1016/j.wasman.2019.03.035>.
- 534 [16]M.N. Siddiqui, H.H. Redhwi. Pyrolysis of mixed plastics for the recovery of useful
535 products. Fuel Process Technol, 90 (4) (2009), pp. 545-552,
536 <https://doi.org/10.1016/j.fuproc.2009.01.003>.
- 537 [17]P.T. Williams, E.A. Williams. Interaction of plastics in mixed-plastics pyrolysis. Energ
538 Fuel, 13 (1) (1999), pp. 188-196, <https://doi.org/10.1021/ef980163x>.
- 539 [18]Klaimy, S., Lamonier, J.F., Casetta, M., Heymans, S. and Duquesne, S., 2021. Recycling
540 of plastic waste using flash pyrolysis–Effect of mixture composition. Polymer
541 Degradation and Stability, 187, p.109540.
542 <https://doi.org/10.1016/j.polymdegradstab.2021.109540>
- 543 [19]Saad, J.M., Williams, P.T., Zhang, Y.S., Yao, D., Yang, H. and Zhou, H., 2021.
544 Comparison of waste plastics pyrolysis under nitrogen and carbon dioxide atmospheres:
545 A thermogravimetric and kinetic study. Journal of Analytical and Applied Pyrolysis, 156,
546 p.105135. <https://doi.org/10.1016/j.jaap.2021.105135>

- 547 [20]Kusenber, M., Zayoud, A., Roosen, M., Thi, H.D., Abbas-Abadi, M.S., Eschenbacher, A.,
548 Kresovic, U., De Meester, S. and Van Geem, K.M., 2022. A comprehensive experimental
549 investigation of plastic waste pyrolysis oil quality and its dependence on the plastic waste
550 composition. *Fuel Processing Technology*, 227, p.107090.
551 <https://doi.org/10.1016/j.fuproc.2021.107090>
- 552 [21]Dyer, A.C., Nahil, M.A. and Williams, P.T., 2021. Catalytic co-pyrolysis of biomass and
553 waste plastics as a route to upgraded bio-oil. *Journal of the Energy Institute*, 97, pp.27-36.
554 <https://doi.org/10.1016/j.joei.2021.03.022>
- 555 [22]R.M. Pan, M.F. Martins, G. Debenest. Pyrolysis of waste polyethylene in a semi-batch
556 reactor to produce liquid fuel: Optimization of operating conditions. *Energy Convers*
557 *Manag*, 237 (2021), p. 114114, <https://doi.org/10.1016/j.enconman.2021.114114>.
- 558 [23]I. Muhammad, N. Makwashi, G. Manos. Catalytic degradation of linear low-density
559 polyethylene over HY-zeolite via pre-degradation method. *J Anal Appl Pyrolysis*, 138
560 (2019), pp. 10-21, <https://doi.org/10.1016/j.jaap.2018.11.025>.
- 561 [24]Janarthanan, R., Maheshwari, R.U., Shukla, P.K., Shukla, P.K., Mirjalili, S. and Kumar,
562 M., 2021. Intelligent Detection of the PV Faults Based on Artificial Neural Network and
563 Type 2 Fuzzy Systems. *Energies*, 14(20), p.6584. <https://doi.org/10.3390/en14206584>
- 564 [25]Neshat, M., Nezhad, M.M., Abbasnejad, E., Mirjalili, S., Groppi, D., Heydari, A.,
565 Tjernberg, L.B., Garcia, D.A., Alexander, B., Shi, Q. and Wagner, M., 2021. Wind turbine
566 power output prediction using a new hybrid neuro-evolutionary method. *Energy*, 229,
567 p.120617. <https://doi.org/10.1016/j.energy.2021.120617>

- 568 [26]Neshat, M., Nezhad, M.M., Abbasnejad, E., Mirjalili, S., Tjernberg, L.B., Garcia, D.A.,
569 Alexander, B. and Wagner, M., 2021. A deep learning-based evolutionary model for
570 short-term wind speed forecasting: A case study of the Lillgrund offshore wind farm.
571 Energy Conversion and Management, 236, p.114002.
572 <https://doi.org/10.1016/j.enconman.2021.114002>
- 573 [27]Khatir, S., Tiachacht, S., Le Thanh, C., Ghandourah, E., Mirjalili, S. and Wahab, M.A.,
574 2021. An improved Artificial Neural Network using Arithmetic Optimization Algorithm
575 for damage assessment in FGM composite plates. Composite Structures, 273, p.114287.
576 <https://doi.org/10.1016/j.compstruct.2021.114287>
- 577 [28]Kundu, R., Singh, P.K., Mirjalili, S. and Sarkar, R., 2021. COVID-19 detection from lung
578 CT-Scans using a fuzzy integral-based CNN ensemble. Computers in Biology and
579 Medicine, 138, p.104895. <https://doi.org/10.1016/j.combiomed.2021.104895>
- 580 [29]Ala, A., Alsaadi, F.E., Ahmadi, M. and Mirjalili, S., 2021. Optimization of an
581 appointment scheduling problem for healthcare systems based on the quality of fairness
582 service using whale optimization algorithm and NSGA-II. Scientific Reports, 11(1), pp.1-
583 19. <https://doi.org/10.1038/s41598-021-98851-7>
- 584 [30]Pan, R., Duque, J.V.F. and Debenest, G., 2022. Waste Plastic Thermal Pyrolysis Analysis
585 by a Neural Fuzzy Model Coupled with a Genetic Algorithm. Waste and Biomass
586 Valorization, 13(1), pp.135-148. <https://doi.org/10.1007/s12649-021-01522-x>
- 587 [31]L. Quesada, A. Perez, V. Godoy, F.J. Peula, M. Calero, G. Blazquez. Optimization of the
588 pyrolysis process of a plastic waste to obtain a liquid fuel using different mathematical

589 models. *Energy Convers Manag*, 188 (2019), pp. 19-26,
590 <https://doi.org/10.1016/j.enconman.2019.03.054>.

591 [32]C.X. Wang, H.W. Lei, M.R.O. Qian, E.G. Huo, Y.F. Zhao, Q.F. Zhang, et al. Application
592 of highly stable biochar catalysts for efficient pyrolysis of plastics: A readily accessible
593 potential solution to a global waste crisis. *Sustain Energy Fuels*, 4 (2020), pp. 4614-4624,
594 <https://doi.org/10.1039/D0SE00652A>.

595 [33]S. Uslu. Optimization of diesel engine operating parameters fueled with palm oil-diesel
596 blend: Comparative evaluation between response surface methodology (RSM) and
597 artificial neural network (ANN). *Fuel*, 276 (2020), p. 117990,
598 <https://doi.org/10.1016/j.fuel.2020.117990>.

599 [34]J.A. Onwudili, N. Insura, P.T. Williams. Composition of products from the pyrolysis of
600 polyethylene and polystyrene in a closed batch reactor: Effects of temperature and
601 residence time. *J Anal Appl Pyrolysis*, 86 (2009), pp. 293-303,
602 <https://doi.org/10.1016/j.jaap.2009.07.008>.

603 [35]P.T. Williams, E. Slaney. Analysis of products from the pyrolysis and liquefaction of
604 single plastics and waste plastic mixtures. *Resour Conserv Recycl*, 51 (4) (2007), pp.
605 754-769, <https://doi.org/10.1016/j.resconrec.2006.12.002>.

606 [36]Q.H. Tang, Y.Q. Chen, H.P. Yang, M. Liu, H.Y. Xiao, S.R. Wang, H.P. Chen, S.R. Naqvi.
607 Machine learning prediction of pyrolytic gas yield and compositions with feature
608 reduction methods: Effects of pyrolysis conditions and biomass characteristics. *Bioresour*
609 *Technol*, 339 (2021), p. 125581, <https://doi.org/10.1016/j.biortech.2021.125581>.

- 610 [37]D. Kwon, S. Jung, K.Y.A. Lin, Y.F. Tsang, Y.K. Park, E.E. Kwon. Synergistic effects of
611 CO₂ on complete thermal degradation of plastic waste mixture through a catalytic
612 pyrolysis platform: A case study of disposable diaper. *J Hazard Mater*, 419 (2021), p.
613 126537, <https://doi.org/10.1016/j.jhazmat.2021.126537>.
- 614 [38]D.K. Hong, P. Li, T. Si, X. Guo. ReaxFF simulations of the synergistic effect mechanisms
615 during co-pyrolysis of coal and polyethylene/polystyrene. *Energy*, 218 (2021), p. 119553,
616 <https://doi.org/10.1016/j.energy.2020.119553>.
- 617 [39]Y.M. Wen, S.L. Wang, W.Z. Mu, W.H. Yang, P.G. Jönsson. Pyrolysis performance of peat
618 moss: A simultaneous in-situ thermal analysis and bench-scale experimental study. *Fuel*,
619 277 (2020), p. 118173, <https://doi.org/10.1016/j.fuel.2020.118173>.
- 620 [40]Z.Z. Chen, X.R. Zhang, L. Che, H.H. Peng, S.X. Zhu, F. Yang, X. Zhang. Effect of
621 volatile reactions on oil production and composition in thermal and catalytic pyrolysis of
622 polyethylene. *Fuel*, 271 (2020), p. 117308, <https://doi.org/10.1016/j.fuel.2020.117308>.
- 623 [41]J. Wang, J.C. Jiang, J.H. Ding, X.B. Wang, Y.J. Sun, R. Ruan, A.J. Ragauskas, Y.S. Ok,
624 D.C.W. Tsang. Promoting Diels-Alder reactions to produce bio-BTX: Co-aromatization
625 of textile waste and plastic waste over USY zeolite. *J Clean Prod*, 314 (2021), p. 127966,
626 <https://doi.org/10.1016/j.jclepro.2021.127966>.
- 627 [42]F.F. Xu, X. Ming, R. Jia, M. Zhao, B. Wang, Y.Y. Qiao, Y.Y. Tian. Effects of operating
628 parameters on products yield and volatiles composition during fast pyrolysis of food
629 waste in the presence of hydrogen. *Fuel Process Technol*, 210 (2020), p. 106558,
630 <https://doi.org/10.1016/j.fuproc.2020.106558>.

- 631 [43]H.S. Choi, Y.S. Choi, H.C. Park. Fast pyrolysis characteristics of lignocellulosic biomass
632 with varying reaction conditions. *Renew Energy*, 42 (2012), pp. 131-135,
633 <https://doi.org/10.1016/j.renene.2011.08.049>.
- 634 [44]R.K. Singh, B. Ruj, A.K. Sadhukhan, P. Gupta. Thermal degradation of waste plastics
635 under non-sweeping atmosphere: Part 1: Effect of temperature, product optimization, and
636 degradation mechanism. *J Environ Manage*, 239 (2019), pp. 395-406,
637 <https://doi.org/10.1016/j.jenvman.2019.03.067>.
- 638 [45]S.D.A. Sharuddin, F. Abnisa, W.M.A.W. Daud, M.K. Aroua. A review on pyrolysis of
639 plastic wastes. *Energy Convers Manag*, 115 (2016), pp. 308-326,
640 <https://doi.org/10.1016/j.enconman.2016.02.037>.
- 641 [46]J. Baena-Gonzalez, A. Santamaria-Echart, J.L. Aguirre, S. Gonzalez. Chemical recycling
642 of plastic waste: Bitumen, solvents, and polystyrene from pyrolysis oil. *Waste Manage*,
643 118 (2020), pp. 139-149, <https://doi.org/10.1016/j.wasman.2020.08.035>.
- 644 [47]C.H. Gu, X.H. Wang, Q.S. Song, H.W. Li, Y. Qiao. Prediction of gas-liquid-solid product
645 distribution after solid waste pyrolysis process based on artificial neural network model.
646 *Int J Energy Res*, 45 (9) (2021), pp. 13786-13800, <https://doi.org/10.1002/er.6707>.
- 647 [48]K.H. Lee, D.H. Shin. Characteristics of liquid product from the pyrolysis of waste plastic
648 mixture at low and high temperatures: Influence of lapse time of reaction. *Waste Manage*,
649 27 (2) (2007), pp. 168-176, <https://doi.org/10.1016/j.wasman.2005.12.017>.
- 650 [49]F. Pinto, F. Paradela, I. Gulyurtlu, A.M. Ramos. Prediction of liquid yields from the
651 pyrolysis of waste mixtures using response surface methodology. *Fuel Process Technol*,

- 652 116 (2013), pp. 271-283, <https://doi.org/10.1016/j.fuproc.2013.07.012>.
- 653 [50]A. Heidari, R. Stahl, H. Younesi, A. Rashidi, N. Troeger, A.A. Ghoreyshi. Effect of
654 process conditions on product yield and composition of fast pyrolysis of Eucalyptus
655 grandis in fluidized bed reactor. *J Ind Eng Chem*, 20 (4) (2014), pp. 2594-2602,
656 <https://doi.org/10.1016/j.jiec.2013.10.046>.
- 657 [51]M.S. Abbas-Abadi, K.M. Van Geem, M. Fathi, H. Bazgir, M. Ghadiri. The pyrolysis of
658 oak with polyethylene, polypropylene and polystyrene using fixed bed and stirred
659 reactors and TGA instrument. *Energy*, 232 (2021), p. 121085,
660 <https://doi.org/10.1016/j.energy.2021.121085>.
- 661 [52]A.K. Varma, P. Mondal. Pyrolysis of sugarcane bagasse in semi batch reactor: Effects of
662 process parameters on product yields and characterization of products. *Ind Crops Prod*,
663 95 (2017), pp. 704-717, <https://doi.org/10.1016/j.indcrop.2016.11.039>.
- 664 [53]A. Trubetskaya, P.A. Jensen, A.D. Jensen, M. Steibel, H. Spliethoff, P. Glarborg.
665 Influence of fast pyrolysis conditions on yield and structural transformation of biomass
666 chars. *Fuel Process Technol*, 140 (2015), pp. 205-214,
667 <https://doi.org/10.1016/j.fuproc.2015.08.034>.
- 668 [54]K.B. Ansari, S.Z. Hassan, Bhoi, R., E. Ahmad. Co-pyrolysis of biomass and plastic
669 wastes: A review on reactants synergy, catalyst impact, process parameter, hydrocarbon
670 fuel potential, COVID-19. *J Environ Chem Eng*, 9 (6) (2021), p. 106436.
671 <https://doi.org/10.1016/j.jece.2021.106436>.
- 672 [55]F. Abnisa, P.A. Alaba. Recovery of liquid fuel from fossil-based solid wastes via pyrolysis

673 technique: A review. *J Environ Chem Eng*, 9 (6) (2021), p. 106593.
674 <https://doi.org/10.1016/j.jece.2021.106593>.

675 [56]J. Haydary, D. Susa, V. Gelinger, F. Čacho, Pyrolysis of automobile shredder residue in a
676 laboratory scale screw type reactor. *J Environ Chem Eng*, 4 (1) (2016), pp. 965-972.
677 <https://doi.org/10.1016/j.jece.2015.12.038>.

678 [57]J. Su, C. Fang, M. Yang, C. You, Q. Lin, X. Zhou, H. Li. Catalytic pyrolysis of waste
679 packaging polyethylene using AlCl₃-NaCl eutectic salt as catalyst. *J Anal Appl Pyrolysis*,
680 139 (2019), pp. 274-281, <https://doi.org/10.1016/j.jaap.2019.02.015>.

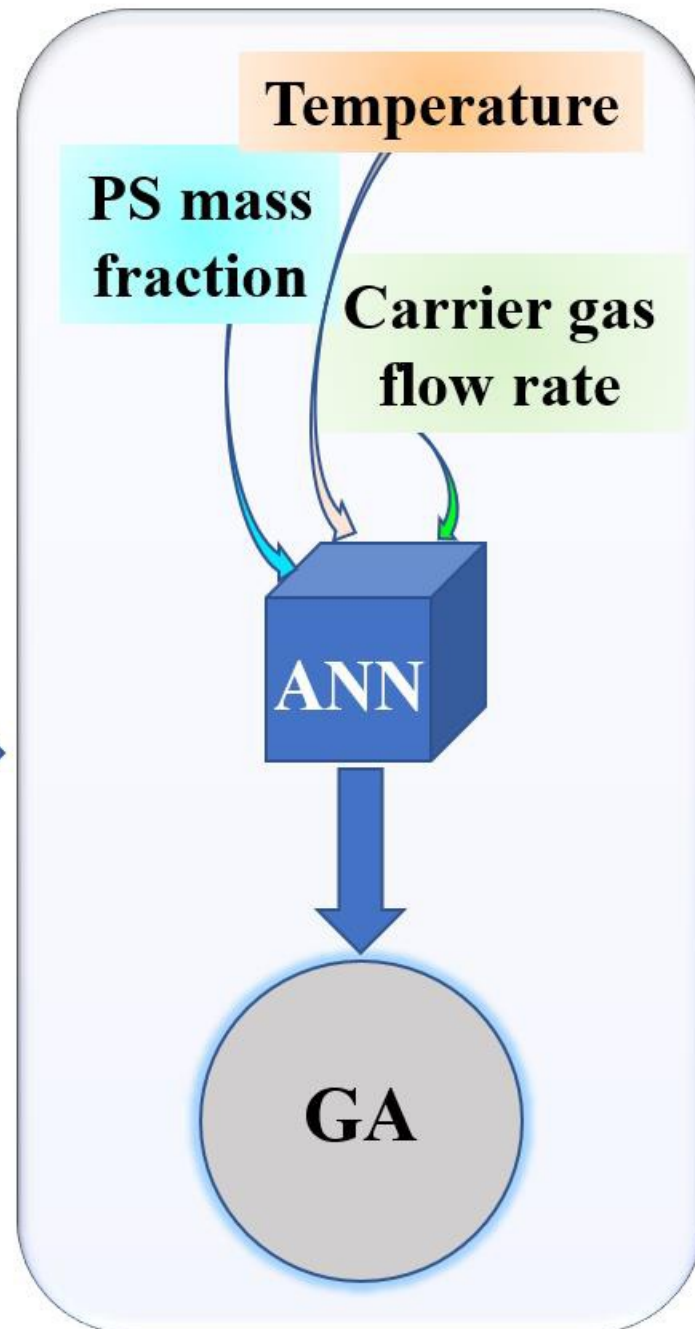
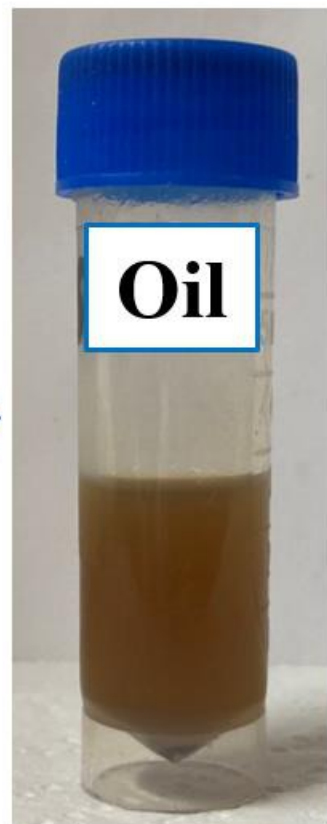
681 [58]P. Das, P. Tiwari. The effect of slow pyrolysis on the conversion of packaging waste
682 plastics (PE and PP) into fuel. *Waste Manage*, 79 (2018), pp. 615-624,
683 <https://doi.org/10.1016/j.wasman.2018.08.021>.

684 [59]M. Maniscalco, F. La Paglia, P. Iannotta, G. Caputo, F. Scargiali, F. Grisafi, A. Brucato.
685 Slow pyrolysis of an LDPE/PP mixture: Kinetics and process performance. *J Energy Inst*,
686 96 (2021), pp. 234-241. <https://doi.org/10.1016/j.joei.2021.03.006>.



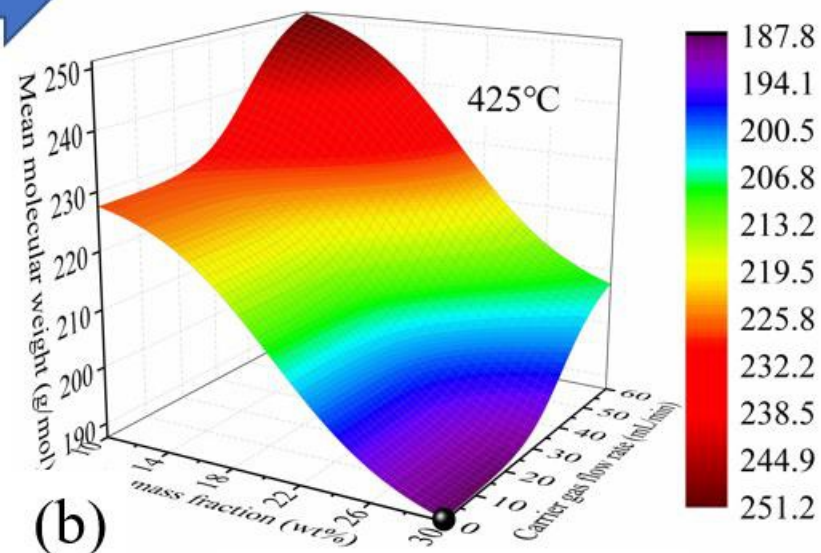
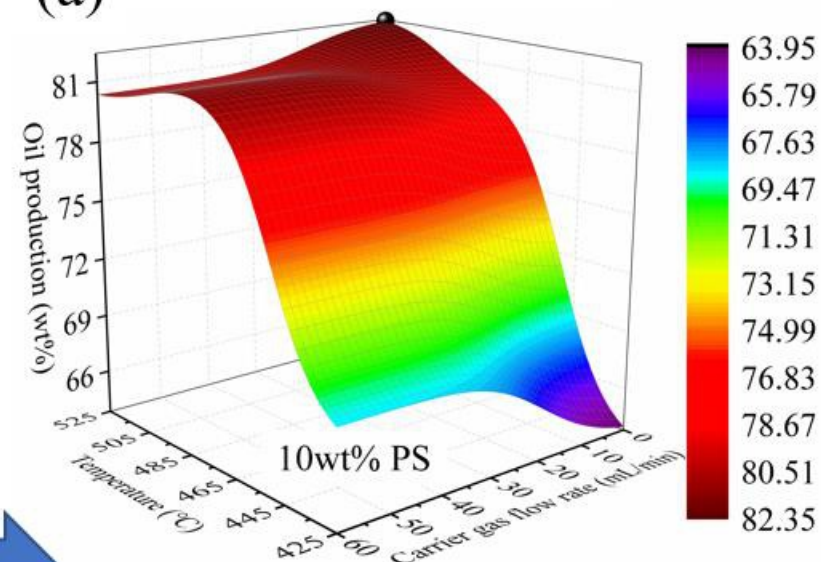
Waste plastics recovered from MSW

Pyrolysis



WPE/WPS co-pyrolysis for oil production

(a) Highest oil yield



(b) Lightest oil