From Waste to Clean Fuel: Using Microwave Chemistry to Achieve Process Decarbonization

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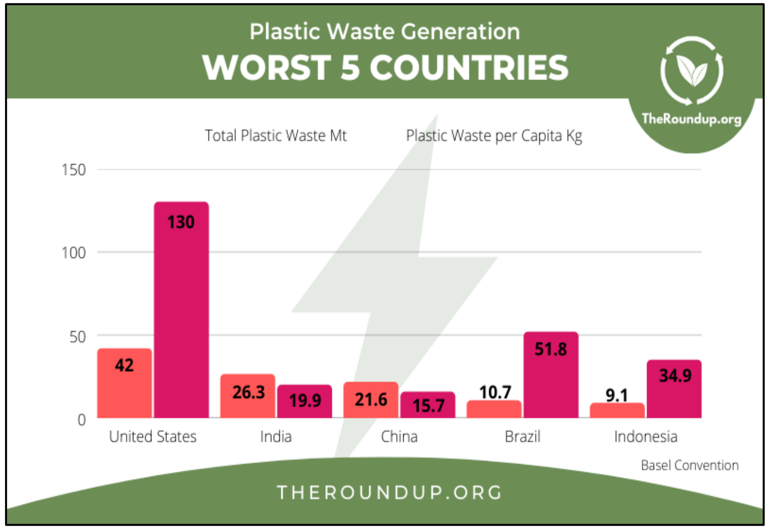
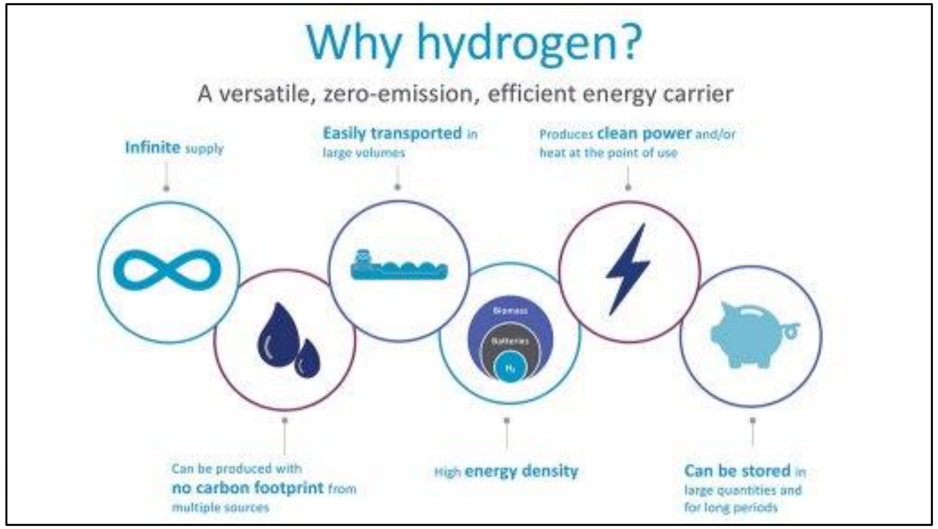
Background

- Global plastic waste generation has reached 353 million metric tons over the last two decades.
- The majority of the plastic waste is (1) landfilled or (2) incinerated. Only 9% of the plastic waste is recycled.
- Microwave (MW) gasification offers higher H_2 yield and enhanced selectivity to syngas over tars with higher energy efficiency as compared to existing conventional processes.





1. IEA Global Hydrogen Review 2021
2. https://wha-international.com/hydrogen-in-industry/

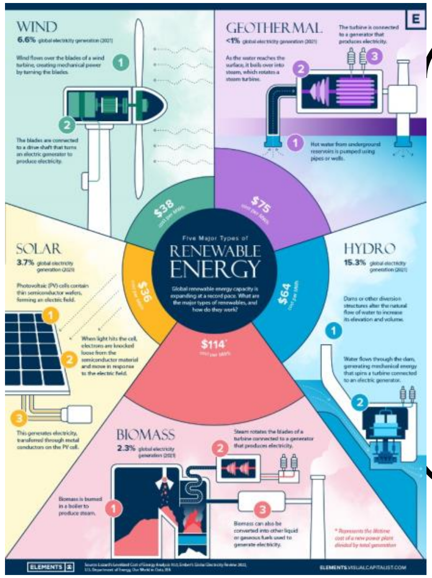
This work presents parametric optimization study of MW catalytic co-gasification of mixed plastics and corn stover for clean H_2.

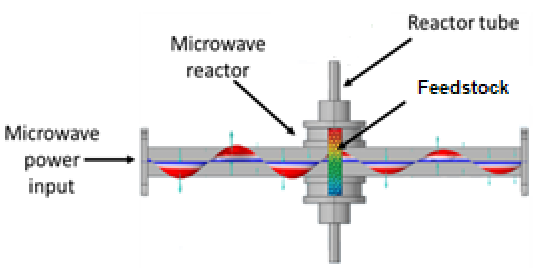
Proposed Approach: Microwave Gasification

Feedstock: Biomass, Waste Plastics

Microwave Reactor

Coupling with Energy Resources





Process Intensification

- Process modularity
- Efficient rapid heating and promoting favorable reaction
- Electrification of process – **cleaner H_2**

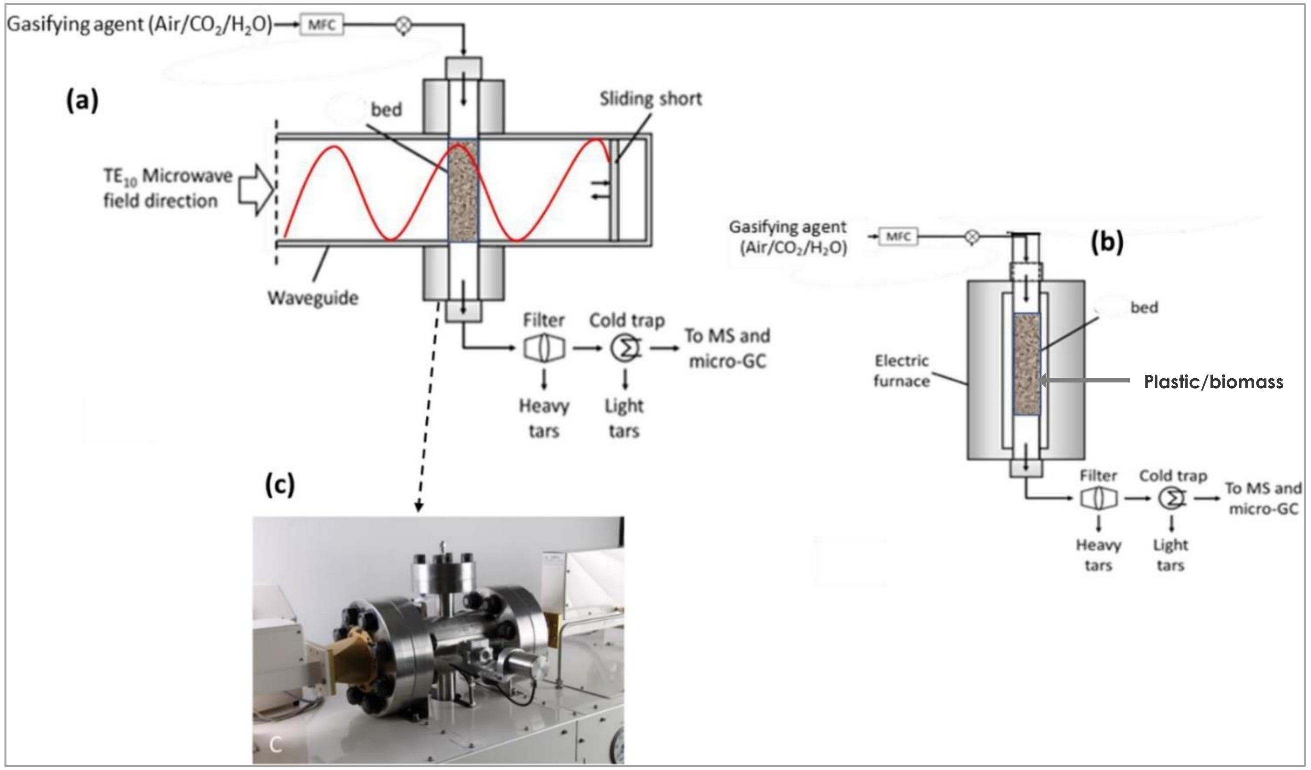
H_2, Syngas → Fuels & Chemicals

Part 1

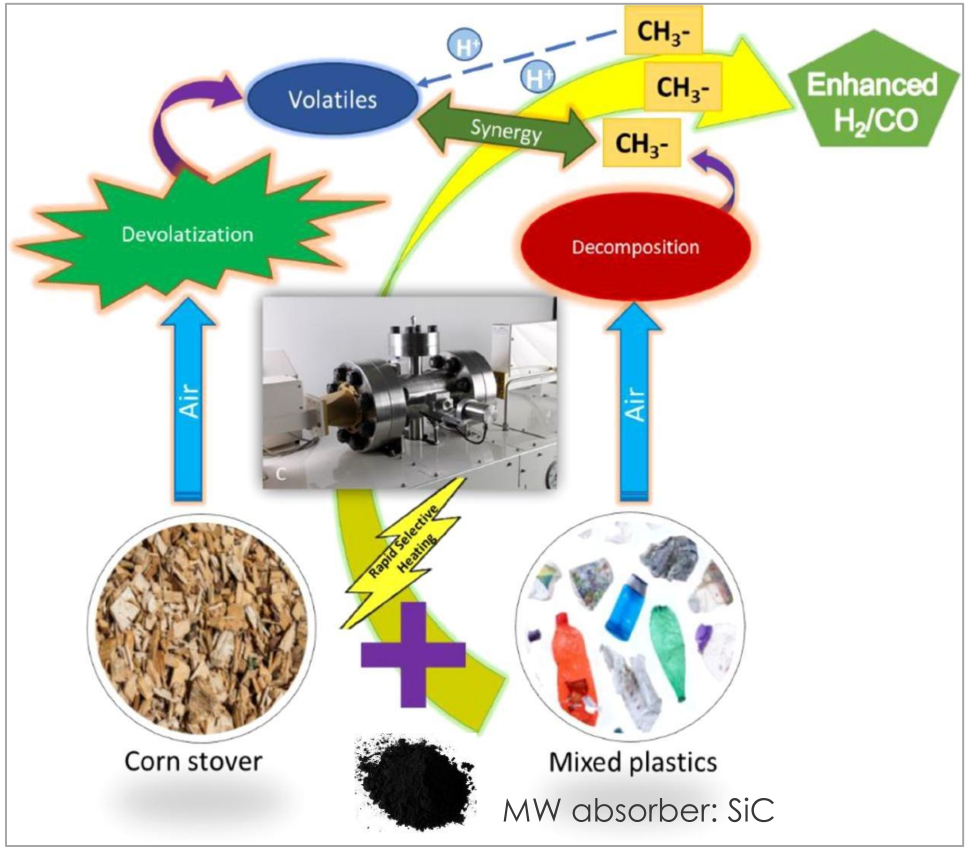
Gasification of Plastic-Corn Stover: Synergy in Microwave

Process Setup

Microwave Reactor



Reaction Mechanism



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Effect of Plastics to Biomass Ratio

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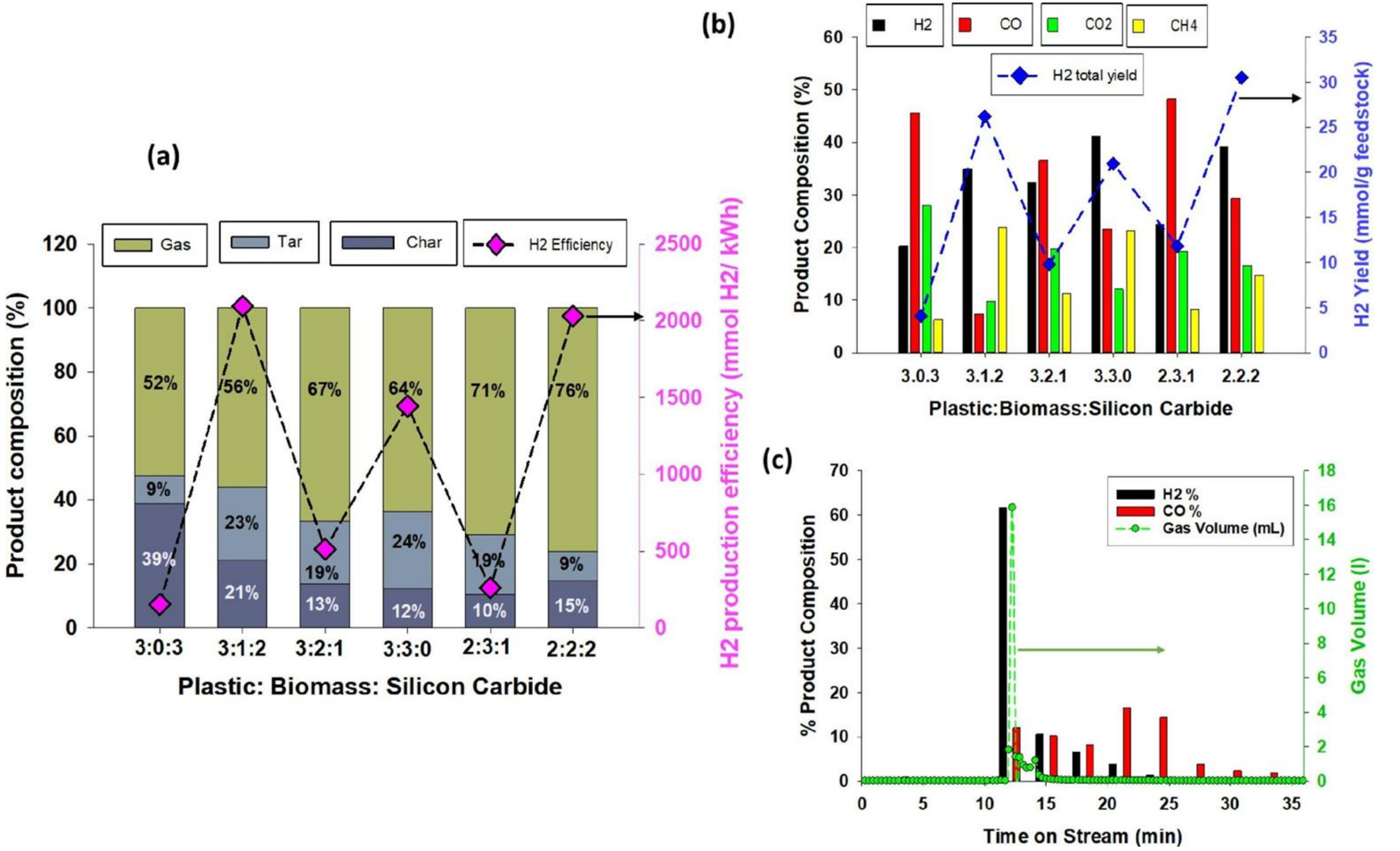
- Optimum conditions:
  - Plastic: corn stover: SiC = 1:1:1
  - 700 °C, air
- Highest gas yield (76%) with most H_2 yield (30.52 mmol/g_{feed})
- Minimal heavy tar formation (9%) and lowest power input (200 W)



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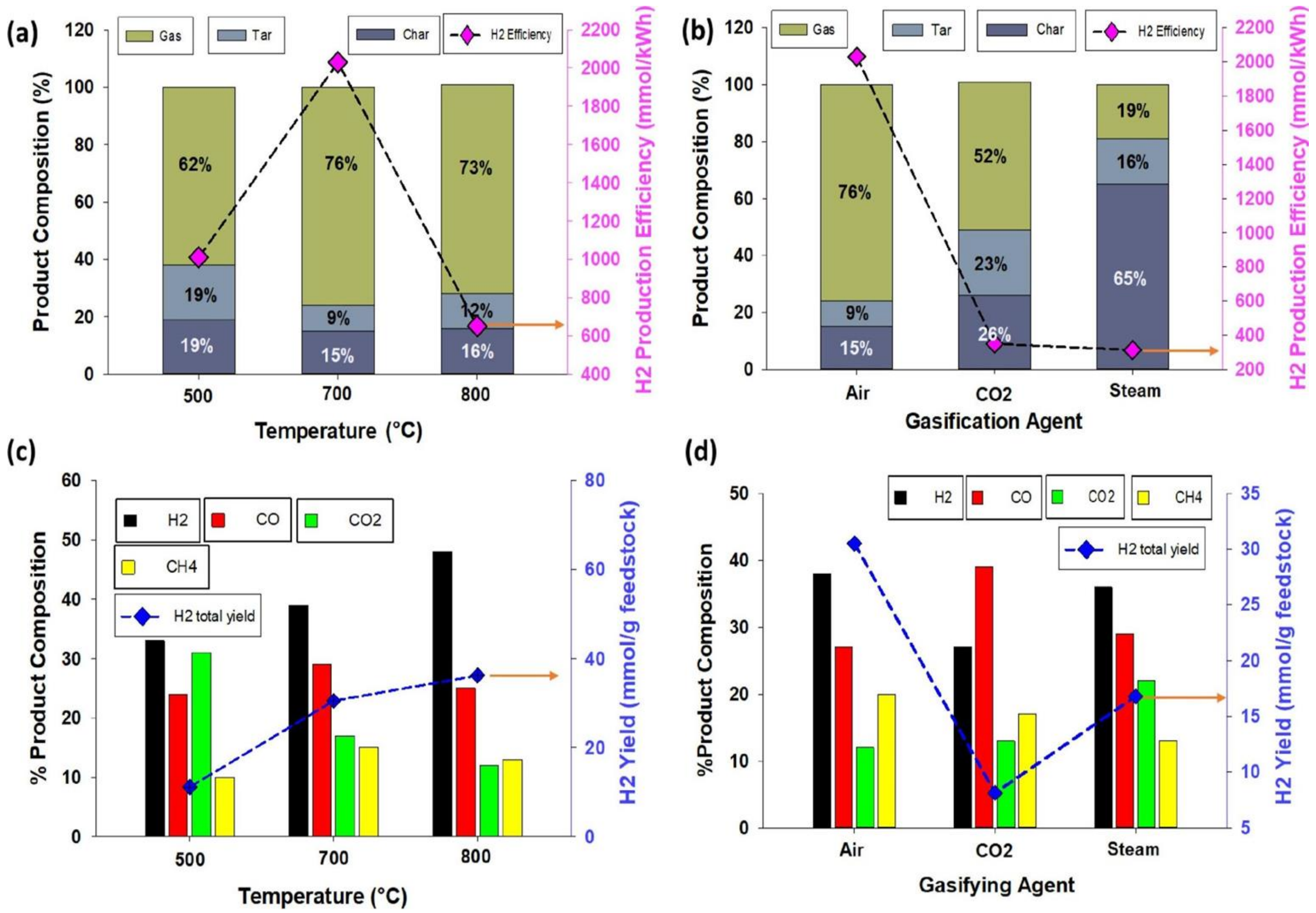
Effect of Temperature and Gasifying Agent



- At higher temperatures, volatiles from biomass devolatilization were enhanced by radicals from plastic decomposition, making higher gas yields for the mixed plastics, and decreasing char and tar yield.
- O_2 in air improves the heating value of the feed, which instantly burns under microwave, allowing intermediates to crack down and produce more H_2.

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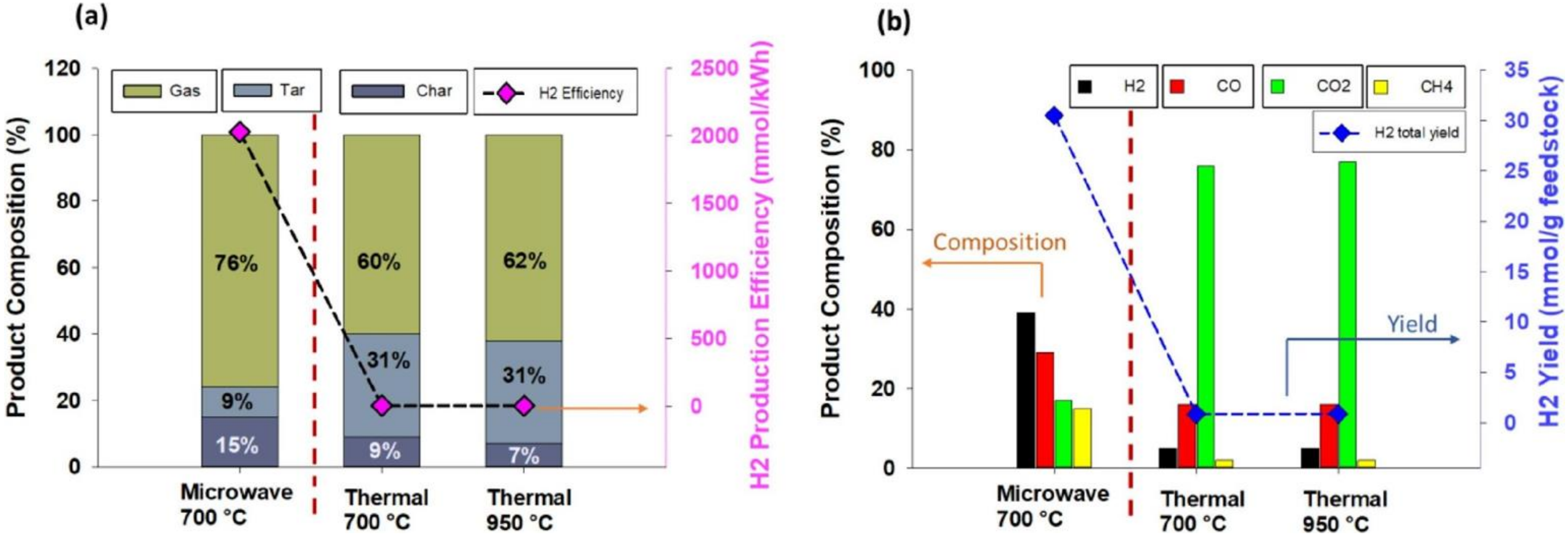
Microwave vs. Conventional Studies



- Rapid and enhanced selective heating of the microwave reactor gasifies plastics and generates the required radicals that contribute to the plastic and corn stover synergy, allowing enhanced H_2 yield (30.5 mmol/g_{feed} vs. 0.9 mmol/g_{feed} at 700 °C).
- During conventional heating, the mild gasification temperature of 700–950 °C alone is not enough to drive the endothermic Boudouard reaction after plastics and corn stover gasify and produce carbon.

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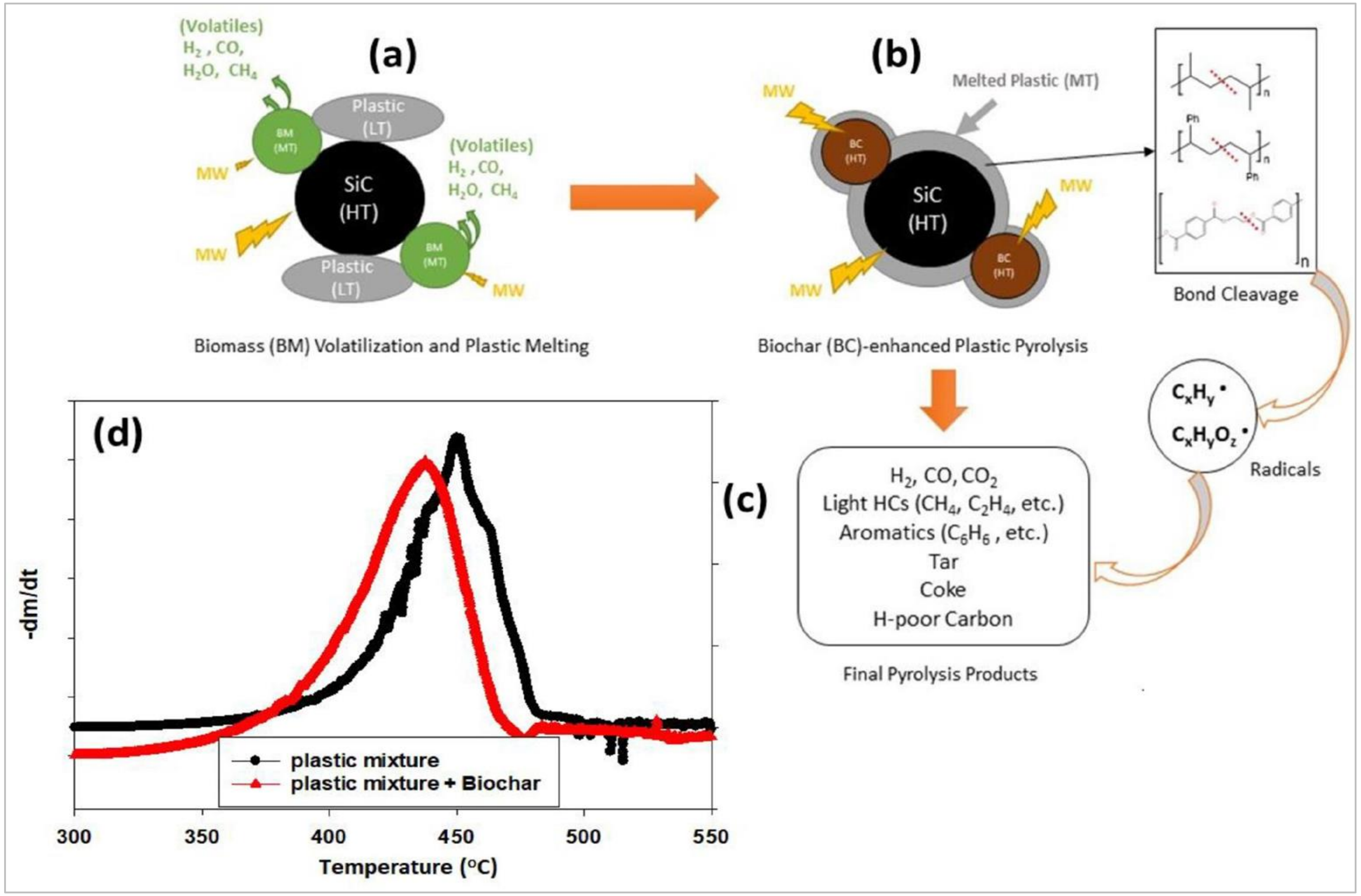
Microwave Gasification Mechanism



- Plastics heat only through proximity to SiC and corn stover, directing the heat flux and mass transfer away from corn stover.
- This mass transfer direction reduces side reactions and repolymerization of intermediates.
- With biochar, plastic decomposition shifts to lower temperatures, altering the product distribution with higher yields of low molecular weight compounds.

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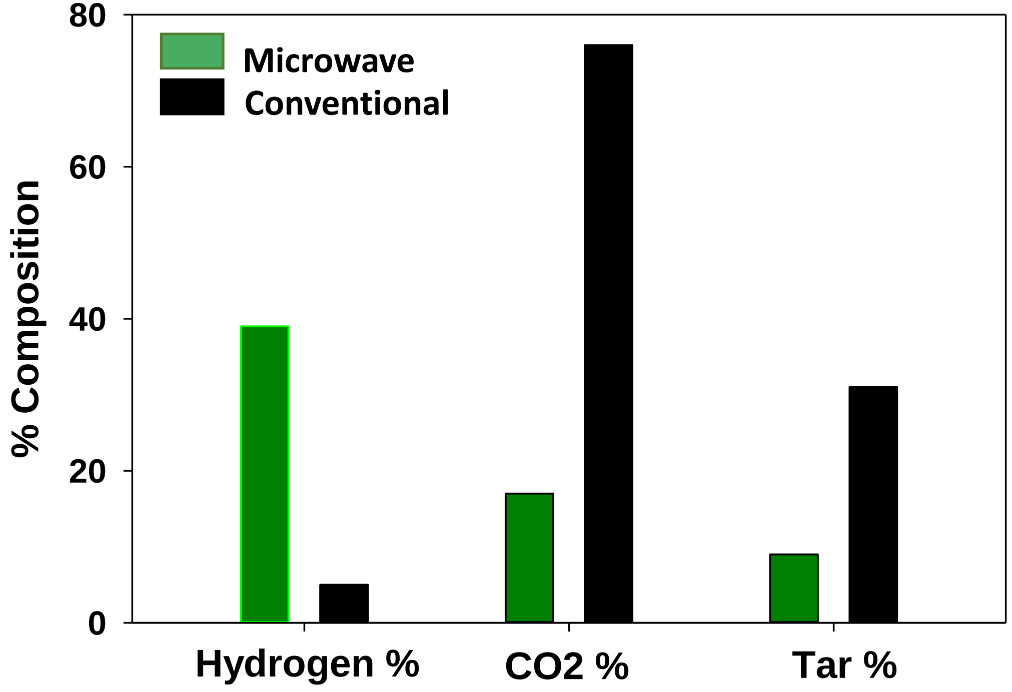
Key Findings: Part 1

- Microwave enhanced synergy between plastic and biomass.
- Optimum 1:1:1 feedstock ratio: High syngas yields and H_2 yield (30.5 mmol/g_{feed}).
- At a temperature range of 700–800 °C, enhanced H_2 formation was observed.
- Higher syngas yields under air (76%) compared to CO_2 (52%) and steam (19%).
- H_2 in the microwave reactor was 30.5 mmol/g $_{feed}$ at 700 °C, whereas H_2 in conventional reactor was 0.9 mmol/g $_{feed}$ at 700–950 °C.
- The synergy between plastic-biomass increased at optimum conditions under the microwave reactor, yielding higher amounts of H_2.

Mixed plastics and biomass gasification



Part 2

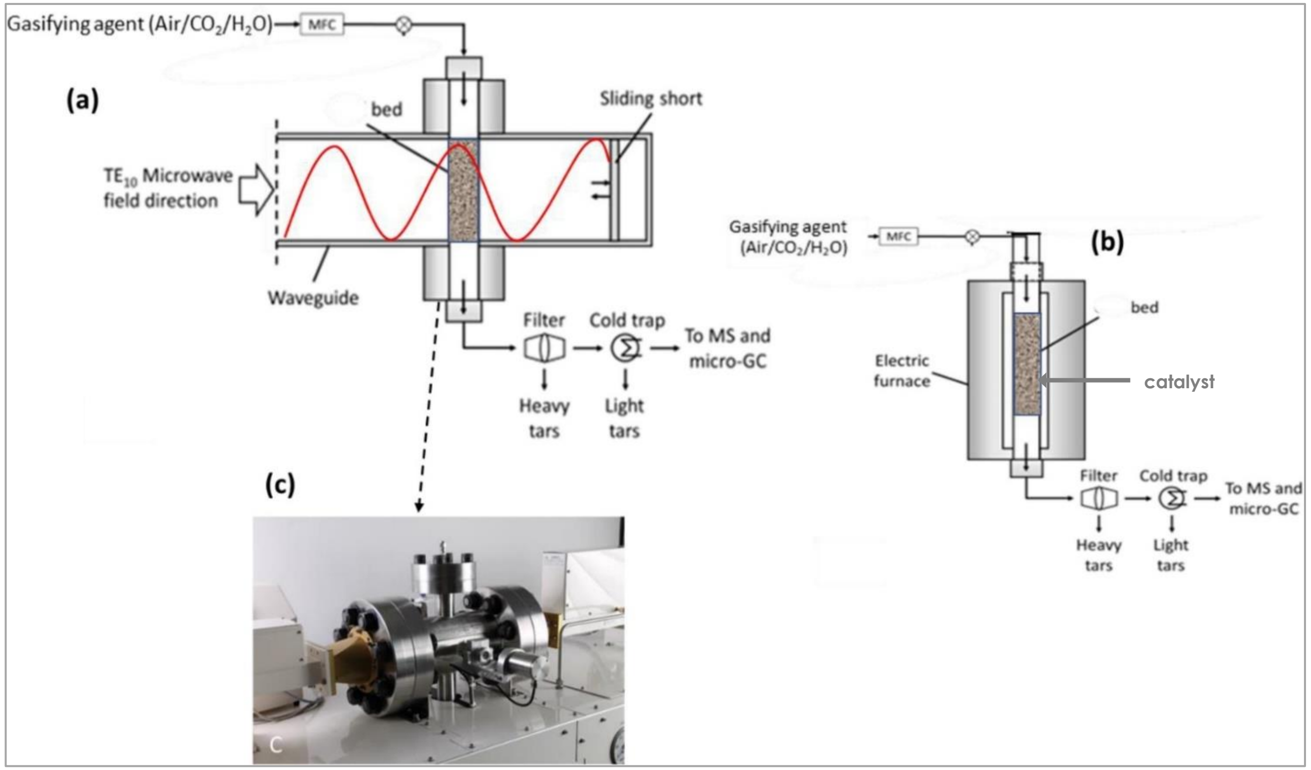
Microwave-Assisted Catalytic Gasification of Plastic-Corn Stover

Goals:

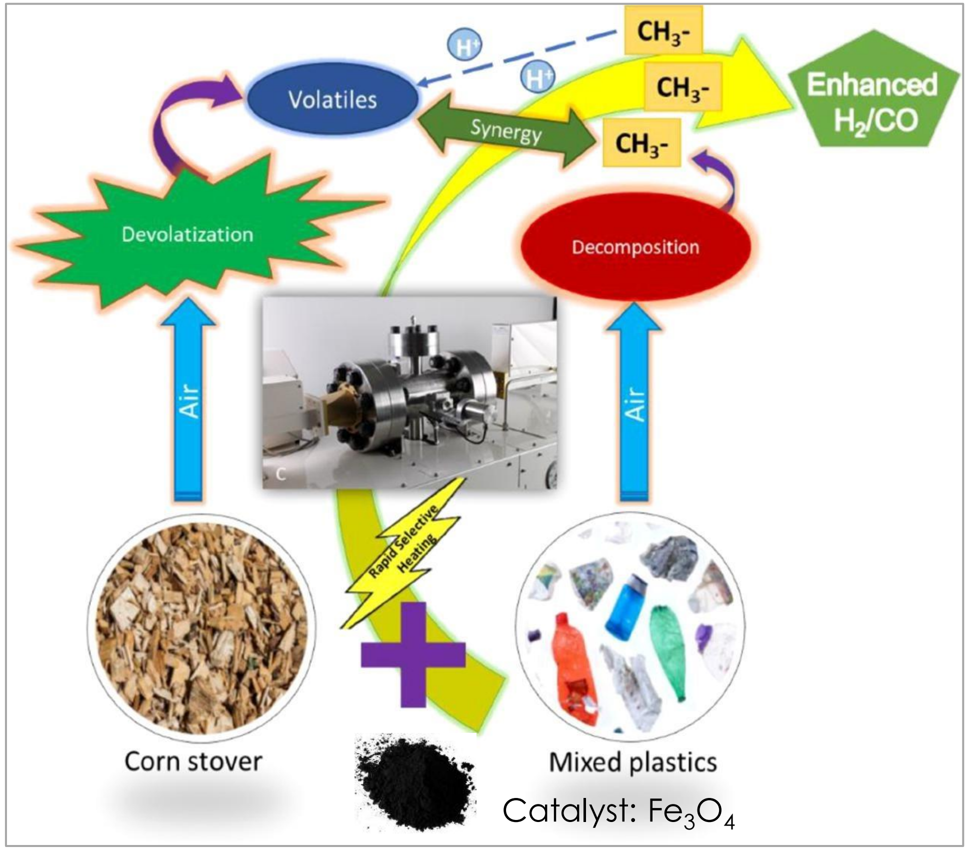
- ✓ Improve H_2 Yield
- ✓ Reduce Tar Formation
- ✓ Enhance Energy Efficiency

Process Setup

Microwave Reactor



Reaction Mechanism



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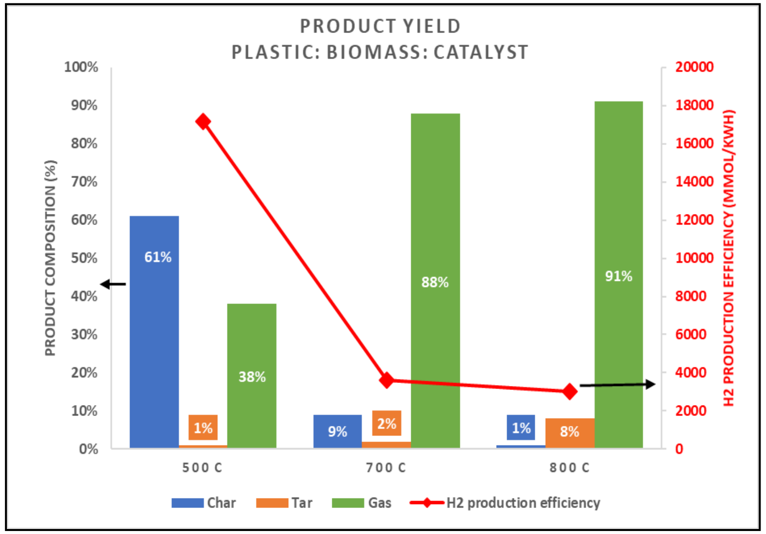
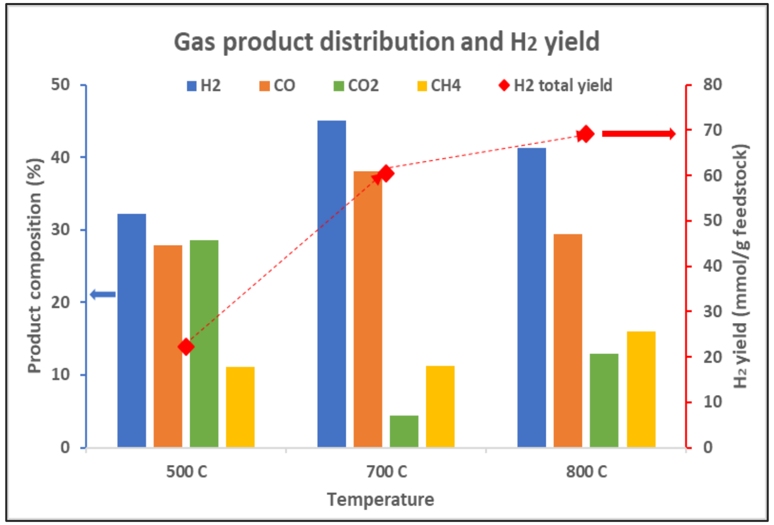
Results: Effect of Temperature

- Highest gas yield (91%) with most H_2 yield (72 $mmol/g_{feed}$) was observed for 800 °C.
- Reactor was unstable at 800 °C, power was fluctuating due to sudden temperature loss.
- Minimal heavy tar formation (2%) and lowest power input (200 W) was required for 700 °C.
- Optimum conditions:
  - **700 °C, 200 SCCM air**





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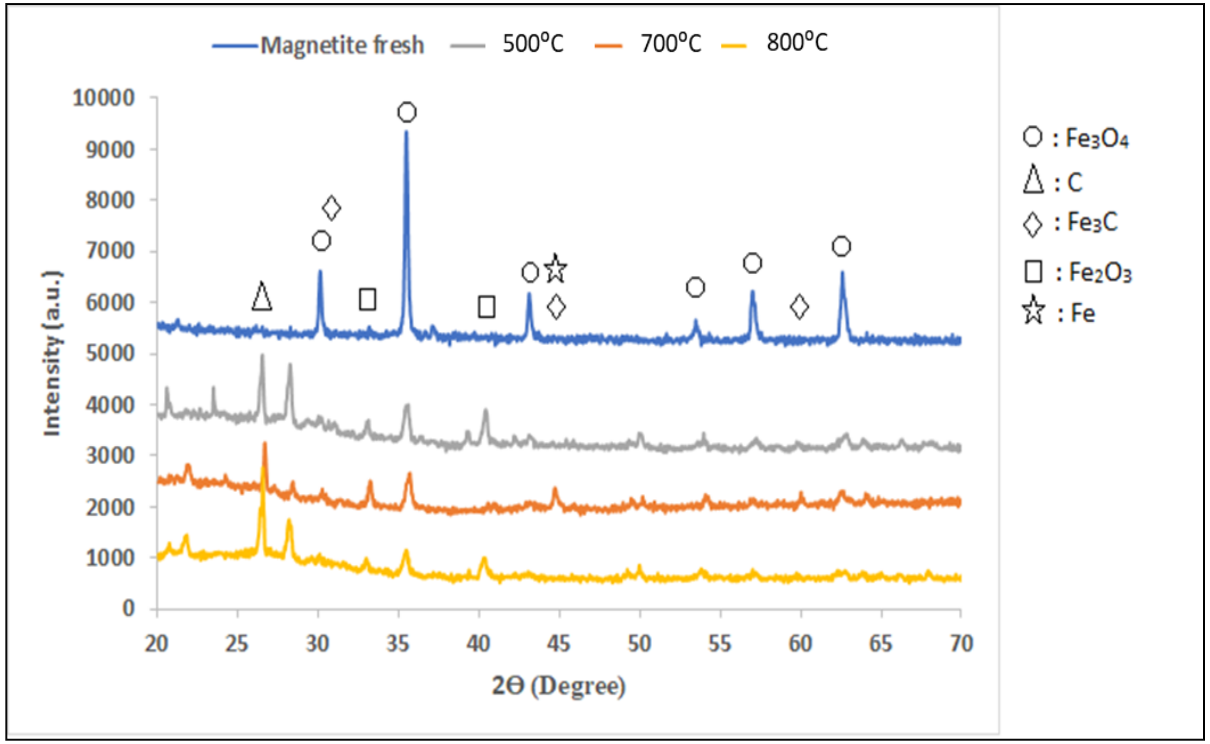
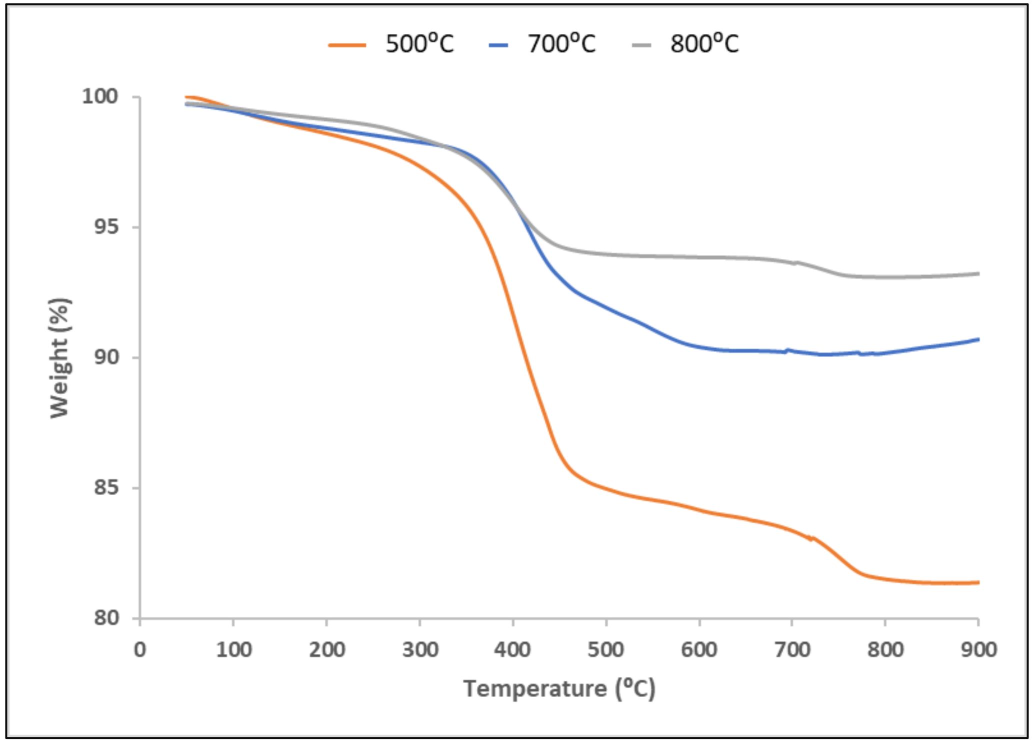
Characterization: Effect of Temperature





- For higher temperature runs, a greater degree of reduction was observed for Fe oxide, **indicating** higher activity due to the availability of more surface oxygen.
- **Filamentous/graphitic C deposition increased with temperature,** corresponding to a greater H_2 formation.

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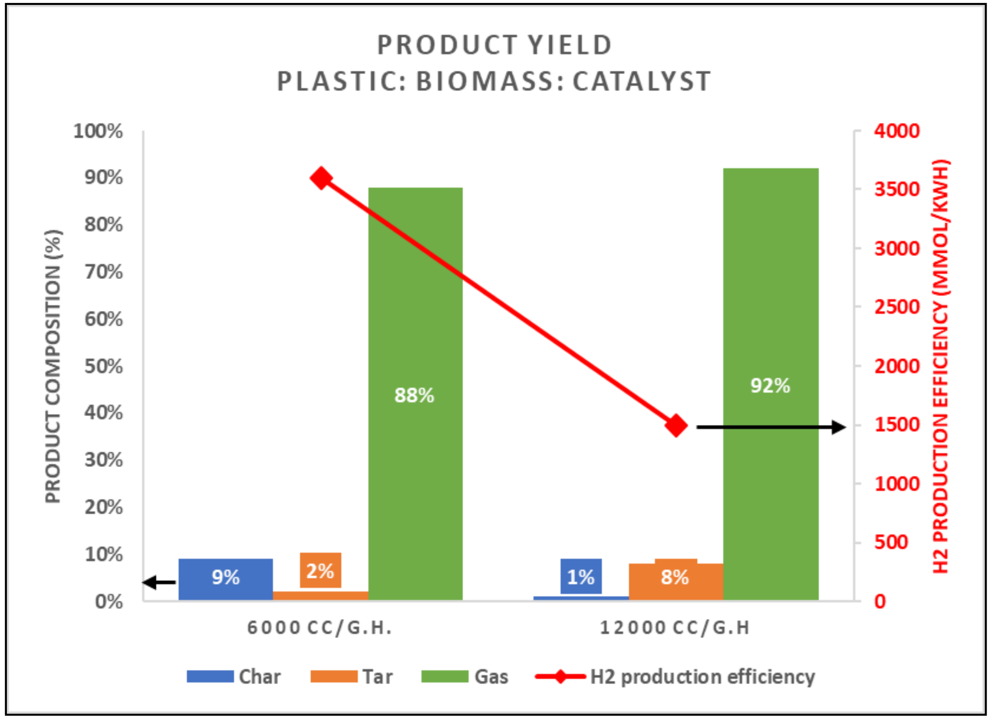
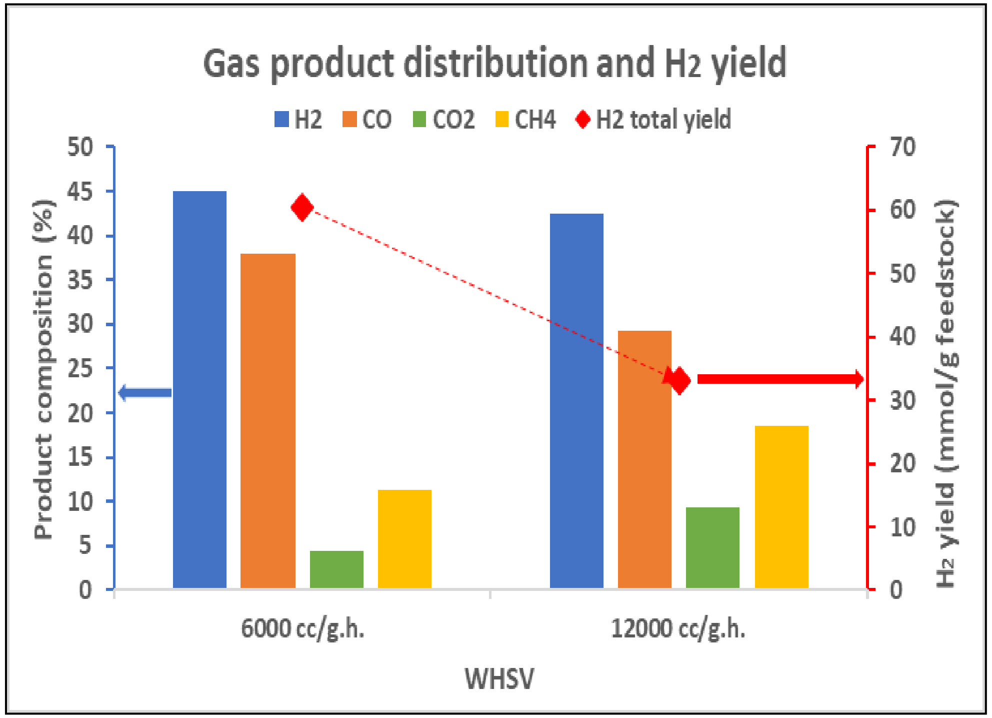
Results: Effect of Space Velocity (WHSV)





- At lower WHSV (6000 cc/g.h. vs. 12000 cc/g.h.), in presence of magnetite, volatiles from biomass devolatilization spent more time with the radicals from plastic decomposition, making higher H_2 yields for the mixed plastics, and decreasing tar yield.
- Tar reduces to produce more H_2-rich syngas at lower WHSV due to an enhanced reaction period in MW.

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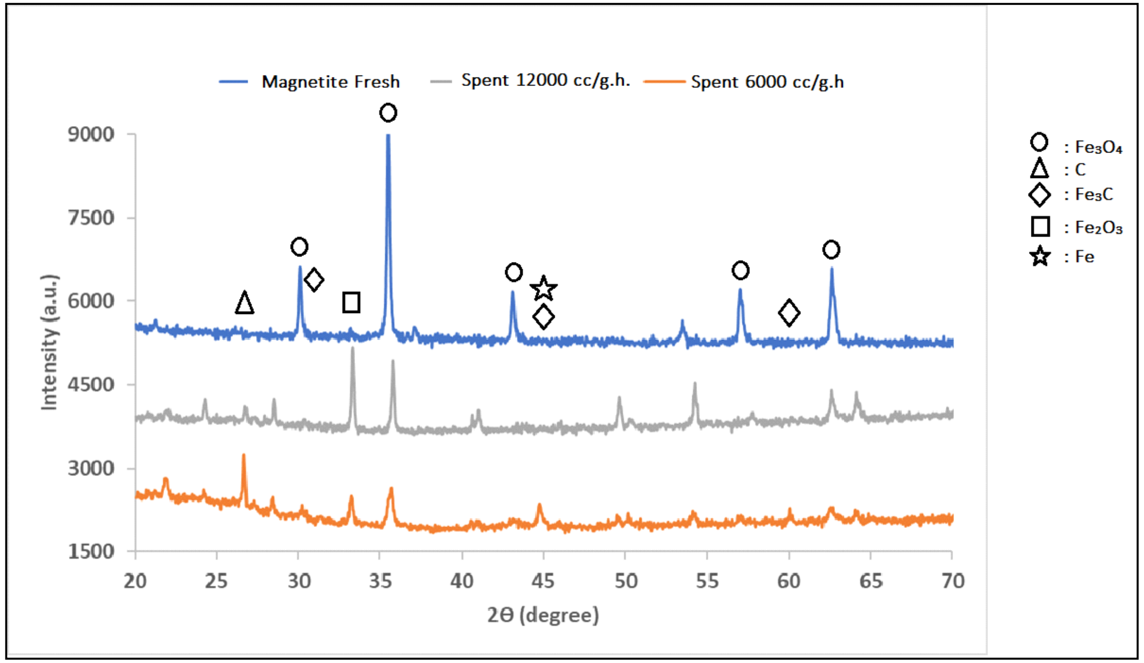
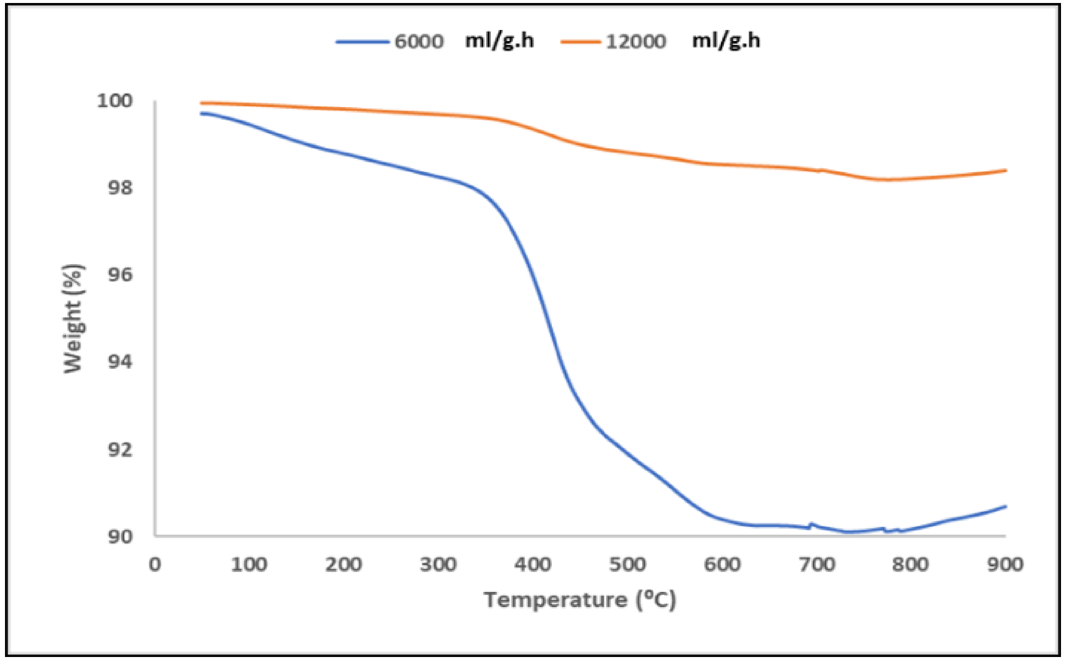
Characterization: Effect of WHSV





- Higher peak intensity on graphitic carbon (2θ=26.5°) was observed in X-ray diffraction (XRD) for lower WHSV (6000 cc/g.h.), indicating higher production of graphitic carbon.
- Fe_3C and metallic Fe peaks were detected in XRD for 200 SCCM run, indicating a higher degree of magnetite reduction.
- Thermogravimetric analysis indicates major graphitic carbon region for 6000 cc/g.h. run, complying with the XRD results.

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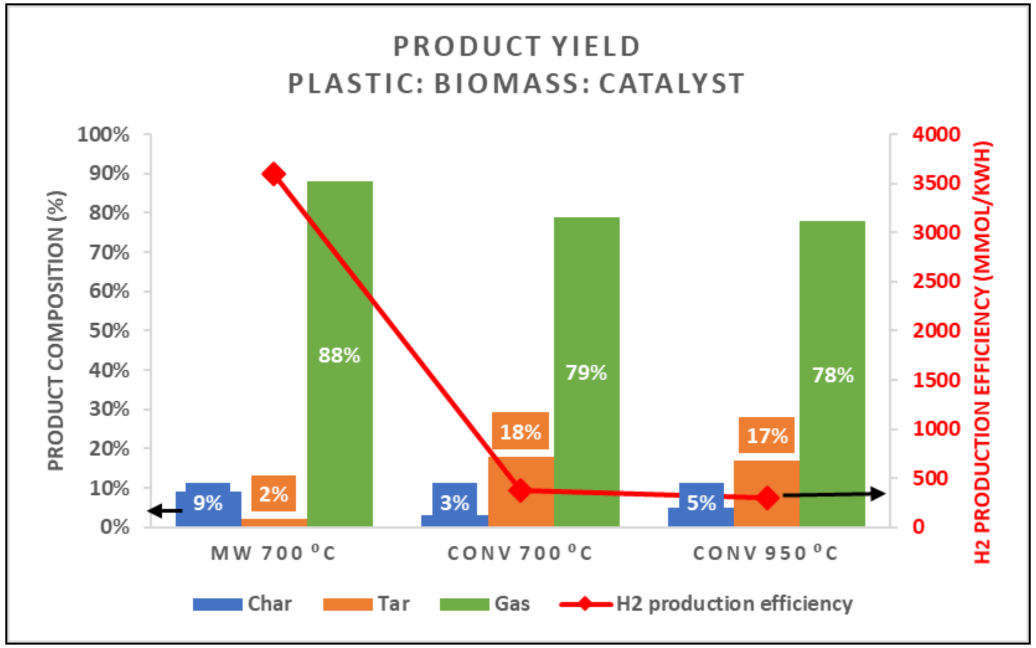
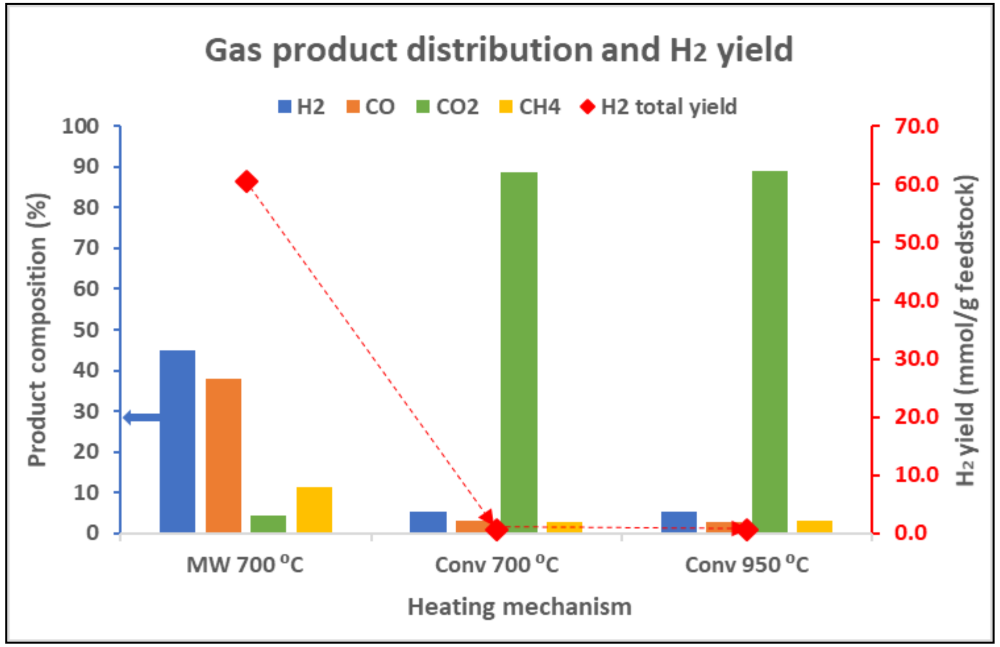
Results: Microwave vs. Conventional Studies





- Along with a greater degree of magnetite reduction, selective heating of the microwave reactor gasifies plastics and generates the required radicals that contribute to the plastic and corn stover synergy, allowing enhanced H_2 yield (61 mmol/g_{feed} vs. 0.9 mmol/g_{feed} at 700 °C under air).

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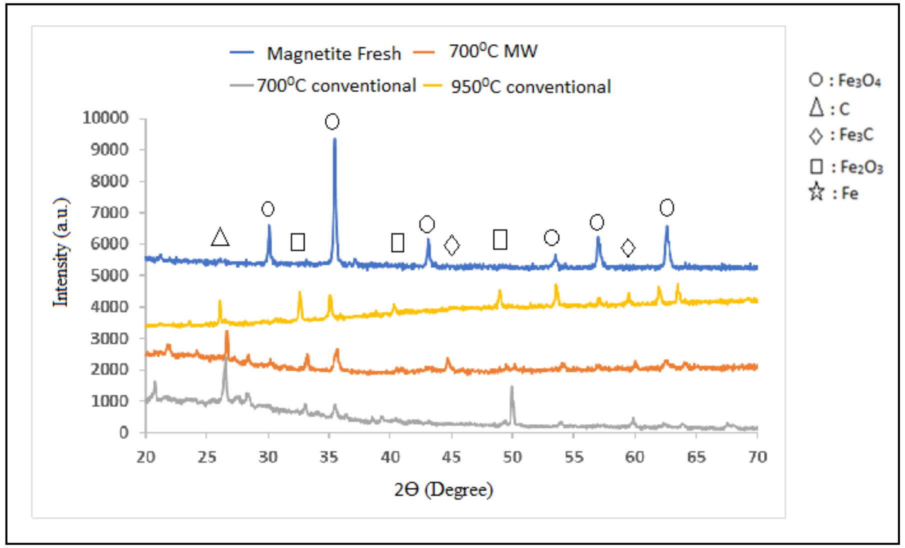
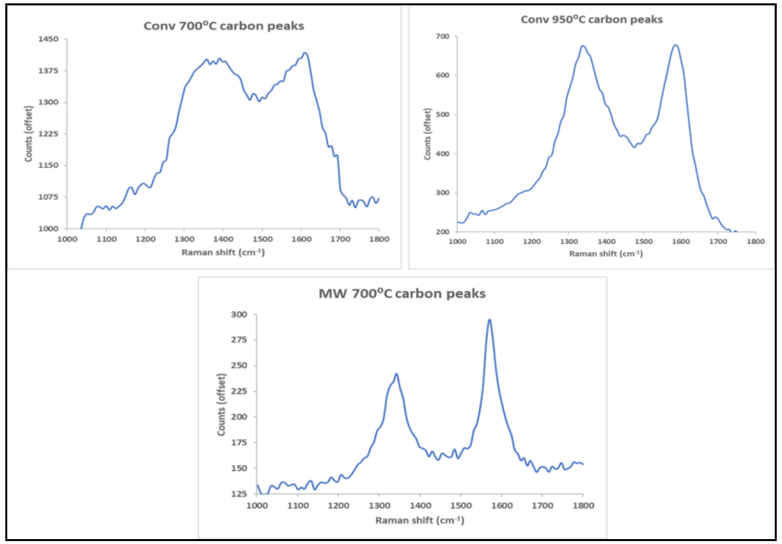
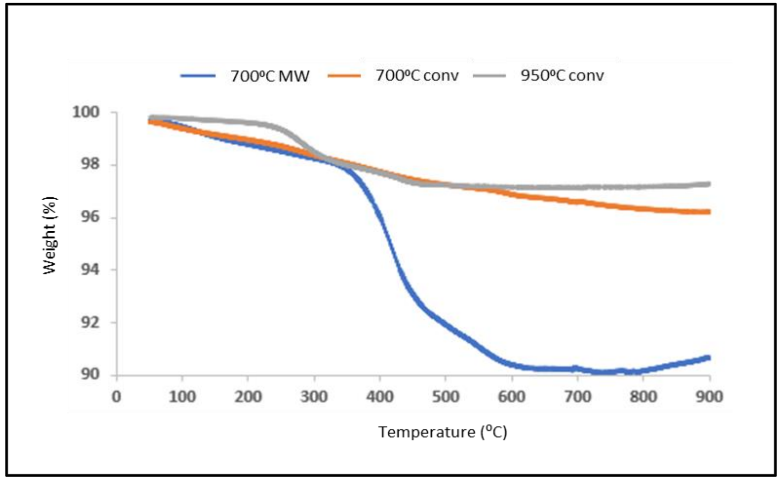
Characterization: Effect of Heating Media





- Reduction of magnetite to reach its active Fe/Fe_3C phases is **absent** in the conventional run (XRD).
- Along with Thermogravimetric Analysis, Raman also suggests the formation of **maximum graphitic carbon** (I_G/I_D= 1.6).
- Formation of graphitic carbon is responsible for enhanced MW heating, as graphite is an excellent MW absorber, resulting in higher gasification activity.



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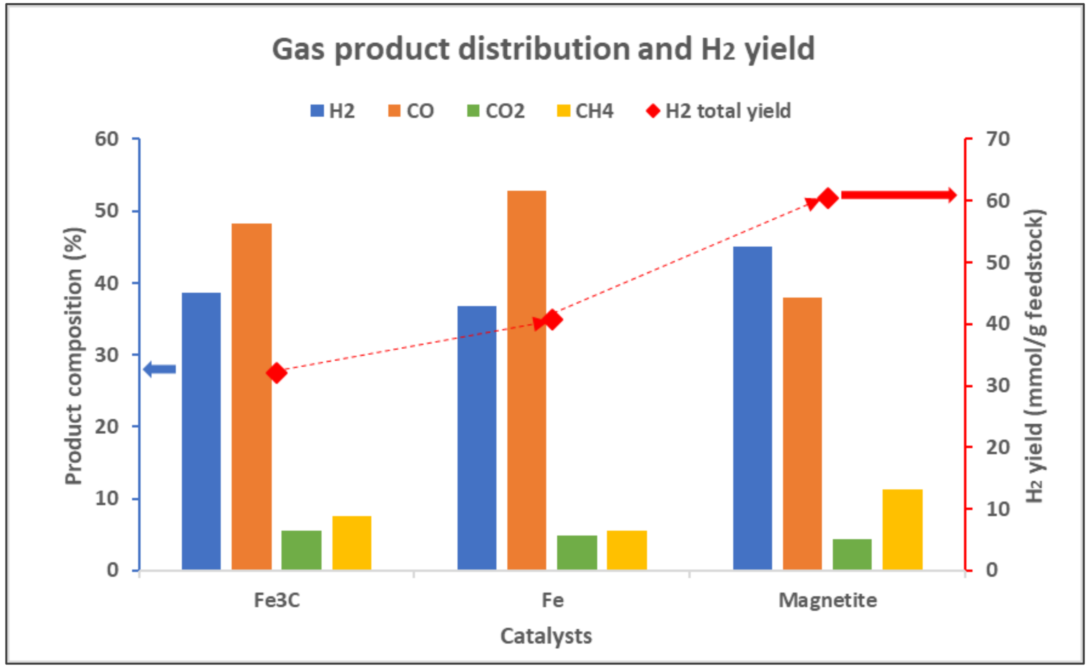
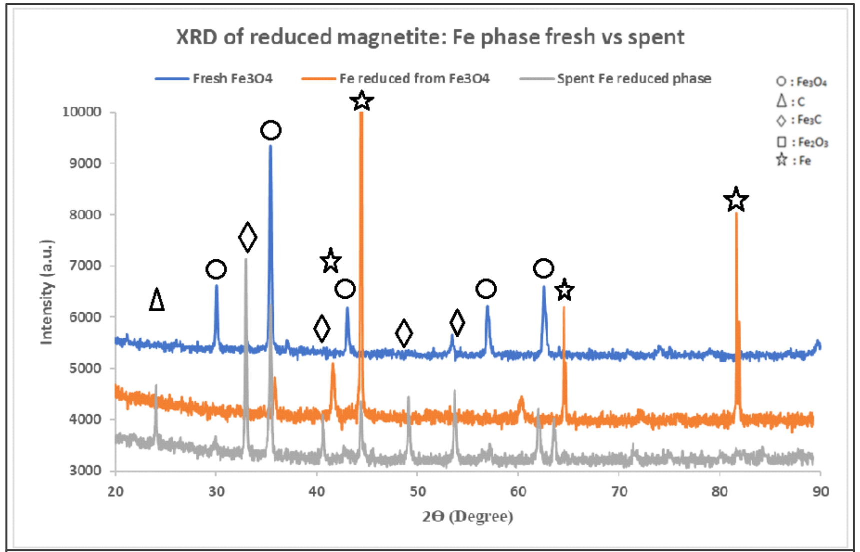
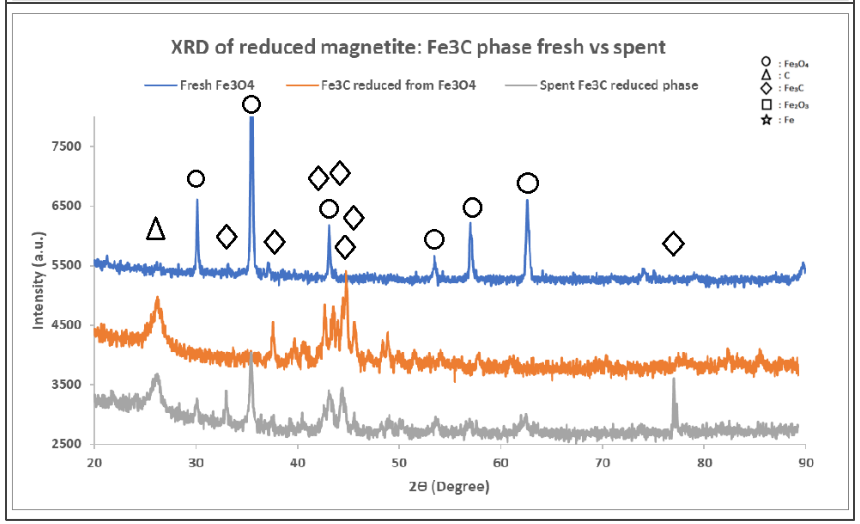
Understanding the Active Fe Phase Under MW Heating







- The metallic Fe/Fe_3C produced ***in-situ*** strongly couple with microwaves to further enhance the catalytic activity.

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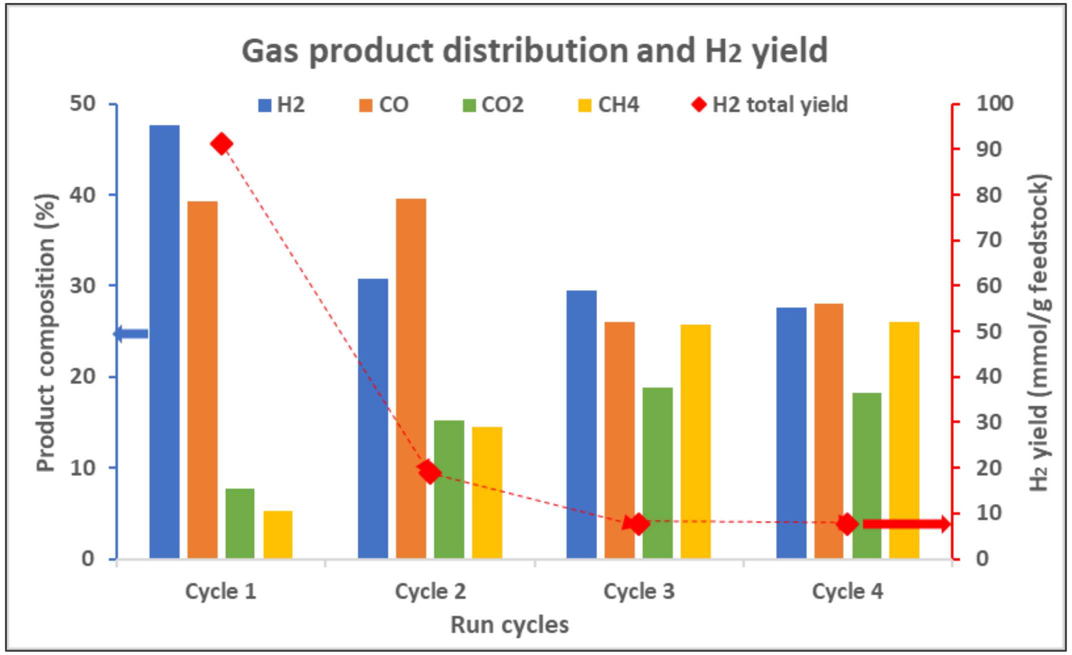
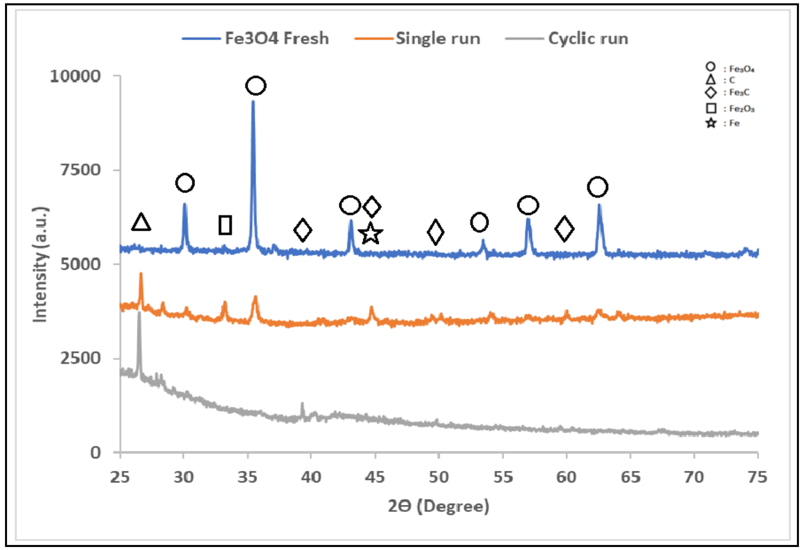
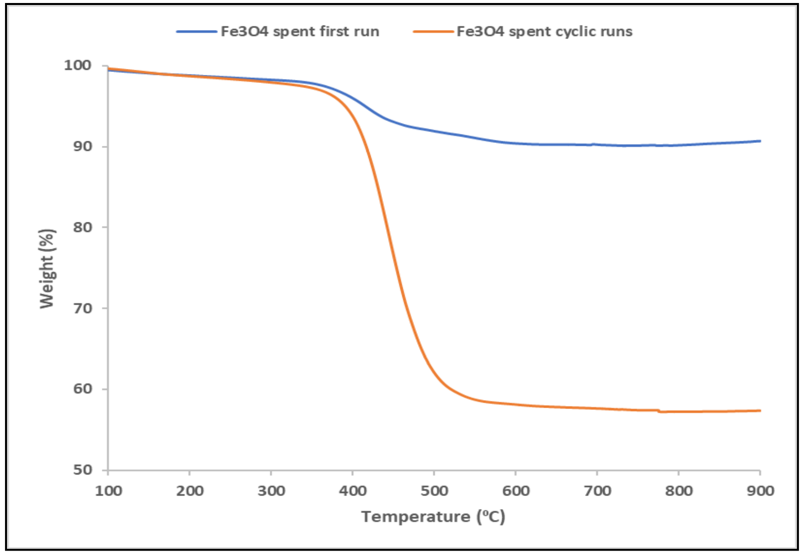
Catalytic Performance Run Cycles



- Magnetite active sites that are lost after the continuous cycles of gasification reaction directly relate to the loss in total hydrogen yield.





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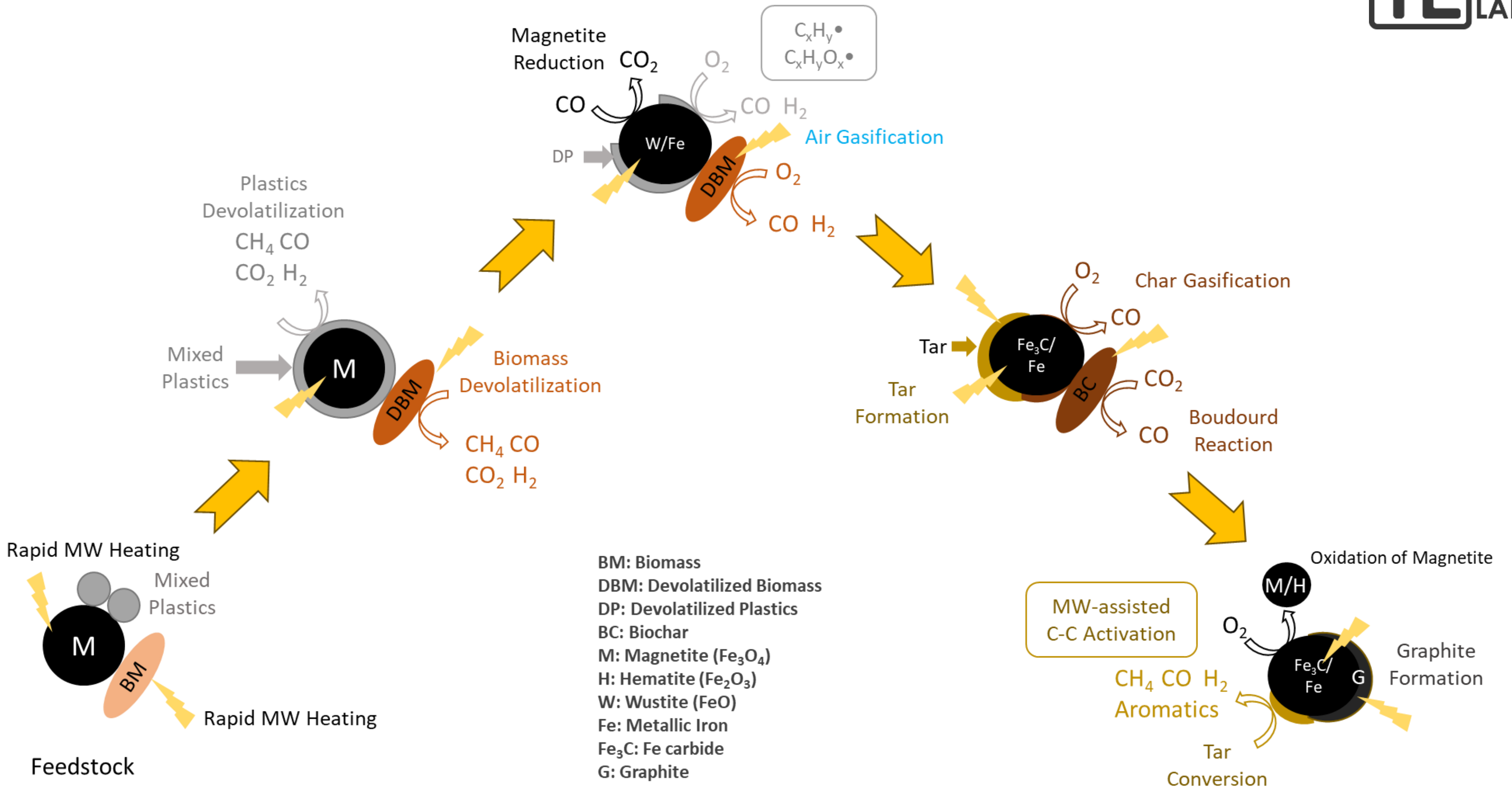
Proposed Mechanism (MW)



BM: Biomass
DBM: Devolatilized Biomass
DP: Devolatilized Plastics
BC: Biochar
M: Magnetite (Fe_3O_4)
H: Hematite (Fe_2O_3)
W: Wustite (FeO)
Fe: Metallic Iron
Fe_3C: Fe carbide
G: Graphite

Abedin et al., 2024 Energy, *Under Review*

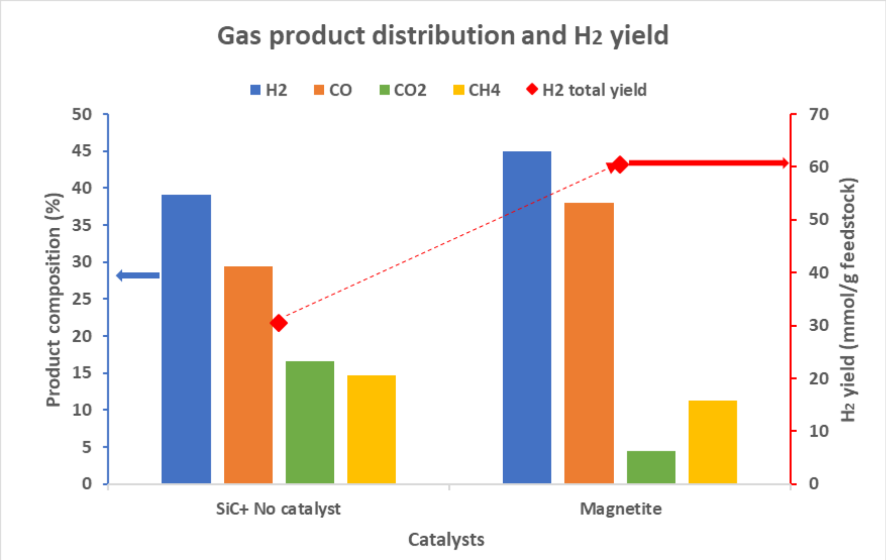
Key Findings: Part 2

- At a temperature range of 700–800 °C, enhanced H_2 yield was observed per gm feedstock.
- Higher syngas yields were detected under lower WHSV (80% vs. 73%).
- H_2 in the microwave reactor was 30.5 mmol/g_{feed} at 700 °C, whereas H_2 in conventional reactor was 0.9 mmol/g_{feed} at 700–950 °C.
- Tar amount decreased and gas formation increased with MW vs. conventional runs.
- Fe oxide is reduced to a greater degree and forms graphitic carbon that couples with MW to produce higher H_2 yields under MW.

Magnetite ***enhances*** MW synergy between plastic and biomass as compared to non-catalytic system (SiC), yielding more H_2 and reducing tar by forming:

- Additional surface oxygen via rapid reduction
- Higher graphitic carbon that couples with MW

Catalytic vs. Non-catalytic
MW plastics and biomass gasification



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Acknowledgments

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The mWave Technology Team

- Diverse team of more than a dozen scientists and engineers
- Access to extensive techno-economic analysis & computational modeling capabilities

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