

Breaking the Dry Biomass Barrier

Extending Autothermal Pyrolysis to High-Moisture and Contaminated Waste Feedstocks

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Pyrolysis is a heat transfer problem first

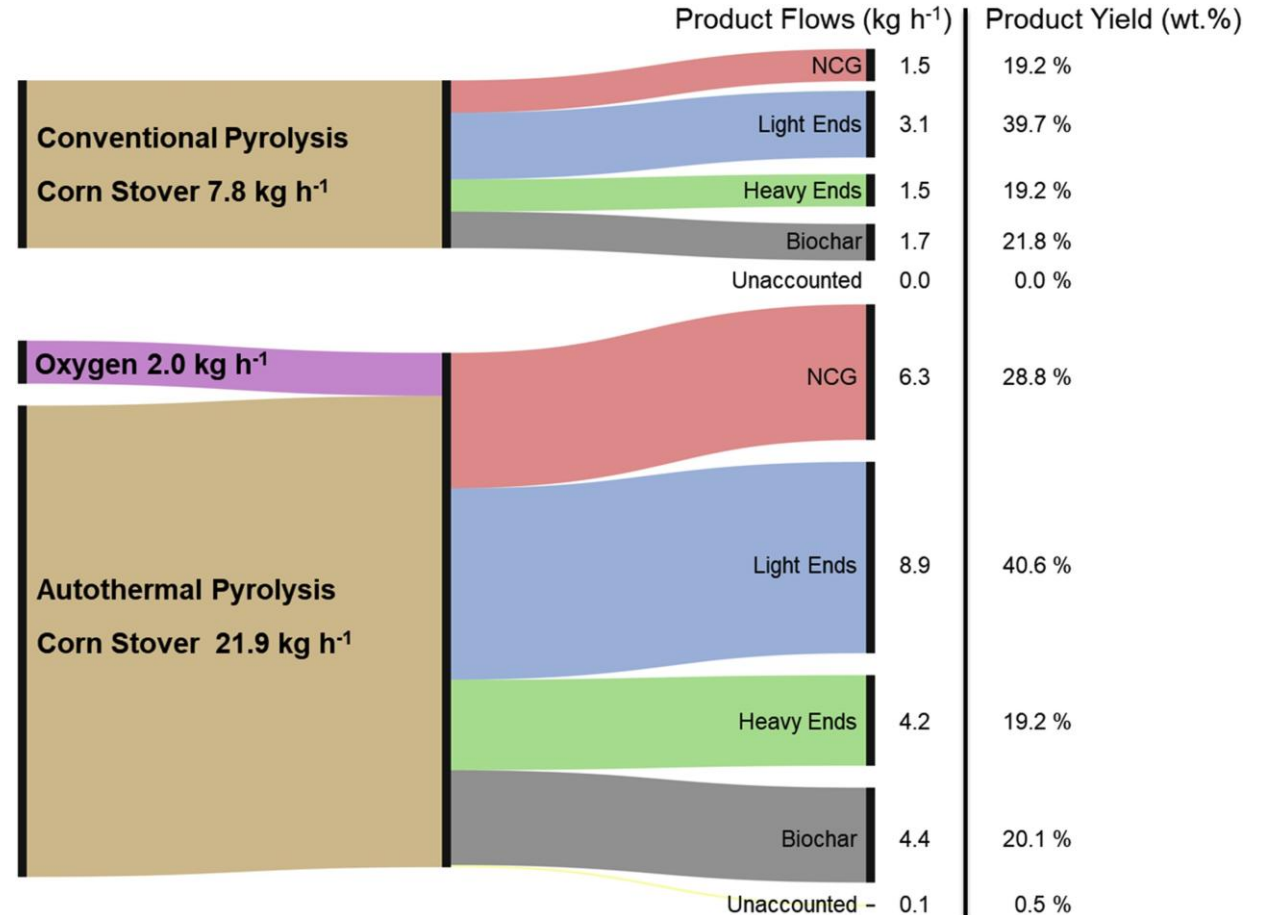
Autothermal operation replaces wall heat transfer with volumetric heat release

The Constraint

- Strongly endothermic; heat must arrive in seconds
- Wall flux caps reactor diameter
- Throughput scales with area, not volume

Autothermal Pyrolysis (ATP)

- Air metered into the bed at ER $\approx 10\%$
- Partial oxidation releases enthalpy in situ
- Heat release scales with volume — no gas recycle



Reference: Polin, Joseph P., et al. *Journal of Analytical and Applied Pyrolysis* 143 (2019): 104679.

Established on dry lignocellulose; extended to new wastes

Study of three feedstocks conventional fast pyrolysis handles poorly or not at all

BASELINE

Pilot-scale ATP of dry red oak and corn stover: 2–3× throughput intensification at comparable bio-oil yields, ER ≈ 10%, no external heat.

1

High-moisture digestate

Can ATP absorb feedstock water?

- Anaerobic digestate to 40 wt.% moisture

2

PFAS-bearing biosolids

*Can ATP decontaminate, not just
convert?*

- Wastewater digested biosolids containing PFAS and high ash

3

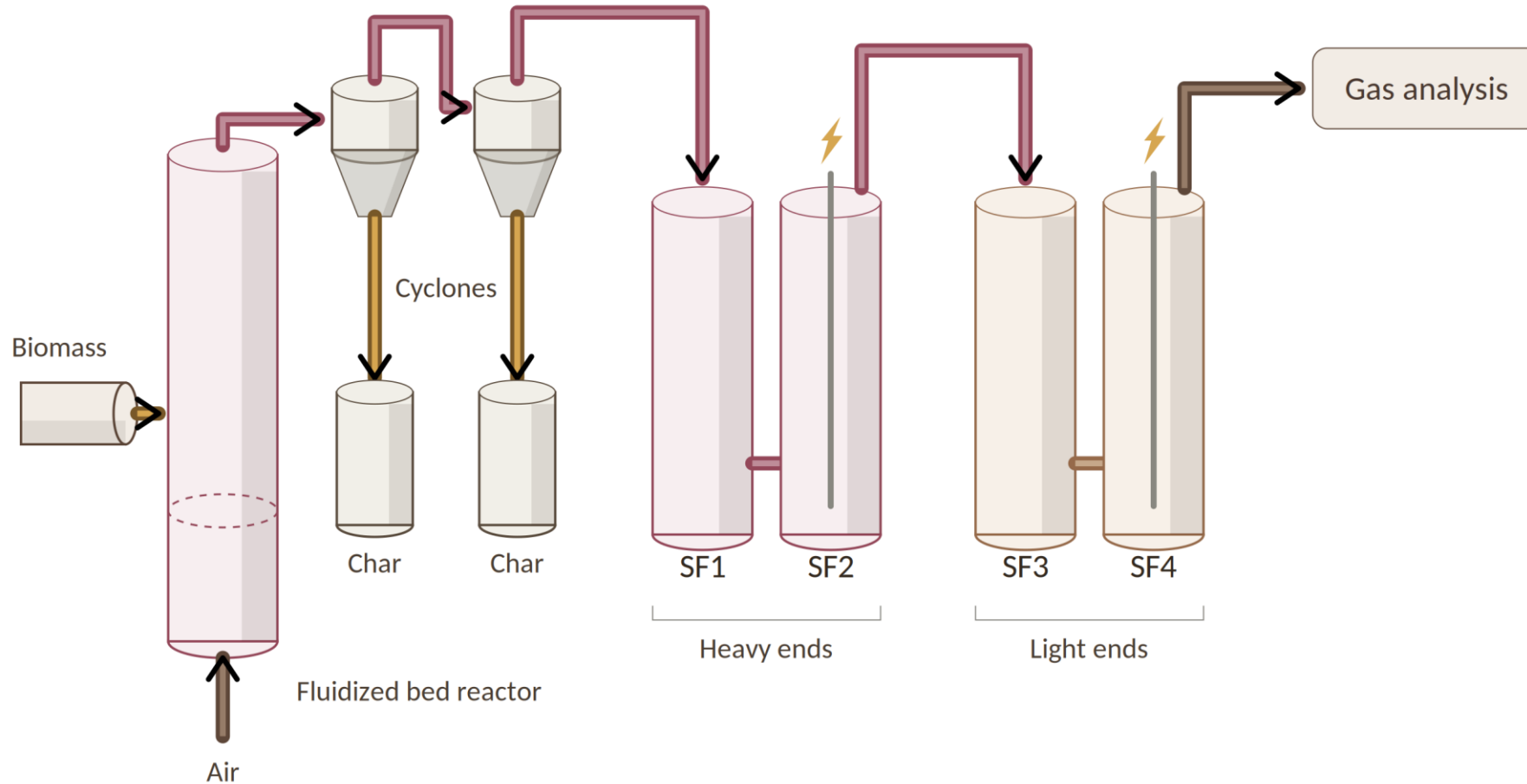
Post-consumer polyolefins

*Can ATP break the thermal
ceiling?*

- Unwashed HDPE and PP from MRF bales

Utilizing ISU's patented conversion and collection technology

Fluidized bed reactor, two cyclones in series, and a four-stage fractionating condenser train



≈ 500 °C

reaction temperature
(600 °C for polyolefins)

500–750 g/h

feed rate across all
three feedstocks

Autothermal

air metered into the bed;
no external heat input

*Only feedstock and temperature
change between studies.*

Schematic of laboratory and pilot-scale systems used in this work

STUDY 01

High-moisture digestate

Can autothermal operation absorb the energy penalty of feedstock water?

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Dairy digestate with corn-stover-like ash

Solid fraction from a commercial Eastern Iowa digester co-fed with manure, food waste, and corn stover

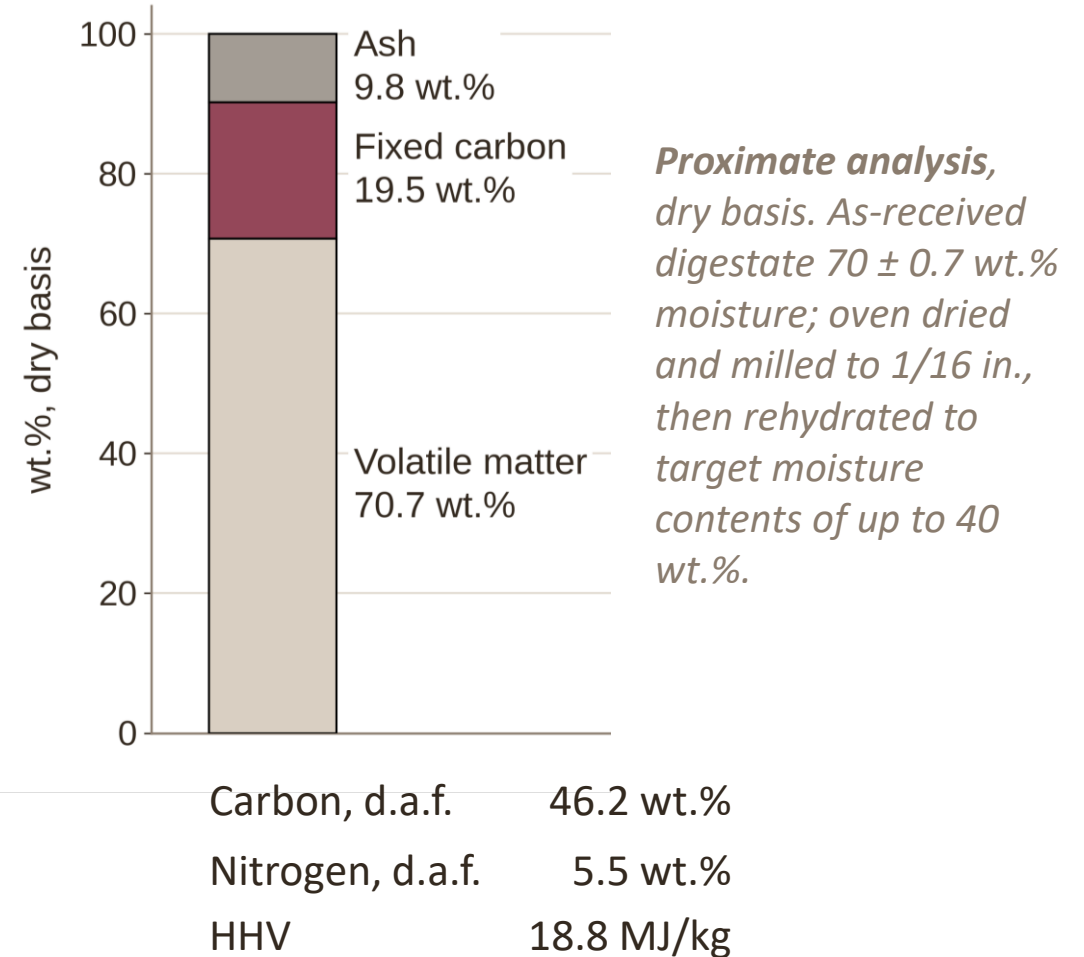


Image: Scott Co., Iowa; ISU, Omar de Kok-Mercado

Why it suits ATP

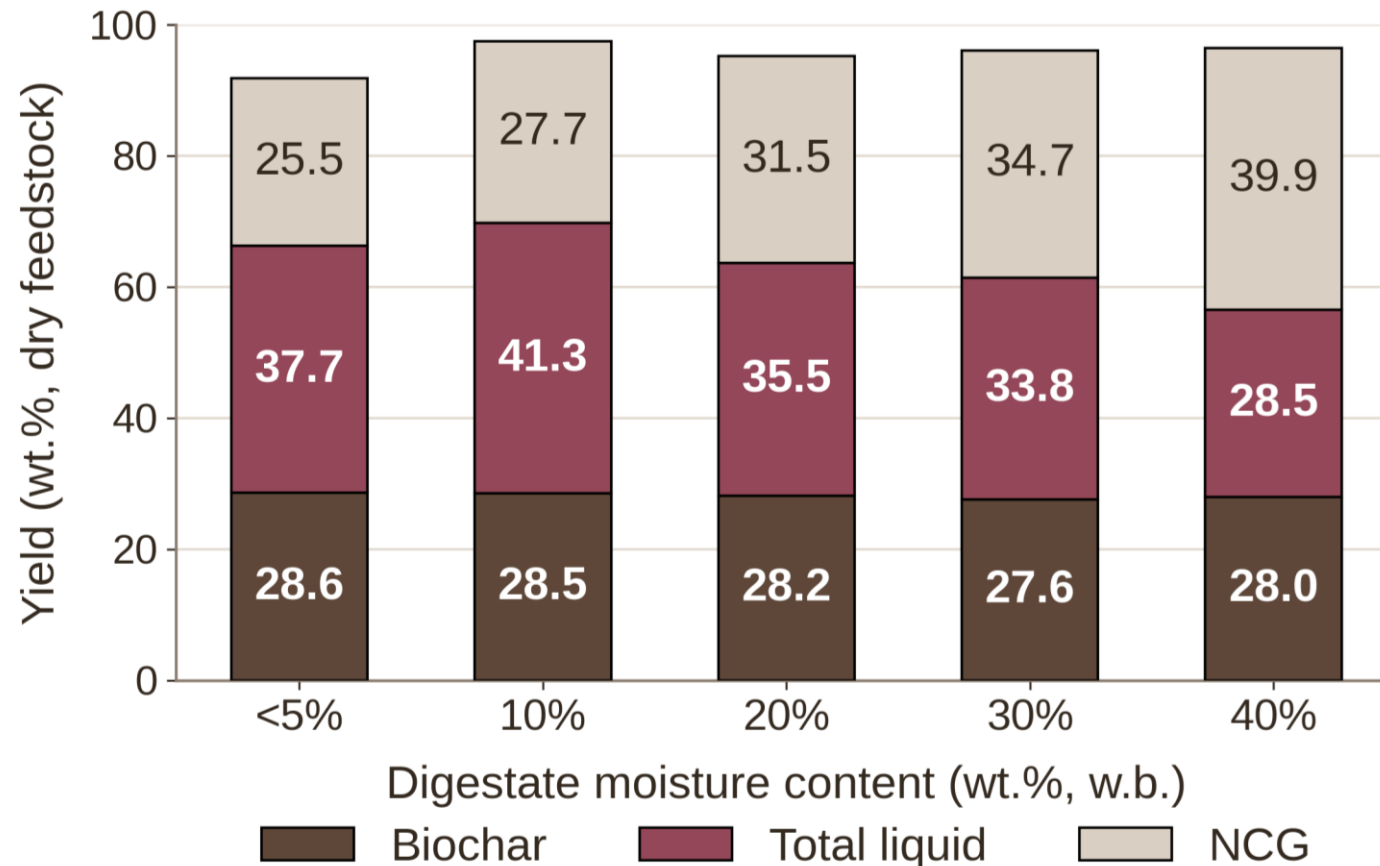
- Ash matches ISU corn stover (9.7 wt.%), already run at ER 0.068

Digestate Key Characteristics



Autothermal operation unhindered with wet feedstock

Varying digestate moisture contents up to 40 wt.% for autothermal pyrolysis



What the data shows

- No change in biochar yield
- Decreasing liquid yield 41.3 → 28.5 wt.%
- NCG rises 25.5 → 39.9 wt.%, driven by CO₂

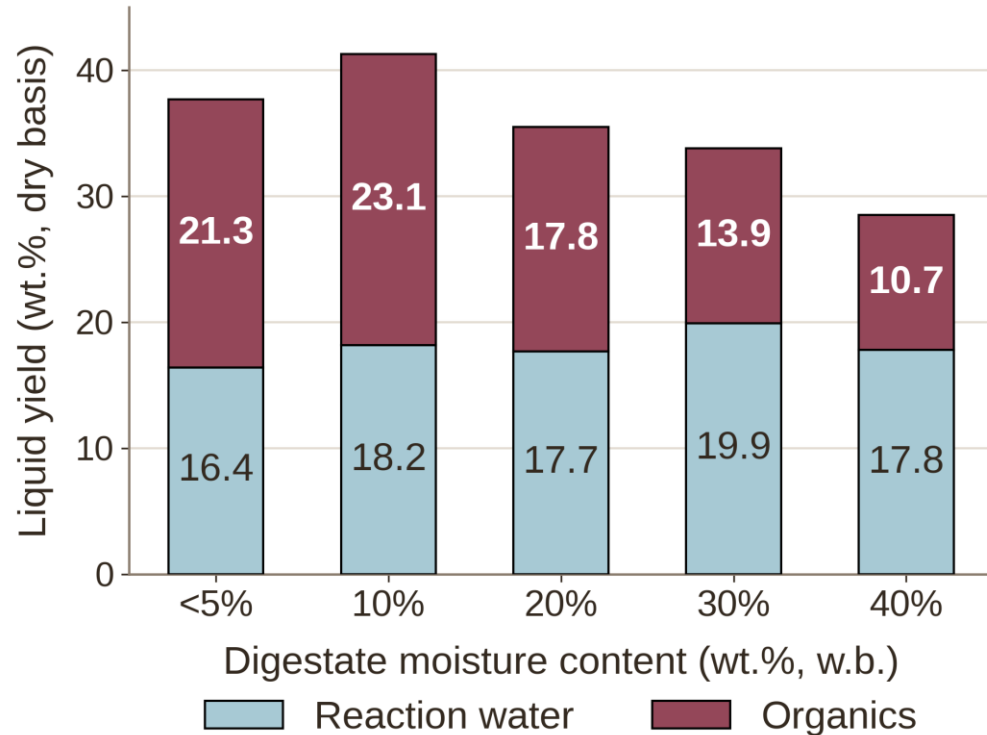
Mechanism

- Evaporating water keeps O₂ off the char surface
- Oxidation consumes vapor-phase carbon instead

Data from McMahon (2025) Fig. 4-1 component data. Mass closure 91.8–97.5%.

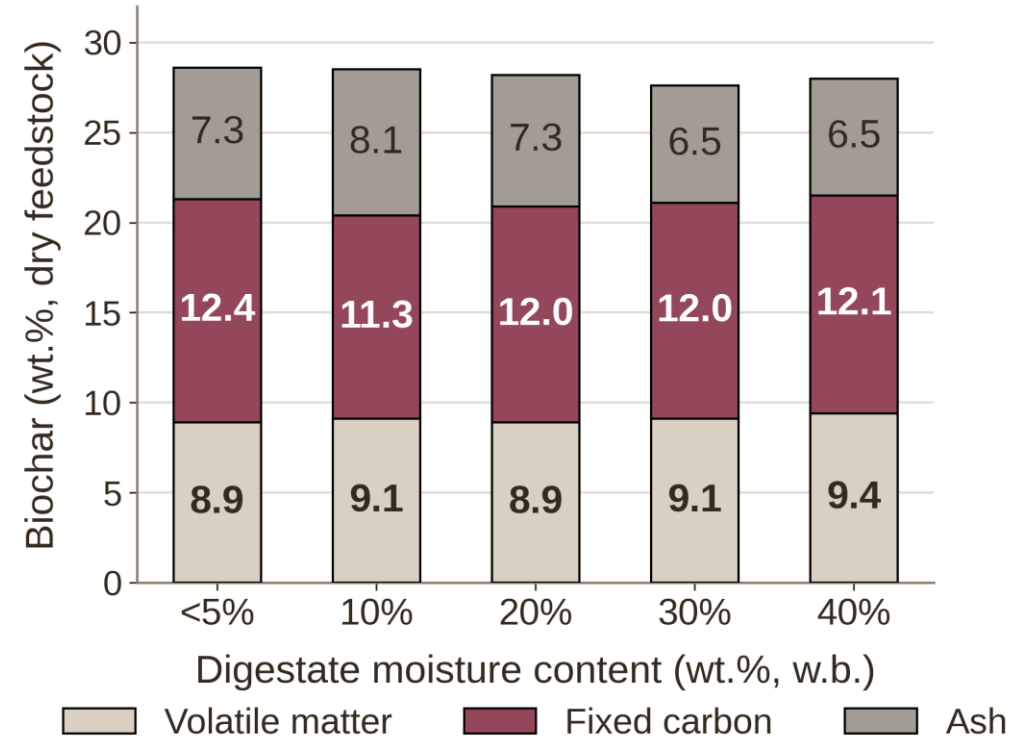
Biochar yield and quality are preserved — the organics pay the bill

Pyrolysis Liquid Distribution



Increasing digestate moisture content resulted in decreased heavy and light organic yield; increased CO₂ yield

Biochar Characterization



Fixed carbon and volatile matter statistically unchanged. All chars sit in the IBI “stable” band; VM/FC 0.72–0.81.

Data from McMahon (2025) Figs. 4-2 and 4-5. Bars sum to total product yield.

STUDY 02

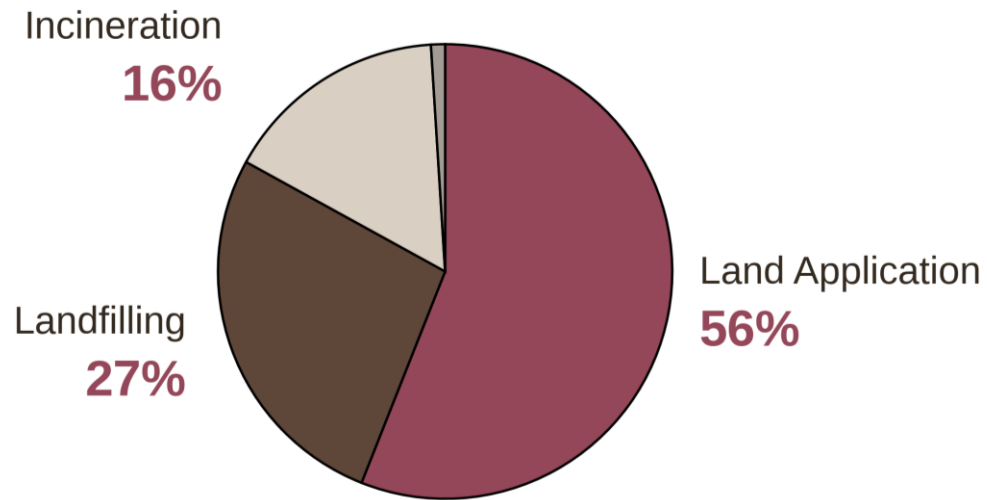
Per- and polyfluoroalkyl substance (PFAS)- bearing wastewater biosolids

Can autothermal operation decontaminate a waste stream, not just convert it?

The biosolids management problem

6.4 million dry tons a year in the U.S. — every existing pathway is under pressure

Wastewater Biosolids Disposal Methods



\$58–\$95

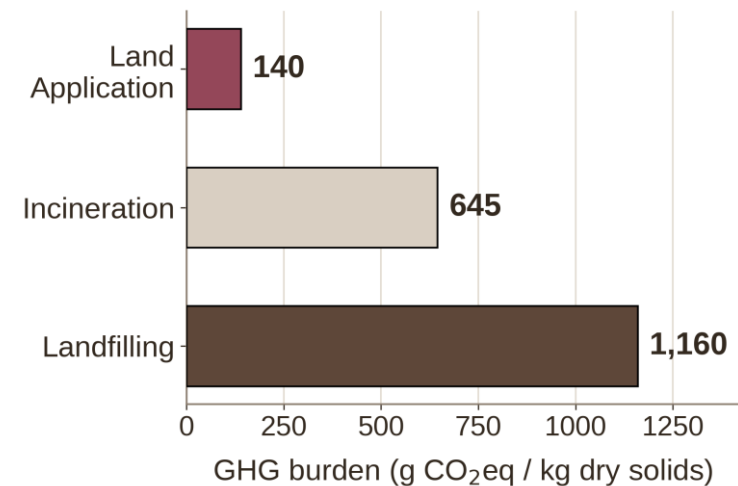
per wet ton to landfill or incinerate

83%

go to pathways that remove no PFAS

The PFAS problem

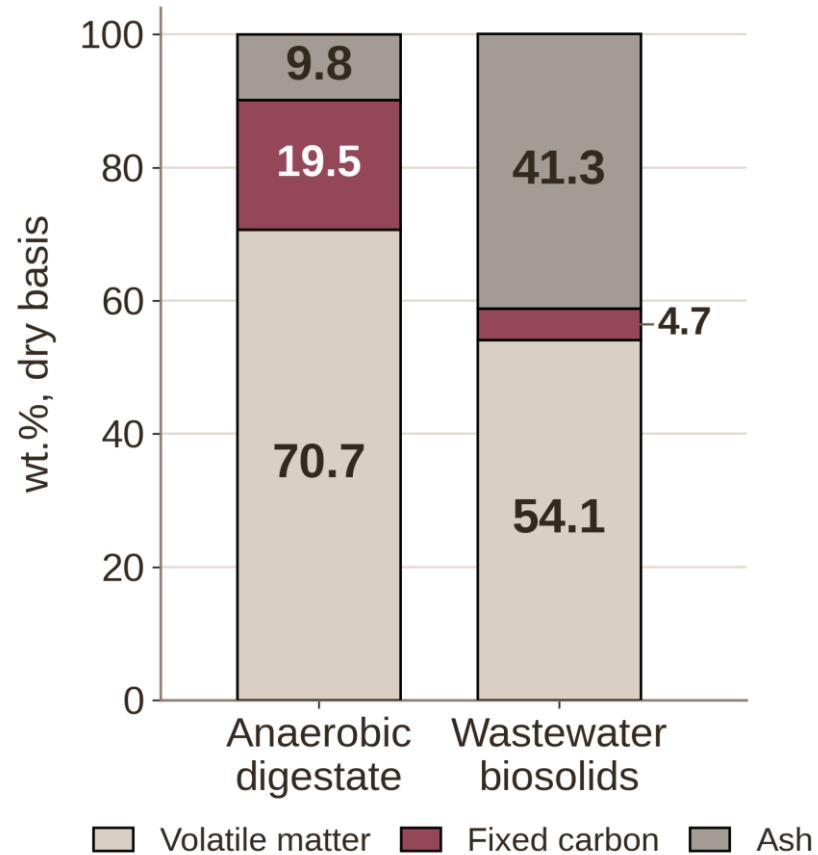
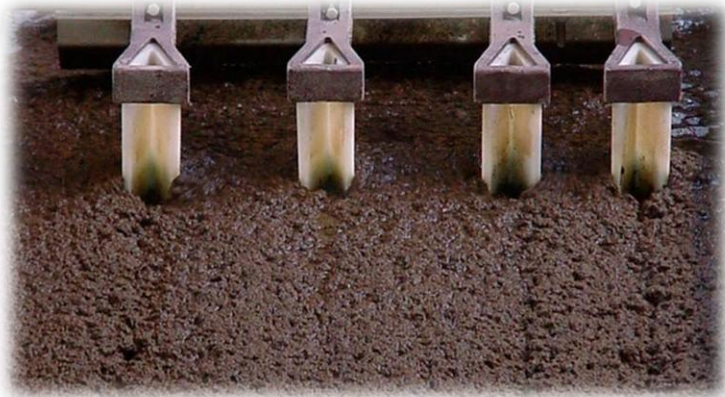
- Maine banned land application in 2022; Connecticut in 2024
- Ten-plus states now restrict or monitor
- PFOA and PFOS designated CERCLA hazardous substances, 2024



U.S. EPA, 2022. Costs: National Biosolids Data Project (NEBRA), 2018. GHG values from internal DOE proposal.

Biosolid feedstock nearly half ash and low fixed carbon

Dried, anaerobically digested biosolids from the Philadelphia Water Department



Composition, dry basis (wt.%)

Volatile matter 54.5 ± 1.1

Fixed carbon 4.7 ± 0.8

Ash **41.6 ± 0.5**

Carbon 26.0 ± 0.9

Nitrogen 3.5 ± 0.1

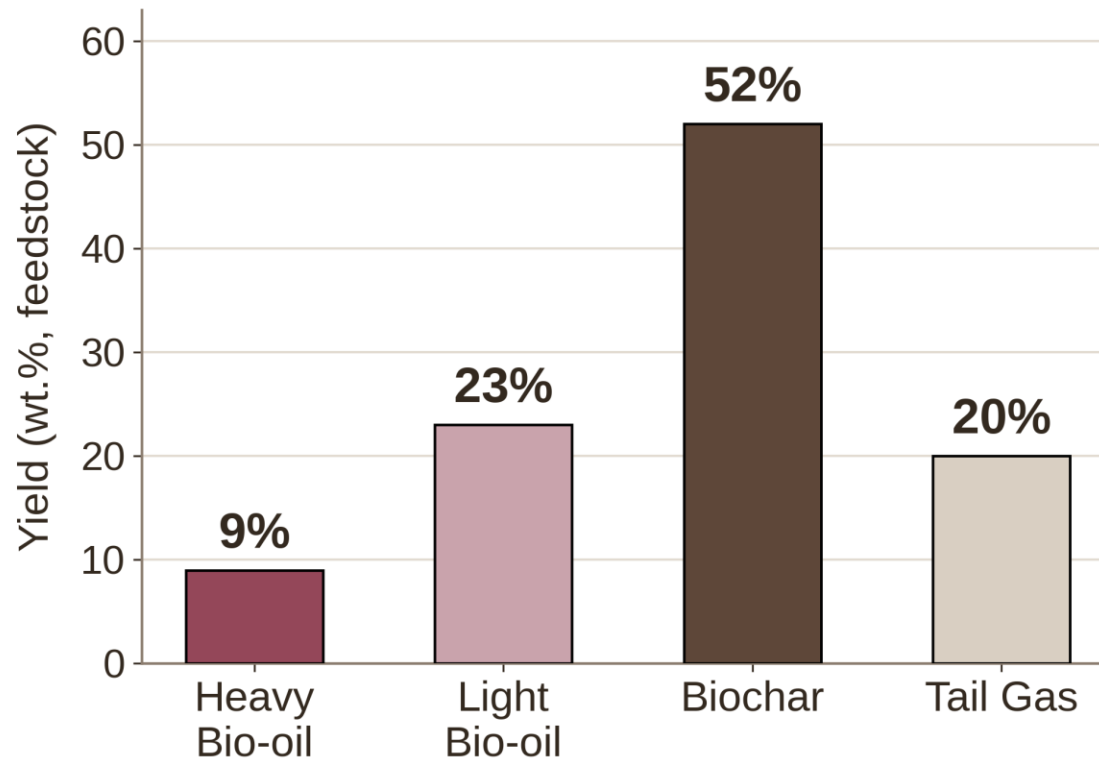
HHV, calculated 10.5 MJ/kg

Images depict wet and dried (used in this study) wastewater biosolids.

Autothermal operation confirmed at high pyrolysis enthalpy

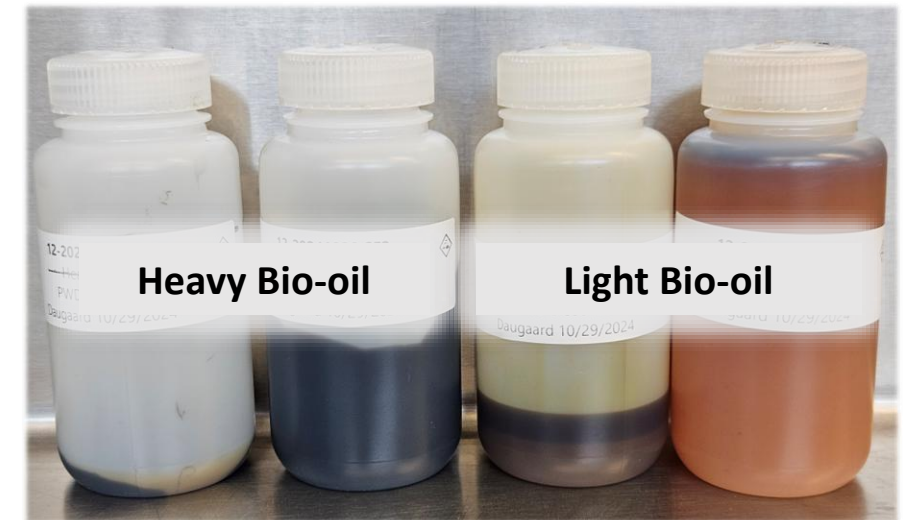
Determined enthalpy for pyrolysis experimentally when comparing conventional and autothermal operation

Autothermal Pyrolysis Product Yields



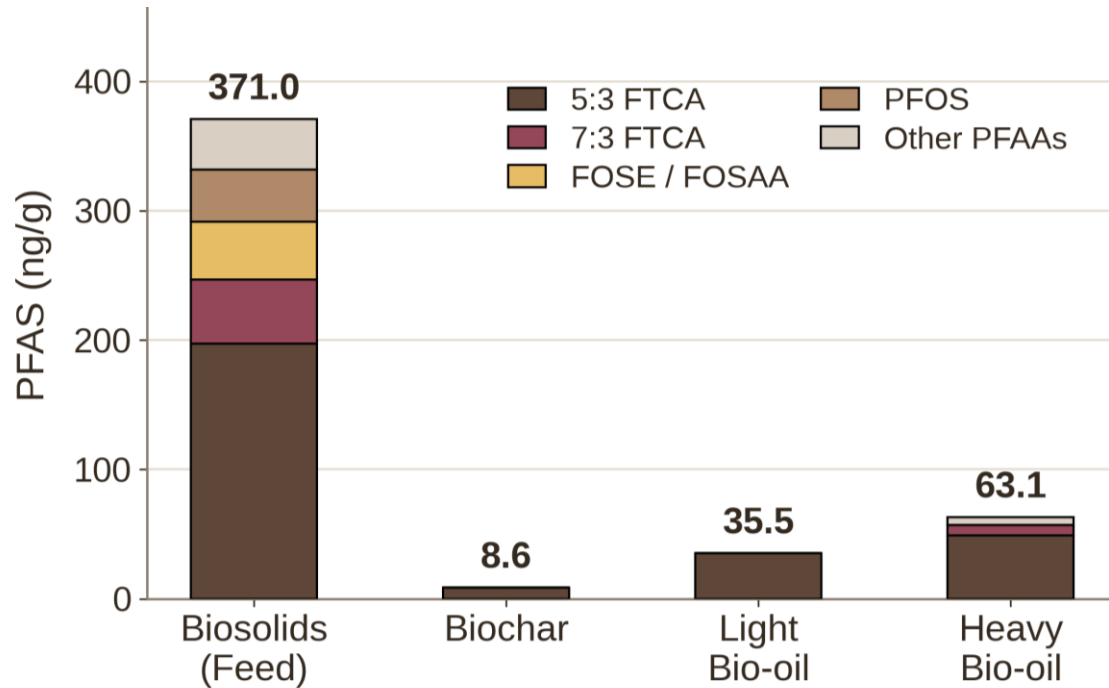
Tail gas composition on a nitrogen-free basis: CO₂ 53%; CO 17%; H₂ 21%; other 9%.

- Enthalpy for pyrolysis is approximately 2.76 MJ/kg
- Roughly double corn stover and near the top of the reported biosolids range



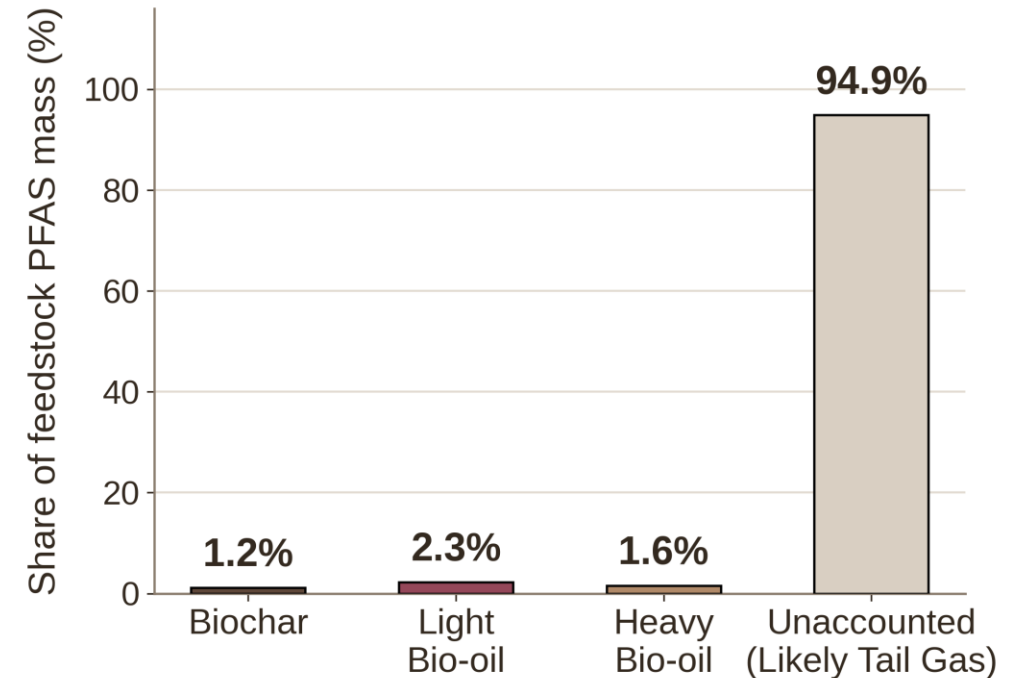
PFAS leaves the solid phase — ideal for land application and vapor oxidation

Characterization and Concentration of PFAS



- 12 detected compounds in feedstock, 370.9 → 8.6 ng/g in the char. Precursors are 79% of feedstock PFAS; regulated PFAAs are 21%.

PFAS Mass Balance



- Biochar only contained 1.2% of PFAS from feedstock.** 98.8% of PFAS goes to vapors during autothermal operation

STUDY 03

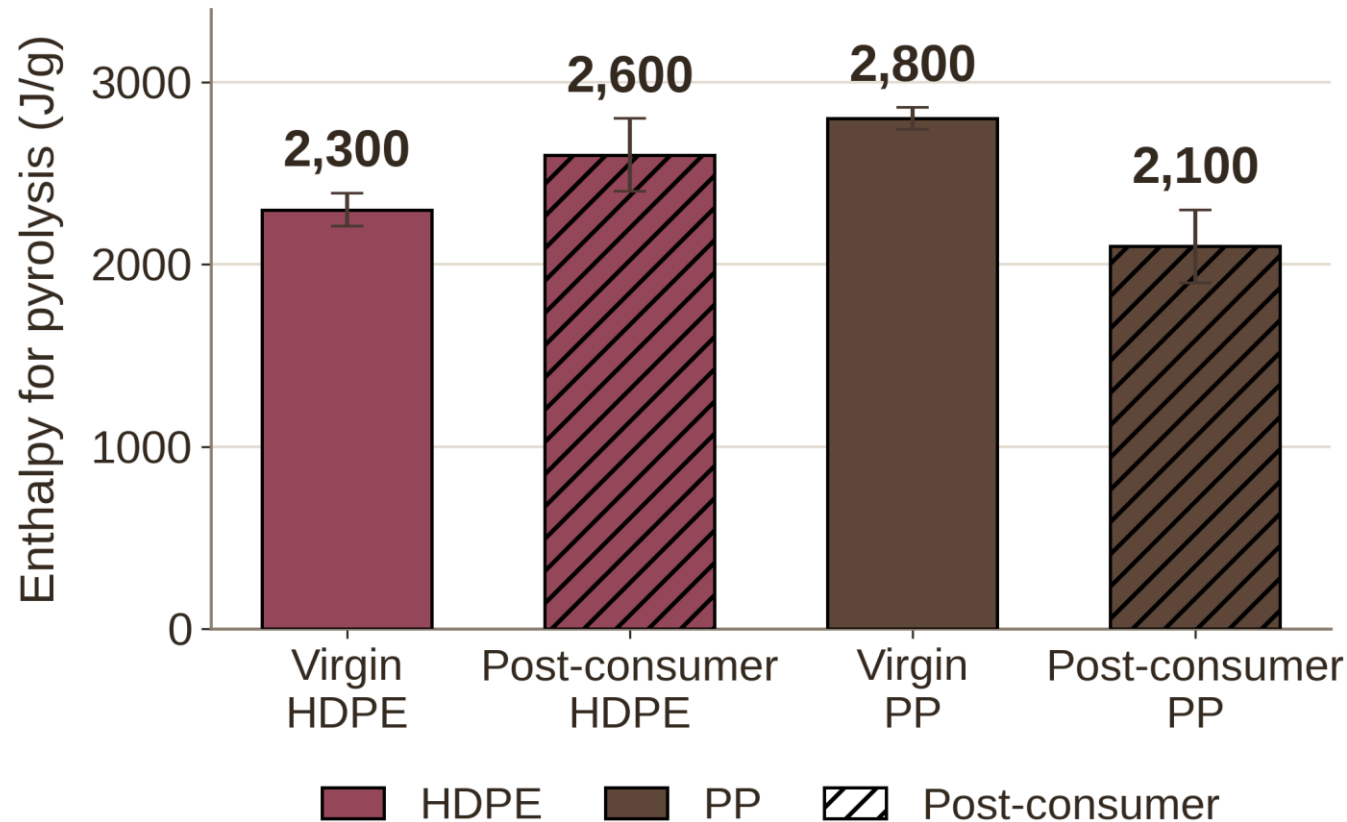
Post-consumer waste (PCW) polyolefins

Can partial oxidation break the thermal ceiling that keeps plastics pyrolysis from scaling?

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Polyolefins continue to accumulate; pyrolysis is energy intensive

>75% of all plastic ever produced sits in landfills or the environment



The Barriers

- Mechanical recycling degrades polymer properties with every pass
- Lengthy thermal depolymerization times
- Enthalpy for pyrolysis measured continuously: 2,100–2,800 J/g at 600 °C

The Consequence

- Polyolefin waste is landfilled rather than reprocessed
- Higher carbon intensity in processing

Source: Brown et al., *Cell Rep. Phys. Sci.* 5, 101856 (2024). Brown et al., *Energy & Fuels* (2025).

Two polyolefins, virgin and post-consumer

Post-consumer HDPE and PP hand-sorted from Iowa MRF bales, milled to 3–5 mm, processed unwashed



Feedstock characterization

	Virgin HDPE	Virgin PP	PCW HDPE	PCW PP
Mw (Da)	65,000	270,000	247,000	130,000
HHV (MJ/kg)	44 ± 2.6	45 ± 0.9	43 ± 2	38 ± 3
Ash (wt.%)	—	—	3 ± 2	1.8 ± 0.5
Chlorine (ppm)	—	—	869	170

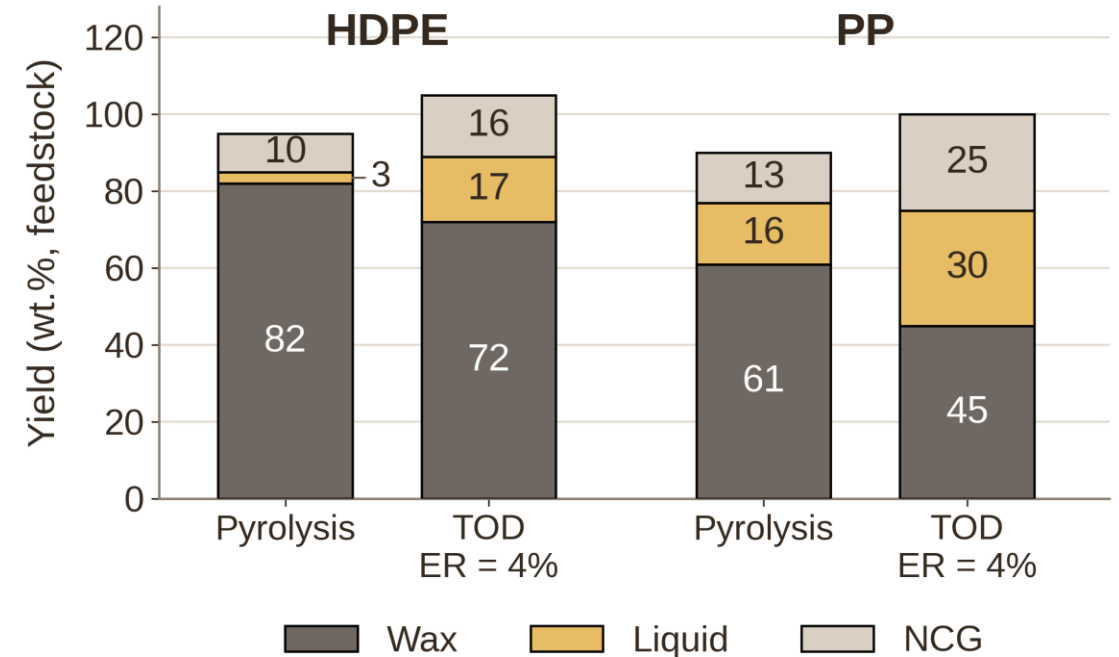
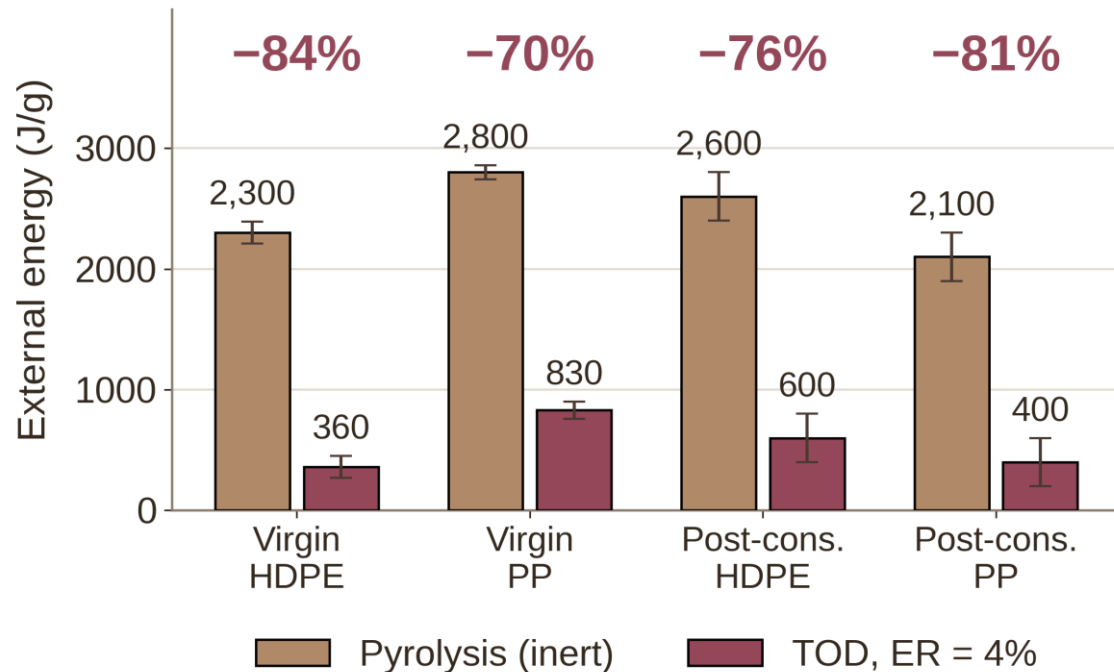
The waste stream

- PET, cellulose, labels, adhesives, food residue
- Ash 1.8–3 wt.%; chlorine to 869 ppm

Virgin: Brown et al. (2024). Post-consumer: Brown et al. (2025). Em dash = below limit of detection.

Thermal Oxo-degradation (TOD) cuts external energy up to 84%

Lab-scale bubbling fluidized bed results at 600 °C and ~1 s vapor residence time



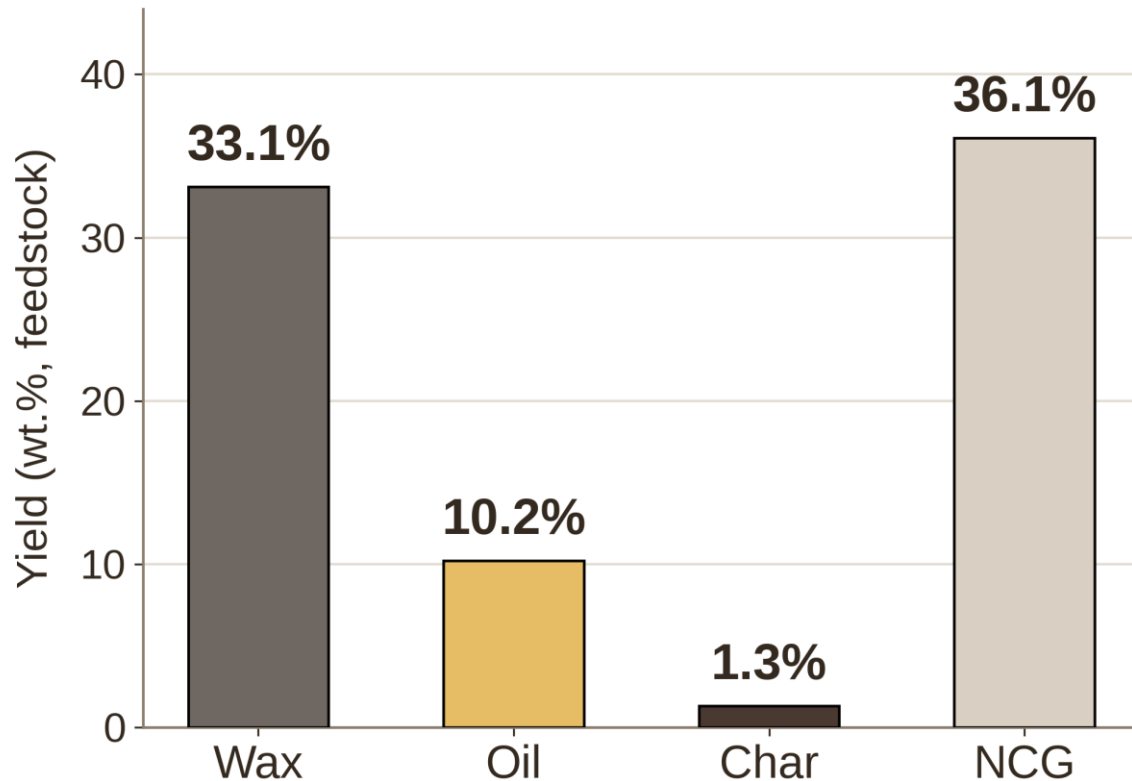
Only 2.9 wt.% of HDPE carbon and 2.6 wt.% of PP carbon is converted to CO and CO₂ — less than the 4.9 and 5.5 wt.% that full oxidation would require.

Total condensable yield >75 wt.% with primarily wax production. Wax oxygen content stays below 0.01 wt.% and HHV holds at 45 MJ/kg.

Virgin: Brown et al. (2024). Post-consumer: Brown et al. (2025).

Piloted at 2.5 kg/h using unwashed post-consumer waste

ISU pilot-scale fluidized bed under TOD conditions at 600 °C, 1:1 HDPE:PP



2.5 kg/h

sustained feed, 5× lab scale

~6 h

continuous, no plugging

2 L & >6 L

oil and wax recovered

Single pilot run

- Wax 33 wt.% vs ~60 wt.% at lab scale
- Hold-up in collection vessels plus extra vapor cracking
- 80.7 wt.% recovery — due to hold-up and light hydrocarbon vapors not calibrated for on micro-GC

Conclusions

01 Feedstock-flexible well beyond dry biomass

Digestate at 40 wt.% moisture, biosolids with PFAS and high ash, unwashed polyolefins

02 Internal heat generation covers increased enthalpies

All demand $\sim 2\times$ the pyrolysis enthalpy of dry lignocellulose — where wall heat transfer binds

03 The penalty falls on condensables, not the char

Biochar invariant across digestate moisture

Open and continuing work

- Additional digestate trials
- Effect of moisture content on product composition
- Additional wastewater biosolids projects in process
- PFAS fate and destruction

Acknowledgments

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High-moisture digestate

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PFAS-bearing biosolids

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Post-consumer plastics

J.L. Brown, H. Radhakrishnan and co-workers · CUWP · U.S. DOE DE-EE0009285

Questions

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