Valorization of Waste Plastic for the Synthesis of Sustainable Aviation Fuel (SAF)

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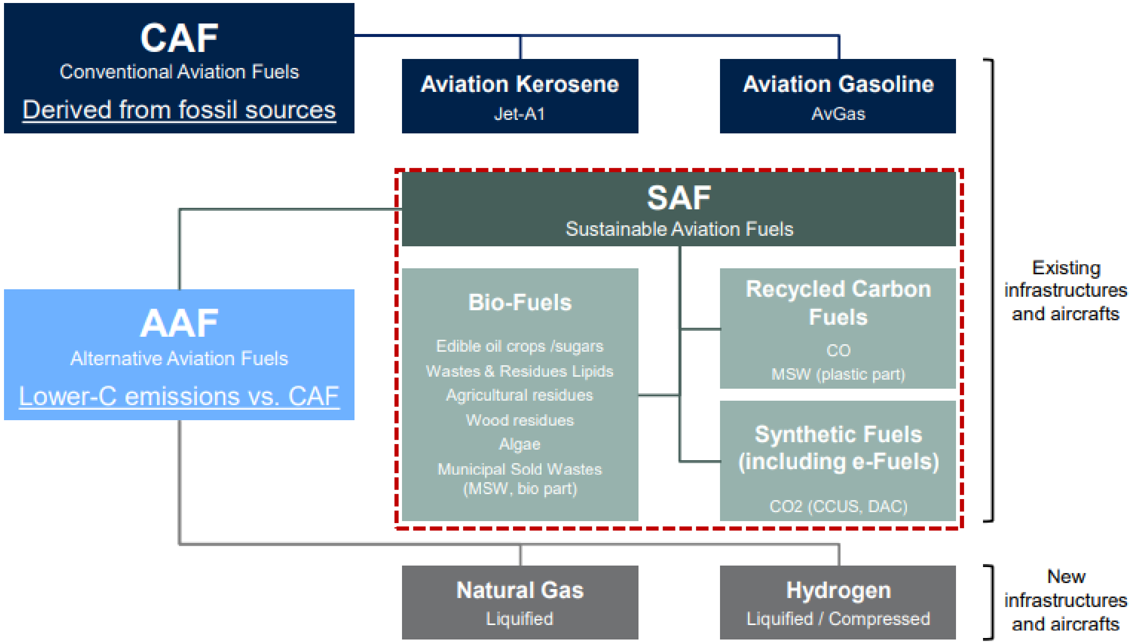
Content



Aviation Industry Goals

GOAL 1	GOAL 2	GOAL 3
PRE-2020 AMBITION	IN LINE WITH THE NEXT UNFCCC COMMITMENT PERIOD	ON THE 2°C PATHWAY
1.5% ANNUAL AVERAGE FUEL EFFICIENCY IMPROVEMENT FROM 2009 TO 2020.	STABILISE NET AVIATION CO_2 EMISSIONS AT 2020 LEVELS WITH CARBON-NEUTRAL GROWTH.	REDUCE AVIATION'S NET CO_2 EMISSIONS TO 50% OF WHAT THEY WERE IN 2005, BY 2050.
T O I	T O I + M	T O I

Advantages

Comparison vs fossil kerosene	❶ Battery-electric	❷ H_2 fuel cell	H_2 turbine	❸ Sustainable aviation fuel
Climate impact[i]	100% reduction[i]	75%-90% reduction	50%–75% reduction	30%-60% reduction[ii]
Aircraft design	Low-battery density limits ranges to 500km–1,000km	Feasible only for commuter to short-range segments	Feasible for all segments except for flights >10,000km	Only minor changes
Aircraft operations	Same or shorter turnaround times	1-2x longer refuelling times for up to short range	2–3x longer refuelling times for medium and long range	Same turnaround times
Airport infrastructure	Fast-charging or battery exchange system required	LH_2 distribution and storage required		Existing infrastructure can be used

Major advantages   Major challenges

Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation, INSIGHT REPORT NOVEMBER 2020

SAF Approved Pathways

Summary of technical progress since 2014

Production route	Plant in 2014	Plant in 2018
Alcohol-to-Jet	1. None	2. Several at pilot scale[7] 3. Ekobenz[8] plant in commissioning (23 kt/year) 4. Several other companies including Lanzatech and Gevo planning commercial-scale plant[9]
Gasification + FT	5. 1 plant operational (TRI plant processing black liquor ~20 kt/year) 6. 1 plant planned (UPM, since cancelled)	7. TRI black liquor gasifier shut down 8. Fulcrum[10] and Red Rock[11] have plant under construction (combined 75 kt/year capacity)
Pyrolysis	9. None focusing on aviation fuels	10. Still no pyrolysis plant upgrading to jet 11. Ensyn/Envergent have ability to produce 'green diesel'[12], but no plant focussing on this 12. IH² pilot plant in India[13]
Sugars to hydrocarbons	13. Amyris had operating commercial-scale aerobic fermentation plant (33 kt/year)	15. Amyris plant has since been sold to DSM[14]; Construction of two other aerobic fermentation plant is ongoing but these are not focused on aviation fuel.[15]
Oil-based processes	15. Many plant globally 16. 2.5 mt/year of HEFA capacity worldwide, and 1.3 mt more planned	17. Over 4.5 mt capacity in dedicated hydro-treating plant 18. Over 2 mt co-processing at refineries
Power-to-liquids: Fischer-Tropsch	19. None	20. Sunfire planning a demonstration facility in Norway (8 kt/year)[16]

SUSTAINABLE AVIATION FUELS ROAD-MAP, Fueling the future of UK aviation

7 Technical pathways to date [SAF Approved]

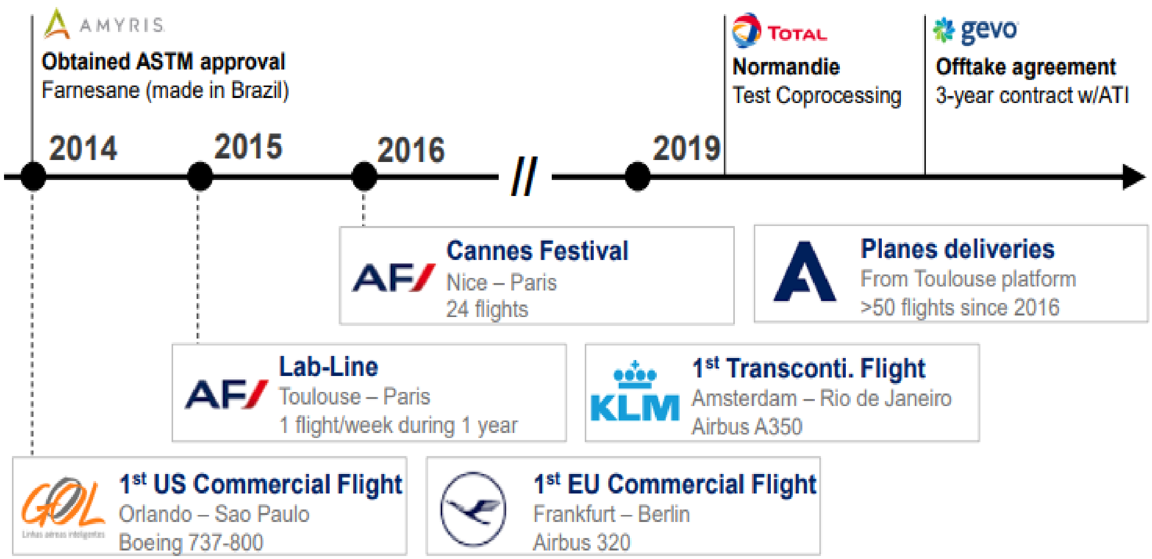
Year approved	Technology pathway		Blend limit	Key players
2009	FT	Fischer-Tropsh Synthesized Paraffinic Kerosene (FT-SPK)	50%	Fulcrum Bioenergy, Velocys, Red Rock Biofuels
2011	HEFA	Hydroprocessed Esters and Fatty Acids (HEFA-SPK)	50%	Neste, World Energy, Total
2014	SIP	Hydroprocessed Fermented Sugars Synthesized Isoparaffins (HFS-SIP)	10%	Amyris, Total
2015	FT-A	ST SPK with Aromatics (FT-SPK/A)	50%	
2016/18	ATJ	Alcohol to Jet Synthesized Paraffinic Kerosene (ATJ-SPK) Isobutanol and Ethanol	50%	gevo, LanzaTech
2020	CHJ	Catalytic hydrothermolysis jet fuel (CHJ), a type of synthetic kerosene	50%	ARA, Chevron
2020	HHC	HHC-SPK: similar to HEFA but utilizes biological derived hydrocarbons from algae	10%	IHI

2018/20	Co processing of renewable content with crude oil-derived middle distillates	5%	Chevron, bp, Phillips 66, Total, Fulcrum Bioenergy

Sustainable Aviation Fuel Review of Technical Pathways

Commercialization of SAF

Successful commercial flights since 2014



Fuel Name	Date certified	Maximum blend level
Fischer-Tropsch - Synthetic paraffinic kerosene (FT-SPK)	2009	50%
Hydroprocessed Esters & Fatty Acids (HEFA) - Synthetic paraffinic kerosene (SPK)	2011	50%
Synthetic Iso-Paraffinic fuels (SIP)	2014	10%
Fischer-Tropsch - Synthetic paraffinic kerosene with added aromatics (FT-SPK/A)	2015	50%
Alcohol-to-jet	2016 (updated 2018 to include more feedstocks and higher blend %)	50%

Sustainable Aviation Fuel Review of Technical Pathways

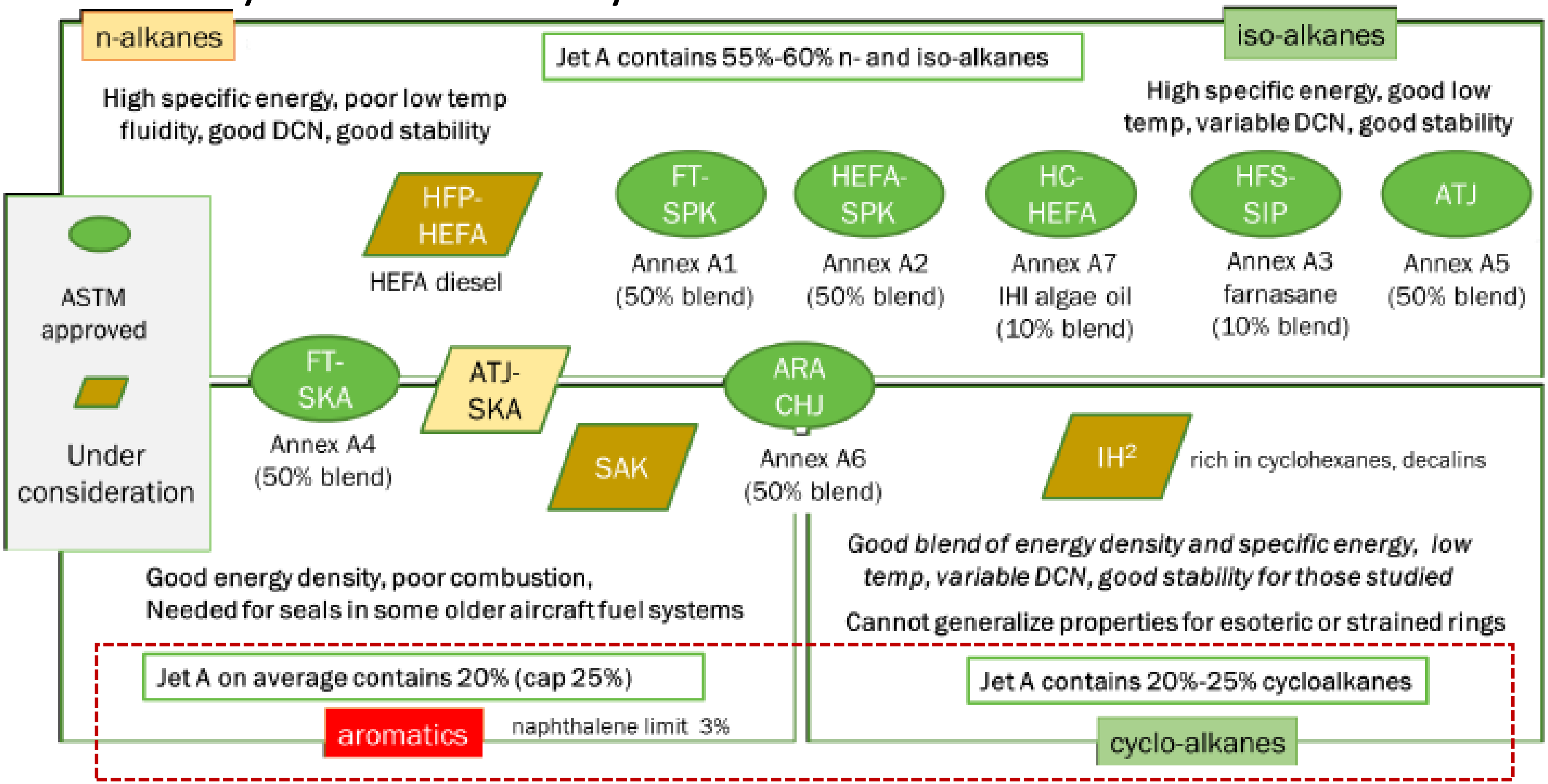
SAF in D4054 Qualification Process

ASTM Progress	Pathway	Feedstock	Task Force Lead
Phase 2 Testing	Hydro-deoxygenation Synthetic Kerosene (HDO-SK)	Sugars and cellulosics	Virent
	Catalytic Hydrothermolysis Synthetic Kerosene (CH-SK)	Renewable fats oils and greases FOG	ARA
Phase 1 OEM Review	High Freeze Point Hydroprocessed Esters and Fatty Acids Synthetic Kerosene (HFP HEFA-SK)	Renewable fats oils and greases	Boeing
Phase 1 Research Report	Hydro-deoxygenation Synthetic Aromatic Kerosene (HDO-SAK)	Sugars and cellulosics	Virent
Phase 1 Testing	Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	Sugars and lignocellulosics	Byogy, Swedish Biofuels
	Integrated Hydropyrolysis and Hydroconversion (IH^2)	Multiple	Shell
	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)	Hydrocarbon-rich algae oil	IHI

Sustainable Aviation Fuel Review of Technical Pathways

Hydrocarbons for SAF

Summary of four classes of SAF hydrocarbons

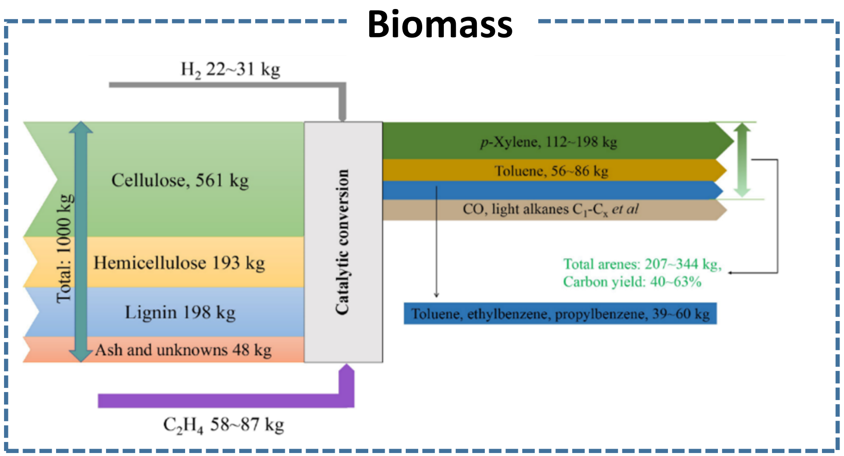


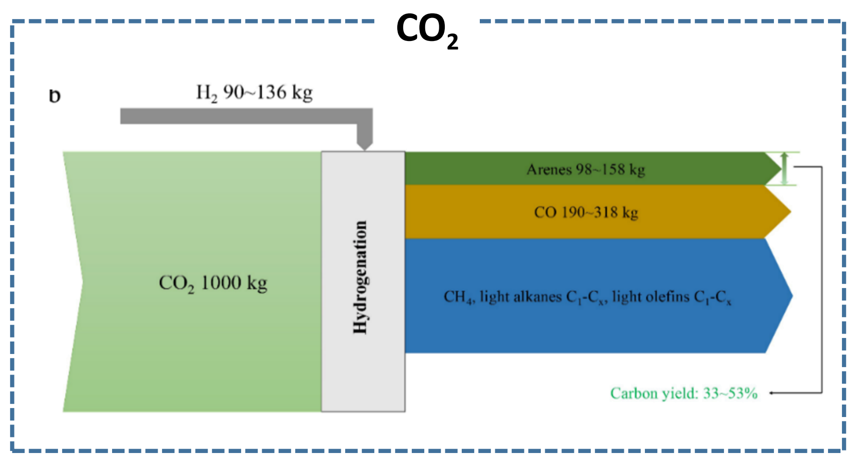
Can be obtained from

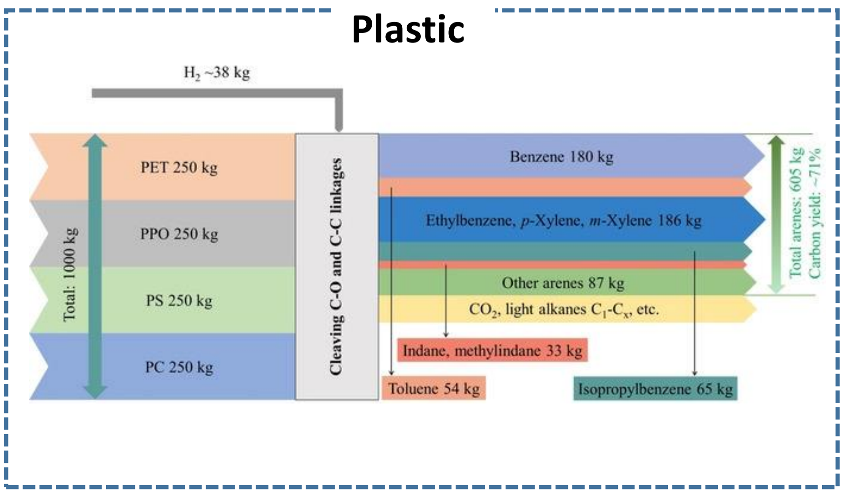
1. Biomass
2. Carbon dioxide
3. Waste Plastic

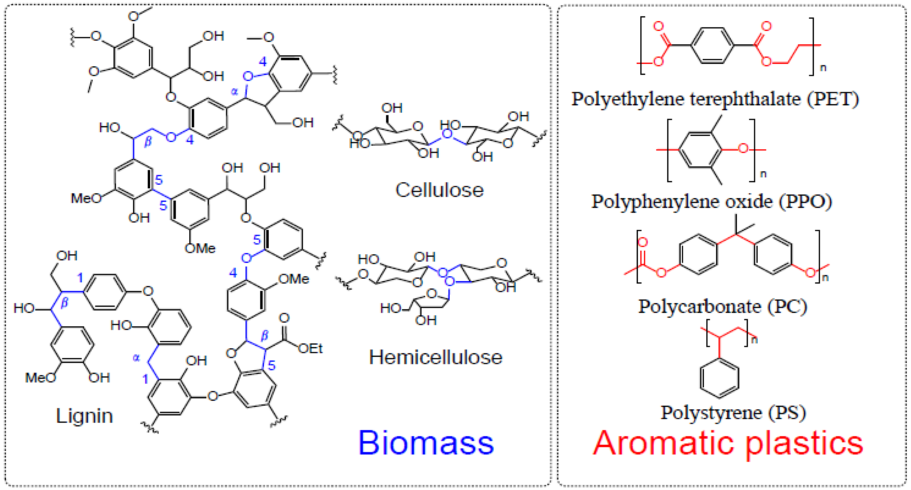
Sustainable Aviation Fuel Review of Technical Pathways

Aromatics and Cyclo-alkanes for SAF









Compared to biomass and CO_2, aromatic plastic waste has prominent advantages

- Simpler molecular structure contrasting the complexity of biomass
- Much lower oxygen contents
- Abundant aromatic functionality
- Selective production jet fuels

Angew. Chem. Int. Ed. 10.1002/anie.202011063

Solving Two Problems at One

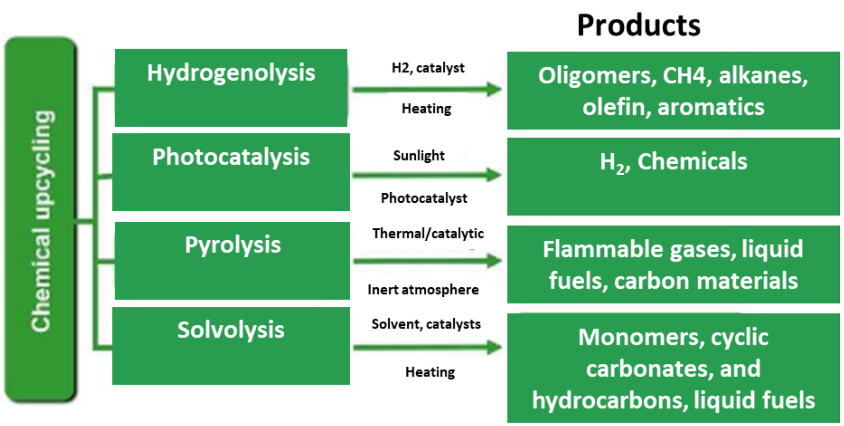
1960-2018 Data on Plastics in MSW by Weight (in thousands of U.S. tons)

Management Pathway	1960	1970	1980	1990	2000	2005	2010	2015	2017	2018
Generation	390	2,900	6,830	17,130	25,550	29,380	31,400	34,480	35,410	35,680
Recycled	-	-	20	370	1,480	1,780	2,500	3,120	3,000	3,090
Composted	-	-	-	-	-	-	-	-	-	-
Combustion with Energy Recovery	-	-	140	2,980	4,120	4,330	4,530	5,330	5,590	5,620
Landfilled	390	2,900	6,670	13,780	19,950	23,270	24,370	26,030	26,820	26,970

- Only ~ 7 % of the generated plastics are being recycled to date
    - **Incineration:** combustion of organic substances contained in waste materials; converts the waste into ash, flue gas, and heat
    - **Landfill:** plastic wastes are buried under the ground
    - **Mechanical Recycling**: processing of plastic waste into secondary raw material or products without significantly changing the chemical structure of the material

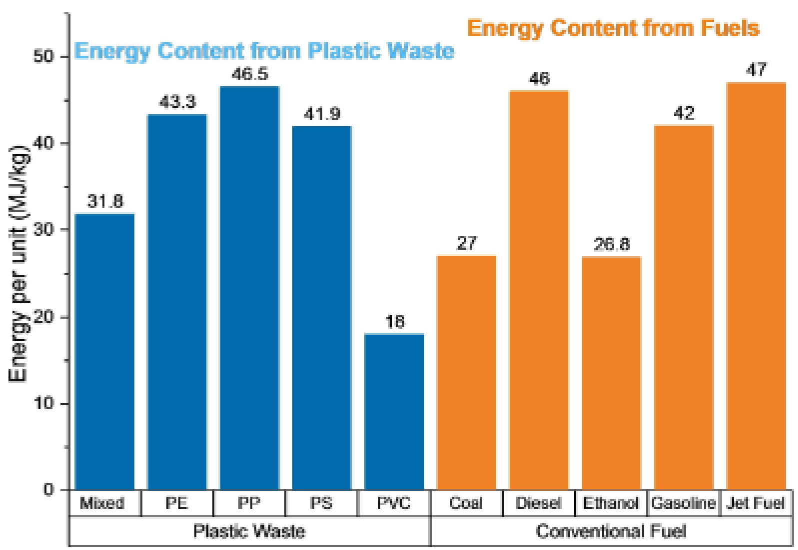
Plastic to SAF Technologies

Existing pathways for plastic waste recycling

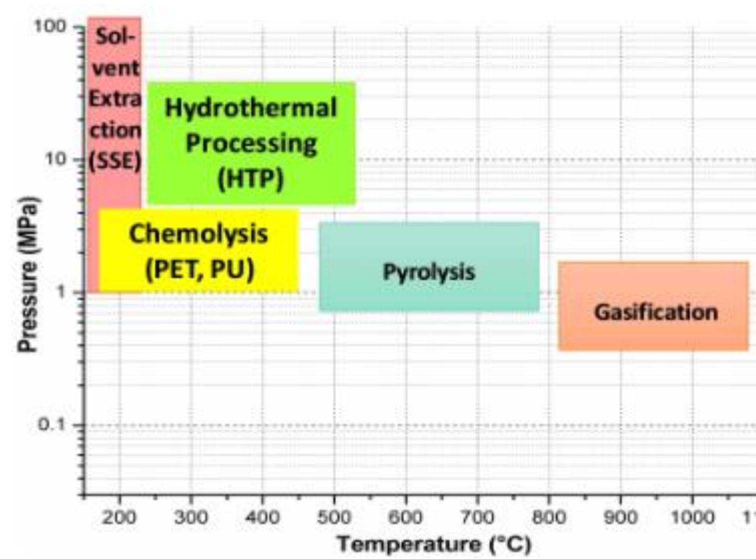


- **Chemical degradation** → pyrolysis → allows to handle relatively mixed plastic waste streams → poor selectivity
- **Alternative strategies** → hydrolysis, alcoholysis, hydrogenation and aminolysis → have been developed to handle specific aromatic plastics in particular PET → sorting as a prerequisite

Energy density of plastics and conventional fuels



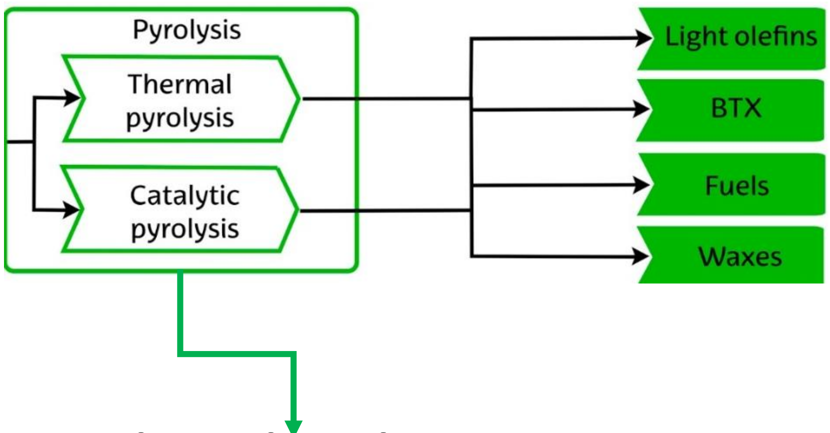
Reaction temperature and pressure of different methods



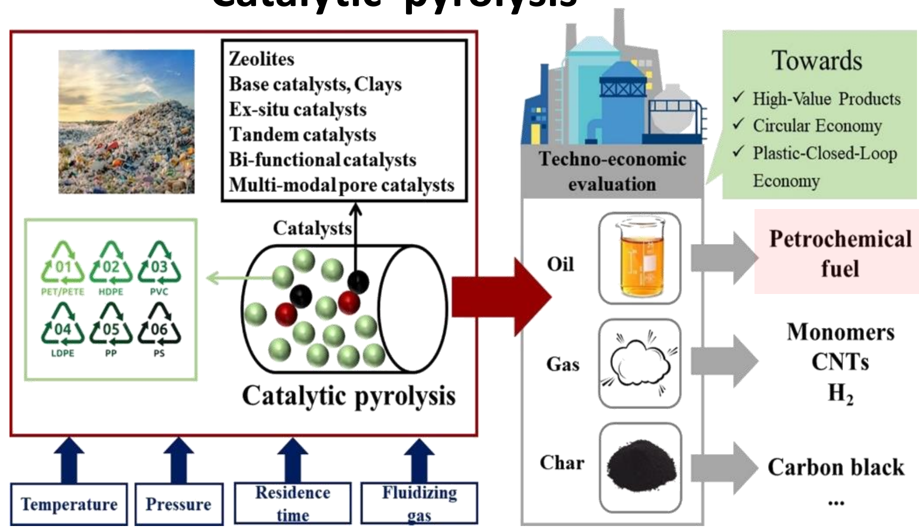
Energy Conversion and Management 254 (2022) 115243

Pyrolysis

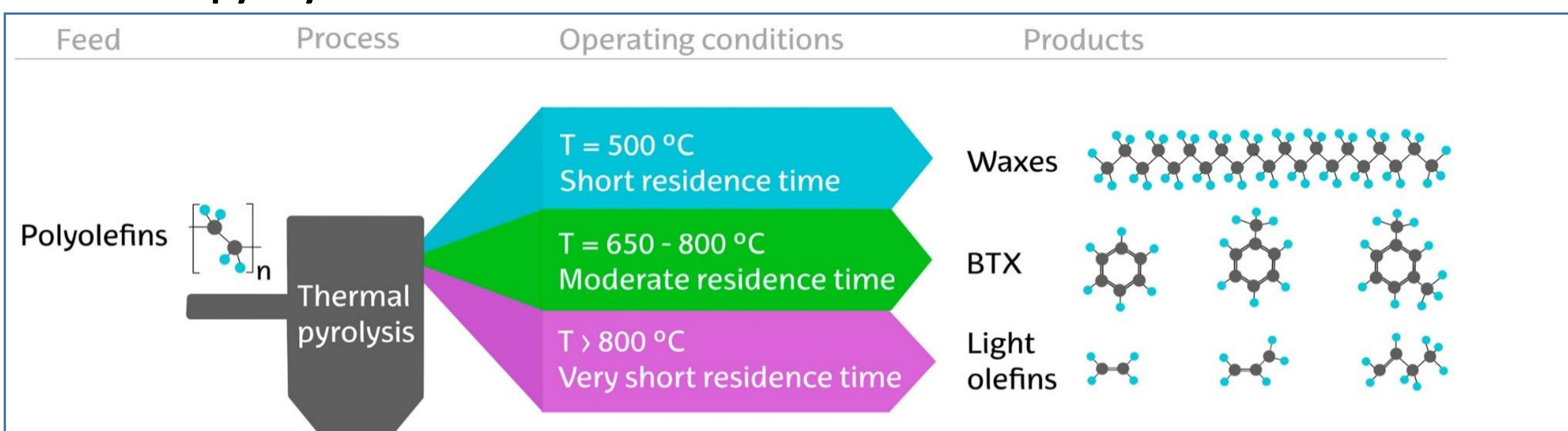
- Pyrolysis generally refers to the thermal processes to degrade polymers at relatively high temperatures under an inert atmosphere into gases, liquid products, and solid chars.



Catalytic pyrolysis

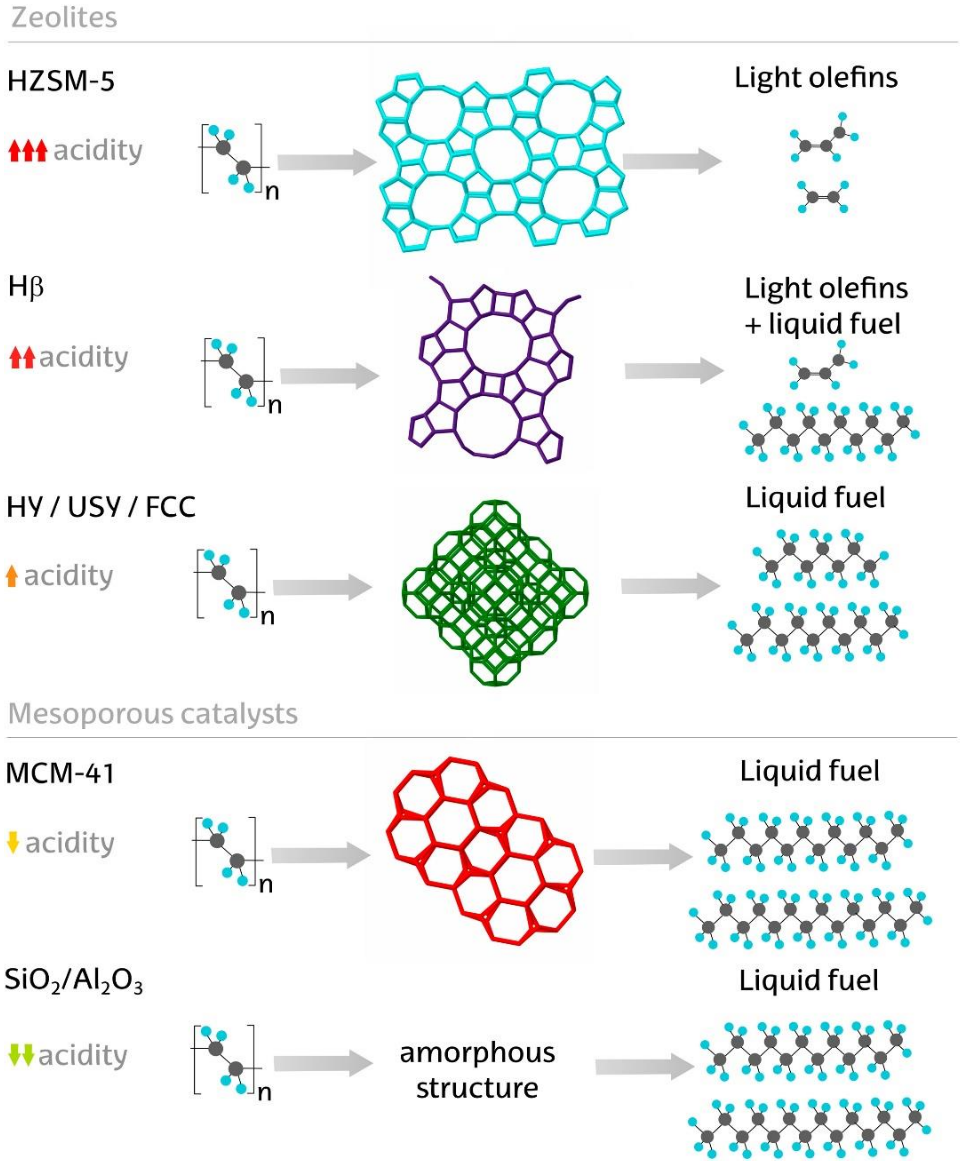


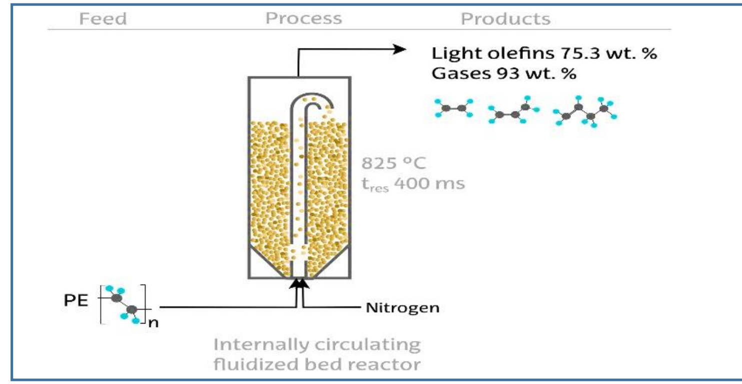
Thermal pyrolysis

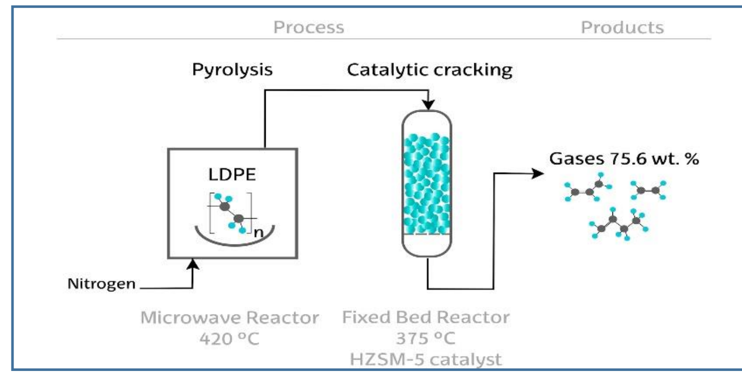


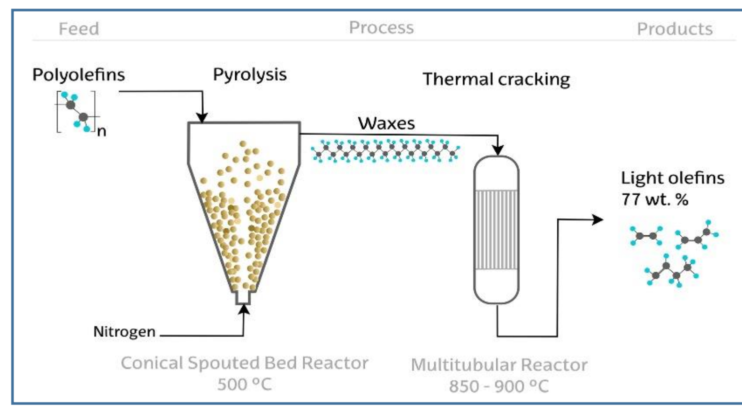
C. Kassargy,S. Awad,G. Burnens,K. Kahine,M. Tazerout,Fuel2018,224, 764–77

Pyrolysis Reactors and Product Yield



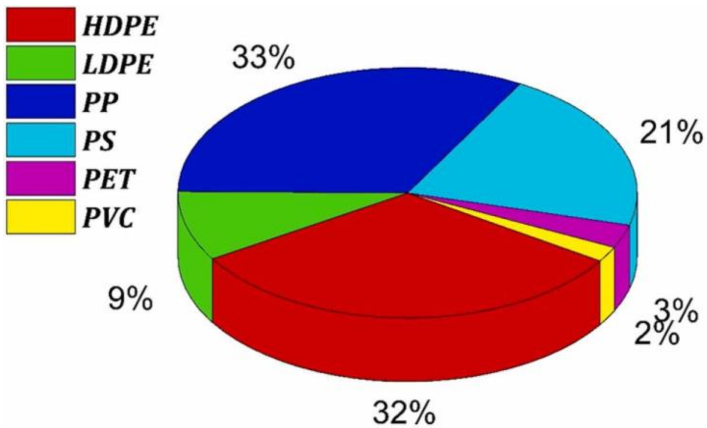


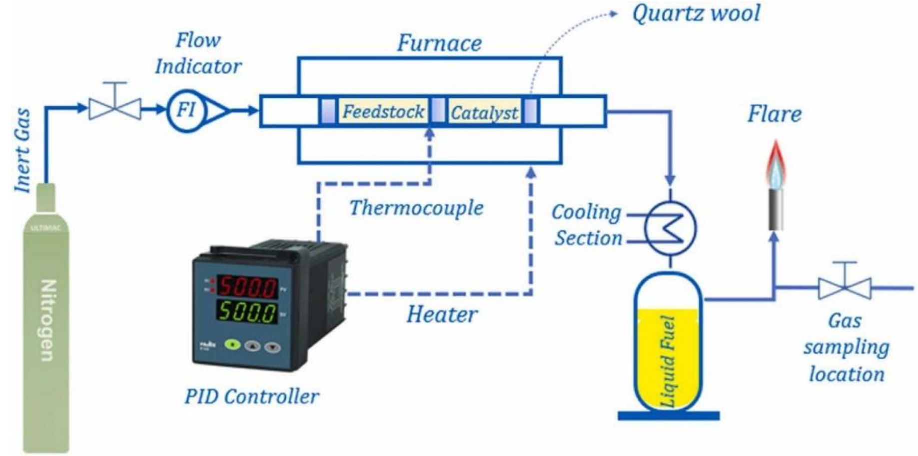


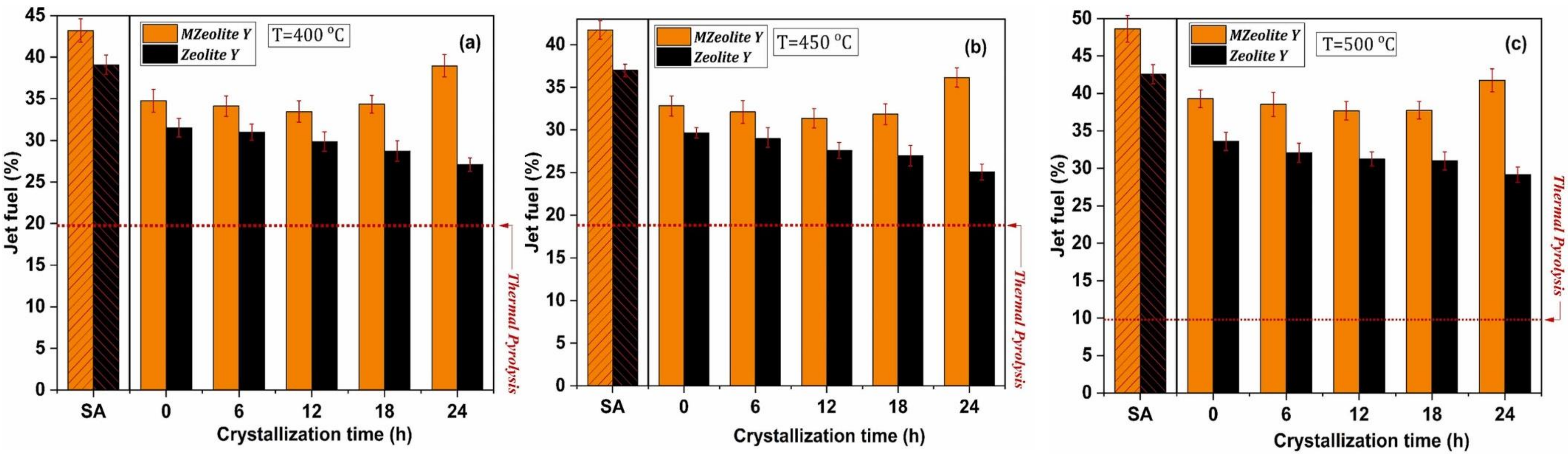


Renewable and Sustainable Energy Reviews 73 (2017) 346–368354

Catalytic Pyrolysis of Mixed Plastic





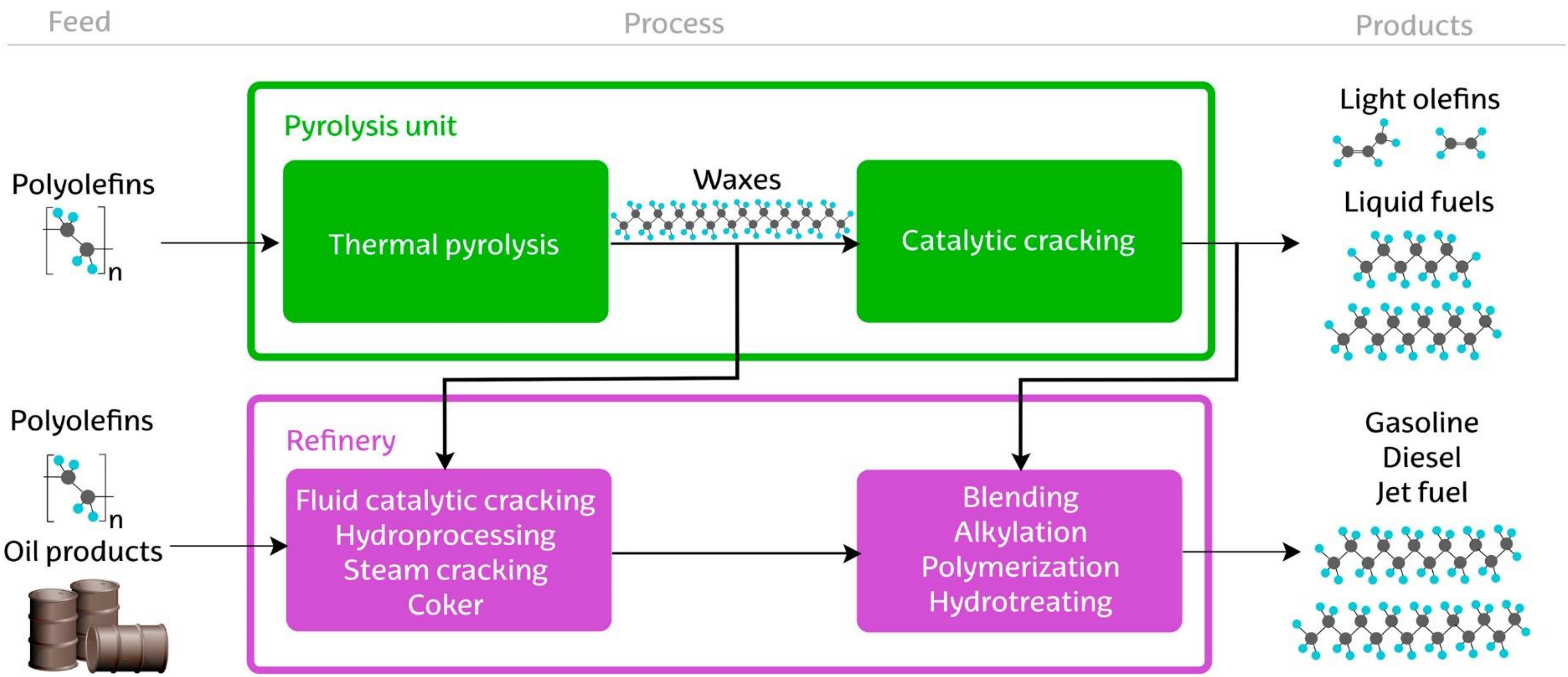


pyrolysis of municipal polymer waste at (a) 400 °C, (b) 450 °C, and (c) 500 °C for different catalysts and their comparison with thermal pyrolysis.

Process Safety and Environmental Protection 164 (2022) 449–467

Co-Pyrolysis

- The co-pyrolysis of plastic furnishes a beneficial strategy to possibly improve the quality of gas or liquid fuels, attenuate carbon emissions, and aid the waste management
- The synergistic effect has enabled fast heating rate and rapid process time.

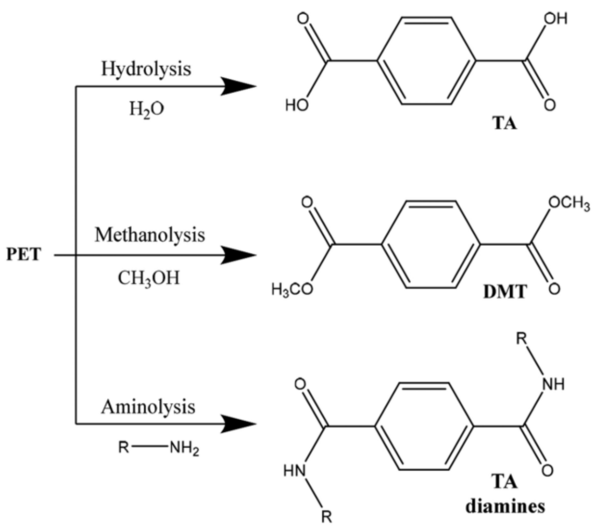


Limitations of pyrolysis

- Energy-intensive process
- Low selectivity to SAF
- Environment problem (environmental emission standard)

Solvolysis

- Chemical depolymerization (solvolysis) involves using a reagent to decompose the polymer matrix.
- The name of the technique depends on the reagent used: hydrolysis when the reagent is water, alcoholysis when it is an alcohol, and glycolysis when glycol is used.



Feedstock	Particle size [mm]	Solvent	Reaction conditions (*T*, *P*, *t*)	Solid content[a] [wt%]	Plastic/ water	Yield or conv. [%]	Major product
polyolefins PE, PP	N/A	water	450 °C 2 MPa 45 min	8	0.57 (1:2)	87 (PP) 50 (PP/PE)	C_4–C_{25}
HDPE, PP	N/A	water	450 °C 1.55– 23 MPa 45–60 min	8	0.57 (1:1.75) 2.35 (1:2)	87	C_6–C_7
HDPE + sugarcane bagasse	N/A	ethanol	280 °C 75 min	15	0.05 (1:20)	69.54	hydrocarbons phenols
PP	N/A	water	380– 500 °C	3	0.25 (1:4)	91	naphtha
PBT, PC, PET, PLA, PMMA, POM, PPO, PVA, SB	3	distilled water	400 °C 25 MPa 15 min	4	0.1 (1:10)	95 (PC)	toluene isopropyl phenol isopropenyl phenol
PP, PC, PS, PET	0.02	pure water	350– 450 °C 25 MPa 0.5–1 h	3	0.35 (1:3)	86 (PS) 60 (PC)	terephthalic acid ethylene glycol bisphenol methylene
ABS, HDPE, LDPE, PA6, PA66, PET, PC, PP, PS, PU, PVC	2	water	350 °C 14–20 min	3	0.058 (1:17)	80 (PC)	bisphenol-A ethylene glycol benzoic acid
PS	2–5	ethanol	250– 375 °C 15–75 min	2	4 (1:0.25) 0.25 (1:4)	85 (at 0.5:1	α methyl-styrene aromatics alkenes

S. Ügdüler,K. M. Van Geem,R. Denolf,M. Roosen,N. Mys, K. Ragaert,S.De Meester,GreenChem.2020,22, 5376–5394

Limitations of Solvolysis

- Developed to handle specific aromatic plastics in a particular PET
- Sorting as a prerequisite
- Not applicable for aliphatic plastics

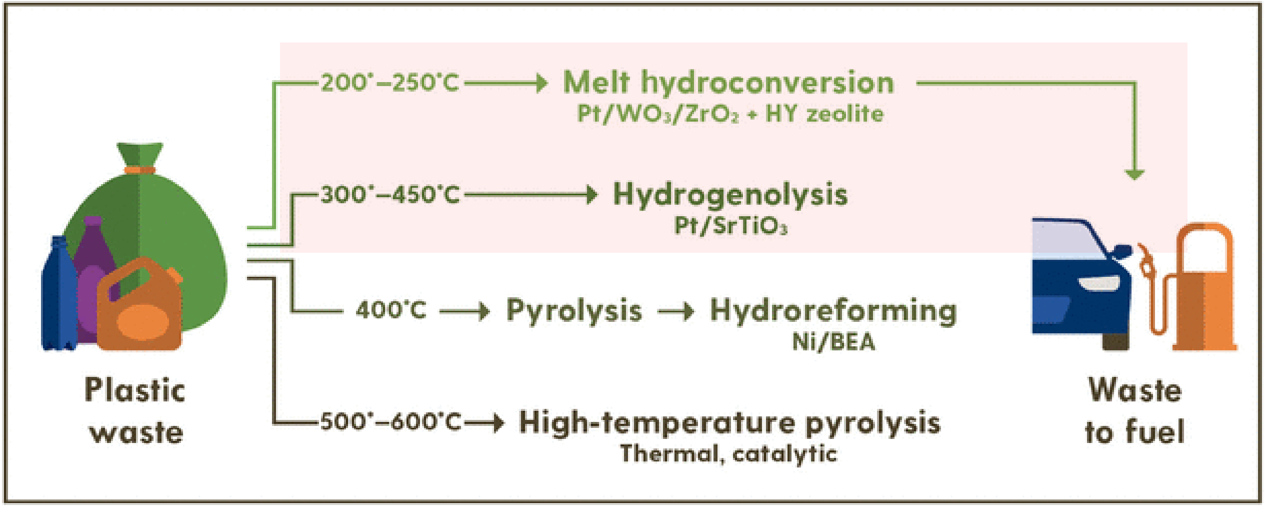
J Polym Sci.2020;58:1347–1364.

Hydrogenolysis

- Hydrogenolysis is a catalytic chemical method to break down the CC bond or C heteroatom bonds such as CO(hydrodeoxygenation, HDO) in the feedstock by using H_2.
- Although thermochemical conversion is promising for handling mixed plastic waste, it typically occurs at high temperatures (300–800°C).

Advantages

- Mild reaction temperature
- Highly selective
- Ease of product separation
- Adaptable to a number of plastics
- Wide range of C atalyst selection and design



Solvent-assisted Hydrogenolysis

Effect of solvent

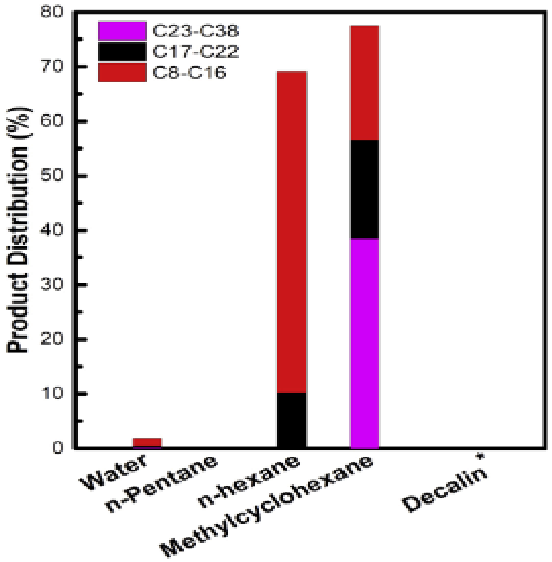
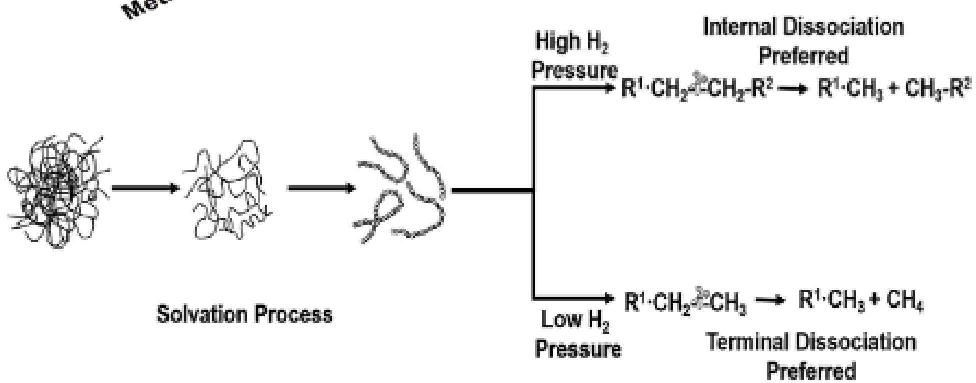


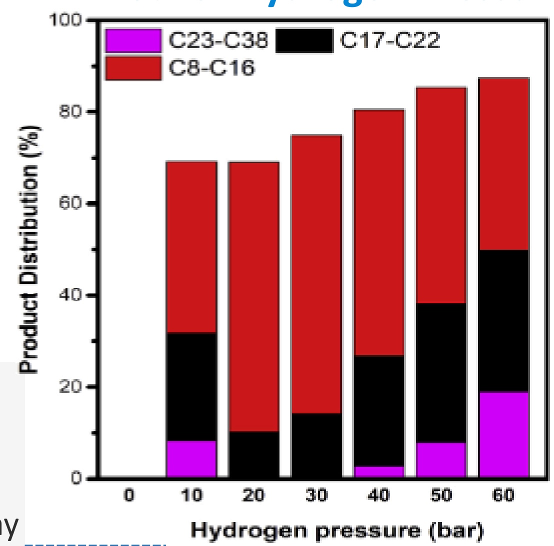
Table 2. Performance of the screened catalysts in the depolymerization of HDPE

Entry	Feedstock	Catalyst	Temperature (°C)	Time (h)	C8–C16 (wt %)	C17–C22 (wt %)	C23–C38 (wt %)
1	HDPE	5% Cu/C	220	1	0	0	0
2	HDPE	5% Fe/C	220	1	0	0	0
3	HDPE	5% Ni/C	220	1	0	0	0
4	HDPE	5% Pt/C	220	1	0	0	0
5	HDPE	5% Pd/C	220	1	0	0	0
6	HDPE	5% Rh/C	220	1	0	0	0
7	HDPE	5% Ru/C	220	1	60.8	14.1	0
8	HDPE	5% Pt/C	250	6	0.2	0.16	0.23
9	HDPE	5% Pd/C	280	1	0.29	0.01	0.1
10	HDPE	5% Pt/C	280	1	0.28	0.37	0.42
11	HDPE	5% Rh/C	280	1	21.7	20.2	33.4

Reaction conditions: 0.1 g HDPE, 0.05 g catalyst, 25 mL *n*-hexane, $p(H_2)$ 30 bar, 700 rpm.



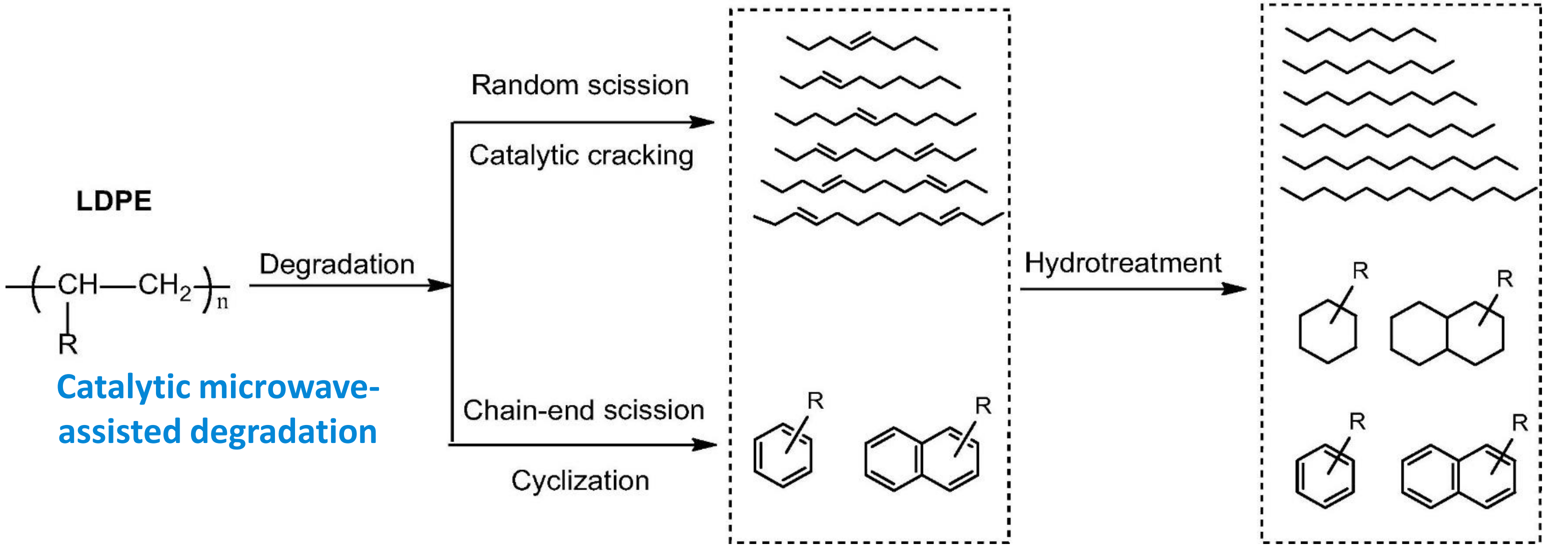
Effect of Hydrogen Pressure

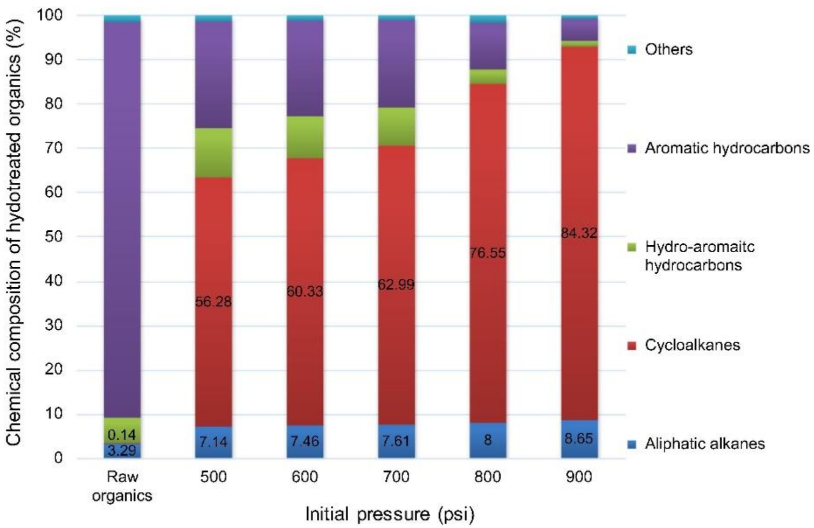


- Ru/C was a highly active catalyst for the liquid-phase hydrogenolysis of HDPE
- Solvent effects were prominent in the depolymerization of HDPE
- H_2 partial pressure played a significant role in the HDPE depolymerization pathway

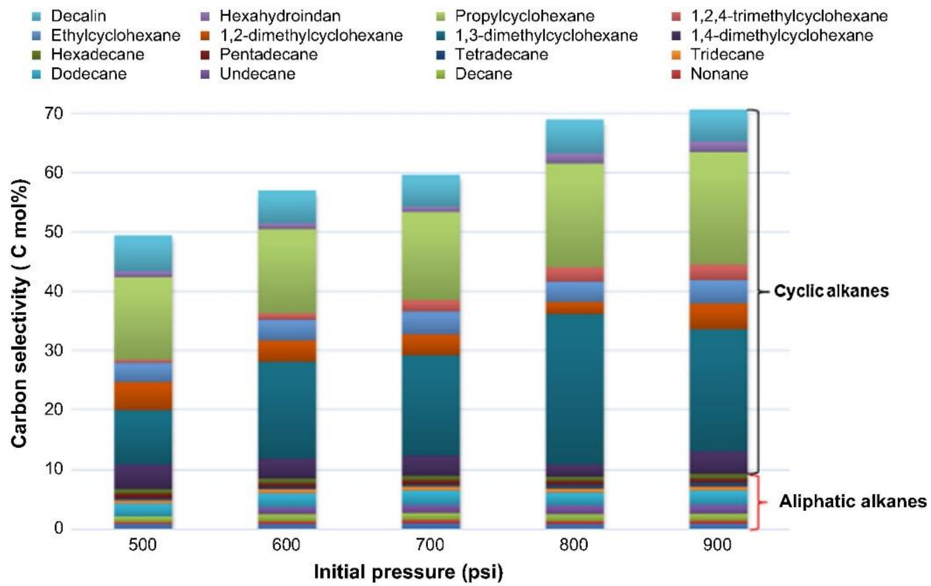
***Chem Catalysis* 1, 437–455, July 15, 2021**

Degradation/Hydrogenation



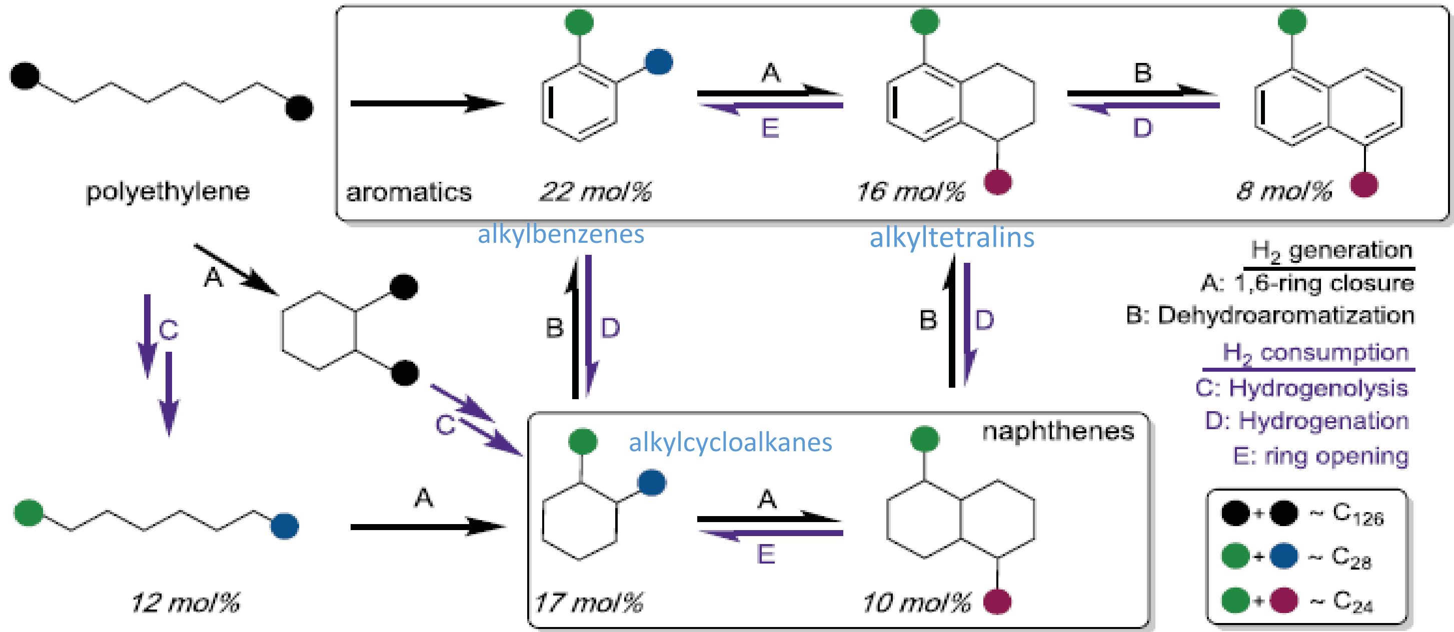


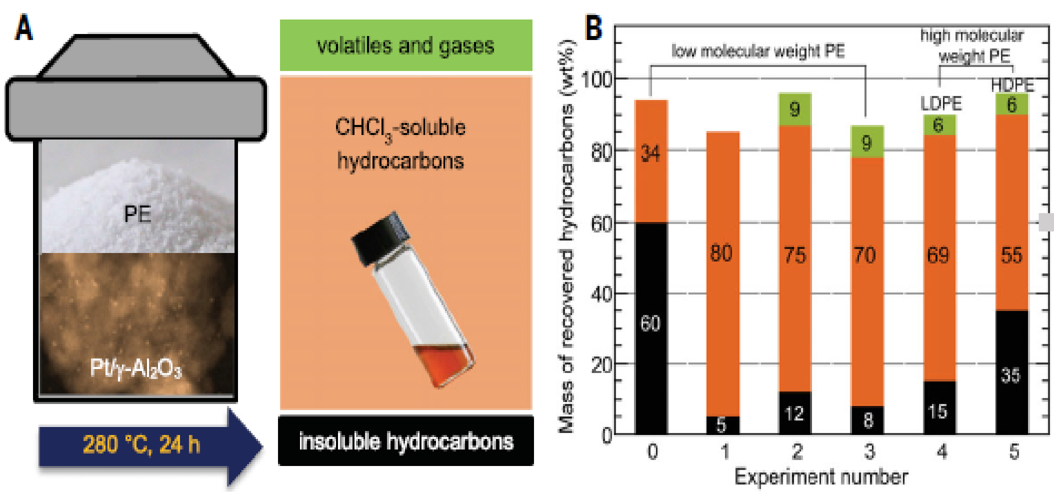
Reactant: raw organics from catalytic microwave degradation of LDPE over 20 wt% ZSM-5 catalyst; reaction temperature, 200 °C; Raney Ni 4200 catalyst, 10 wt% with respect to reactant mass; reaction time, 2 h.

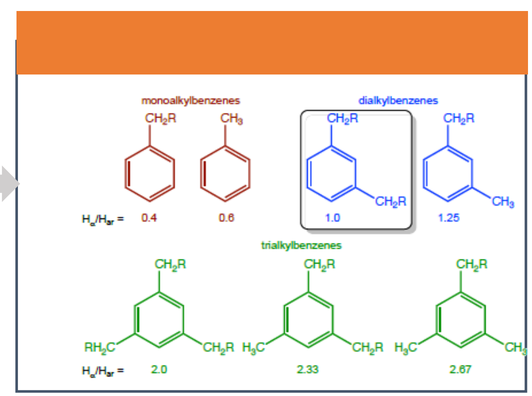


X. Zhang et al. / Fuel 188 (2017) 28–38 29

Tandem Hydrogenolysis/Aromatization

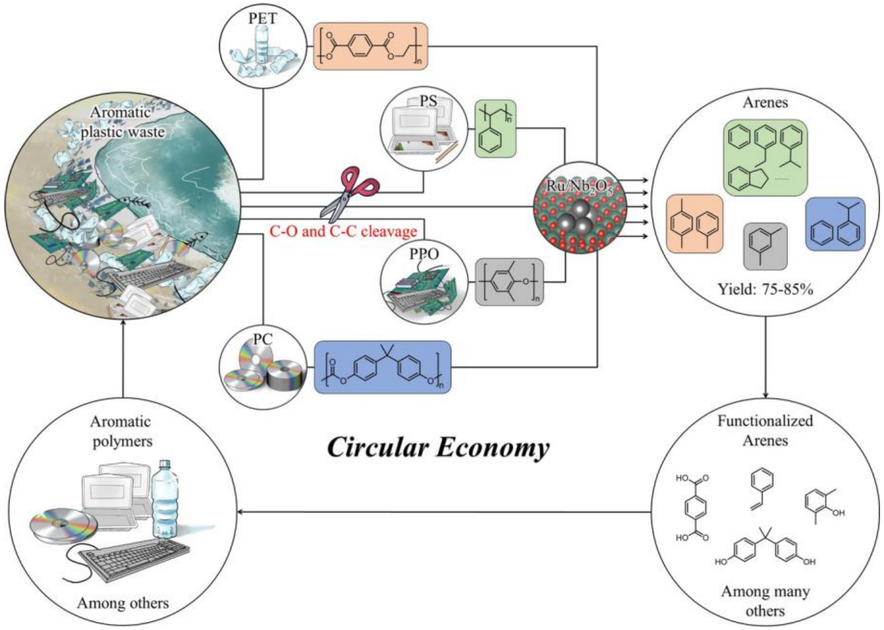


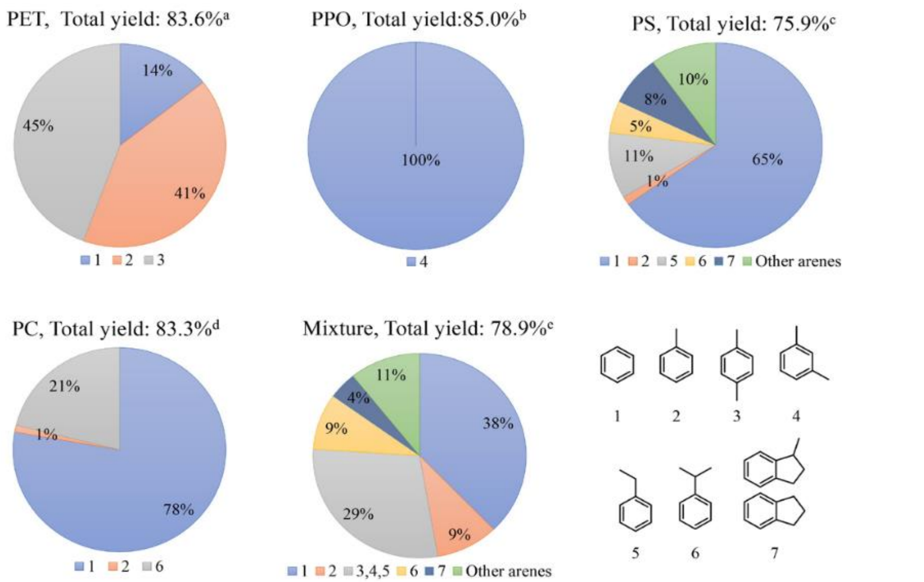




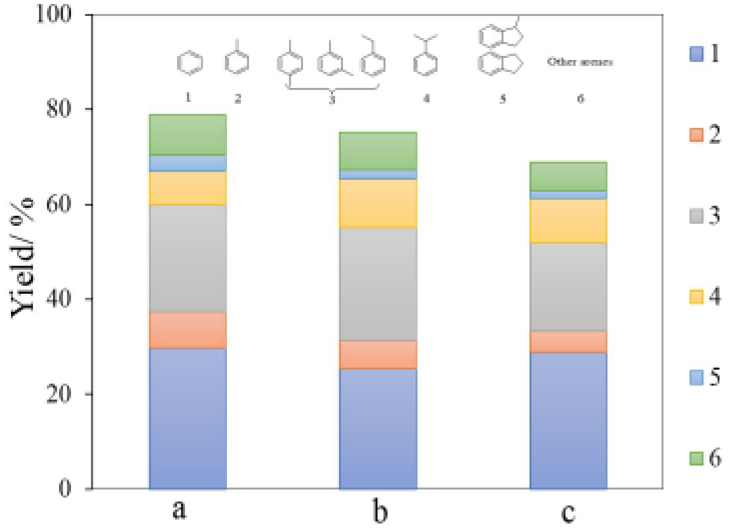
Solvent-free disassembly of polyethylene catalyzed by Pt/g-Al_2O_3 in an unstirred mini-autoclave reactor at 280°C.

Zhang et al., Science 370, 437–441 (2020)





Reaction conditions: 15 mg PET, 15 mg PC, 15 mg PS, 15 mg PPO, 60 mg Ru/Nb_2O_5, 4 g octane, 0.5 MPa H_2, 320 ºC, 16 h.

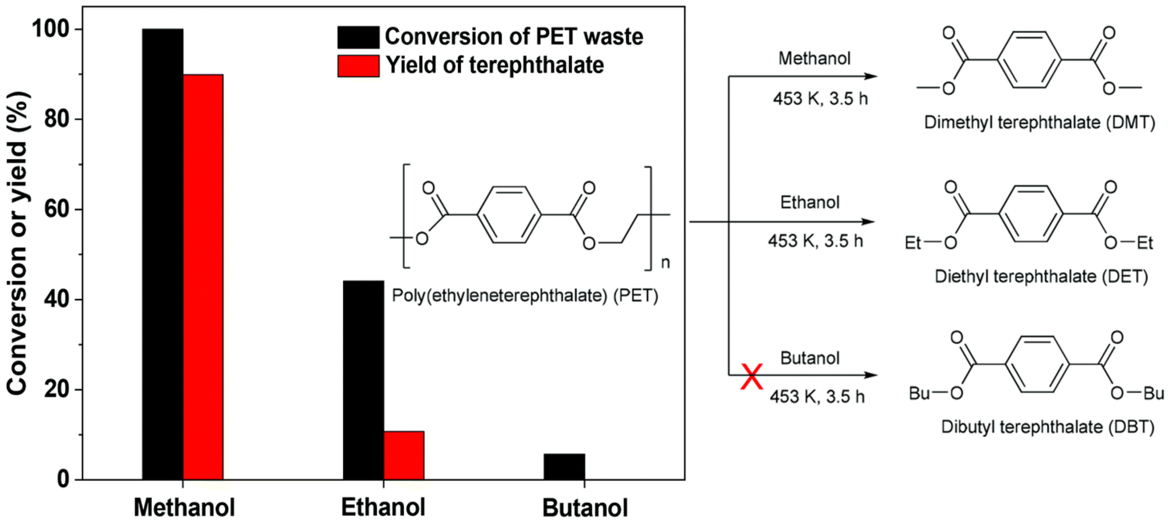


- They reported one-pot hydrogenation of mixed plastic waste to arenes
- Ru/Nb_2O_5 catalyst plays two roles in the selective cleavage of C–O/C–C bonds in aromatic plastic waste into arenes:
- (a) 60 mg Ru/Nb_2O_5, 4 g octane, (b) 60 mg Ru/Nb_2O_5, 2 g octane; (c) 30 mg Ru/Nb_2O_5, 4 g octane.

Angew. Chem. Int. Ed. 10.1002/anie.202011063

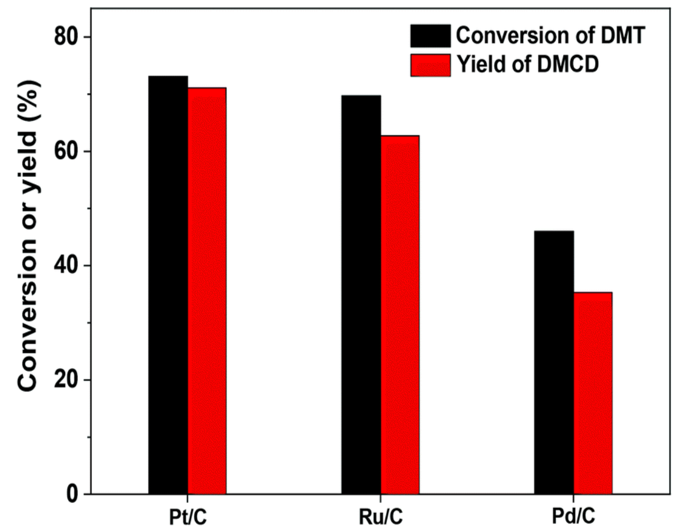
Alcoholysis/Solvent-free Hydrogenation

Alcoholysis of PET waste

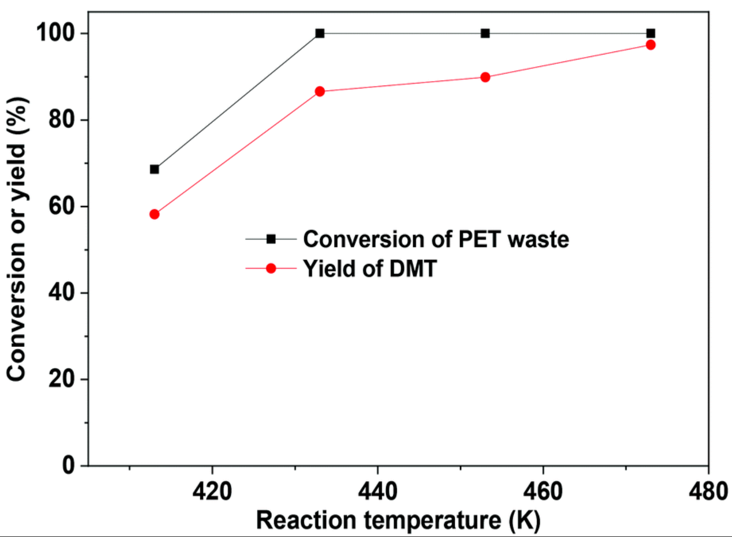


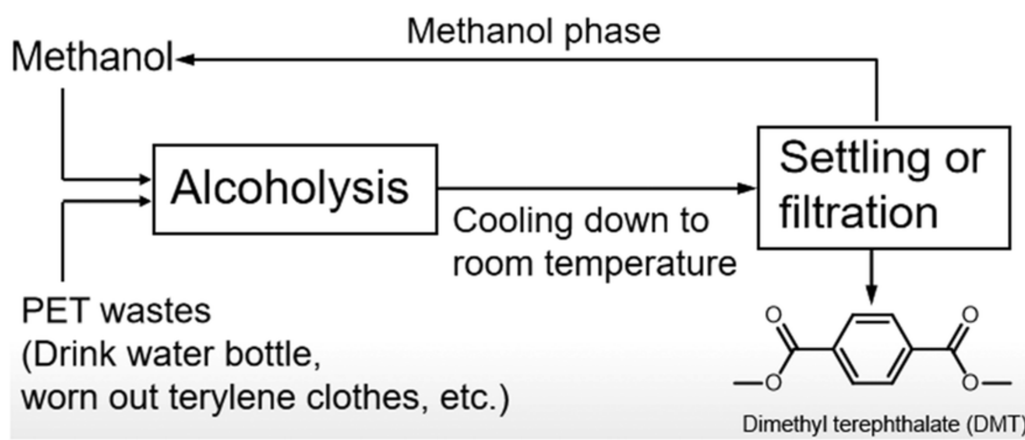
453 K, 3.5 h; 1 g PET waste and 40 mL alcohol

Hydrogenation of DMT



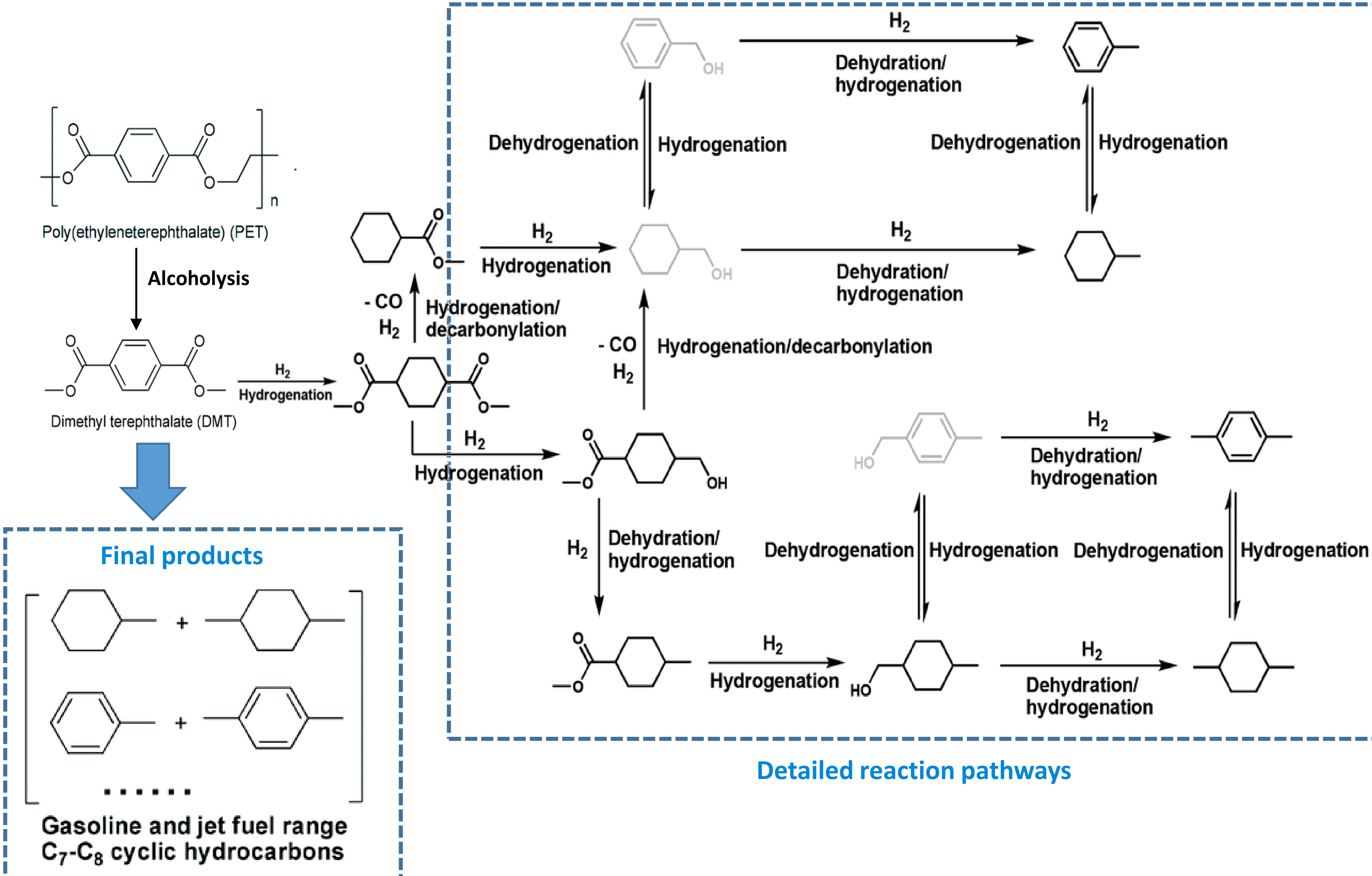
373 K, 5 MPa H_2, 7 h; 30 g DMT and 1 g catalyst





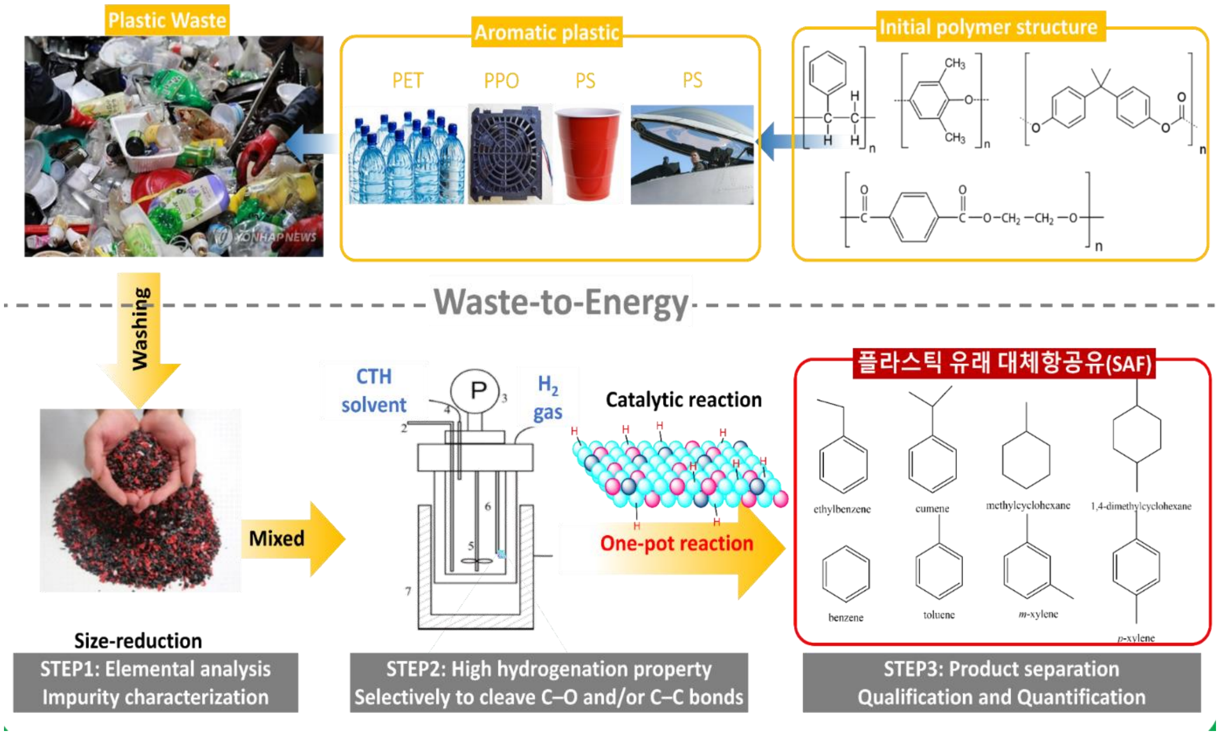
Green Chem., 2019, 21, 2709–2719

Alcoholysis/Solvent-free Hydrogenation



MCREL Approach

One-pot catalytic conversion of aromatic plastic waste back to arenes for aviation fuels



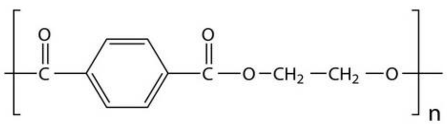
➢ **The selective degradation of aromatic plastic waste into target arenes is exceedingly rare**

- Identify a catalyst that enables the selective cleavage of C–O and/or C–C bonds while **preserving the aromatic rings**

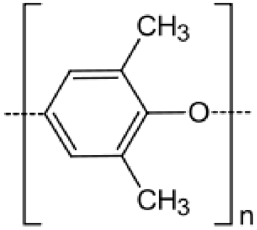
From C–O/C–C activation chemistry,

- Combination of metal sites with high hydrogenation property and acidic sites with the strong ability to activate C–O/C–C bonds is required

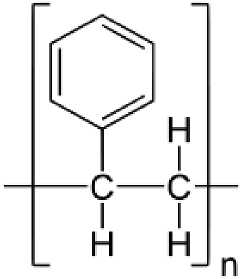
PET



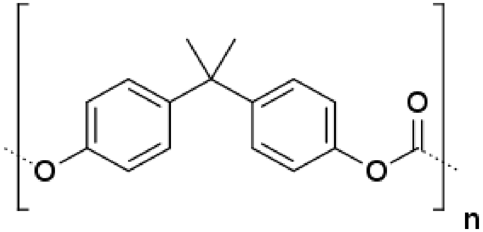
PPO



PS



PC



Why?

Constructed from aromatic monomers by interunit C–O and/or C–C linkages

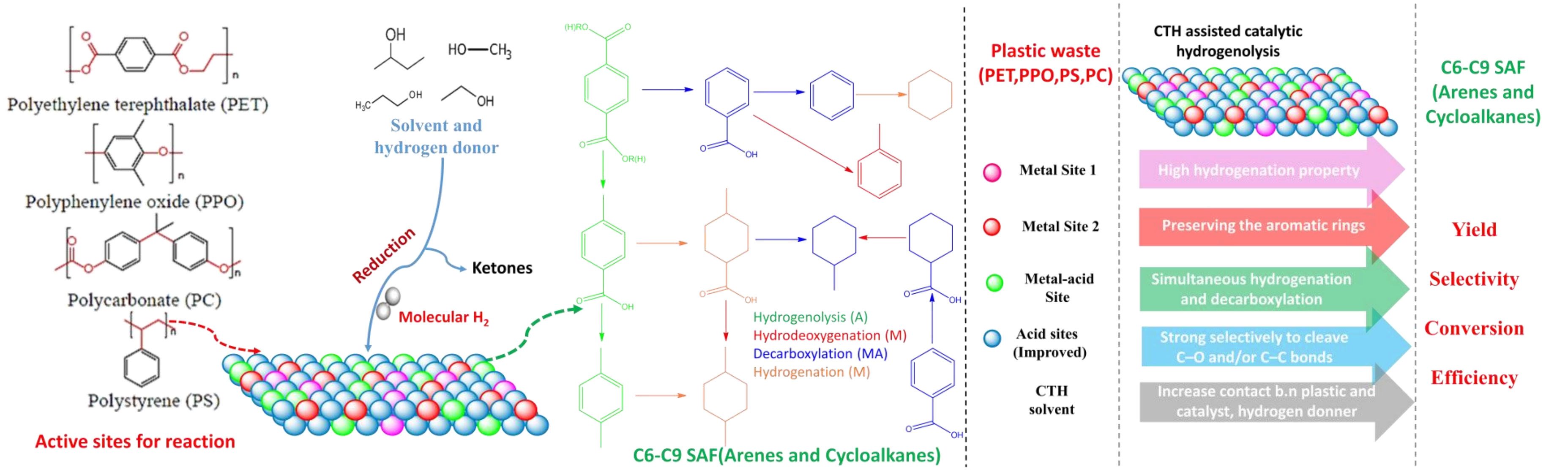
Many widely used plastics

- Polyethylene terephthalate (PET)
- Polystyrene (PS)
- Polycarbonate (PC)
- Polyphenylene oxide (PPO)

They comprise all common types of linkages in aromatic plastics

- Ester linkage
- Ether linkage,
- C–C
- combinations of C–O and C–C linkages

Reaction Mechanism



For C-O bond cleavage,

- Lewis acid sites (support) enable the selective adsorption and activation of C-O bond
- Then, with the help of dissociated H species over Ru, the cleavage of C-O bonds in aromatic plastics is efficiently achieved

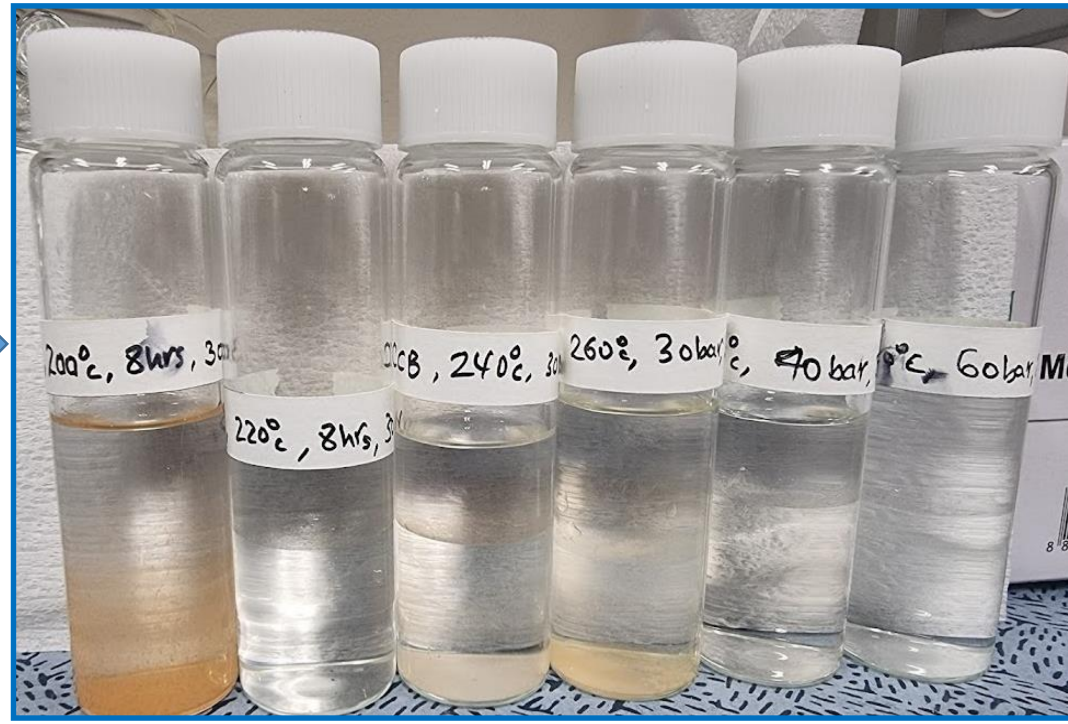
For C-C bond cleavage,

- The benzene ring is first adsorbed on Lewis acid sites
- Then the adsorbed benzene ring is protonated by Brønsted acid sites to proceed the activation of the C-C bond
- Following that, the dissociated H species on metal clusters attack the weakened C-C bond to break it

Reaction Results

Recycled plastic

Size reduction, reaction mixture preparation



Product separation using ethyl acetate as organic solvent

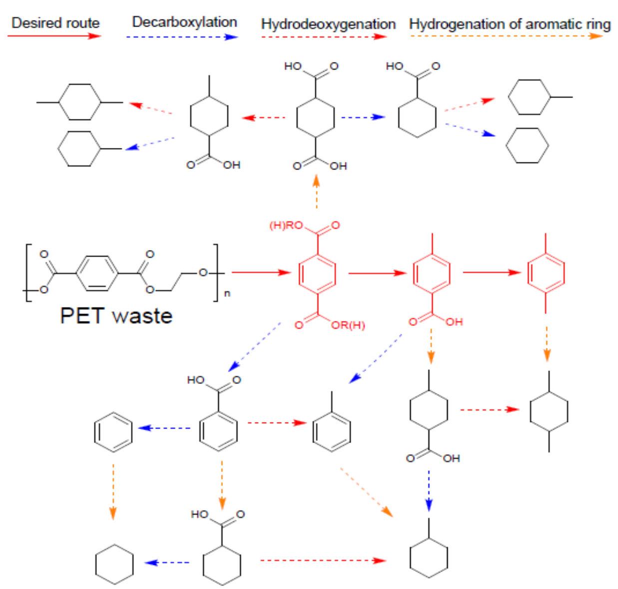
Water as a solvent

- Polar solvent that binds reasonably strongly with polar functionalities in PET thus, weakening the inter-chain interactions
- Does not react with hydrogen over metal-solid acid catalysts at the reaction temperature

Reaction Results

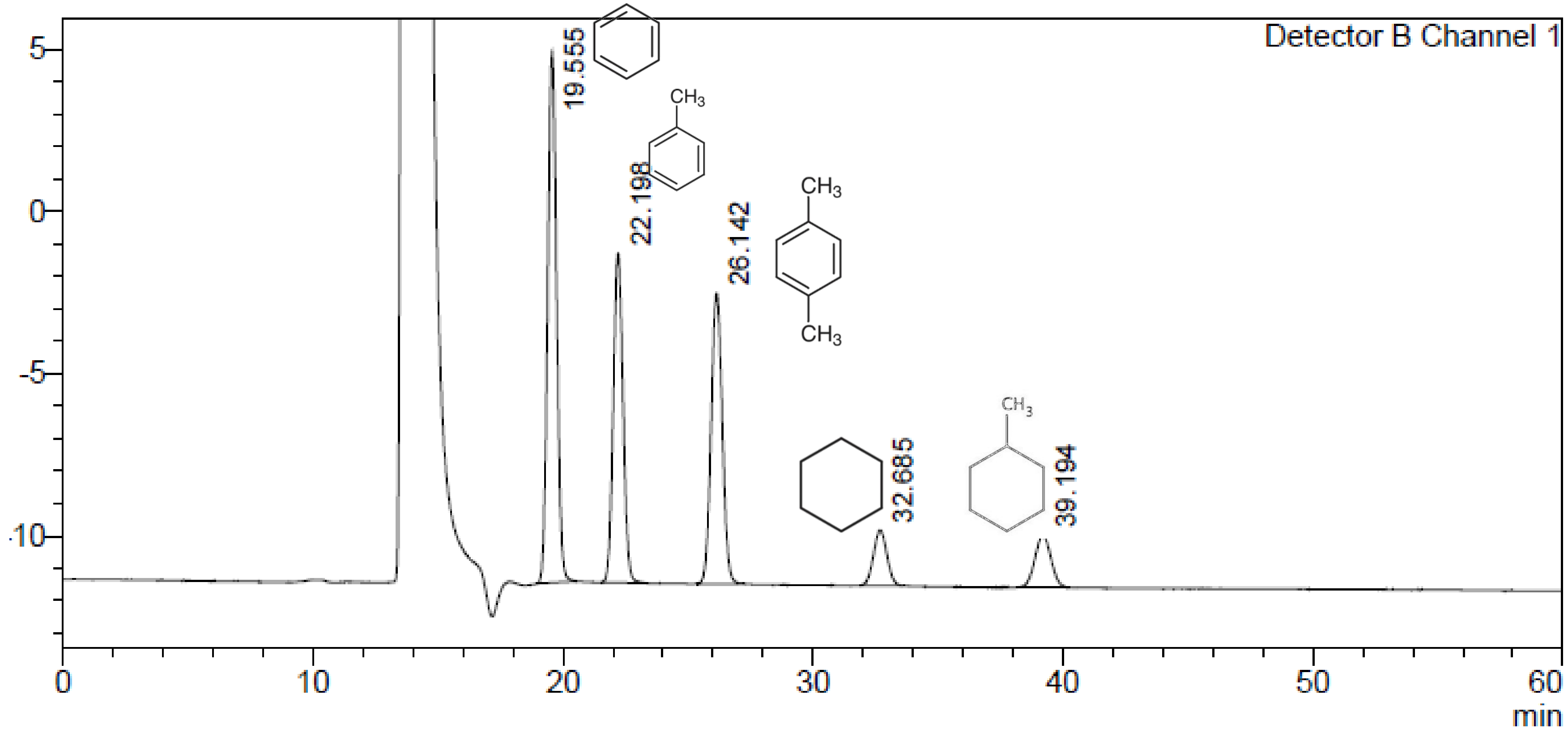
Catalysts	PET conversion (%)	P-xylene S (%)	Toluene S (%)	m-Cyclohexane S (%)	Others
Ru/SNb_2O_5	**72.0**	**53.2**	**19.2**	**4.10** (MCH+CH)	**23.5**
Pd/SNb_2O_5	57.1	6.3	4.5	8.7 (MCH+CH)	80.4
Ru/ZSM-5	81.0	5.7	7.1	32.1 (MCH+CH)	55.1
Pd/ZSM-5	62.0	1.9	1.6	24.9 (MCH+CH)	71.5
Ru/ZrO	56.3	11.1	13.2	16.8 (MCH+CH)	58.9
Pd/ZrO	37.3	4.2	2.7	20.5 (MCH+CH)	72.6

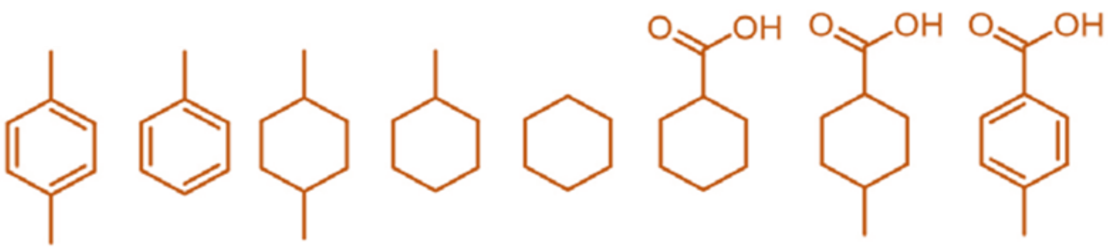
Reaction conditions: 0.2 g PET, 0.2 g catalyst, 20 g H_2O, 240 ºC, 12 h, 40 bar H_2



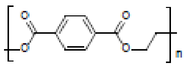
1. Lewis acid sites (NbOx species) enable the selective adsorption and activation of C-O bond
2. For C-C bond cleavage, benzene ring is first adsorbed on Lewis acid sites (NbOx species) of Nb_2O_5
3. Then the adsorbed benzene ring is protonated by Brønsted acid sites on Nb_2O_5
4. Following that, the dissociated H species on Ru attack the weakened Csp2-Csp3 bond to break it.

HPLC Chromatogram of the Product Mixture





Reaction Results

Substrates	Structures	Theoretical contents in pure plastic (wt %)		Elemental analysis (wt %)	
		C	H	C	H
Coca-Cola bottle		62.50	4.17	61.94	4.16

Catalysts	CCB conversion (%)	P-xylene S (%)	Toluene S (%)	m-Cyclohexane S (%)	Others
Ru/SNb_2O_5	**86.2**	**47.2**	**21.3**	**10.2 (MCH+CH)**	**21.3**
Pd/SNb_2O_5	70.1	8.9	9.7	18.1(MCH+CH)	63.3
Ru/ZSM-5	94.0	7.5	7.1	36.2 (MCH+CH)	49.2
Pd/ZSM-5	77.0	3.8	4.9	31.9 (MCH+CH)	59.4
Ru/ZrO	71.3	15.3	14.6	20.0 (MCH+CH)	50.1
Pd/ZrO	52.3	6.7	9.1	19.7 (MCH+CH)	64.5

Reaction conditions: 0.2 g CCB, 0.2 g catalyst, 20 g H_2O, 240 ºC, 10 h, 40 bar H_2

Water as a solvent

- Is a polar solvent that binds strongly with polar functionalities in PET thus, weakening the inter-chain interactions
- Does not react with hydrogen over metal-solid acid catalysts at the reaction temperature
- Poor performance of Pd catalysts was due to the fast hydrogenation of aromatic rings leading to ring opening and resulting in the formation of chemically more robust C–O linkages

Reaction Results

Temperature	CCB conversion (%)	P-xylene S (%)	Toluene S (%)	m-Cyclohexane S (%)	Others
220	61.6	39.1	11.3	1.2 (MCH+CH)	48.4
240	**86.2**	**47.2**	**21.3**	**10.2 (MCH+CH)**	**21.3**
260	91.3	41.7	28.1	7.2 (MCH+CH)	23.0
280	97.1	36.0	29.3	9.1 (MCH+CH)	25.6

Reaction conditions: 0.2 g CCB, 0.2 g catalyst Ru/Nb_2O_5, 20 g H_2O, Varying T, 8 h, 30 bar H_2

Pressure	CCB conversion (%)	P-xylene S (%)	Toluene S (%)	m-Cyclohexane S (%)	Others
30	76.1	31.0	9.7	1.6 (MCH+CH)	57.7
40	**86.2**	**47.2**	**21.3**	**10.2 (MCH+CH)**	**21.3**
50	88.3	37.0	17.3	27.3 (MCH+CH)	18.4
60	90.1	24.6	12.0	35.6 (MCH+CH)	27.8

Reaction conditions: 0.2 g CCB, 0.2 g Ru/Nb_2O_5, 20 g H_2O, 220 ºC, 8 h, varying P.

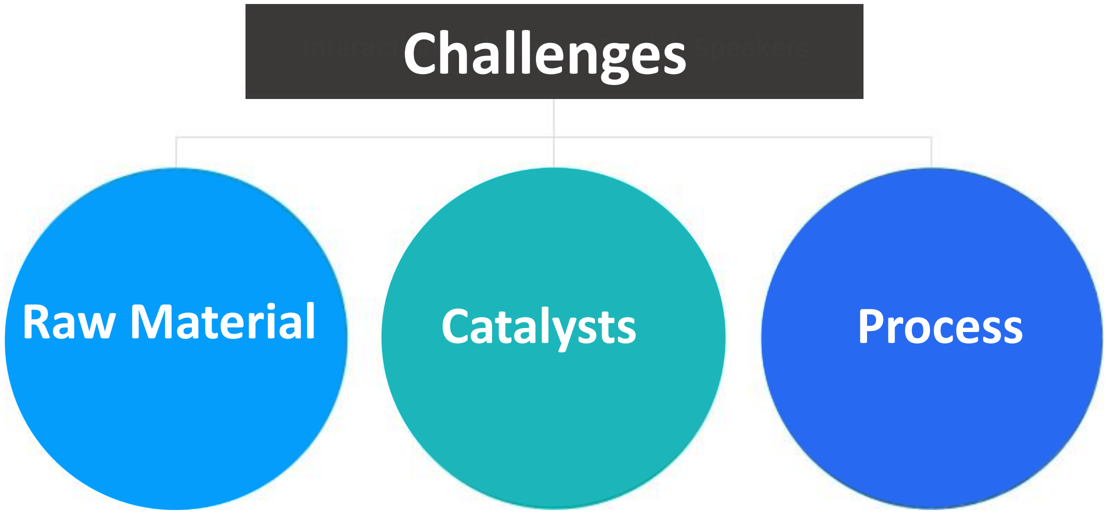
- The plastic conversion increased monotonically as a function of temperature
- Lower temperature led to low reaction rates, higher temperature favored the undesirable decarboxylation
- Higher pressure favored the hydrogenation of aromatic ring, lower pressure was not able to complete deoxygenation

Hydrogenolysis Summary

Substrate	Catalyst	Reaction conditions	Products	Yield [%]	Solvent
PE, PP	silica-supported Zr-H	150–190 °C, 1 bar H_2, 5–15 h	short-chain alkanes	40–84	none
HDPE	Ni and NiMo sulfides/HZSM-5 + Si–Al support	375 °C, ≈70 bar H_2, 1 h	gasoline-range fuels	42–65	none
PE	Pt/HZSM-5; Pt/HY; Pt/HMCM-41	120–340 °C, H_2 flow	paraffins, olefins, and alkyl aromatics	N.A.	none
PS, LDPE, PEP	$PtRe/SiO_2$	170 °C, ≈35 bar D_2, 17 h	poly (cyclohexylethylene); low-M_w oligomers	>90	isooctane
squalane	Ru/CeO_2	240 °C, 35 bar H_2, 3–48 h	branched, short-chain alkanes	≈70	none
squalane	$Ru–V/SiO_2$	240 °C, 35 bar H_2, 96 h	branched short-chain alkanes	>70	none
PEs, PP	Ru/CeO_2	200–240 °C, 20–35 bar H_2, 8–144 h	liquid fuels and waxes	83–92	none
PEs	$Pt/SrTiO_3$	300 °C, ≈12 bar H_2, 96 h	narrow-range lubri-cant-like products	42–99	none
PET	hydrogenation: Pt/C; HDO: $RuCu/SiO_2$	methanolysis: 140–200 °C, 3.5–14 h hydrogenation: 80–160 °C, 50 bar H_2, 1–10 h HDO: 350–400 °C, 40 bar H_2, 8–22 h	C_7/C_8 cycloalkanes and aromatics	overall ≈94	methanol
PC	HDO: Pt/C + H-β	methanolysis: 140–200 °C, 3 h; HDO: 100 °C, 30 bar H_2, 1 h	polycycloalkanes	overall ≈72	methanol
PC	Raney Ni + USY	1st step: 190 °C, Raney Ni, 1 h 2nd step: 190 °C, USY added, 1–5 h (H_2-free for the two steps)	C_6–C_{15} cyclic hydro-carbons	≈75	isopropanol
PC	Rh/C + H-USY	200 °C, 35 bar H_2, 12 h	propane-2,2-diyldicy-clohexane	≈95	water
PEs	Ru/C	200–225 °C, 20–30 bar H_2, 2–16 h	gaseous and liquid alkanes, CH_4	alkanes: ≈82 CH_4: ≈100	none
PE	$SnPt/\gamma-Al_2O_3 + Re_2O_7/\gamma-Al_2O_3$	200 °C, 20–40 bar He, 15 h	low-M_w oligomers	N.A.	*n*-pentane
PET, PS, PC, PPO, and mixtures	Ru/Nb_2O_5	280–320 °C, 3 bar H_2, 8–16 h	arenes	75–85	H_2O/octane
PET	Ru/Nb_2O_5	220 °C, 20 bar N_2, 12 h	BTX	≈91	water
LDPE/HDPE	$Pt/\gamma-Al_2O_3$	280 °C, H_2-free, 24 h	alkylaromatics and alkylnaphthenes	55–80	none
PET	single-site MoO_2/C	260 °C, 1 bar H_2, 24–96 h	TPA and ethylene	85–90	none
PS	Ru/SNb_2O_5	320 °C, 40 bar H_2, 20h	Arenes and cyclic-alkanes	~ 72	water
PET	Ru/SNb_2O_5	240 °C, 40 bar H_2,12h		~76	
CCB	Ru/SNb_2O_5	240 °C, 40 bar H_2,8h		~ 86	

MCREL

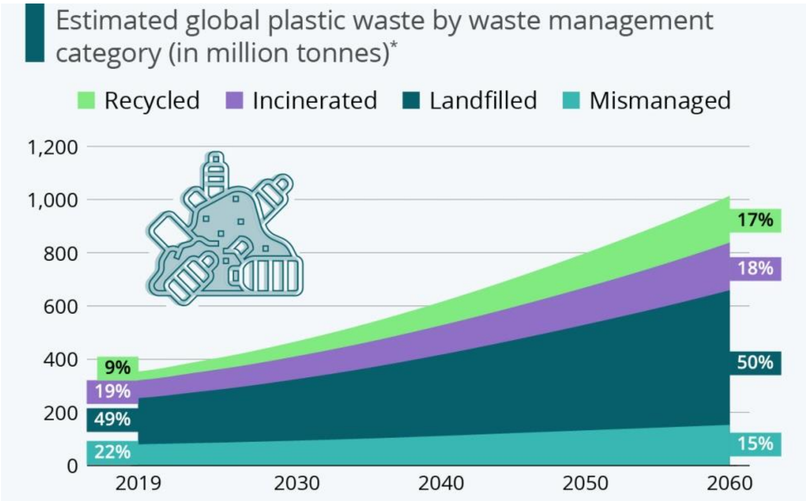
Challenges



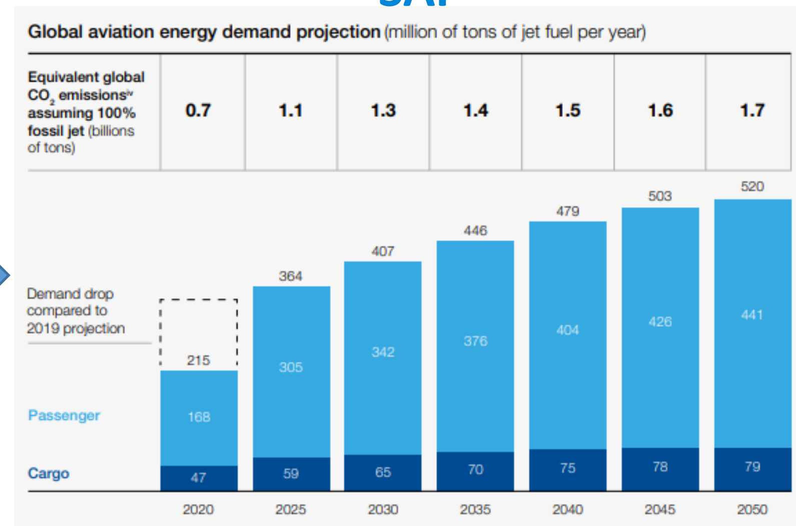
1. The solid-solid contact problem between plastic and solid catalyst remains a challenge
2. Designing an advanced solvent system to increase plastic swelling and solubility is highly desirable
3. Establish hydrogen transfer systems using renewable alcohols and acids as hydrogen sources
4. Economical and advanced catalysts with higher activity need to be explored
5. Improving plastic waste conversion efficiency and selectivity to SAF for mixed plastic
6. Systematic experimental process development and condition optimization

Outlooks

Plastic waste

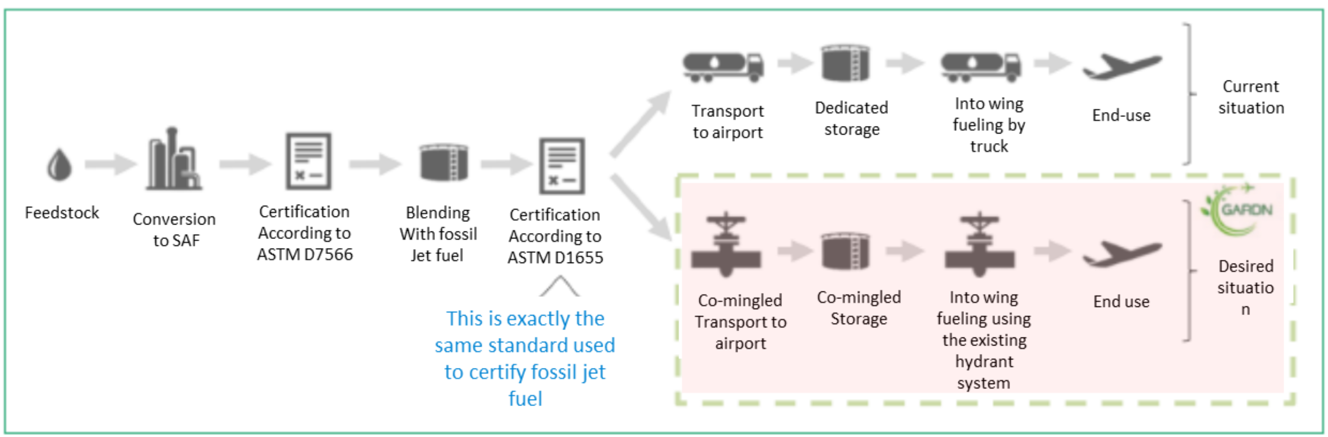


SAF



Given a policy framework, SAF is perhaps on the cusp of rapid expansion and replication

- Many members of entire supply chains are working towards SAF development (academia, national labs, entrepreneurs, big oil, fuel suppliers, pipeline companies, aviation partners)



Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation, INSIGHT REPORT NOVEMBER 2020

Conclusion

- Various chemical methods including hydrogenolysis, pyrolysis, solvolysis, and others have been employed to convert a single or mixture of plastic wastes into valuable chemicals.
- The hydrogenolysis reaction of waste plastic can be combined with other reactions such as solvolysis and thermal degradation to increase the selectivity to SAF.
- Ru has shown significant results for most plastic to SAF hydrogenolysis reactions.
- Nb_2O_5 catalyst support plays two roles in the selective cleavage of C–O/C–C bonds in aromatic plastic waste into arenes.
- Ru/Nb_2O_5 does not only catalyze the selective conversion of single-component plastic waste into bulk chemicals (PET to p-xylene and PPO to m-xylene), but also enables the conversion of mixed aromatic plastics into arenes.
- Innovative transformation routes are anticipated in the future to generate more diversified and high-value products from plastic wastes.