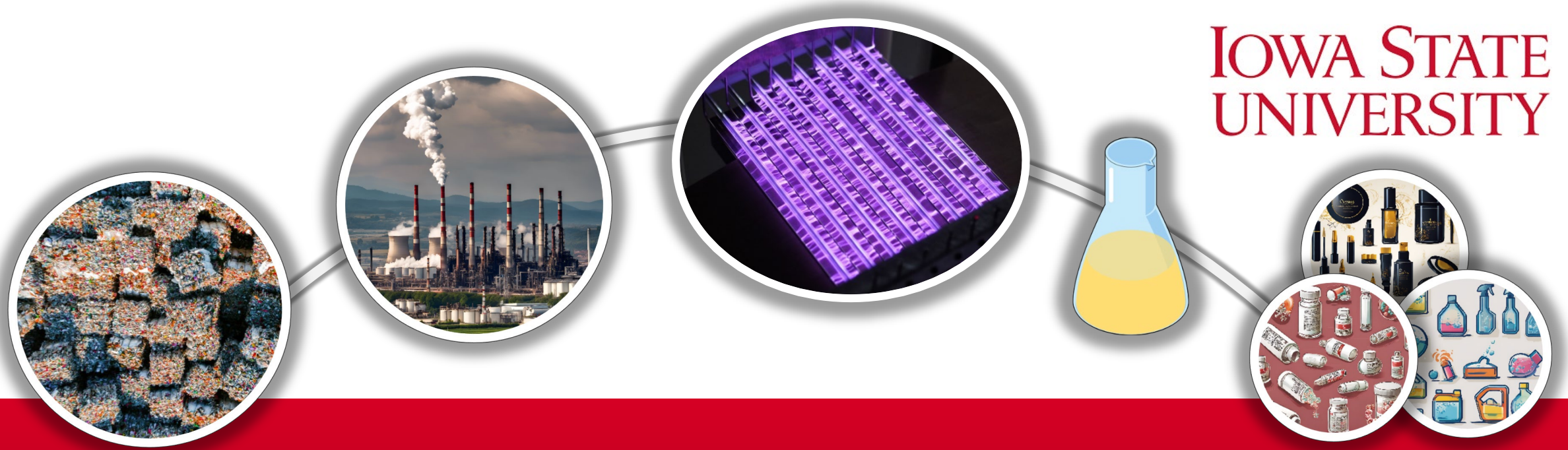

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Synergistic Upcycling of Waste Plastics and CO_2 into Oleochemicals via Non-Thermal Plasma

Harish Radhakrishnan, Xianglan Bai*

***tc*biomass 2024**
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Co-authors

Alif Duereh, Sultan Ul Iffat Uday, A Lusi, Haiyang Hu, Hui Hu

Plastic Wastes and Current Recycling

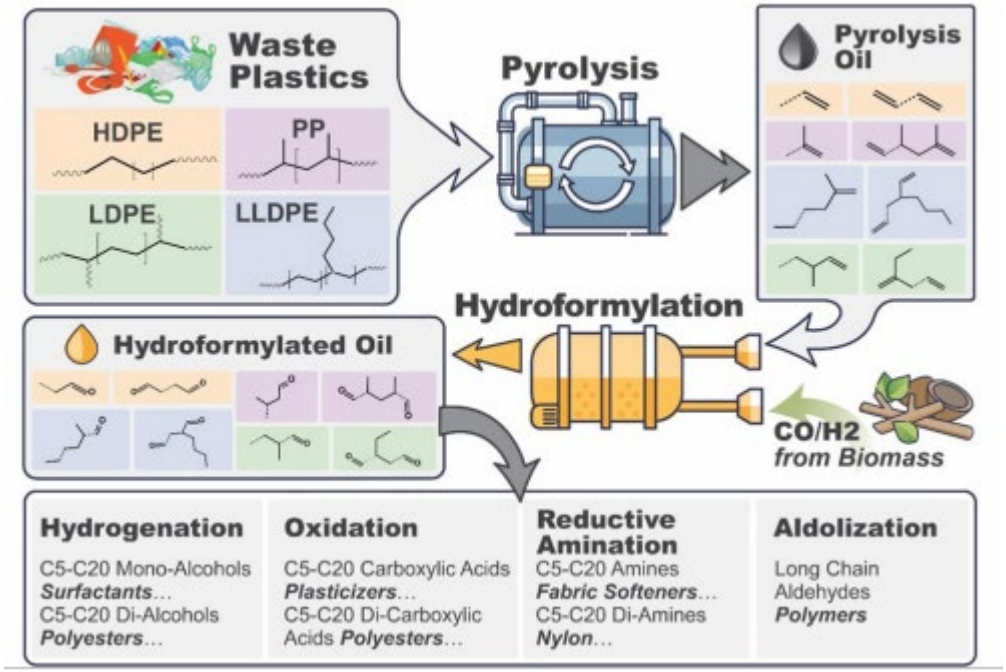
- Plastic waste globally: 2Mt in 1950, 260 Mt in 2018 and 350 Mt in 2023. [1, 2, 3]
- 48 Mt in the US (majority polyolefins), contributing to 12.2% of all MSW. [2]
- Only 8.7% of plastic waste recycled in the US, mostly by mechanical routes. [4]

[1] McKinsey & Company, [2] US EPA, Environmental Protection Agency
[3] OurWorldinData, [4] US EPA, Environmental Protection Agency

Production of Oleochemicals from Polyolefin Waste

"Polyolefin pyrolysis yields low value hydrocarbons, but rich in olefins"

Houqian Li *et al.*, *Science* 381, 660-666 (2023)



New Trends for Value-addition

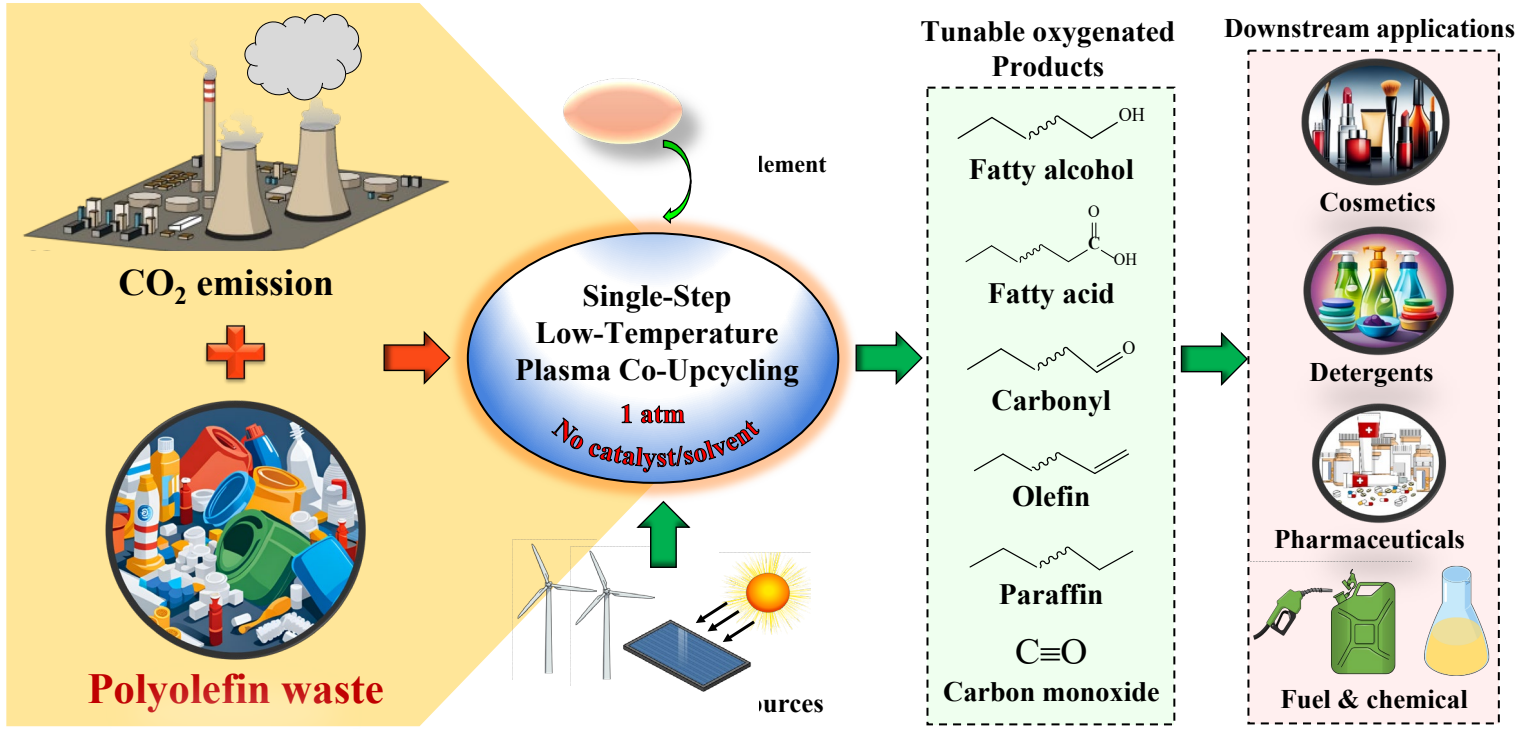
Synthetic Oleochemicals

- *Ziegler process*
  - Oligomerize ethylene to olefins
  - Oxidative hydrolysis to alcohols
- *Oxo process*
  - Olefins hydroformylation
  - Hydrogenation to alcohols
- *Catalytic oxidation* (Co/Mn) of paraffins to fatty acids, alcohols, and ketones
- Multi-step, high pressure, $$$ catalysts

Plasma Upcycling of Waste Plastics and GHG CO_2

"DOE to disperse $12 billion for carbon capture and utilization projects in coming years"
Source: GAO

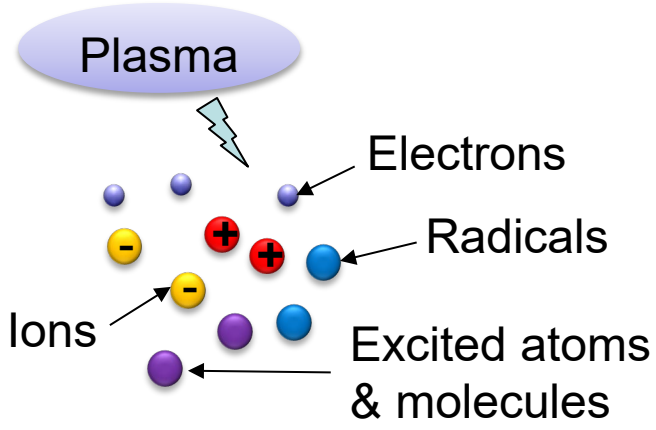
- Single-step electrified process to produce oleochemicals.
- Simultaneously upcycles waste plastics and utilizes CO_2 as a feedstock.
- CO_2 as oxidant/carbon source.
- Carbon-negative chemicals via CO_2 utilization.



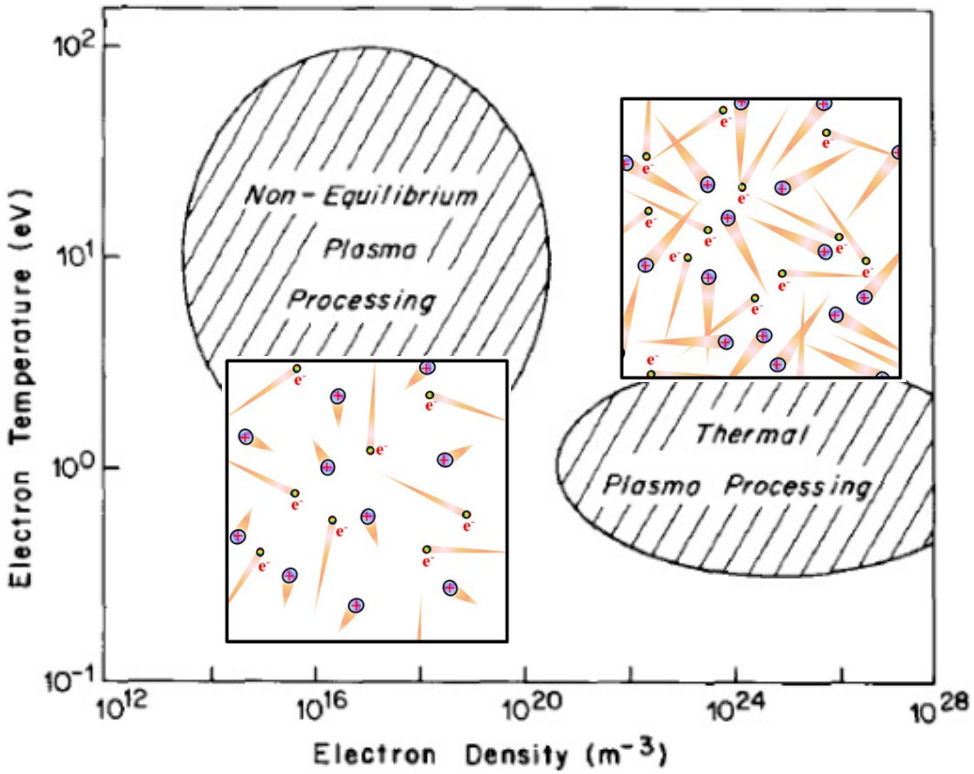
Proposed plasma-based routes to produce oleochemicals and syngas CO from polyolefin waste and CO_2

Plasma and its Classification

Plasma in nature



Plasma species

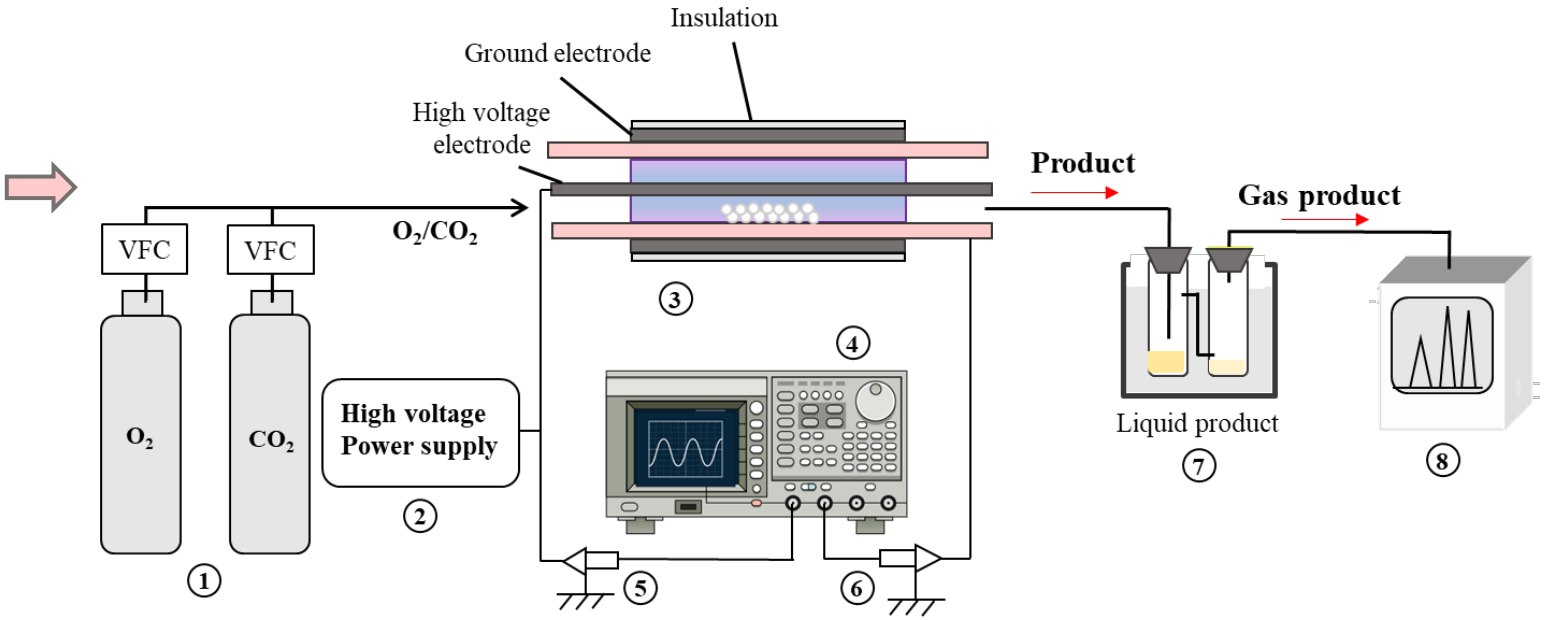


Non-thermal vs thermal Plasma

Plasma discharge creates an ionized and chemically rich environment.

Non-thermal Plasma-based Polyolefins Conversion Setup

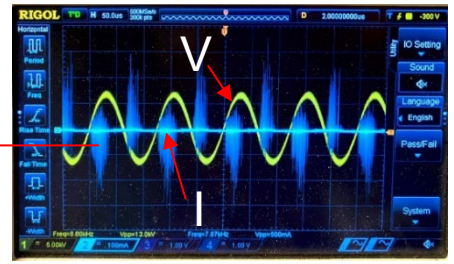
Waste Polyolefins
(pulverized)



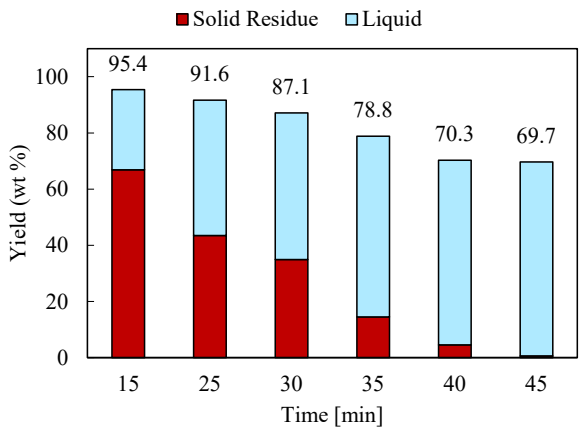
Experimental setup

1. gas cylinders
2. high-voltage plasma power supply
3. plasma reactor
4. oscilloscope
5. high-voltage probe
6. current probe
7. condenser
8 μ-GC.

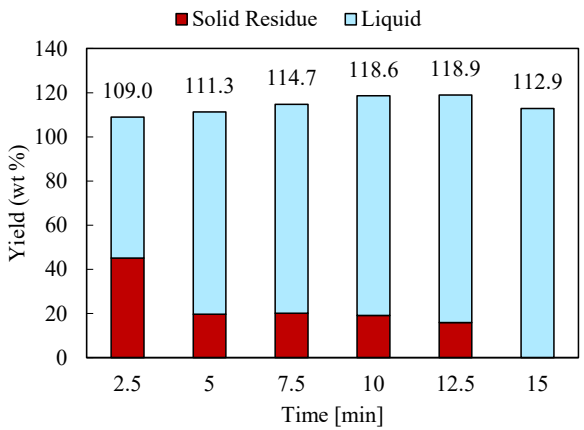
Current spikes due to gas breakdown and discharge



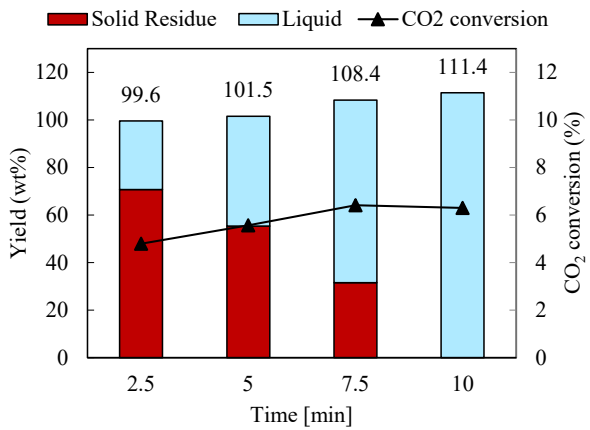
Plastic Conversion under Different Plasma Gases



Argon



Air

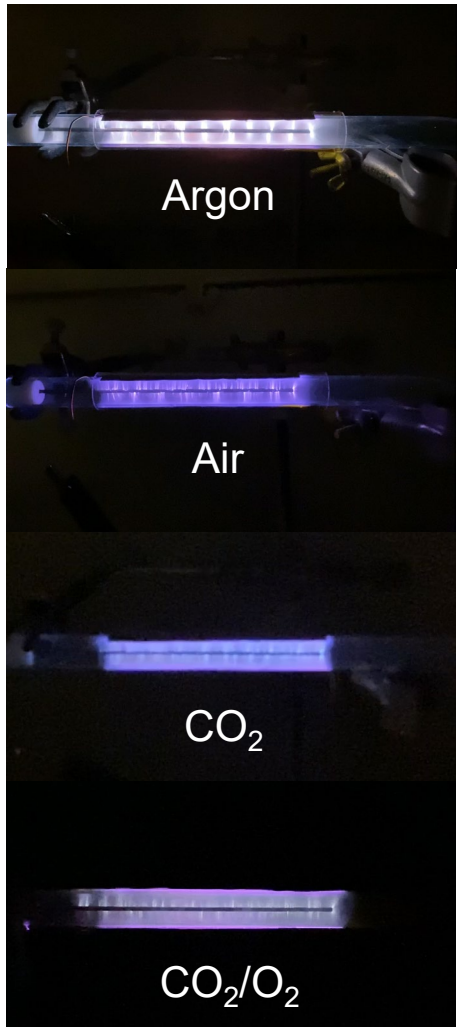


CO_2

T = 350 °C; V = 15 kV; f = 8 kHz; Q (t_R) = 50 mL/min (13s)

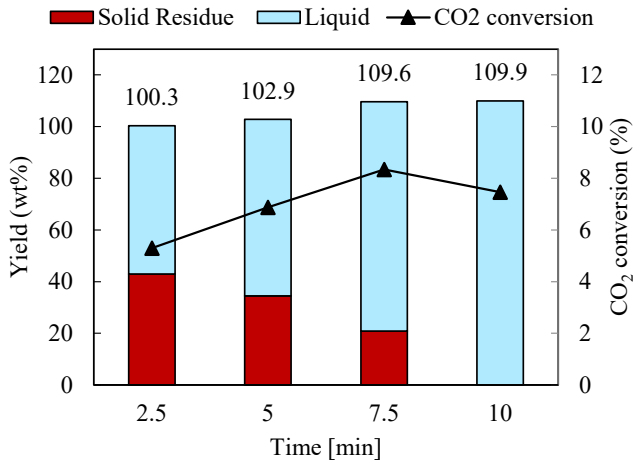
Plasma Atmosphere Comparison

- PE decomposed under different plasma atmospheres.
- CO_2 plasma (10 min) converted PE faster than argon (45 min) and air (15 min) plasma under the same plasma condition.

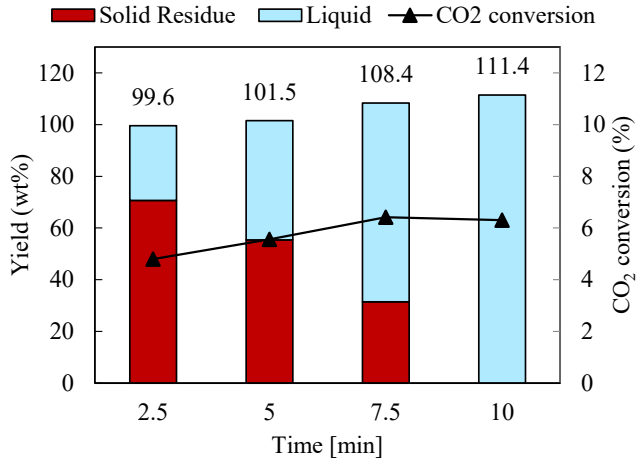


PE Conversion under CO_2 Plasma: Effect of Gas Residence

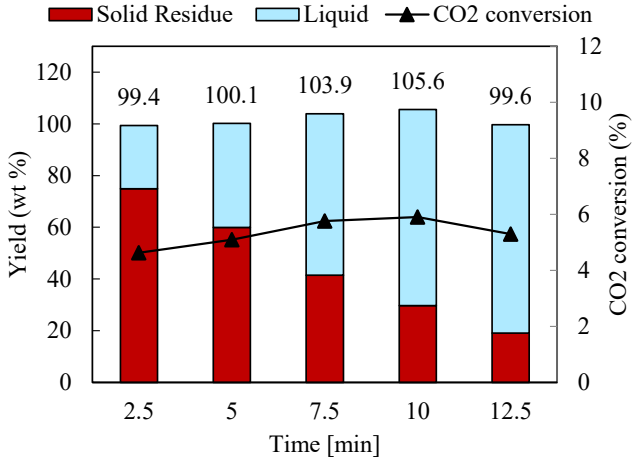
- Both CO_2 and PE conversion increased when flow rates decreased.
- Highest CO_2 conversion of 7.5 wt% at 20s gas residence where the liquid yield was 109.9 wt%.
- Highest liquid at 13s gas residence while CO_2 conversion reduced with decreasing gas residence.



32.5 mL/min (20s)



50 mL/min (13s)

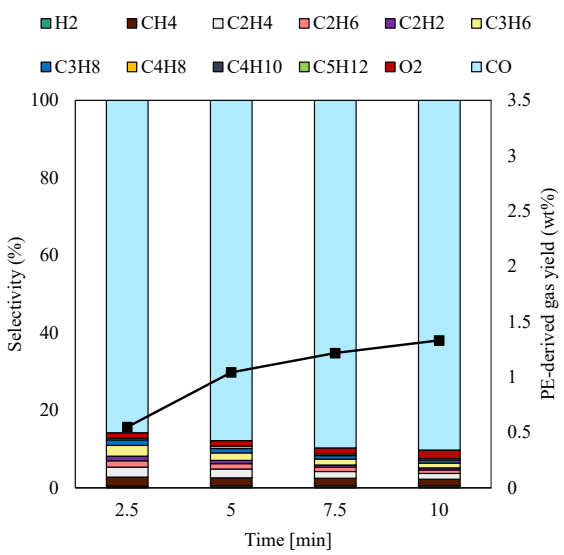


65 mL/min (10s)

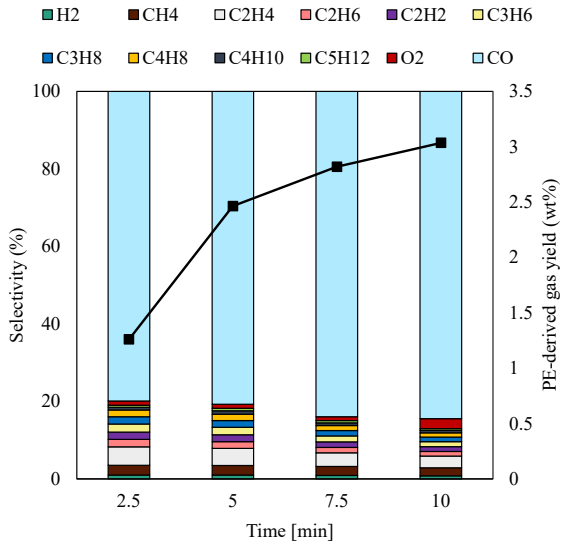
T = 350 °C; V = 15 kV; f = 8 kHz

Gas Residence Time Comparison

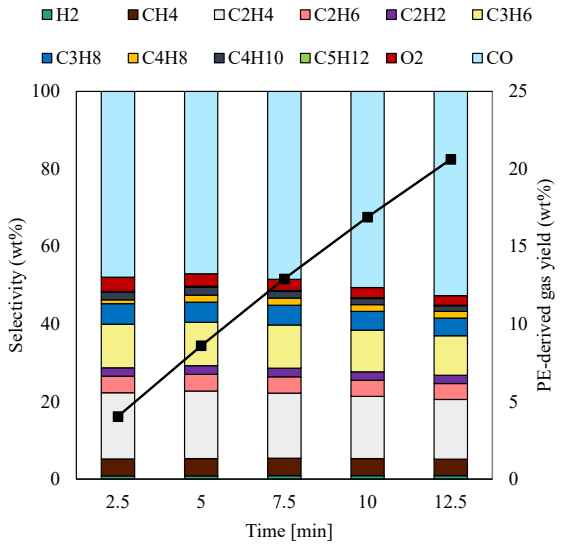
PE Conversion under CO_2 Plasma: Gas Products



32.5 mL/min (20s)



50 mL/min (13s)



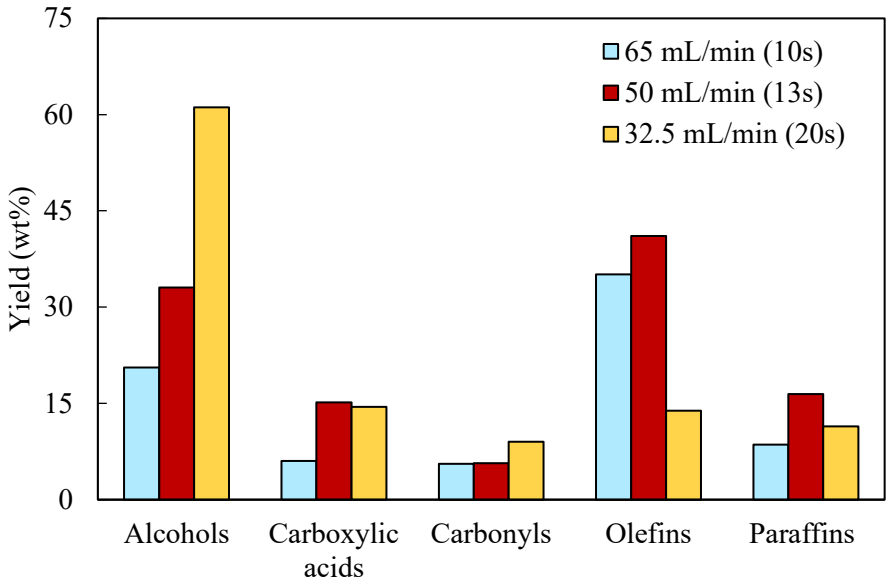
65 mL/min (10s)

T = 350 °C; V = 15 kV; f = 8 kHz

Gas Residence Time Comparison

- Hydrocarbon gas yield reduced with higher gas residences, from 21% to 1.3%.
- Syngas CO selectivity also increased to 85%.

PE Conversion under CO_2 Plasma: Liquid Products



Feedstock	t_R=20s	t_R=13s	t_R=10s
	wt%	wt%	wt%
Liquid product carbon number distribution			
C_5-C_{12}	50.1	28.2	15.6
C_{13}-C_{20}	24.4	23.4	13.1
C_{21}-C_{28}	19.2	22.3	12
C_{28}+	16.2	37.2	39.9
Elemental analysis of liquid product (wt%)			
C (%)	79.6	80.9	82.8
H (%)	13	13	13
O (%)	7.8	6.2	3.9

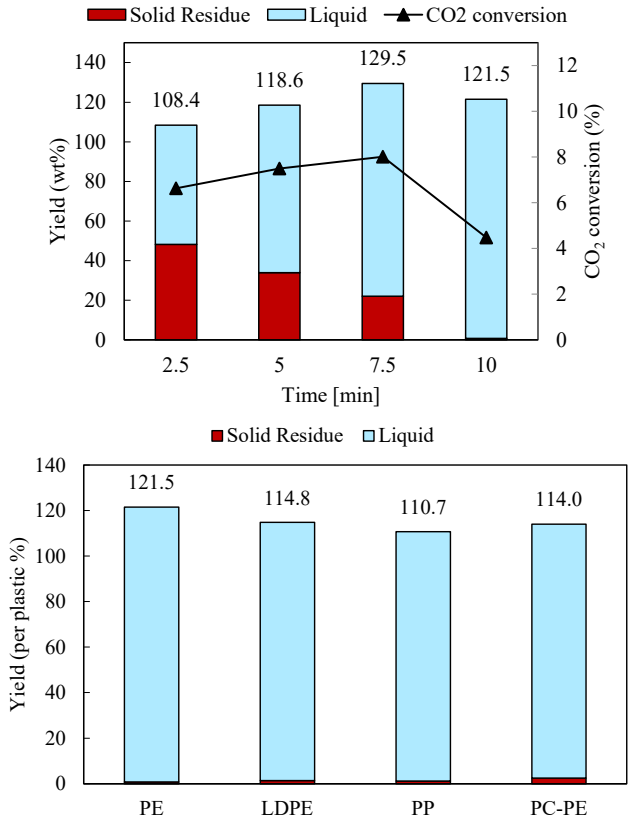
T = 350 °C; V = 15 kV; f = 8 kHz

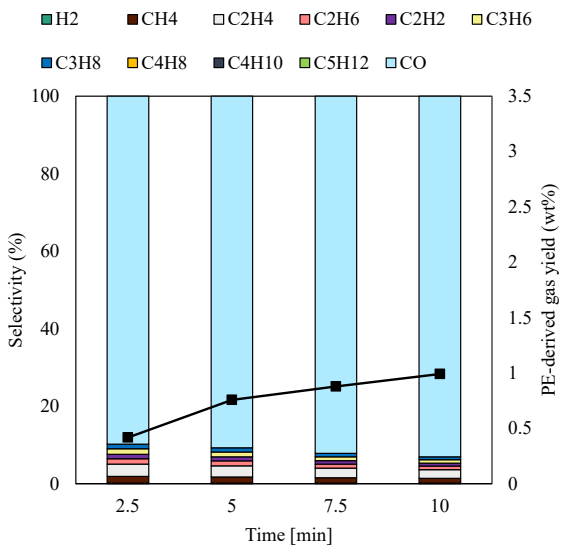
Gas Residence Time Comparison

- Liquid products: fatty alcohols (major), fatty acids, carbonyls, olefins, and paraffins.
- Lower molecular weight products are produced with increasing gas residence.

PE Conversion under CO_2/O_2 Plasma

- Adding 8 vol% O_2 to CO_2 plasma increased liquid yield to 121.5 wt%.
- CO_2/O_2 plasma produces lower PE-derived hydrocarbon gas yield than CO_2.
- Gas streams are CO-rich with more than 90% selectivity from CO_2/O_2 plasma. Syngas?
- LDPE, PP, and mixed waste PE converted with 110-115 wt% liquid yields.

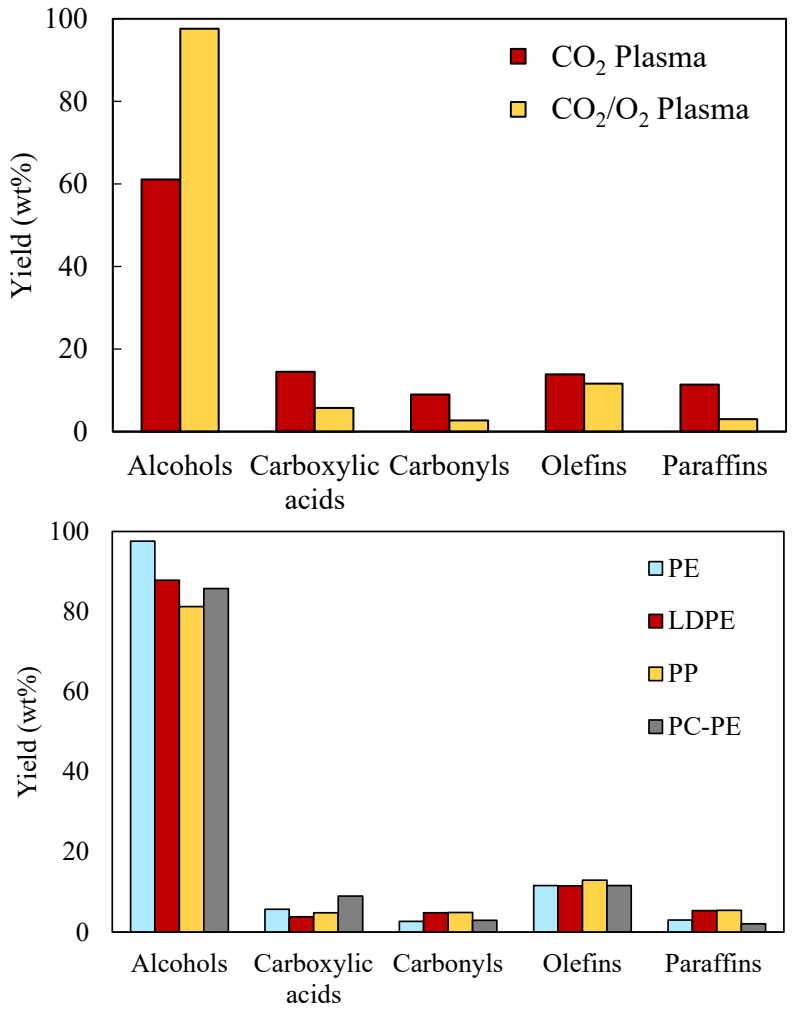




T = 350 °C (PE)/325 °C (others)
V = 15 kV; f = 8 kHz;
Q (t_R) = 50 mL/min (13s)

Time-resolved product yields and gas product selectivity

PE Conversion under CO_2/O_2 Plasma



Feedstock	HDPE	LDPE	PP	PC-PE
	wt%	wt%	wt%	wt%
Liquid product carbon number distribution				
C_5-C_{12}	64.4	66.8	60.1	76.6
C_{13}-C_{20}	37.1	30.5	32.7	22.4
C_{21}-C_{28}	13.2	7.6	15.6	6.4
C_{28}+	6.1	4.7	2.6	7.8
Elemental analysis of liquid product				
C (%)	76.7	76.5	77	76.1
H (%)	12.1	12.2	12.1	12.1
O (%)	11.2	10.5	10.9	11

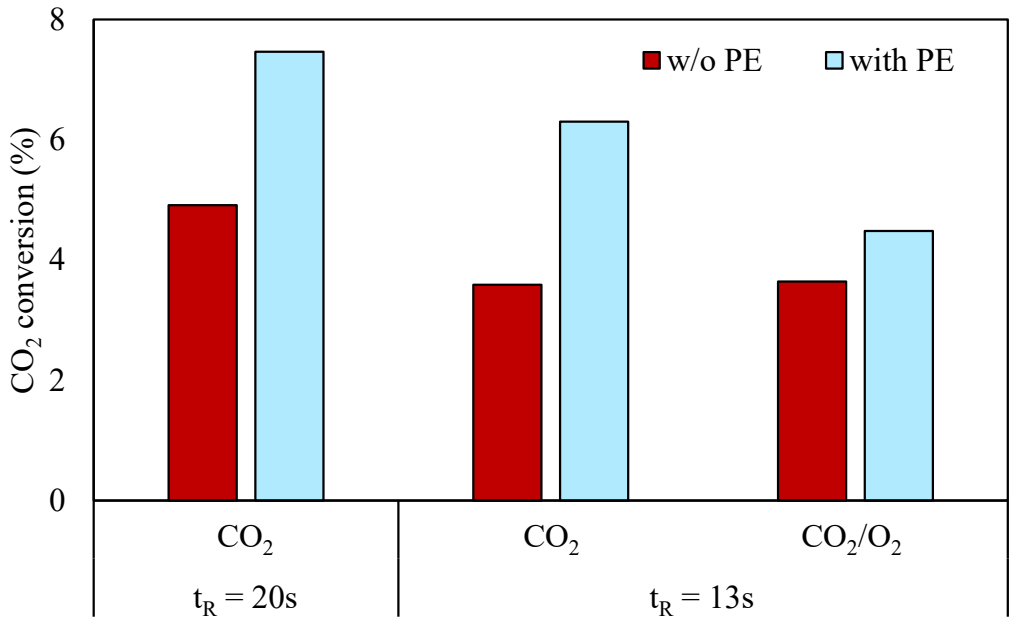
T = 350 °C (for HDPE) and 325 °C (for others)
V = 15 kV; f = 8 kHz;
Q (t_R) = 50 mL/min (13s)

- Maximum fatty alcohol yield increased from 61.1 to 97.6 wt% after O_2 induction.
- Oxygen content in the liquid increased from 7.8 to 11.2%.
- LDPE and PP produced lighter oxygenates.

GC mass yield of different functional groups in the liquid product

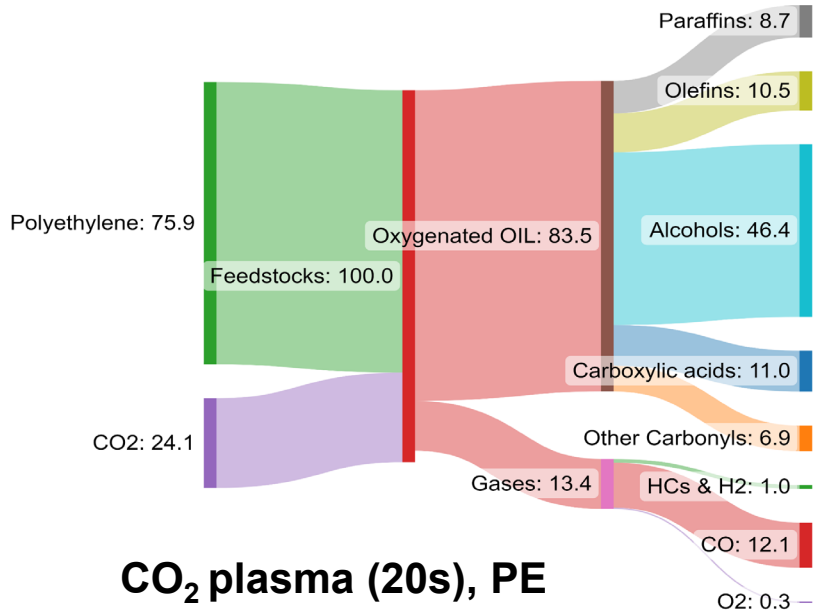
Effect of Plastic on CO_2 Conversion

- CO_2 conversion was measured under the same plasma condition without and with plastic in the reactor.
- Co-conversion with plastic showed a synergistic increase in CO_2 conversion.
- Adding O_2 resulted in lower CO_2 conversion

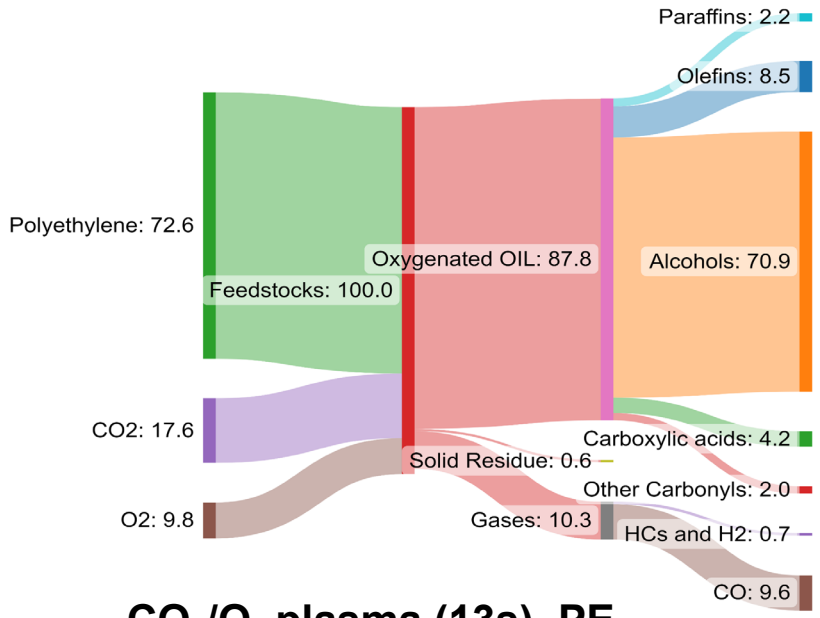


CO_2 conversion without and with plastic

Mass balance of the plasma process



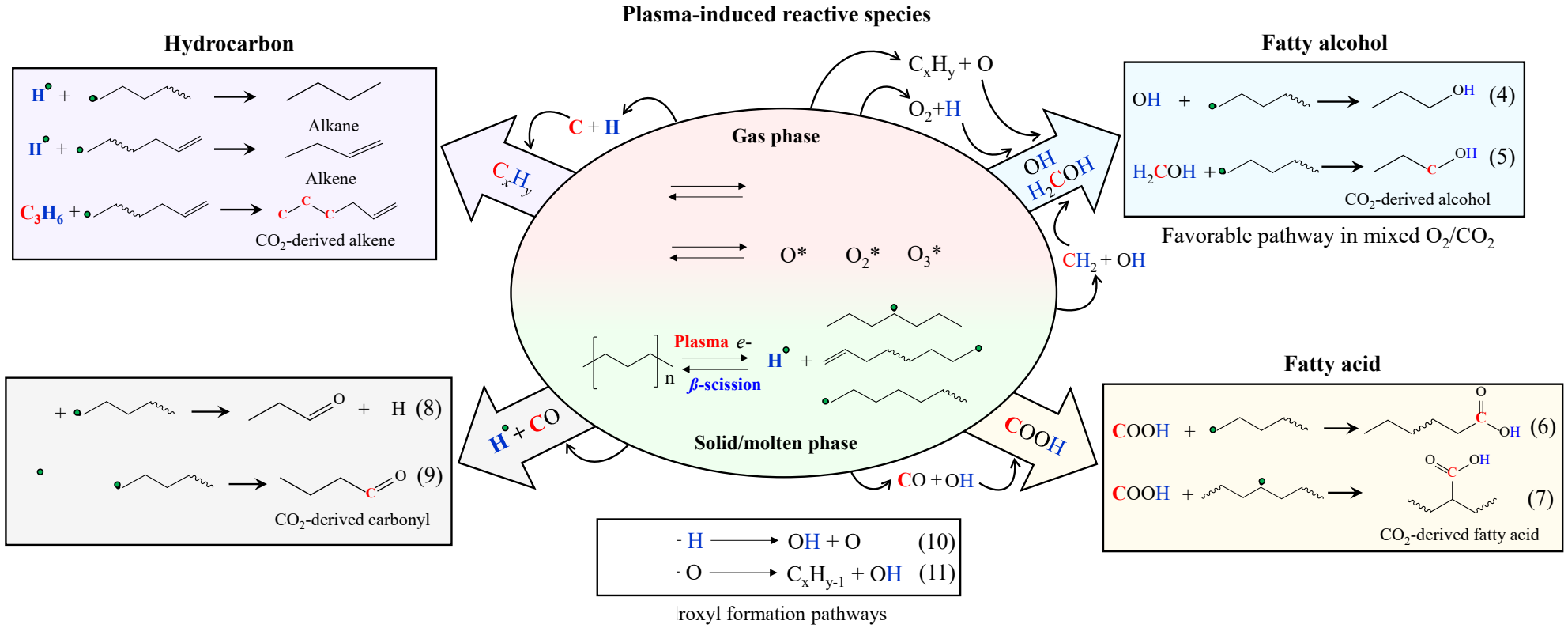
CO_2 plasma (20s), PE



CO_2/O_2 plasma (13s), PE

- Mass closure normalized to converted plastic and converted CO_2 or CO_2/O_2.
- Fatty alcohols constitute majority of the liquids from both CO_2 or CO_2/O_2.
- Syngas CO is the major product among gases.

Reaction Mechanism for Co-upcycling of Polyolefin and CO_2



*Plasma-induced reactive species including atoms, ions, radicals and molecules in their different states

Isotopic-study based reaction pathways for co-upcycling of polyolefins with CO_2 or CO_2/O_2 plasma

Conclusion

- Co-upcycling caused a synergistic increase in both CO_2 and plastics conversion.
- CO_2 and CO_2/O_2 had a higher conversion rate than argon or air plasma.
- Plastic acted as a scavenger and carbon sink to increase CO_2 conversion.
- CO_2 plasma-based deconstruction of HDPE can increase the liquid yield per plastic mass beyond 100% due to oxygen and carbon induction.
- Adding 8 vol% O_2 to CO_2 increased fatty alcohol yield to 97.6 wt% from 61.1 wt% without catalyst.
- Potentially carbon-negative route to produce industrial chemicals by utilizing waste CO_2 and polyolefin plastics.
- A patent-pending technology is developed to produce oleochemicals from waste plastics using CO_2 and electricity.

Acknowledgements

This research is funded by

Advisor | *Prof. Xianglan Bai*

Co-authors | *Samirah Gnangbe, Alif Duereh, Sultan Ul Iffat Uday, A Lusi, Haiyang Hu, Hui Hu, Mark Mba-Wright*

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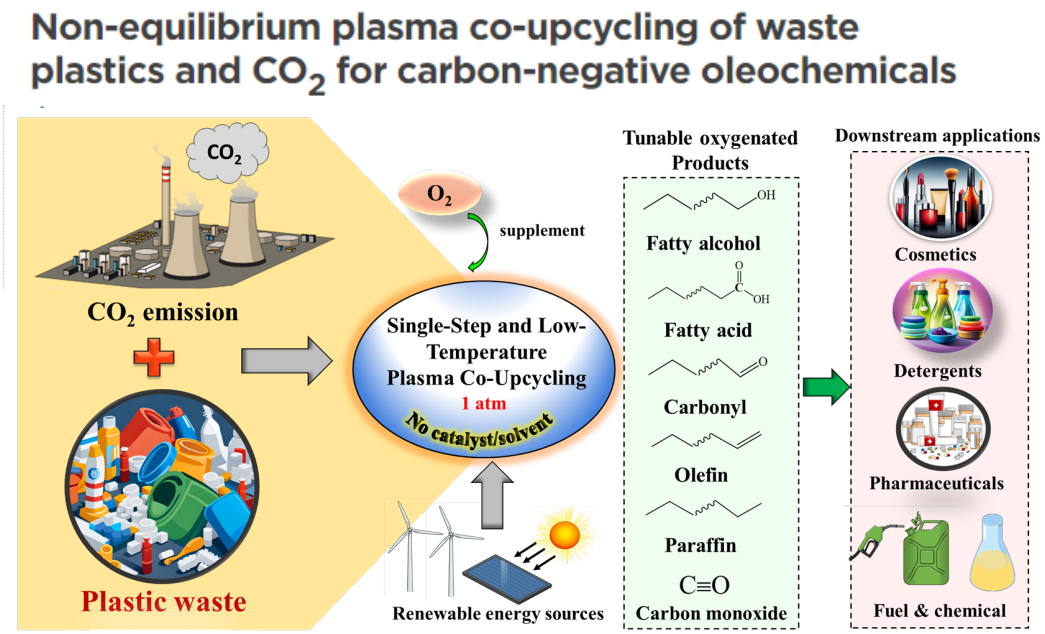
Questions?

Issue 16, 2024

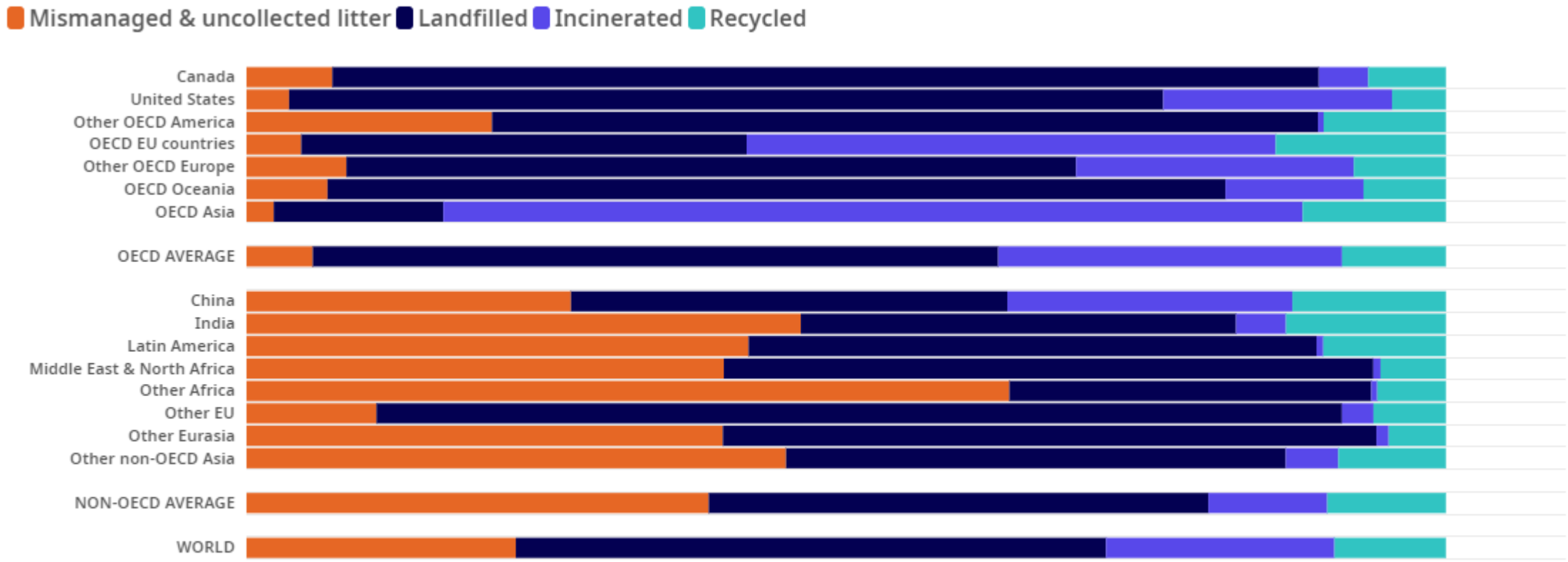
From the journal:
Green Chemistry

Full Paper



Supplementary Information

Background

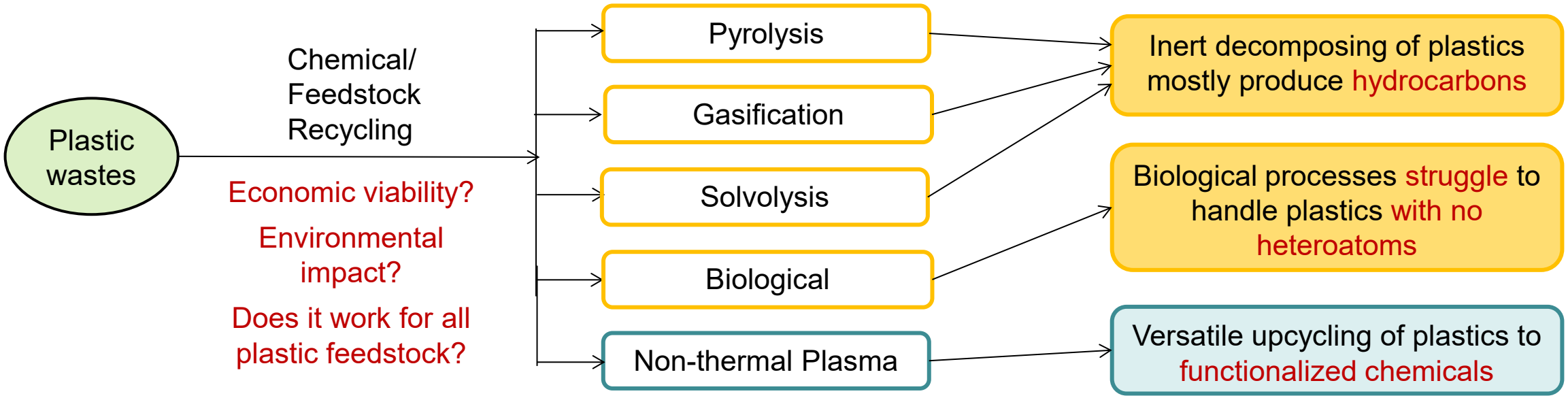


Source: OECD Global Plastics Outlook Database

OECD

Plastic Wastes and Current Recycling

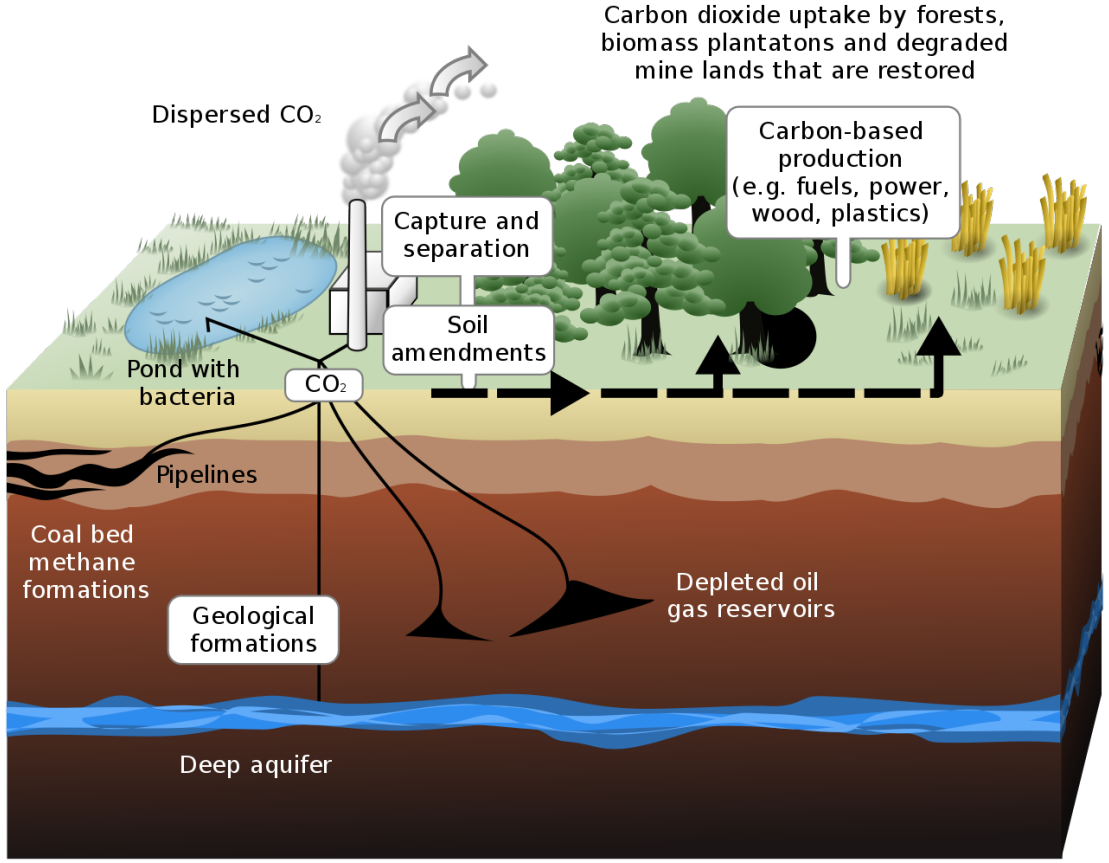
- Plastic waste globally: 2Mt in 1950, 260 Mt in 2018 and 350 Mt in 2023. [1, 2, 3]
- 48 Mt in the US (majority polyolefins), contributing to 12.2% of all MSW. [2]
- Only 8.7% of plastic waste recycled in the US, mostly by mechanical routes. [4]



[1] McKinsey & Company
[2] US EPA, Environmental Protection Agency
[3] OurWorldinData
[4] US EPA, Environmental Protection Agency

CO_2 Utilization for Carbon Sequestration

- CO_2 releases mostly from fossil fuel combustion
- CO_2 accounts for approximately 55% of the yearly anthropogenic greenhouse gas emissions responsible for global warming
- GHG emissions have a detrimental effect on the ecosystem and weather patterns
- CO_2 utilization can reduce its concentration in the atmosphere, and using CO_2 as a carbon source can help reach global carbon neutrality goals

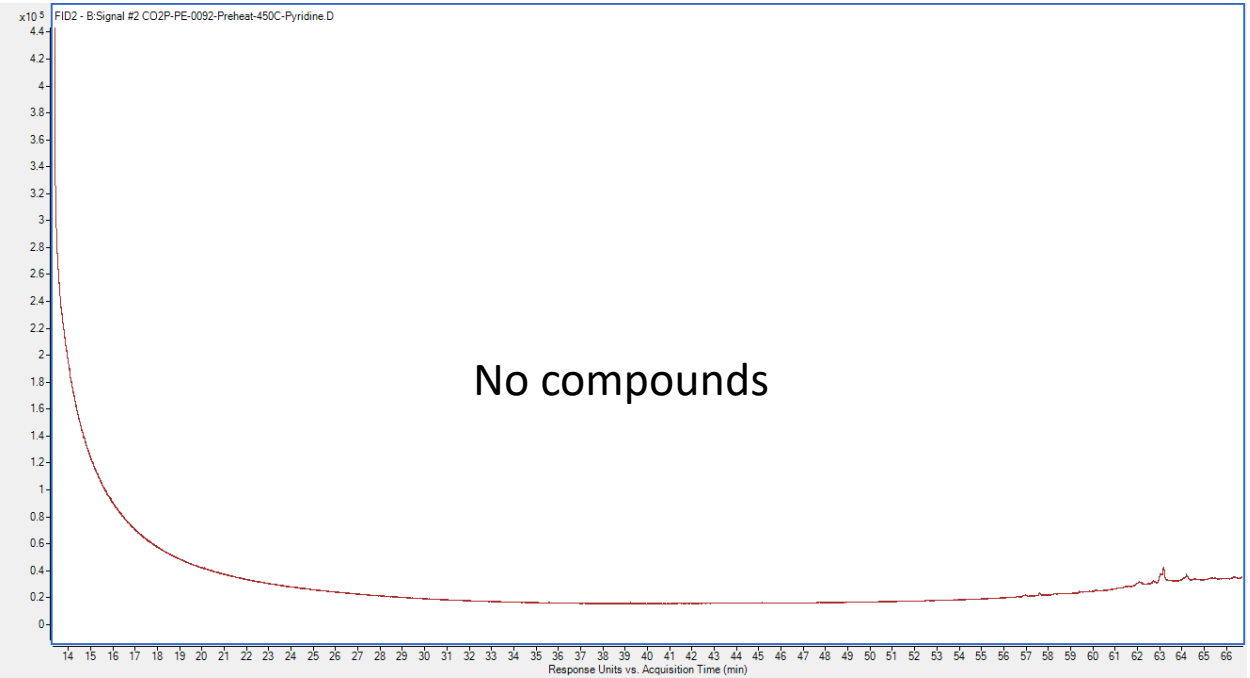


Current carbon sequestration ideas [1]

[1] LeJean Hardin and Jamie Payne. Oak Ridge National Laboratory. http://www.ornl.gov/info/ornlreview/v33_2_00/research.htm

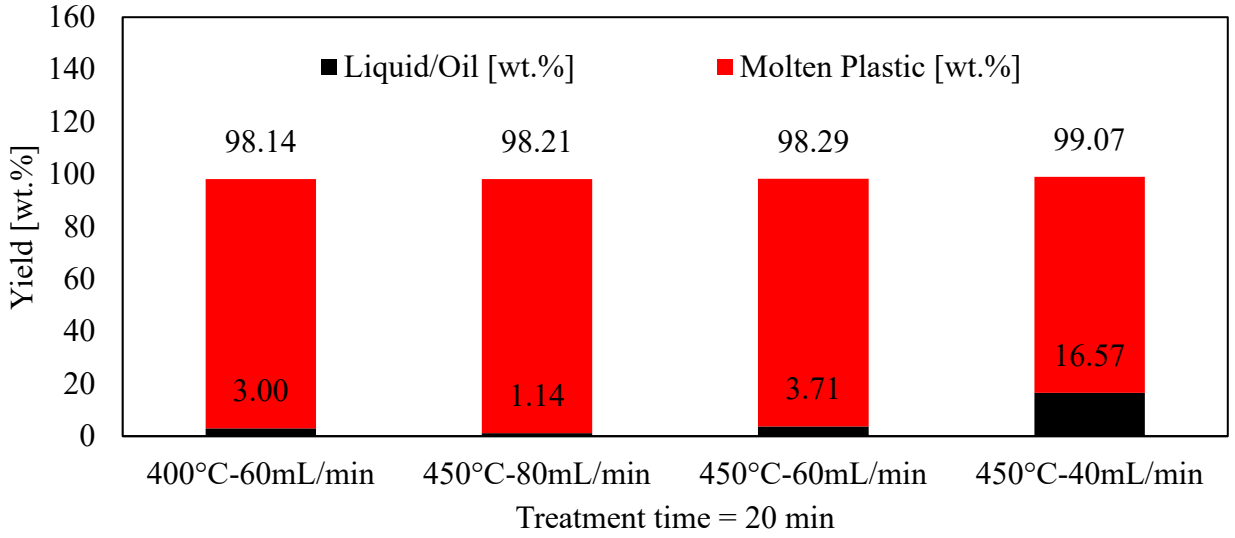
Preheating of the Reactor prior to the Plasma Actuation

- Pre-heating of the reactor to melt the plastic.
- A higher atmospheric temperature can lower the electricity conditions for the plasma actuation.
- Increasing the temperature of the gas will fasten the process of plasma breakdown.
- Prior to applying the plasma, the plastic did not devolatilize, which is proven by the GC/MS analysis of the molten plastic.



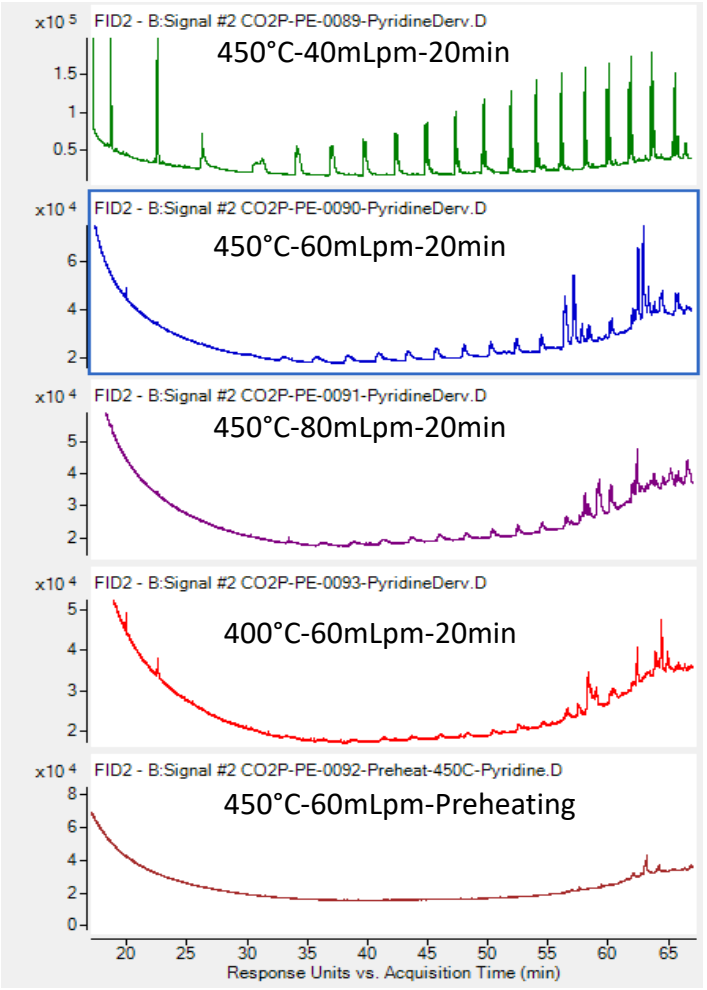
GCMS spectra of the sample with only pre-heating

Thermal Conversion with CO_2 for Comparison



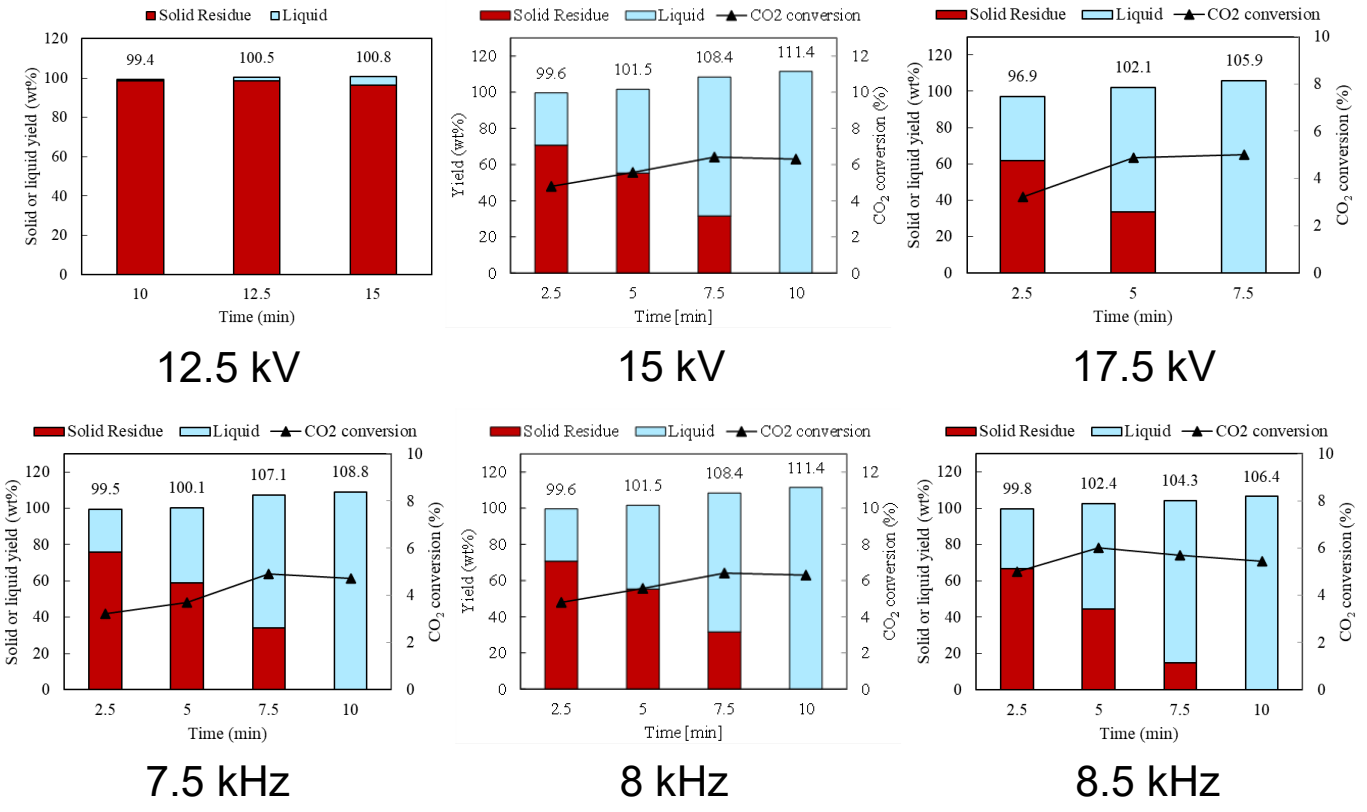
- Thermal cases do not yield oxygenated products. Only hydrocarbons were produced.
- The liquid yields were also lower compared to the CO_2 plasma-based conversion of HDPE.

Thermal cases



PE Conversion under CO_2 Plasma

- CO_2 plasma can decompose Polyethylene (PE) within 10 minutes.
- Highest liquid yield of 111.4 wt% per PE mass was achieved.
- The conversion rate of both PE and CO_2 increased with increased plasma voltage or frequency.



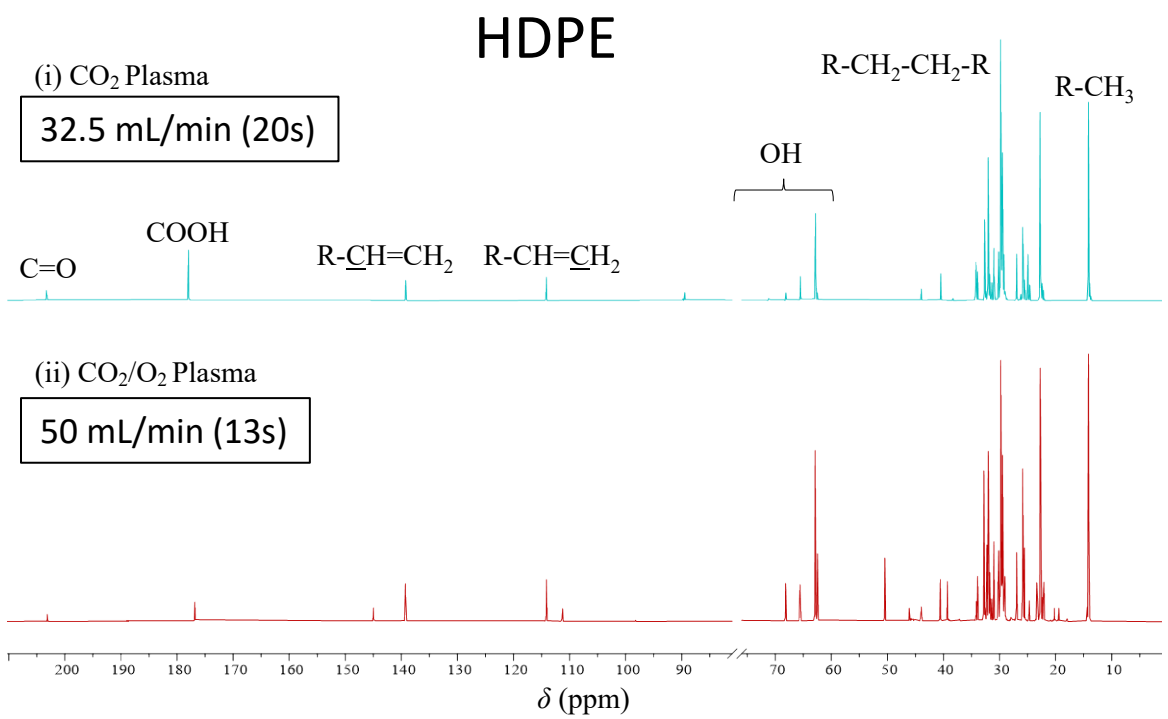
12.5 kV | 15 kV | 17.5 kV

7.5 kHz | 8 kHz | 8.5 kHz

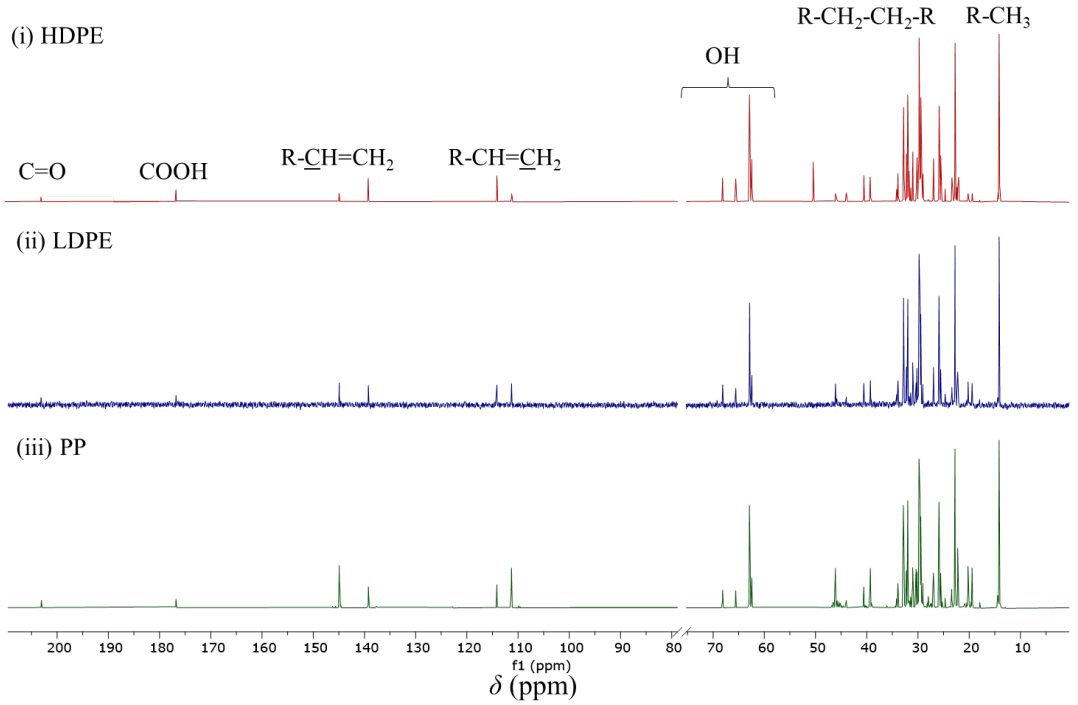
T = 350 °C; Q (t_R) = 50 mL/min (13s)
Fixed *f* = 8 kHz for **voltage comparison**
Fixed V = 15 kV for **frequency comparison**

NMR analysis of liquid products

All spectra: T = 350 °C; V = 15 kV; f = 8 kHz



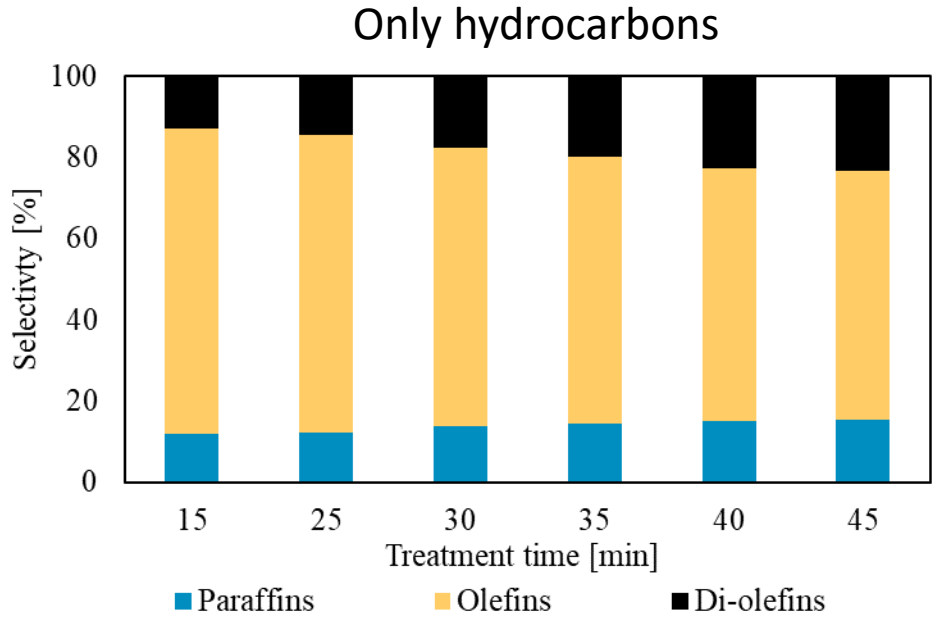
Functional Group	Plasma type	
	CO_2	CO_2/O_2
Alcohols	54.3	74.9
Carboxylic acids	16.2	5.1
Other oxygenated compounds	3.3	1.6
Hydrocarbons	26.2	18.5



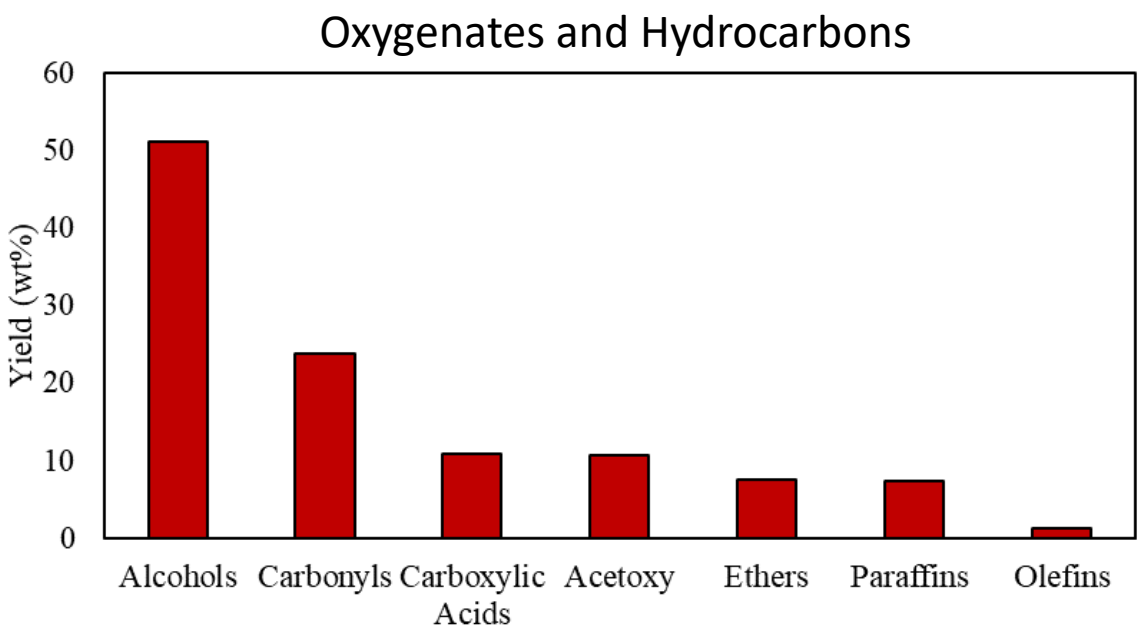
Functional Group	Feedstock	
	LDPE	PP
Alcohols	72.6	69.8
Carboxylic acids	2.6	3.3
Other oxygenated compounds	0.4	3.6
Hydrocarbons	24.4	23.3

Different Polyolefin Comparison: CO_2/O_2, Q (t_R) = 50 mL/min (13s)

Liquid Product Analysis of Air and Argon Plasma



Argon



Air (15 min)

T = 350 °C; V = 15 kV; f = 8 kHz; Q (t_R) = 50 mL/min (13s)

Plasma Atmosphere Comparison

Characterization of liquids obtained from different feedstock and reaction conditions

Condition *	Liquid yield (wt%)	Product carbon number distribution (wt%)				Elemental analysis (wt%)		
		C_5-C_{12}	C_{13}-C_{20}	C_{21}-C_{28}	C_{28}+	C (%)	H (%)	O (%)
B	111.4	28.2	23.4	22.6	37.2	80.9	12.9	6.2
C	105.9	39.6	33.3	20.1	12.9	82.2	13.1	4.7
D	108.8	22.4	21.9	21.2	43.3	81.2	13	5.8
E	106.4	39.1	25.2	27.1	15.0	80.6	13.1	6.3
F	80.6	15.6	13.1	12.0	39.9	82.8	13.3	3.9
G	109.9	50.1	24.4	19.2	16.2	79.6	12.6	7.8
H	101.2	29.8	24.2	10.5	36.7	81.5	13.1	5.4
I	86.1	18.5	16.8	43.3	7.5	84.9	13.5	1.7
J	120.7	64.4	37.1	13.2	6.0	76.7	12.1	11.2
K	115.3	61.0	41.2	12.9	0.0	78.1	12.1	9.8
L	110.8	56.7	29.2	16.5	8.4	76.8	12.2	11.0
M	105.8	31.5	53.8	15.2	5.2	78.8	12.5	7.5
N	98.1	36.5	40.8	17.0	3.8	78.7	12.5	7.6
O	113.5	76.7	22.5	6.5	7.8	76.8	12.2	11
P	109.5	66.8	30.5	7.6	4.7	77.2	12.3	10.5
Q	104.4	61.1	23.3	11.1	8.9	80.5	12.4	7.1
R	111.1	60.1	32.7	15.6	2.6	77	12.1	10.9

***Reaction conditions**

A: PE, 350 °C, CO2 gas, 50 mL/min or 13s, 12.5 kV, 8 kHz, 15 min (not included)

B: PE, 350 °C, CO2 gas, 50 mL/min or 13s, 15 kV, 8 kHz, 10 min

C: PE, 350 °C, CO2 gas, 50 mL/min or 13s, 17.5 kV, 8 kHz, 7.5 min

D: PE, 350 °C, CO2 gas, 50 mL/min or 13s, 15 kV, 7.5 kHz, 10 min

E: PE, 350 °C, CO2 gas, 50 mL/min or 13s, 15 kV, 8.5 kHz, 10 min

F: PE, 350 °C, CO2 gas, 65 mL/min or 10s, 15 kV, 8 kHz, 12.5

G: PE, 350 °C, CO2 gas, 32.5 mL/min or 20s, 15 kV, 8 kHz, 10 min

H: PE, 300 °C, CO2 gas, 50 mL/min or 13s, 15 kV, 8 kHz, 20 min

I: PE, 400 °C, CO2 gas, 50 mL/min or 13s, 15 kV, 8 kHz, 10 min

J: PE, 350 °C, CO2/O2 gas, 50 mL/min or 13s, 15 kV, 8 kHz, 10 min

K: PE, 350 °C, CO2/14%O2 gas, 50 mL/min or 13s, 15 kV, 8 kHz, 7.5 min

L: PE, 350 °C, CO2/O2 gas, 32.5 mL/min or 20s, 15 kV, 8 kHz, 7.5 min

M: LDPE, 325 °C, CO2 gas, 32.5 mL/min or 20s, 15 kV, 8 kHz, 10 min

N: PP, 325 °C, CO2 gas, 32.5 mL/min or 20s, 15 kV, 8 kHz, 10 min

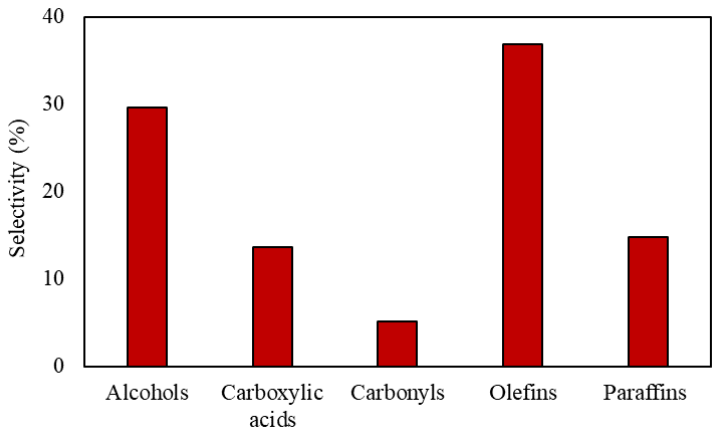
O: LDPE, 350 °C, CO2/O2 gas, 50 mL/min or 13s, 15 kV, 8 kHz, 10 min

P: PP, 350 °C, CO2/O2 gas, 50 mL/min or 13s, 15 kV, 8 kHz, 10 min

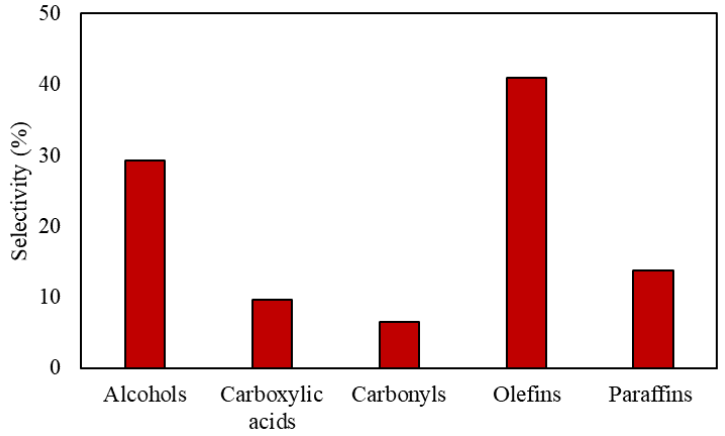
Q: PC-PE, 325 °C, CO2 gas, 32.5 mL/min or 20s, 15 kV, 8 kHz, 10 min

R: PC-PE, 350 °C, CO2/O2 gas, 50 mL/min or 13s, 15 kV, 8 kHz, 10 min

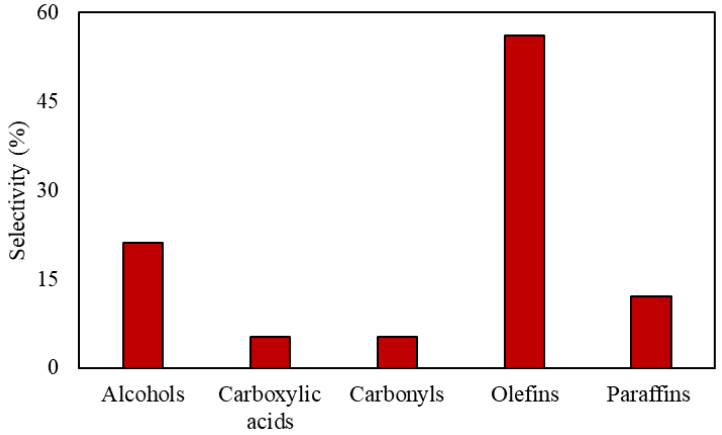
Effect of Plasma Intensity on Liquid Products



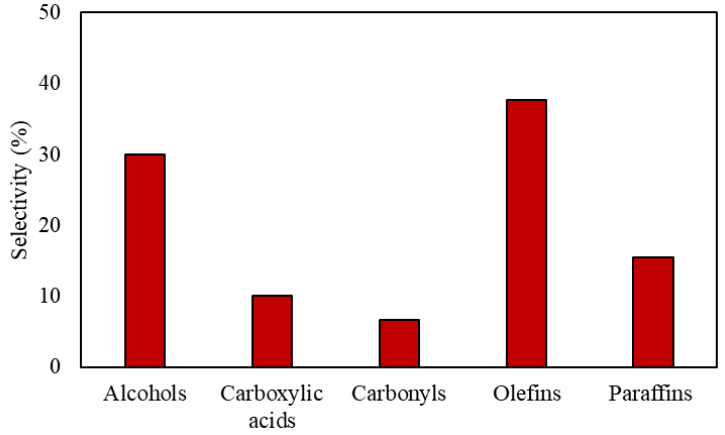
15 kV, 8kHz



7.5 kHz



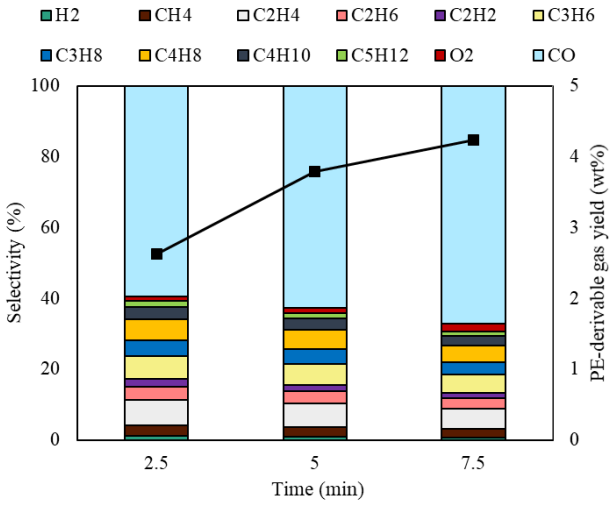
17.5 kV



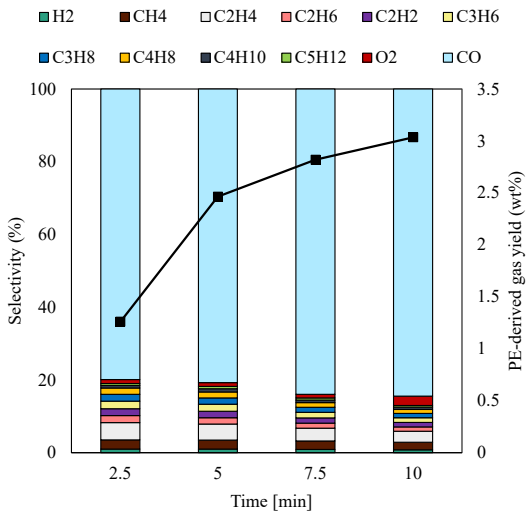
8.5 kHz

T = 350 °C; Q (t_R) = 50 mL/min (13s)
Fixed *f* = 8 kHz for voltage comparison
Fixed V = 15 kV for frequency comparison

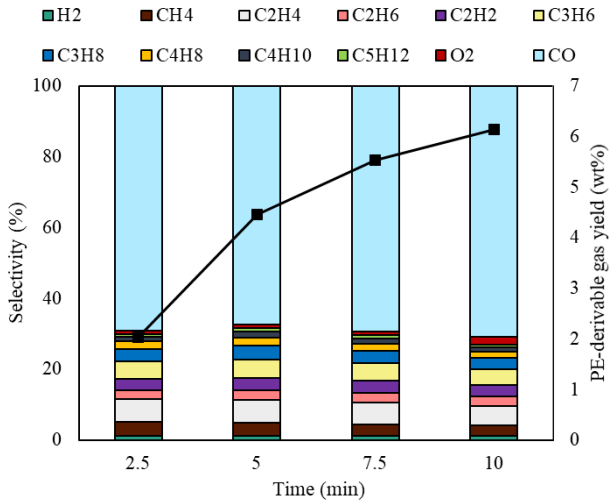
Effect of Plasma Intensity on Gas Products



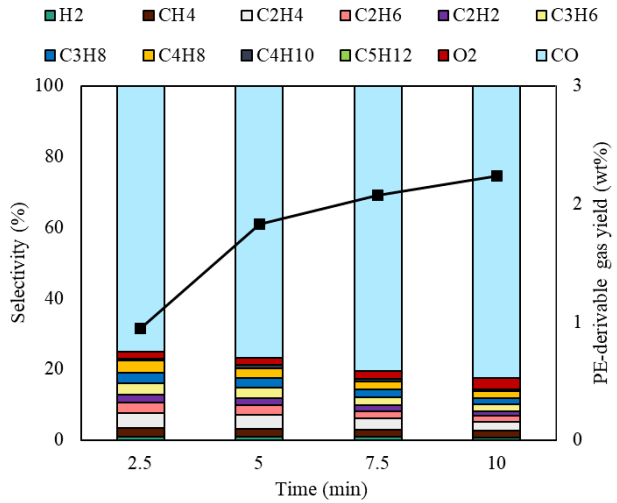
17.5 kV



15 kV, 8kHz



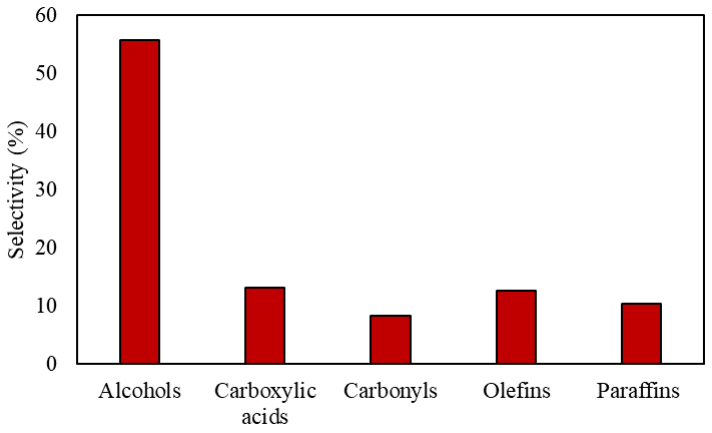
8.5 kHz



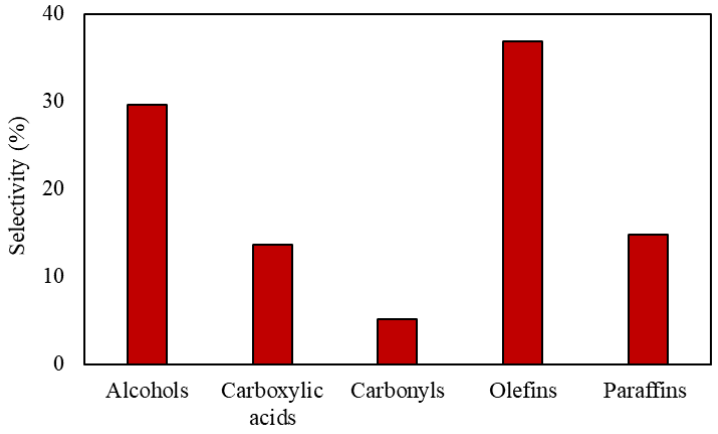
7.5 kHz

T = 350 °C; Q (t_R) = 50 mL/min (13s)
Fixed *f* = 8 kHz for voltage comparison
Fixed V = 15 kV for frequency comparison

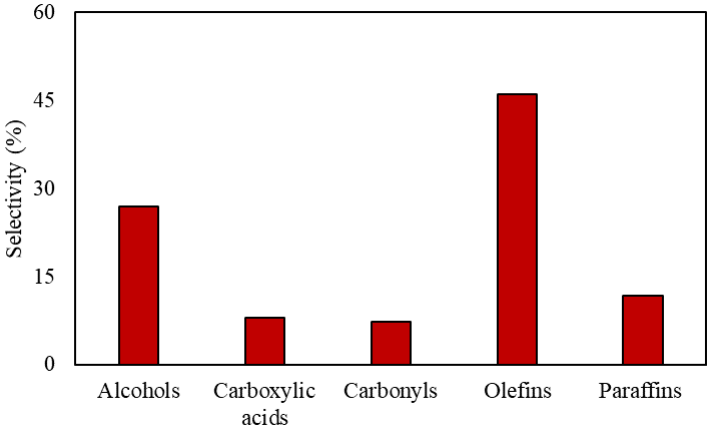
Effect of Flow Rate (Gas Residence) on Liquid Products



32.5 mL/min (20s)



50 mL/min (13s)

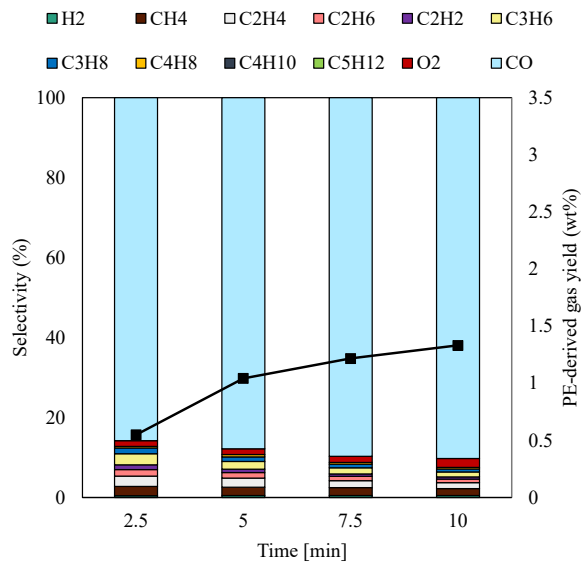


65 mL/min (10s)

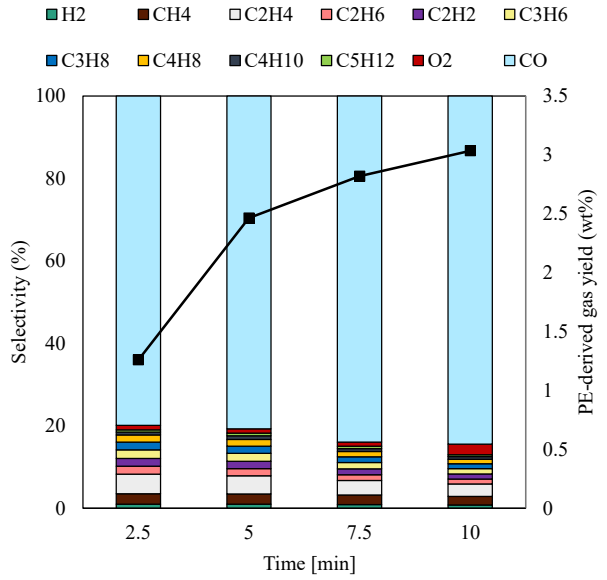
T = 350 °C; V = 15 kV; f = 8 kHz

Gas Residence Time Comparison

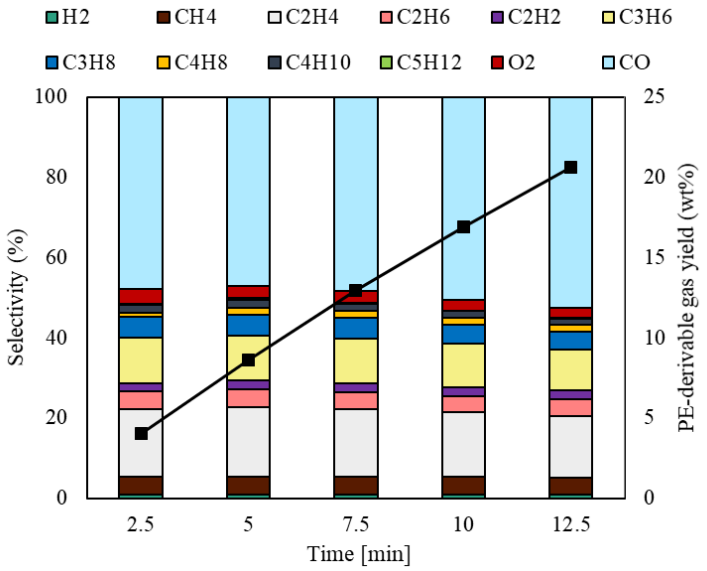
Effect of Flow Rate (Gas Residence) on Gas Products



32.5 mL/min (20s)



50 mL/min (13s)

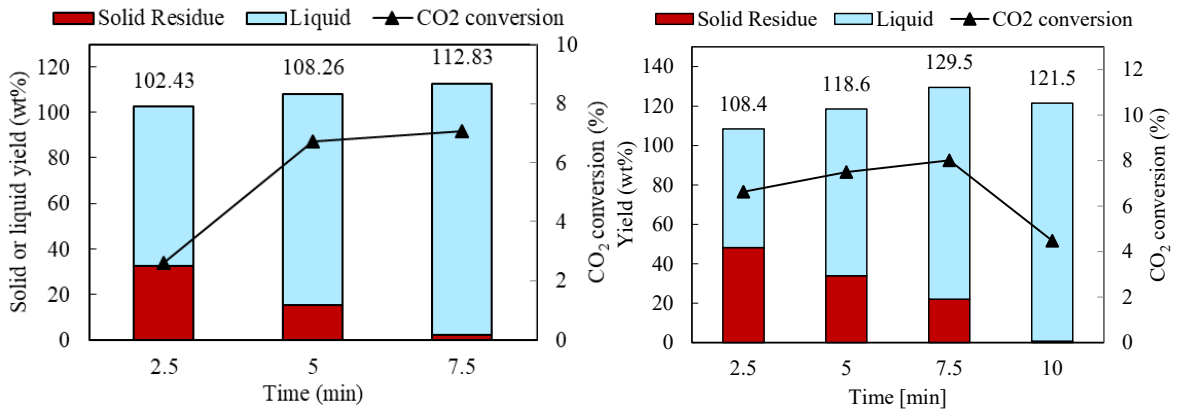


65 mL/min (10s)

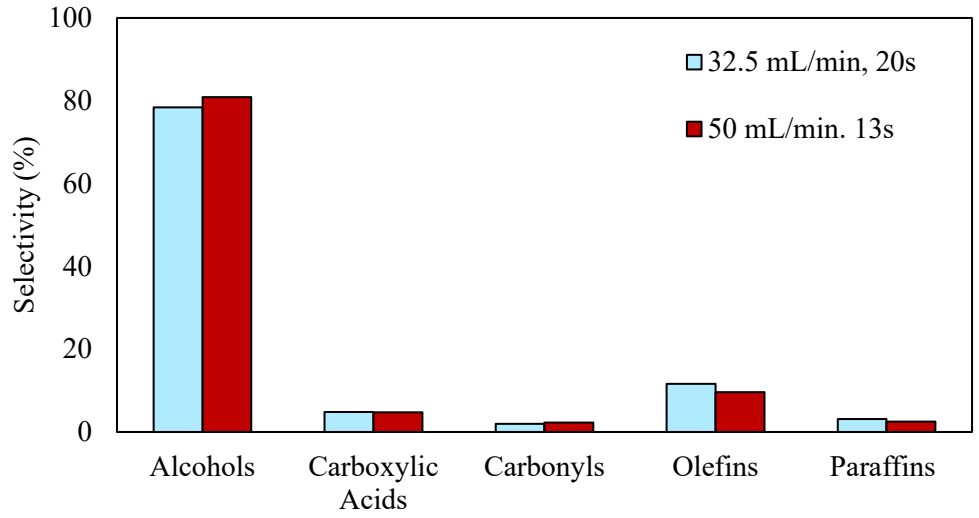
T = 350 °C; V = 15 kV; f = 8 kHz

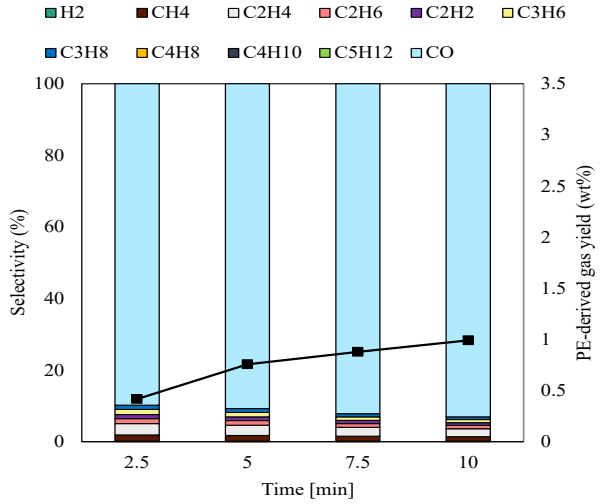
Gas Residence Time Comparison

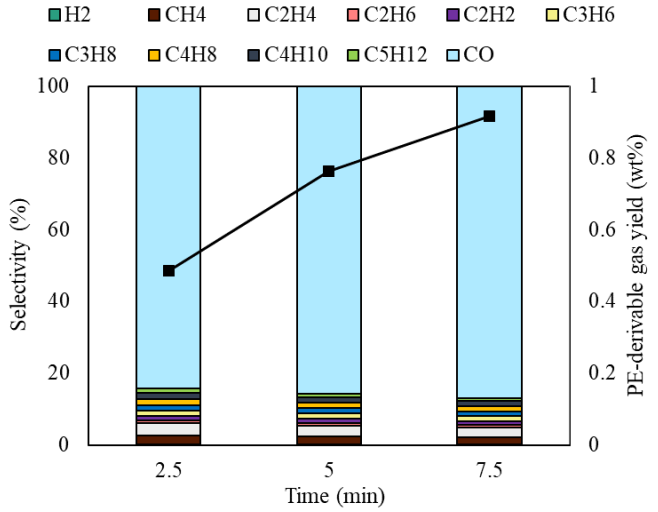
Effect of flow rate in CO_2/O_2 plasma



32.5 mL/min (20s) 50 mL/min (13s)



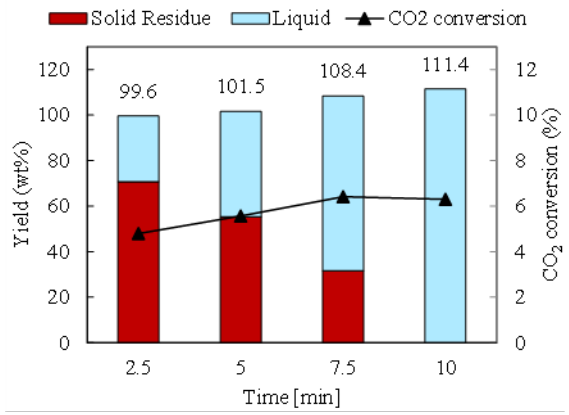




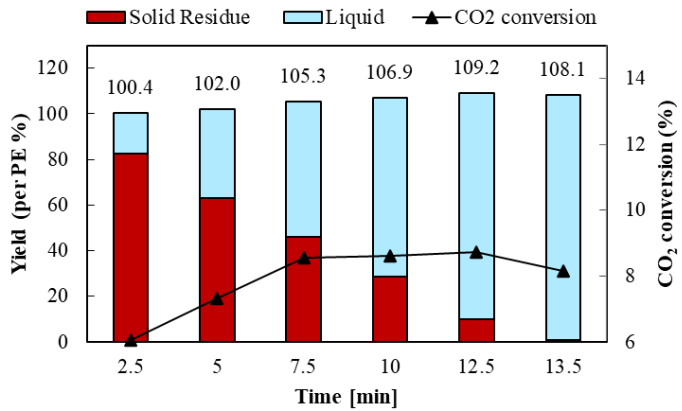
T = 350 °C; V = 15 kV; f = 8 kHz

Gas Residence Comparison

Effect of increased mass loading in CO_2 plasma



150 mg

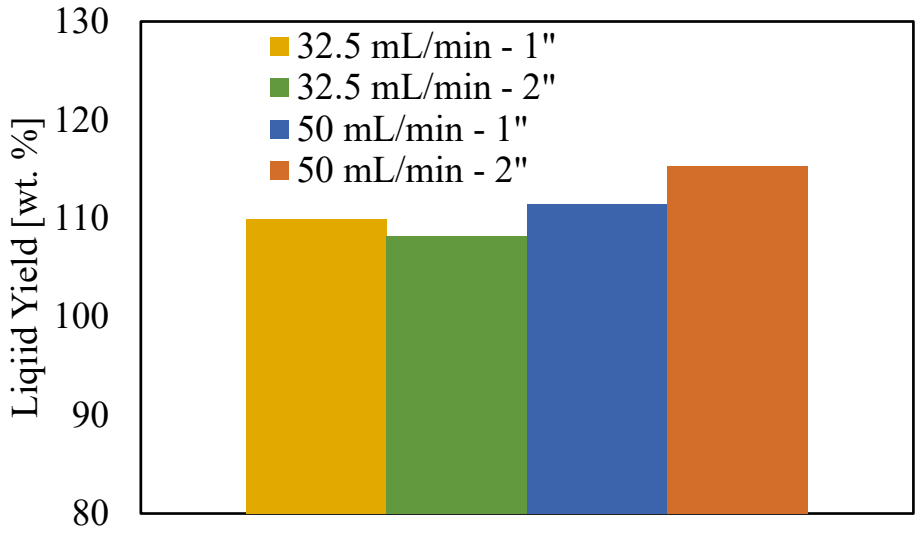


300 mg

Q (t_R) = 50 mL/min (13s)

Mass loading Comparison

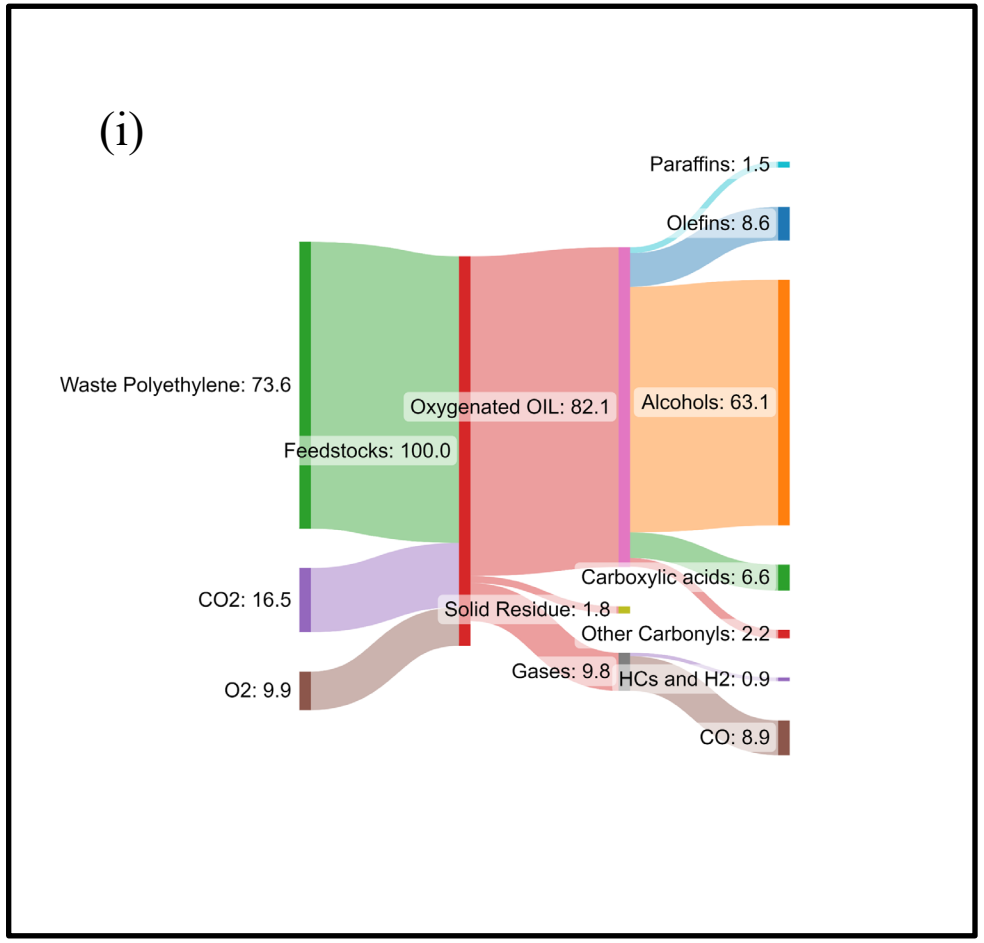
Effect of sample surface length in CO_2 plasma

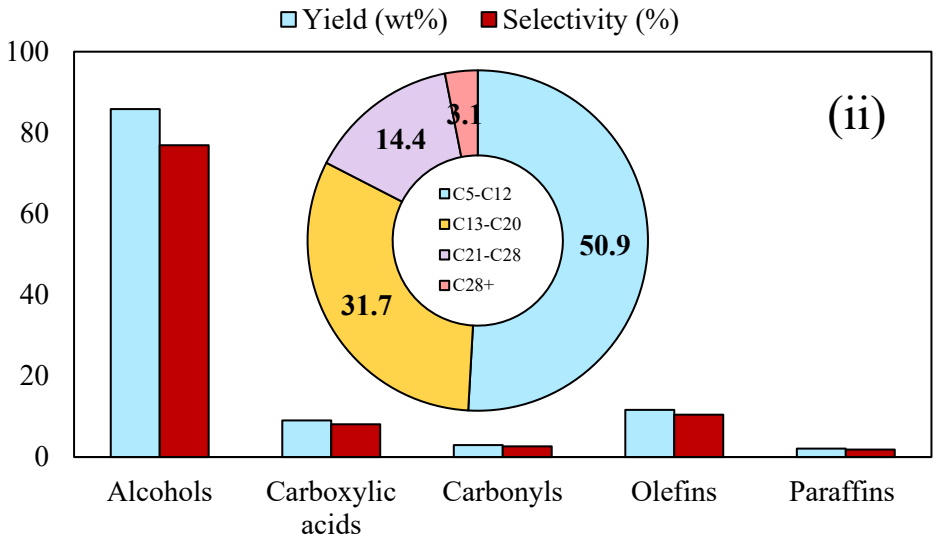


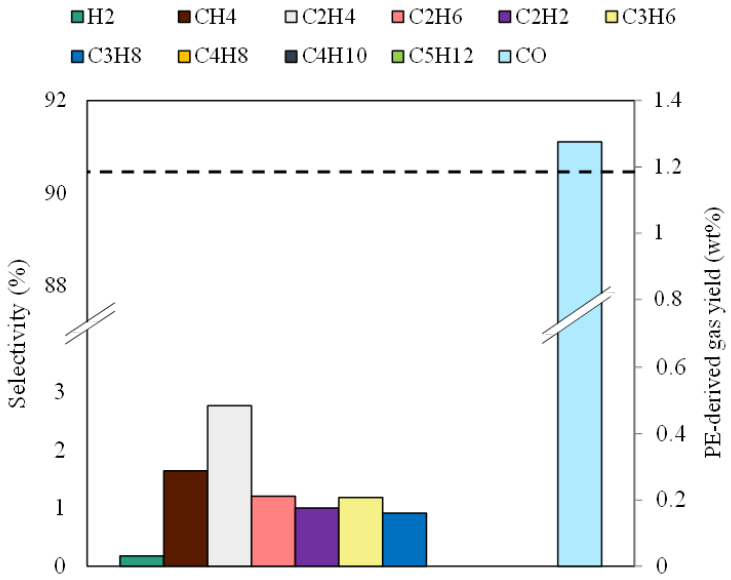
Q (t_R) = 50 mL/min (13s)

Sample surface length Comparison

Both: T = 350 °C; V = 15 kV; f = 8 kHz;



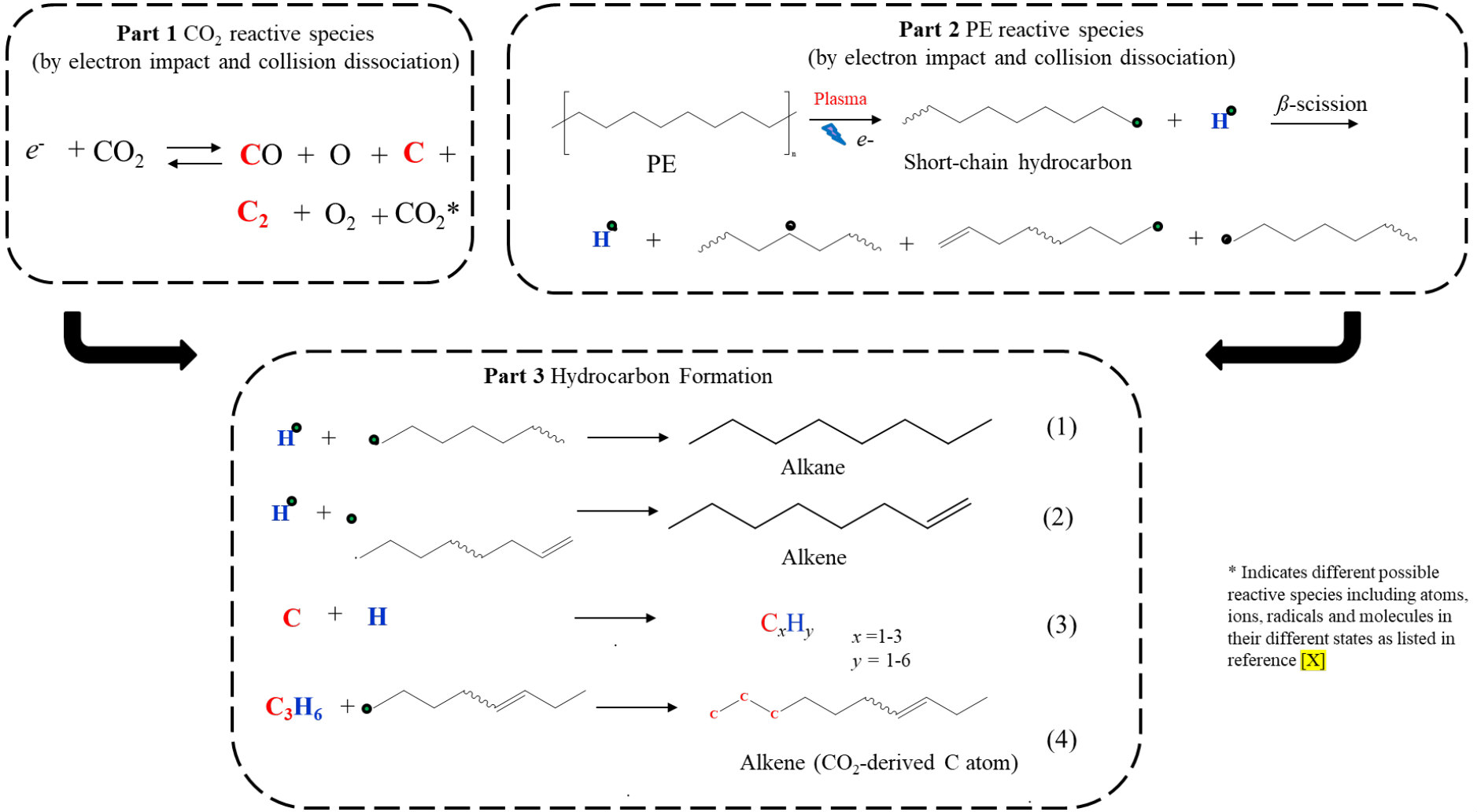




Applications of plasma-based co-upcycling for PC-PE and CO_2.

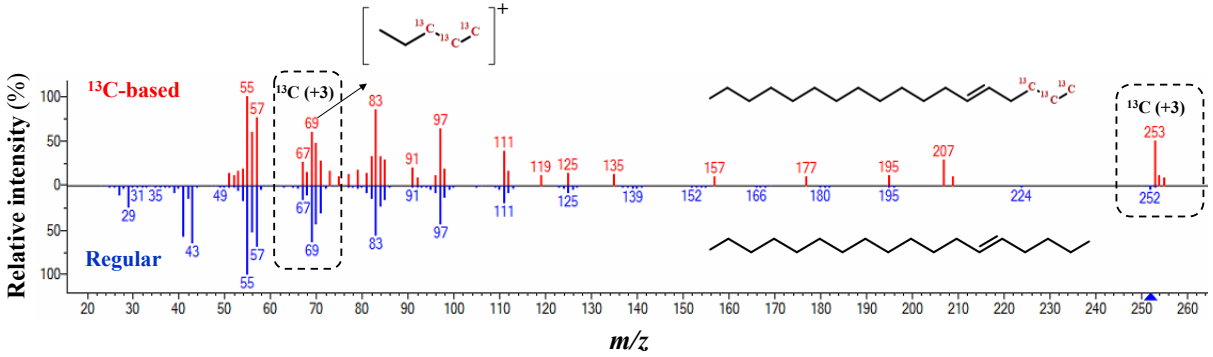
(A) (i) mass yield and selectivity of liquid products from PC-PE using CO_2/O_2 plasma, (ii) selectivity of fatty alcohols with four different carbon number range for PC-PE, and gas product selectivity from PC-PE. Collected using the residence time of 13 s (flow 50 mL/min) and reaction time of 10 min. The initial reactor temperature is 325 ℃ for converting PC-PE.

Detailed Reaction Mechanism



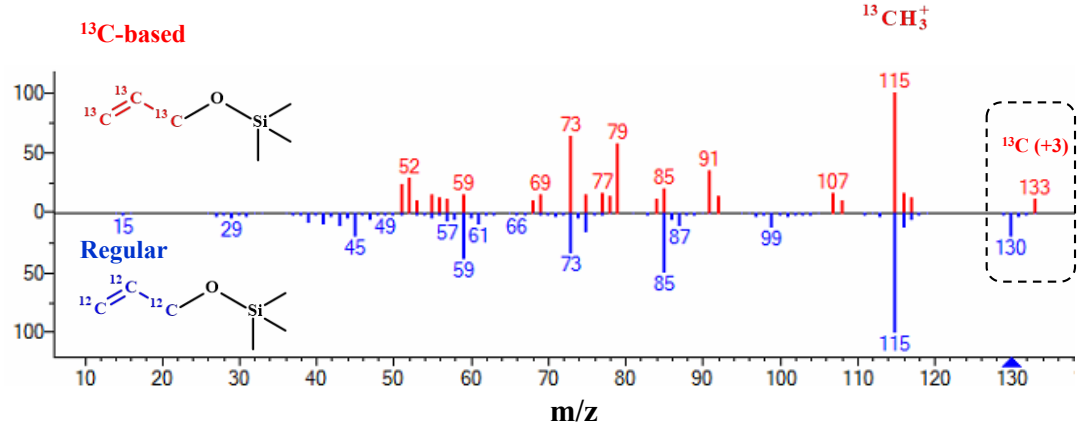
* Indicates different possible reactive species including atoms, ions, radicals and molecules in their different states as listed in reference [X]

Isotopic study for reaction mechanism



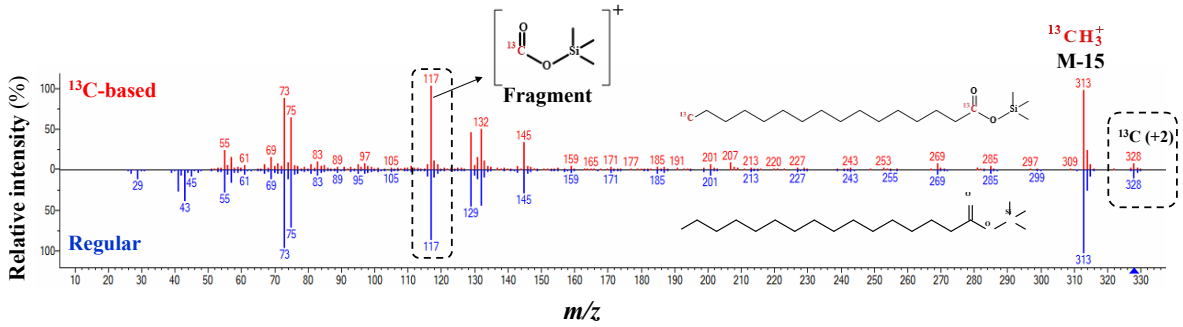
- Isotopic study was performed in a closed batch reactor
- $^{13}CO_2$ and PE were used as the feedstock
- MS was used to analyze resultant products

Mass spectra of 5-octadecene ($C_{18}H_{36}$, Mw = 252) compared between $^{13}CO_2$ plasma-based (upper) and regular (lower) molecules.

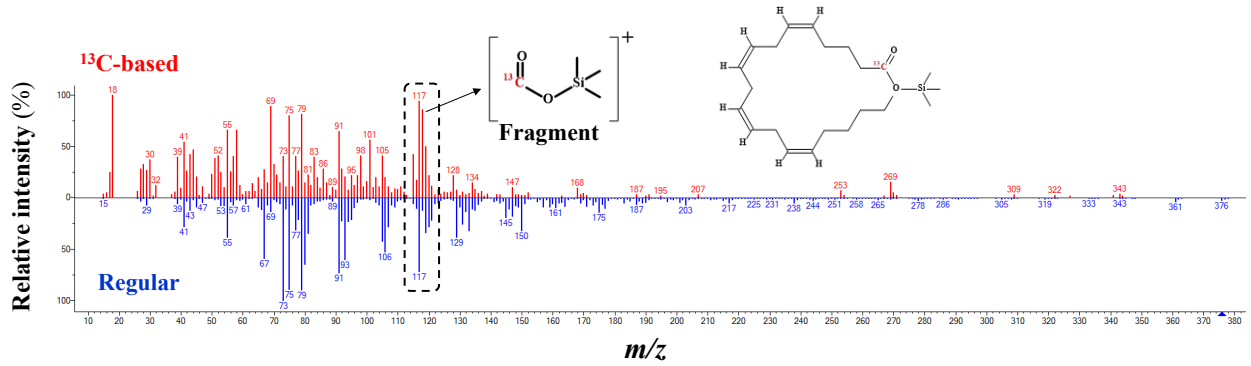


Mass spectra of allyl alcohol, TMS derivative ($C_6H_{10}OSi$, Mw = 130) compared between $^{13}CO_2$ plasma-based (upper) and regular (lower) molecules.

Isotopic study for reaction mechanism

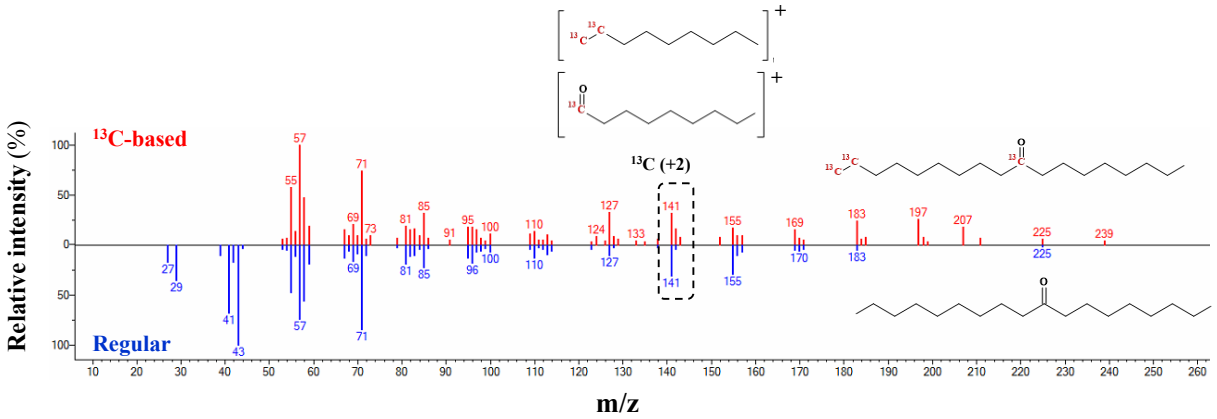


Mass spectra of palmitic acid, TMS derivative ($C_{19}H_{40}O_2Si$, Mw = 328) compared between $^{13}CO_2$ plasma-based (upper) and regular (lower) molecules.



Mass spectra of Arachidonic acid, TMS derivative ($C_{23}H_{40}O_2Si$, Mw = 376) compared between $^{113}CO_2$ plasma-based (upper) and regular (lower) molecules.

Isotopic study for reaction mechanism



Mass spectra of 9-octadecanone ($C_{18}H_{36}O_1$, Mw = 268) compared between $^{13}CO_2$ plasma-based (upper) and regular (lower) molecules.

Reproducibility of the plasma process

Reproducibility of the experiment using PE conversion by CO_2 plasma and t_R = 13s as an example. The reaction conditions: voltage 15 kV, frequency 8 kHz, CO_2 inlet flow rate of 50 mL/min, initial reactor temperature 350 °C, reaction time 10 min.

Test No.	PE mass (g)	Reactor mass (g)		Condenser mass (g)		Liquid mass (g)	Liquid yield (%)	CO_2 conversion (%)
		Before	After	Before	After			
1	0.1532	26.2991	26.3065	180.4964	180.6585	0.1695	110.6	6.25
2	0.1481	26.5579	26.5993	169.8593	169.9832	0.1653	111.6	6.30
3	0.1528	26.7436	26.7846	181.8198	181.95	0.1712	112.0	6.27
Average (%)							111.4	6.27
Standard error (%)							±0.7%	±0.03%

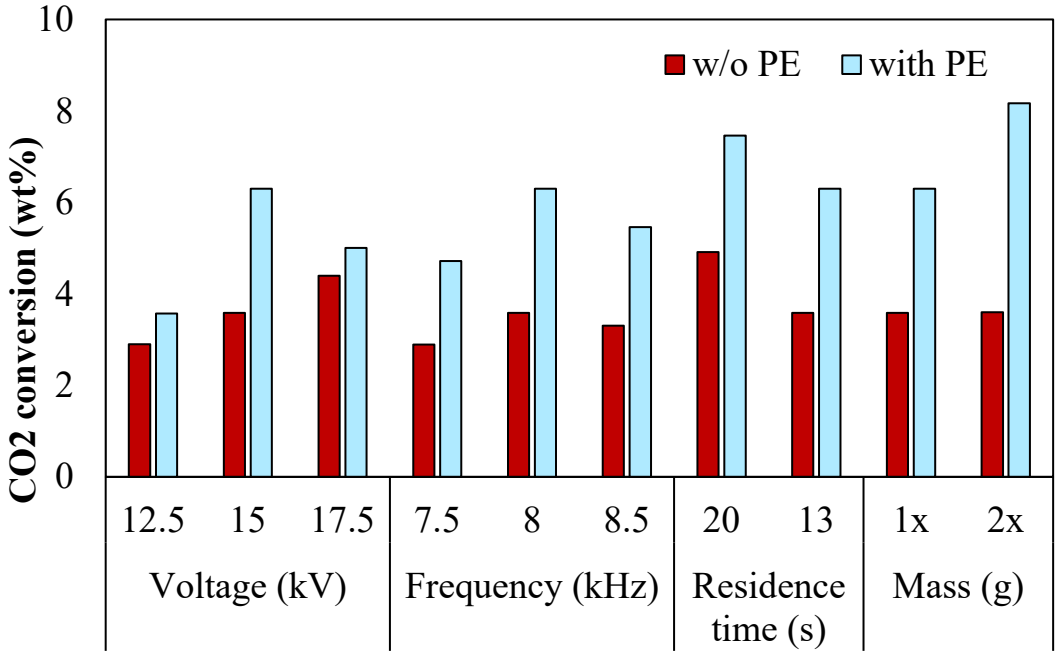
Mass closures of plasma-based co-conversion of plastics and CO_2 including all reactants and measured products. The gas, liquid and solid residue yields are calculated based on the total reactant masses, which are converted PE and CO_2 for the CO_2 plasma case, and converted PE, CO_2 and O_2 for the CO_2/O_2 plasma cases.

Plastic	t_R	**Plasma**	**Gas (%)**	**Liquid (%)**	**Solid Residue (%)**	**Total (%)**
PE	20 s	CO_2	13.4	83.5	0.0	96.9
PE	13 s	CO_2/O_2	10.3	87.7	0.6	98.6
PC-PE	13 s	CO_2/O_2	9.8	82.1	1.8	93.7

Moisture content of liquid products obtained from PE or PC-PE conversion using CO_2 plasma or CO_2/O_2 plasma. Reaction conditions: 15 kV, 8kHz, 10 min, t_R is given.

Moisture (%)	PE			PC-PE
	t_R = 20s	t_R = 13s		t_R = 13s
	CO_2 plasma	CO_2 plasma	CO_2/O_2 Plasma	CO_2/O_2 Plasma
	0.6	0.2	0.5	0.7

Effect of plastic on CO_2 conversion during plasma-based co-upcycling



Energy consumption of PE conversion by CO_2/O_2 plasma

- Energy consumed by the plasma process was measured for CO_2/O_2 plasma with HDPE as a reference.
- Energy spent in MJ was calculated per kg of feedstock converted, considering plasma energy and sensible heat.
- The milligram scale reactor consumed 237.23 MJ/kg of energy.
- When the process was scaled to a gram-scale reactor, the energy consumed dropped to 44 MJ/kg, showing the potential for energy savings with scale-up.

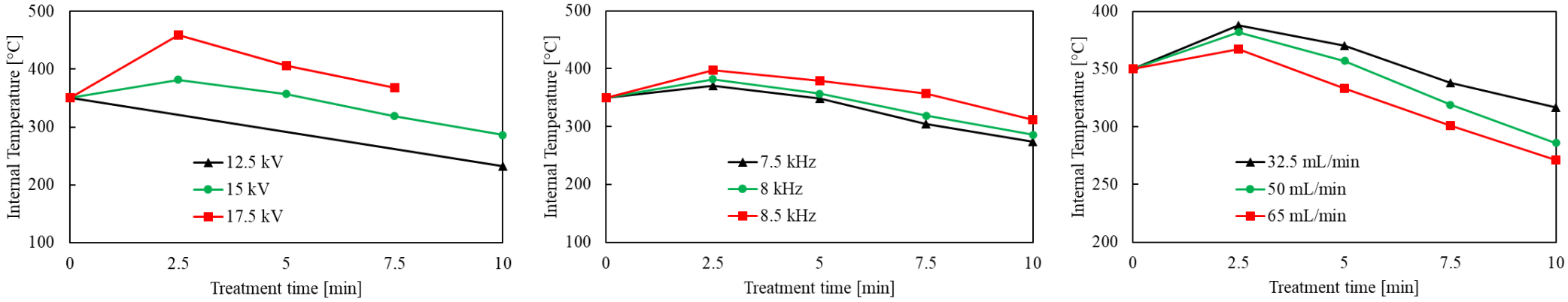
Energy consumption of PE conversion by CO_2/O_2 plasma in two reactor scales.

	Run A	**Run B**
PE (kg)	1.55×10^{-4}	1.015×10^{-3}
Converted CO_2 (kg)	3.8×10^{-5}	1.08×10^{-4}
Converted O_2 (kg)	2.1×10^{-5}	3.0×10^{-5}
Thermal energy (for pre-plasma heating) (MJ)	3.02×10^{-4}	1.479×10^{-3}
CO_2: sensible heating*	1.57×10^{-4}	5.24×10^{-4}
O_2: sensile heating*	8×10^{-6}	4.3×10^{-5}
PE: sensile heating	1.1×10^{-4}	7.31×10^{-4}
PE: latent heating for melting	2.7×10^{-5}	1.82×10^{-4}
Plasma energy (MJ)	5.0303×10^{-2}	4.9234×10^{-2}
Total energy consumption (MJ)	5.0604×10^{-2}	5.0713×10^{-2}
Energy consumption per feeds (MJ/kg)	237.23	43.97

Reaction conditions:

Run A (0.15 gram) - 50 mL/min CO_2 with 8% v/v O_2, 15 kV, 8 kHz, 10 min;
Run B (1 gram) - 100 mL/min CO_2 with 12% v/v O_2, 15 kV, 7 kHz, 7.5 min.
* Calculated for the total flow-in CO_2 or O_2 gas mass at the inlet during the pre-plasma heating stage.

Measured Plasma Reactor Temperature



Initial reactor temperature: 350°C; Fixed Flow Rate = 50 mL/min; Fixed Voltage = 15 kV; Fixed Frequency = 8 kHz

- Without external heating, the measured reactor temperature first increased and then decreased.
- Higher voltage and frequency resulted in higher reactor temperatures.
- Higher plasma density under lower flow led to higher reactor temperatures.