



*J. Serb. Chem. Soc.* 89 (7–8) 1053–1066 (2024)  
JSCS–5771

## Co-pyrolysis of various plastic waste components as an environmentally sustainable source of alternative fuels

IVANA JOVANČIĆEVIĆ<sup>1</sup>, MALIŠA ANTIĆ<sup>2</sup>, GORDANA GAJICA<sup>3</sup>  
and JAN SCHWARZBAUER<sup>1\*</sup>

<sup>1</sup>RWTH Aachen University, Institute of Organic Biochemistry in Geo-Systems, Lochnerstrasse 4–20, 52056, Aachen, Germany, <sup>2</sup>University of Belgrade, Faculty of Agriculture, Nemanjina 6, 11 080, Zemun, Belgrade, Serbia and <sup>3</sup>University of Belgrade, Institute of Chemistry, Technology and Metallurgy, Njegoševa 12, 11000 Belgrade, Serbia

(Received 7 February, revised 1 March, accepted 12 April 2024)

**Abstract:** In this study, pyrolysis and co-pyrolysis of commonly used plastic materials (polyethylene terephthalate – PET, high density polyethylene – HDPE, and polystyrene – PS) were conducted to analyse the chemical composition of the corresponding pyrolyzates. Different ratios of plastic materials were applied to obtain a composition of aliphatic and aromatic degradation products that closely resemble those of conventional fossil fuels. The systematic chemical variations can act as base for evaluating this approach as a sustainable source of alternative fuels. HDPE revealed an aliphatic composition of degradation products, while PS and PET produced only aromatic compounds. Quantitative analysis of the obtained pyrolyzates revealed a clear correlation of initial proportion with the resulting quantitative product composition. The generation of individual pyrolysis products gave a high reproducibility. However, it became evident that the decomposition products of PS consistently emerged as the most prominent among all tested HDPE/PS mixtures. The ratio of HDPE:PS = 1:3 showed 96 % of the aromatic compounds as PS decomposition products. PET revealed a oxygen containing structure of the products, contributing to 83 % of the HDPE:PET = 1:3 mixture. These results gain insights into the potential of plastic waste as a sustainable source for alternative fuels and valuable chemicals.

**Keywords:** co-pyrolysis; synthetic polymers; plastic-derived-fuel; GC–MS; sustainability.

### INTRODUCTION

Over the past few decades, plastic materials have gained attention in various contexts. They offer exceptional versatility, functionality and economic efficiency. Yet, the increase in their use and production lead to massive waste gener-

\* Corresponding author. E-mail: jan.schwarzbauer@emr.rwth-aachen.de  
<https://doi.org/10.2298/JSC240207046J>



ation, posing a significant environmental threat. Furthermore, environmental concerns go beyond plastic waste to include additives added to plastic production to improve their properties. These additives include antioxidants and UV stabilizers for heat, aging and light resistance, pigments and dye stuffs to modify color and functional agents such as plasticizers, surfactants and flame retardants. In Germany, 18.9 million tons (228 kg per capita) of packaging waste were generated in 2019, which significantly exceeds the EU average of 177 kg per capita.<sup>1</sup> Therefore, it is crucial to explore alternatives that have the potential to prevent undesirable landfilling and mitigate the unacceptable littering of the environment.

Pyrolysis of synthetic polymers is one efficient approach to reduce waste, while also allowing for the recovery of monomers and other valuable materials.<sup>2</sup> Given the high carbon and hydrogen content of synthetic polymers, pyrolysis of these materials can produce high-quality liquid oils, with a high calorific value and a high proportion of compounds similar and compatible with fossil fuels.<sup>3</sup> This expands the options for plastic waste management and reduces reliance on petroleum-based resources. In this sense, Rehan *et al.* (2016) investigated the potential of pyrolysis technology for thermal conversion of municipal plastic waste from Makkah city, to obtain liquid fuel. The energy content of 40 MJ kg<sup>-1</sup> of this waste derived fuel was found to be similar to conventional diesel.<sup>4</sup> Further on, Achilias *et al.* (2007) reported a series of alkanes and alkenes recovered by pyrolyzing raw materials made out of polypropylene (PP) in a laboratory fixed bed reactor.<sup>5</sup>

Co-pyrolysis of different feedstocks has recently gained significant attention as a promising approach to enhance both the yields and quality of biofuels. Plastic materials have demonstrated high potential as catalysts in the fuel production through biomass pyrolysis.<sup>6–8</sup> Furthermore, co-pyrolysis of different plastic materials has gained considerable attention as a promising approach to enhance plastic-derived fuel yields and quality, overcoming the problems associated with heterogeneous plastic waste and contributing to a more efficient and sustainable recycling process. Combining various plastics during pyrolysis can lead to synergistic effects, resulting in increased oil yield and improved fuel properties compared to individual plastic pyrolysis.<sup>9,10</sup> Therefore, it is important to evaluate the degree of pyrolytic interactions between different feedstocks and to determine whether the additivity rule can be applied to predict the product yields from co-pyrolysis experiments.

In this study, pyrolysis and co-pyrolysis of commonly used plastic materials (PET, HDPE and PS) were conducted to analyse the chemical composition of the corresponding pyrolysates. These characterisations gain insights into the potential of plastic waste pyrolysis as a sustainable source for alternative fuels and valuable chemicals. In more detail, the experiments in this study involved the use of different ratios of plastic materials to produce a composition of aliphatic and

aromatic degradation products that closely resemble those of conventional fossil fuels. Hence, a comparison between the composition of the plastic derived oils and diesel fuel was conducted to assess their similarity and potential viability as a substitute. Furthermore, the study aimed to investigate any cross-reaction effects arising from the interactions between different polymers during co-pyrolysis. Additionally, the study also examined the presence of additives in plastic waste to gain insights into their potential influence on the pyrolysis process and the resulting plastic-derived oil composition.

## EXPERIMENTAL

### *Chemicals and reference compounds*

Standard reference materials of PE, PS and PET were purchased from Geyer Th. GmbH & Co. KG. Acetone and hexane used for offline pyrolysis were purchased from Geyer Th. GmbH & Co. KG as well.

Plastic waste material such as food packaging, food and cosmetic containers, plastic furniture, plastic bottles, *etc.*, have been collected from several households in Aachen, Germany. The collected material consists of different synthetic polymers such as: HDPE, PS and PET. The collected plastic waste was selected for this study due to its high production and utilization rate as well as its chemical recycling potential.

### *Continuous flow off-line pyrolysis*

Off-line pyrolysis experiments were performed on a MTF 10/15/130 model Carbolite tube furnace. The samples were placed in aluminum-foil vessels in the middle of a quartz tube (150 mm in length and 15 mm in diameter) that was set within the furnace. On one side, the quartz tube was connected to a continuous stream of nitrogen, while the other side was connected to a flask tube filled with 4 mL of acetone and cooled with dry ice and ethanol. Pyrolysis experiments were performed under the following conditions: temperature of 450 °C, no heating rate, duration time 30 min and constant nitrogen flow of 50 mL min<sup>-1</sup>. After pyrolysis, the volume of the pyrolysates sampled in the cold trap was reduced to approximately 2 mL and dried over anhydrous sodium sulphate. For qualitative and quantitative analysis, pyrolysates were measured by gas chromatography/mass spectrometry (GC/MS). Furthermore, GC/MS analysis was also applied for the identification of additives present in plastic waste.

The described procedure was applied to pyrolysis and co-pyrolysis of HDPE, PS and PET standard reference materials and corresponding municipal plastic waste. Co-pyrolysis experiments were performed with compositions of the following ratios:

1. HDPE:PS = 1:1; 1:3; 3:1; 9:1;
2. HDPE:PET = 1:1; 1:3; 3:1; 9:1;
3. HDPE:PS:PET = 1:1:1; 8:1:1.

The maximum sample weight for co-pyrolysis experiments was 100 mg.

### *Sample preparation*

The collected plastic waste samples were categorized according to their specific product labels. The material was first washed and air-dried, cut into smaller particles (approx. 2 cm) with scissors and then shredded into particles smaller than 5 mm. Shredding was carried out under a high flow of nitrogen gas, which was used to cool the samples and prevent them from melting.

### GC/MS analysis

Qualitative and quantitative analysis of the obtained pyrolyzates were performed on an Thermo Quest Trace GC gas chromatograph connected to Thermo Quest Trace MS single quadrupole mass spectrometer, equipped with a ZB-5 capillary column (30 mm×0.25 mm ID 0.25  $\mu\text{m}$  film). The chromatograph conditions were the following: 1  $\mu\text{L}$  splitless injection (splitless time 60 s; injector temperature 270  $^{\circ}\text{C}$ ), oven temperature heated from 80  $^{\circ}\text{C}$  (held 3 min) at 4  $^{\circ}\text{C min}^{-1}$  to 310  $^{\circ}\text{C}$  (held 20 min) and helium carrier gas flow of 1.5  $\text{mL min}^{-1}$ . The mass spectrometer was operated in an electron impact ionization mode ( $\text{EI}^+$ , 70 eV) with a source temperature of 200  $^{\circ}\text{C}$  and an interface temperature of 270  $^{\circ}\text{C}$  scanning from  $m/z$  35 to 500 in full scan mode with a scan rate of 0.67 scan  $\text{s}^{-1}$ .

The identification was based on a detailed interpretation of the mass spectra and comparison with the NIST Mass Spectral Library, as well as comparison with literature data. Calculation of relative quantitative compositions was based on integration of ion chromatograms and corresponding peak areas. A surrogate standard solution containing the reference compounds fluoroacetophenone (5.8  $\text{ng } \mu\text{L}^{-1}$ ), benzophenone-d10 (6.3  $\text{ng } \mu\text{L}^{-1}$ ), and hexadecane-d34 (6.0  $\text{ng } \mu\text{L}^{-1}$ ) was used for quantitative analysis of the obtained pyrolyzates.

## RESULTS AND DISCUSSION

The development and utilization of plastic-derived oils from pyrolysis processes require comprehensive qualitative and quantitative chemical characterization of the pyrolysis products to ensure desired technical specification. This study employs an analytical approach to analyze and quantify compounds present in co-pyrolysis products of common polymers, emphasizing the principal composition of aliphatic and aromatic hydrocarbons as well as functionalized compounds, similar to characterizing crude oil and related fossil matter.

For the pyrolysis experiments, HDPE, PS and PET in varying compositions have been used. The selection of these particular polymers was based on their distinct chemical characteristics, as PE is composed of a long aliphatic chain, in contrast to the aromatic constituents of PS and PET. Furthermore, chemical composition of the pyrolysis resulting oils was investigated (additional data are given in the Supplementary material to this paper).

### Pyrolysis of synthetic polymers

As a preliminary step, offline pyrolysis experiments were performed on reference material as well as raw waste samples consisting of PE, PET, and PS, to analyze accurately the pattern of their degradation products. Further on, the samples have been analyzed for potential impurities that can remarkably affect the chemical composition of the pyrolyzates.

Pyrolysis of both PE reference material, and HDPE waste samples, resulted in the formation of white insoluble flocks forming wax as one of the pyrolysis products. The obtained wax was insoluble in common solvents like acetone, dichloromethane and hexane. The formation of wax during pyrolysis of low-density polyethylene (LDPE) was observed already by Williams and Williams (1997) who reported that the obtained wax product was comprised of long chain ali-

phatic compounds of up to 57 carbon atoms.<sup>11</sup> For a technical usage, the obtained wax was proposed to be utilized as a chemical feedstock in the petrochemical industry, where a wide range of high carbon olefins is highly demanded.<sup>9</sup> Wax was isolated from the acetone fraction and was not discussed in further work.

#### HDPE, PS and PET

Offline pyrolysis of both PE reference material and the corresponding waste material (HDPE) revealed a pattern composed of a sequence of triplets, each consisting of *n*-alkadienes, *n*-alkenes and *n*-alkanes forming a homologues series of increasing chain lengths (see Fig. 1). Generally, the resulting pyrolysate was composed of 47.5 % of *n*-alkanes, followed by 44 % *n*-alkenes and 8.5 % *n*-alkadienes. Based on three measurements, the three compound groups exhibited a relative standard deviation in the range of 30 %.

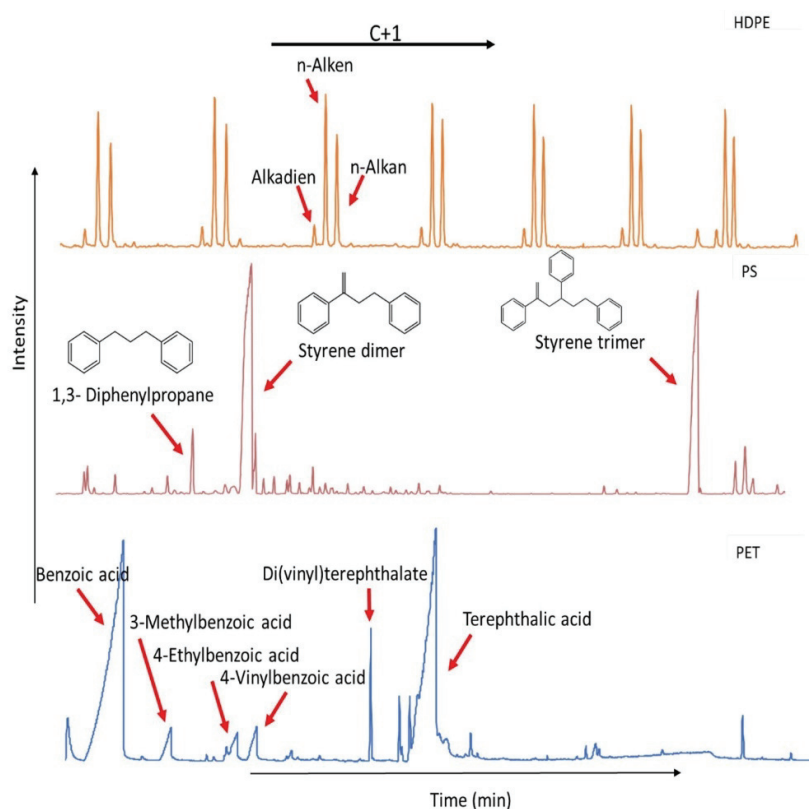


Fig. 1. TIC of pyrolysis experiments conducted on HDPE, PET; and PS.

Pyrolysis experiments on PET manifested a diverse range of monocyclic aromatic degradation products, with benzoic acid, and terephthalic acid identified

as the most prominent products (see Fig. 1) constituting 32 and 56 % of the resulting pyrolysis products, respectively. Notably, multiple repetitions of the experiments revealed variations in their proportions of less than 10 %. These products are in accordance with the on-line degradation products identified, *e.g.*, by Dziwiński *et al.*<sup>12</sup>

When subjected to off-line pyrolysis, PS decomposed to form dark viscous oil. As expected, GC/MS analysis of this oil revealed a more aromatic composition of the pyrolysis products, with three main degradation products identified as 1,3-diphenylpropane, 2,4-diphenylbutene and 2,4,6-triphenylhexene (see Fig. 1). They constituted 4, 40 and 54 % of the resulting pyrolysis products, respectively, with variations in their proportions approximately around 20 %. These products represent the group of styrene oligomers, or more precisely, dimers and trimers of the styrene monomer.<sup>13</sup> In addition to these main product groups, pyrolysis of PS revealed numerous compounds with significantly lower intensities. Some of them were identified as: 1,2-diphenylethylene, bibenzyl, 1,2-diphenylpropane, 1,2-diphenylpropane, 1,2,3,4-tetrahydro-1-phenylnaphthalene, 1,4-diphenyl-1,3-butadiene and 1-phenylnaphthalene. Each of these products accounted for less than 0.5 % of the total pyrolysis and, therefore, were not included in further quantitative analysis. Finally, compared to pyrolysis experiments applied on reference material samples, pyrolysis of plastic waste samples HDPE, PS and PET revealed no visible changes regarding the chemical composition of the degradation products.

#### *Co-pyrolysis experiments*

Co-pyrolysis experiments on defined plastic mixtures produced a blend of all compounds already identified in the single pyrolysis experiments. Noteworthy, no further or new degradation products were observed (as illustrated in Fig. 2) pointing to the absence of cross reaction between the different components during pyrolysis. Both, HDPE/PS and HDPE/PET mixtures revealed an aliphatic pattern within the C<sub>12</sub>–C<sub>27</sub> range as HDPE contribution. The obtained range of aliphatic compounds is very valuable, since these chain length fits the C<sub>18</sub>–C<sub>22</sub> range in the production of important raw materials in the detergent industry such as sodium lauryl ether sulphate and alkyl benzene sulphonic acid.<sup>9</sup>

In the HDPE/PS experiments, the main aromatic products result directly from the pyrolysis of PS, namely 1,3-diphenylpropane, 2,4-diphenylbutene and 2,4,6-triphenylhexene. Within the range of preselected mixture rates from 1:3 to 9:1 a clear dominance of aromatic products was observed, whereby, a decrease in the initial amount of PS resulted in a proportional decrease of these aromatic products. Fig. 3a illustrates this relationship, indicating that a 1:1 ratio of HDPE to PS yielded nearly 90 % aromatic compounds and only 10 % aliphatic compounds consisting in detail of 4.4 % *n*-alkanes, 4.5 % *n*-alkenes, and 1 % *n*-alkadienes.

Pyrolysis applied to a 3:1 mixture yielded approximately 22.7 % aliphatic hydrocarbons and 77.3 % aromatic hydrocarbons. Only in the case of a 9:1 ratio, a similar proportion of aliphatic hydrocarbons as compared to aromatic compounds was observed with 26 % *n*-alkenes, 22 % *n*-alkanes and 3 % *n*-alkadienes. These quantitative observations clearly point to: *i*) a higher relative pyrolysis yield of the aliphatic polymer HDPE and *ii*) a clear correlation of initial proportion with the resulting quantitative product composition.

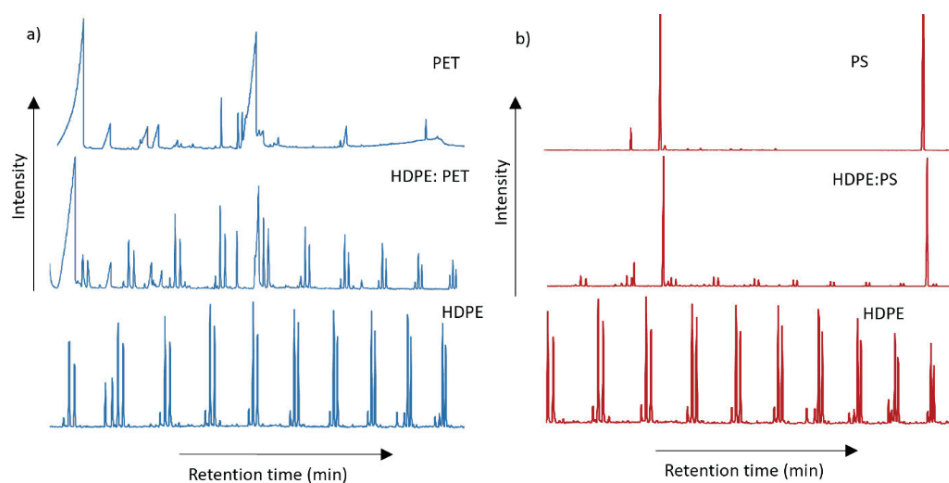


Fig. 2. TIC of the pyrolysis and co-pyrolysis experiments on: a) PET, HDPE:PET and HDPE and b) PS, HDPE:PS and HDPE experiments.

The quantitative results of the pyrolysis products derived from HDPE:PET mixtures are illustrated in Fig. 3b. These findings indicate that oxygen-containing aromatic hydrocarbons represent the most prominent group, accounting for nearly 62 % of the pyrolysis products in the HDPE:PET = 1:1 experiments. Here, benzoic acid was the most abundant oxygen-containing compound identified in the co-pyrolysis experiments. In the case of HDPE:PET = 3:1 ratio, the pyrolysis products were predominantly composed of aliphatic compounds, comprising approximately 60 % of the total amount of the detected pyrolysis products. In the HDPE:PET = 9:1 approach, this predominance of aliphatic compounds reached nearly 76 %. Noteworthy, based on the presented results, the individual products demonstrated high reproducibility. As shown in Fig. 3, the homologous series of aliphatic compounds maintains a consistent order in the sequence of the obtained products.

As a final approach, the co-pyrolysis of all three polymers have been systematically studied. In the co-pyrolysis experiments involving equimolar ratios of all three polymers, no novel degradation products were detected pointing once again to the absence of cross reaction of all components during the pyrolysis process.

Aromatic and oxygen containing compounds derived from PS and PET, dominated with a significant majority (89.3 %) of the pyrolysis products. Within the group of aromatic compounds, approximately 52 % were identified as oxygen-containing aromatic compounds. Only 11.7 % of the pyrolysates were attributed to aliphatic compounds, as depicted in Fig. 3c.

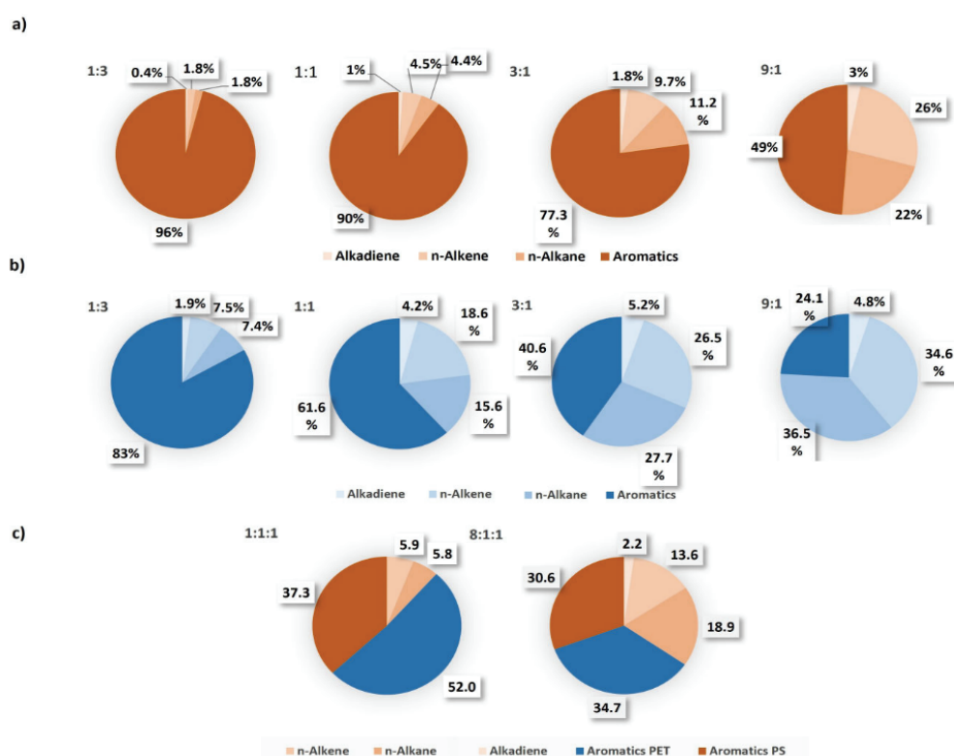


Fig. 3. Pyrolysis product groups of: a) HDPE:PS; b) HDPE:PET; c) HDPE:PS:PET co-pyrolysis experiments given in %. Only compounds constituting 1 % or more of the pyrolysis products composition are highlighted in the figure. The quantities are presented as percentages.

Based on these results, an experimental set-up with a significant higher proportion of HDPE was applied. This pyrolysis of a mixture of HDPE:PET:PS = 8:1:1 yielded a higher amount of aliphatic products (34.7 %), along with oxygenated compounds (34.7 %) and aromatic products resulting from the degradation of PS (30.6 %).

### Additives

Plastic materials benefit from the addition of substances known as additives, which serve to enhance or alter their properties. These substances are introduced



during the manufacturing process to enhance properties like strength, flexibility, and colour, including plasticizers, UV stabilizers, flame retardants, and colorants.<sup>14</sup> However, some additives may pose risks to health and the environment.<sup>14,15</sup> During plastic-derived fuel production via pyrolysis, some additives may not fully degrade, potentially persisting in the resulting oil. In addition to the characteristic pyrolysis products various polymer additives present in the samples were also noticed and it is important to acknowledge these with respect to the proposed production of plastic-derived fuels. The identified additives are listed in Table I.

TABLE I. The identified additives in the obtained pyrolyzates

Additive	IUPAC name	Polymer	Uses	Safety hazards	CAS registry number
2,4-DTBP	2,4-Di-tert-butylphenol	HDPE	Intermediate in the production of UV stabilizers and antioxidants. <sup>16</sup>	Causes skin, eye and respiratory irritation. Very toxic to aquatic life. <sup>16</sup>	96-76-4
Bumetizole UV326	2-(3-tert-butyl-2-hydroxy-5-methylphenyl)-5-chlorobenzotriazole	HDPE	UV stabilizer, enhances the light resistance of polymers. <sup>17</sup>	May lead to metabolic imbalance; toxic to aquatic life. <sup>17</sup>	3896-11-5
$\alpha$ -Hexyl-cinnamaldehyde	2-(Phenylmethylene)-octanal	HDPE, PET	Fragrance, odor agents. <sup>18</sup>	Causes an allergic skin reaction; toxic to aquatic life with long lasting effects. <sup>18</sup>	101-86-0
Isopropyl myristate	1-Methylethyl ester-tetradecanoic acid	HDPE, PET	Thickener and a lubricant in beauty products. <sup>19</sup>	Can cause skin irritation. <sup>19</sup>	110-27-0
Terphenyl	Diphenylbenzene	HDPE, PET, PS	Terphenyl mixtures are used as textile dye carriers and as intermediates for lubricants. <sup>20</sup>	Can cause skin and eyes irritation; may affect the liver and kidneys. <sup>20</sup>	26140-60-3

#### *Aspects of application for plastic-derived fuel production*

For an efficient technical usage of plastic-derived fuels resulting from plastic pyrolysis, the chemical composition needs to be compared to established fossil fuel products, since the basic properties of such fossil fuels are based on their chemical constitution. Diesel fuel typically consists of around 75 % aliphatic hydrocarbons within the C<sub>9</sub>–C<sub>25</sub> range, while approximately 25 % of its compos-

ition comprises aromatic hydrocarbons like benzene, styrene, phenanthrene, fluoranthene, pyrene, benz(*a*)anthracene, chrysene and benzo(*a*)pyrene.<sup>21–23</sup> However, the chemical composition of diesel fuel can vary depending on its origin or source. The findings of this study revealed a striking similarity in the chemical composition between the plastic oils obtained and diesel. These similarities are visualized in Fig. 4, where the chromatograms of one diesel derived from the Caspian Sea is compared with those of the HDPE:PS and HDPE:PET experiments. The chemical composition of the obtained plastic-derived oil shows similarities to diesel especially in terms of its aliphatic composition, mainly in the range of C<sub>12</sub> to C<sub>27</sub> *n*-alkanes. Noteworthy, in the refining process of crude oil, alkenes are generated through the cracking of heavier fractions, but they are not typically found in diesel. Alkenes generally exist in lower concentrations, ranging from 0 to 10 %, and within a narrower carbon number range.<sup>24,25</sup> Unsaturated hydrocarbons prove less suitable for fuel combustion due to their tendency to result in incomplete combustion, thereby generating higher levels of carbon monoxide.<sup>26</sup> To address this limitation, additional improvements in the composition of plastic-pyrolysis oil are necessary, specifically targeting the presence of *n*-alkenes and alkadienes. One possibility is an additional hydrogenation of the double bond. Prior research has demonstrated that this transformative process effectively converts the alkene products present in pyrolysis oil into alkanes.<sup>26–29</sup>

An essential parameter in plastic-derived fuel production is the octane number, which measures a fuel's resistance to auto-ignition and explosive combustion in internal combustion engines. Higher octane numbers indicate greater resistance to auto-ignition under increased pressure and temperature before ignition by the engine spark plug. While straight chain aliphatic compounds exhibit lower octane ratings, aromatic compounds are valued for their higher-octane values. Therefore, the inclusion of aromatic compounds is important in fuel formulations.<sup>30,31</sup> On the other hand, these aromatic constituents are the predominant source of particulate matter (PM) emissions and in that way represent the major air pollutants affecting human health.<sup>32</sup> In this work, the co-pyrolysis mixtures of HDPE:PS and HDPE:PET in ratios of 1:1, 1:3 and 3:1, as well as the pyrolysis of all three polymers in ratios of 1:1:1 and 8:1:1 were found to generate a significant quantity of aromatic compounds, which makes these ratios unsuitable for fuel production.

While conventional fuels typically contain oxygen, sulfur and nitrogen compounds (NSO fraction) within specific ranges,<sup>33,34</sup> plastic-derived oils offer potential advantages in minimizing these elements. While some research has noted high sulfur content in plastic waste pyrolysis,<sup>35</sup> this study did not identify sulfur or nitrogen compounds in the pyrolysates examined. This absence suggests a potential environmental advantage of plastic-derived oils over conventional fuels, particularly regarding emissions of sulfur oxides and other pollutants.

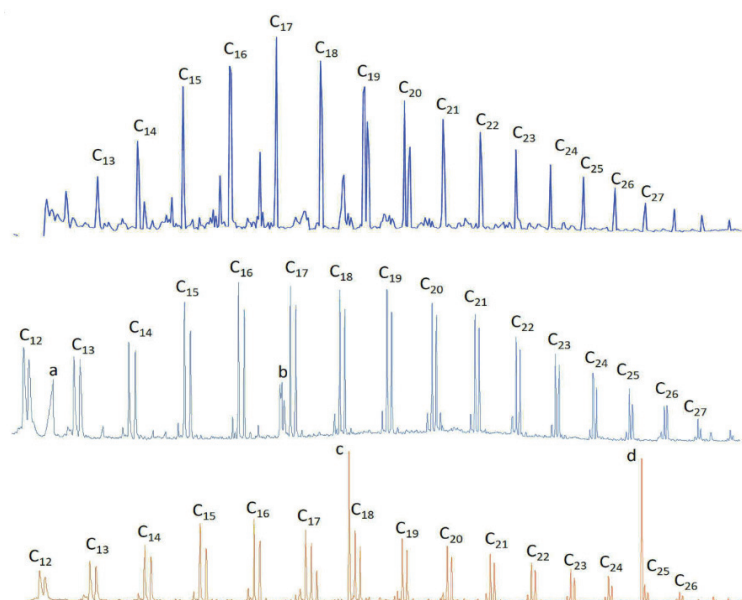


Fig. 4. Top: Total ion chromatogram (TIC) of pure diesel fuel (Caspian Sea). Middle: TIC of co-pyrolysis experiments using a 9:1 mixture of HDPE : PET. C<sub>12</sub>–C<sub>27</sub> represent the carbon numbers of the aliphatic compounds in the pyrolysis product; a – benzoic acid; b – terephthalic acid. Bottom: TIC of co-pyrolysis experiment using a 9:1 mixture of HDPE:PS (C<sub>12</sub>–C<sub>27</sub> represent the carbon numbers of the aliphatic compounds in the pyrolysis product; c – styrene dimer; d – styrene trimer).

The production of fuel through pyrolysis using plastic waste entails numerous technical and environmental factors to consider, including the handling of waste and the effectiveness of the pyrolysis process. Based on the findings obtained in the present study, it's essential to consider the proportions and types of plastics used. Additionally, increasing the proportion of HDPE plastic waste in pyrolysis feedstock can align the chemical composition with desired specifications. Given the high production volume of PE like plastic materials,<sup>36</sup> directing more PE waste towards recycling and sustainable practices would promote environmental benefits and align with industry sustainability goals.

#### CONCLUSION

The findings of this study do not only contribute to the understanding of polymer waste management but also hold promise for environmentally sustainable plastic-derived fuel production. Through systematic pyrolysis experiments of plastic waste samples composed of HDPE, PS, and PET and following chemical characterisation of the pyrolyzates by GC/MS analysis, valuable insights have been gained into the composition of degradation products. These systematic chemical variations can act as base for evaluating this approach as a sustainable

source of alternative fuels. The study highlights distinct behaviors of polymers during pyrolysis with HDPE revealing aliphatic compounds, PS aromatic compounds and PET contributing to oxygen-containing structures. However, an essential observation from the investigation is the substantial influence of PS and PET decomposition in HDPE:PS and HDPE:PET mixtures. This influence accounts for 90 % of the pyrolysate obtained from the HDPE:PS 1:1 mixture and 62 % from the HDPE:PET 1:1 mixture. Increasing the HDPE proportion in the pyrolysis feedstock holds promise for high-quality plastic-derived oil production aligning with conventional fossil fuel constituents.

It is important to emphasize that this approach is a proposition, representing a preliminary step in the pursuit of plastic-derived fuel development. Further comprehensive characterization and optimization of the obtained fuel are likely necessary to fine-tune its properties and performance. In this pursuit, the exploration of various additives may become instrumental, offering opportunities to enhance the fuel's quality and customize it to specific applications.

#### SUPPLEMENTARY MATERIAL

Additional data and information are available electronically at the pages of journal website: <https://www.shd-pub.org.rs/index.php/JSCS/article/view/12806>, or from the corresponding author on request.

*Acknowledgement.* The authors acknowledge the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung) for the support.

#### ИЗВОД

#### КОПИРОЛИЗА РАЗЛИЧИТИХ КОМПОНЕНТИ ПЛАСТИЧНОГ ОТПАДА КАО ЕКОЛОШКИ ОДРЖИВ ИЗВОР АЛТЕРНАТИВНИХ ГОРИВА

ИВАНА ЈОВАНЧИЋЕВИЋ<sup>1</sup>, МАЛИША АНТИЋ<sup>2</sup>, ГОРДАНА ГАЈИЦА<sup>3</sup> и JAN SCHWARZBAUER<sup>1</sup>

<sup>1</sup>RWTH Aachen University, Institute of Organic Biochemistry in Geo-Systems, Lochnerstrasse 4–20, 52056, Aachen, Germany, <sup>2</sup>Универзитет у Београду, Пољопривредни факултет, Немањина 6, 11080, Земун, Београд и <sup>3</sup> Универзитет у Београду, Институт за хемију, технологију и металургију, Њешићева 12, 11000 Београд

У овој студији, пиролиза и ко-пиролиза најчешће коришћених пластичних материјала (полиетилен-терефталат – PET, полиетилен високе густине – HDPE и полистирен – PS) су спроведене ради анализе хемијског састава одговарајућих пиролизата. Примењени су различити односи пластичних материјала да би се добио састав алифатичних и ароматичних производа разградње који су веома слични онима код конвенционалних фосилних горива. Систематске хемијске варијације могу послужити као основа за процену овог приступа као одрживог извора алтернативних горива. HDPE је дао алифатичне производе разградње, док су PS и PET производили само ароматична једињења. Квантитативна анализа добијених пиролизата показала је јасну корелацију почетног односа са добијеним квантитативним саставом производа. Генерисање појединачних производа пиролизе показало је високу поновљивост. Међутим, било је очигледно да су се производи разлагања PS доследно појављивали као најистакнутији међу свим тестираним смешама HDPE:PS. Однос HDPE:PS = 1:3 дао је 96 % ароматичних једињења, која су продукти распадања PS. PET је продуковао производе који углавном садрже

кисеоник, и који доприносе са 86 % пиролизату смеше HDPE:PS = 1:3. Ови резултати дају увид у потенцијал пластичног отпада као одрживог извора алтернативних горива и вредних хемикалија.

(Примљено 7. фебруара, ревидирано 1. марта, прихваћено 12. априла 2024)

#### REFERENCES

1. <https://www.eea.europa.eu/publications/many-eu-member-states/germany>
2. L. Dai, N. Zhou, Y. Lv, Y. Cheng, R. Ruan, Y. Liu, K. Cobb, P. Chen, H. Lei, R. Ruan, *Progr. Energy Combust. Sci.* **93** (2022) 101021 (<https://doi.org/10.1016/j.pecs.2022.101021>)
3. J. Scheirs, W. Kaminsky, *Feedstock recycling and pyrolysis of waste plastics: Converting waste plastics into Diesel and other fuels*, Wiley Pol. Sci., 2006 (ISBN: 0-470-02152-7)
4. M. Rehan, A.-S. Nizami, K. Shahzad, O. K. M. Ouda, I. M. I. Ismail, T. Almeelbi, T. Iqbal, A. Demirbaş, *En. Source, A* **38** (2016) 2598 (<https://doi.org/10.1080/15567036.2016.1153753>)
5. D. S. Achilias, C. Roupakias, P. Megalokonomos, A. A. Lappas, E. V. Antonakou, *J. Hazard. Mater.* **149** (2007) 536 (<https://doi.org/10.1016/j.jhazmat.2007.06.076>)
6. P. Rutkowski, A. Kubacki, *En. Con. Manage.* **47**(6) (2006) 716 (<https://doi.org/10.1016/j.enconman.2005.05.017>)
7. M. Brebu, S. Uçar, C. Vasile, J. Yanık, *Fuel* **89** (2010) 1911 (<https://doi.org/10.1016/j.fuel.2010.01.029>)
8. B. B. Uzoejinwa, X. He, S. Wang, A. E. Abomohra, Y. Hu, Q. Wang, *En. Con. Manage.* **163** (2018) 468 (<https://doi.org/10.1016/j.enconman.2018.02.004>)
9. J. A. Onwudili, N. Insura, P. T. Williams, *J. Anal. Appl. Pyrolysis* **86**(2) (2009) 293 (<https://doi.org/10.1016/j.jaap.2009.07.008>)
10. R. U. Henneberg, R. P. Nielsen, M. E. Simonsen, *J. Anal. Appl. Pyrolysis* **173** (2023) 106037 (<https://doi.org/10.1016/j.jaap.2023.106037>)
11. E. A. Williams, P. T. Williams, *J. Anal. Appl. Pyrolysis* **40–41** (1997) 347 ([https://doi.org/10.1016/s0165-2370\(97\)00048-x](https://doi.org/10.1016/s0165-2370(97)00048-x))
12. E. Dziwiński, J. Howska, J. Gniady, *Pol. Test.* **65** (2018) 111 (<https://doi.org/10.1016/j.polymertesting.2017.11.009>)
13. J. Choi, F. Jitsunari, F. Asakawa, D. S. Lee, *Food Addit. Contam.* **22**(7) (2005) 693 (<https://doi.org/10.1080/02652030500160050>)
14. R. Pfaendner, *Pol. Deg. Stab.* **91** (2006) 2249 (<https://doi.org/10.1016/j.polymdegradstab.2005.10.017>)
15. S. Al-Malaika, F. H. Axtell, R. Rothon, M. Gilbert, in *Brydson's Plastics Materials*, VIII ed., M. Gilbert, Ed., Elsevier, Amsterdam, 2017, pp. 127 (<https://doi.org/10.1016/b978-0-323-35824-8.00007-4>)
16. X. Ren, R. Chang, Y. Huang, A. A. Amato, C. Carivenc, M. Grimaldi, Y. Kuo, P. Balaguer, W. Bourguet, B. Blumberg, *Endocrinology* **164** (2023) 1 (<https://doi.org/10.1210/endocr/bqad021>)
17. C. Apel, J. Tang, R. Ebinghaus, *Env. Poll.* **235** (2018) 85 (<https://doi.org/10.1016/j.envpol.2017.12.051>)
18. *Material Safety Data Sheet*, <https://datasheets.scbt.com/sc-223762.pdf>
19. Z. Wen, L. Fang, H. Zhang, *Drug Deliv.* **16**(4) (2009) 214 (<https://doi.org/10.1080/10717540902836715>)
20. I. Y. R. Adamson, J. Weeks, *Arch. Env. Health* **27** (1973) 69 (<https://doi.org/10.1080/00039896.1973.10666320>)

21. C. A. Baldrich, *Diesel characterization by high resolution mass spectrometry-gas chromatography*, C.T.F Cienc. Tecnol. Futuro [online], vol. **1**, n. 4, 1998, pp. 65 (ISSN 0122-5383)
22. S. C. Gad, Diesel fuel, in *Encyclopedia of Toxicology*, Elsevier eBooks, Amstrdam, 2005, pp. 19 (<https://doi.org/10.1016/b0-12-369400-0/00320-3>)
23. M. Huth, A. Heilos, in *Modern Gas Turbine Systems*, P. Jansohn, Ed., Woodhead Publishing Ltd., Sawston, 2013, pp. 635 (<https://doi.org/10.1533/9780857096067.3.635>)
24. *Diesel fuel and exhaust emissions*, (Environmental Health Criteria, 171), World Health Organization, Geneva, 1996 (ISBN 92-4-157171-3, <https://www.inchem.org/documents/ehc/ehc/ehc171.htm>)
25. C. Zhou, A. Farooq, L. Yang, A. M. Mebel, *Prog. Energy Combust. Sci.* **90** (2022) 100983 (<https://doi.org/10.1016/j.pecs.2021.100983>)
26. V V. L. Mangesh, S. Padmanabhan, P. Tamizhdurai, S. S. Narayanan, R. Arumugam, *J. Hazard. Mater.* **386** (2020) 121453 (<https://doi.org/10.1016/j.jhazmat.2019.121453>)
27. A. Çakıcı, J. Yanık, S. Uçar, T. Karayıldırım, H. Anıl, *J. Mater. Cycles Waste Manage.* **6** (2004) 20 (<https://doi.org/10.1007/s10163-003-0101-y>)
28. A A. R. Ardiyanti, C. A. Хромова, R. H. Venderbosch, V. A. Yakovlev, H. J. Heeres, *Appl. Catal., B* **117–118** (2012) 105 (<https://doi.org/10.1016/j.apcatb.2011.12.032>)
29. I. Hita, A. Gutiérrez, M. Olazar, J. Bilbao, J. M. Arandes, P. Castaño, *Fuel* **145** (2015) 158 (<https://doi.org/10.1016/j.fuel.2014.12.055>)
30. *CONCAWE Review* **11**(2) (2002) 10 (<https://www.concawe.eu/wp-content/uploads/cr112-aromatics-2003-01897-01-e.pdf>)
31. M. J. DeWitt, E. Corporan, J. Graham, D. K. Minus, *Energy Fuels* **22** (2008) 2411 (<https://doi.org/10.1021/ef8001179>)
32. S. Sharma, P. Singh, C. Bhardwaj, B. Khandelwal, S. Kumar, *Energy Fuels* **35** (2021) 3150 (<https://doi.org/10.1021/acs.energyfuels.0c03511>)
33. E. B. Strel'nikova, I. V. Goncharov, O. B. Серебренникова, *Pet. Chem.* **52** (2012) 278 (<https://doi.org/10.1134/S096554411204010X>)
34. A. G. A. Jameel, Y. Han, O. Brignoli, S. Telalović, A. M. Elbaz, H. G. Im, W. L. Roberts, *J. Anal. Appl. Pyrolysis* **127** (2017) 183 (<https://doi.org/10.1016/j.jaap.2017.08.008>)
35. M. Z. H. Khan, M. Sultana, Md. R. Al-Mamun, Md. R. Hasan, *J. Env. Pub. Health* **2016** (2016) 7869080 (<https://doi.org/10.1155/2016/7869080>)
36. Wilke, S. (n.d.). Kunststoffabfälle. *Umweltbundesamt* (<https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/kunststoffabfaelle#kunststoffvielfalt>).