

# Pyrolysis

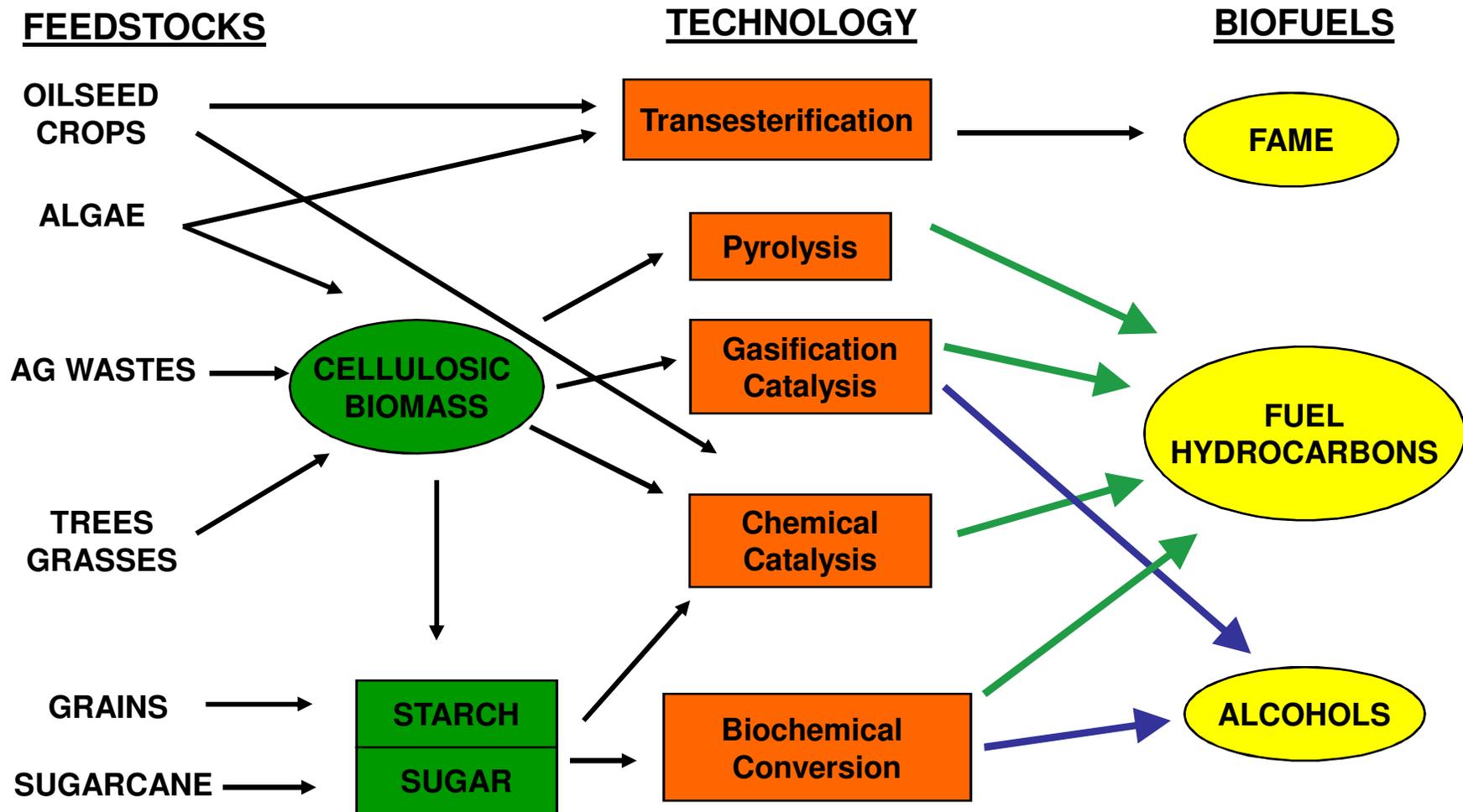
1<sup>st</sup> Brazil-U.S. Biofuels Short Course  
Institute for Advanced Studies University  
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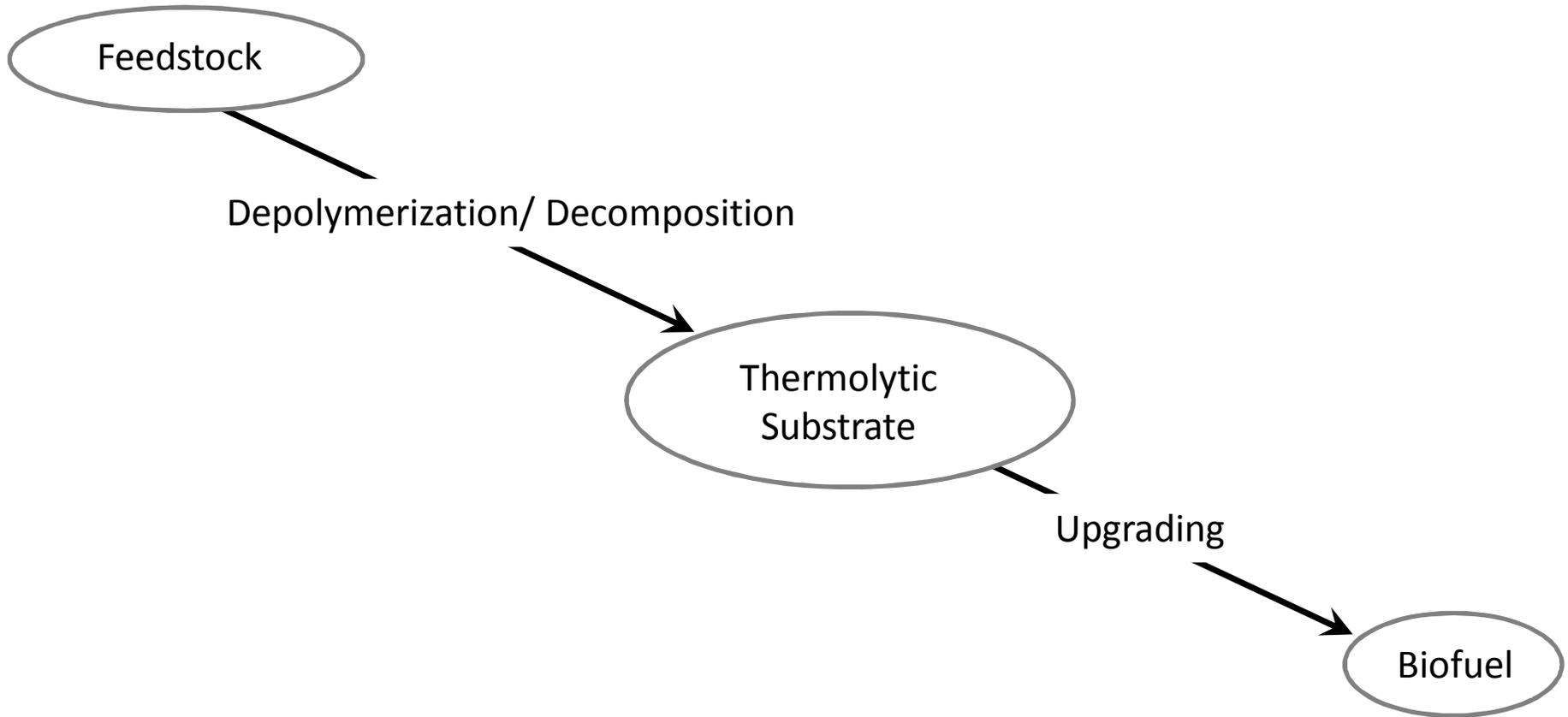
# Outline

- General biomass processing → pyrolysis
- Different kinds of pyrolysis (emphasis on fast pyrolysis)
- Bio-oil properties
- Description of fast pyrolysis
- Mechanisms of fast pyrolysis
- Types of fast pyrolysis reactors
- Biochar as pyrolysis co-product
- Applications of bio-oil

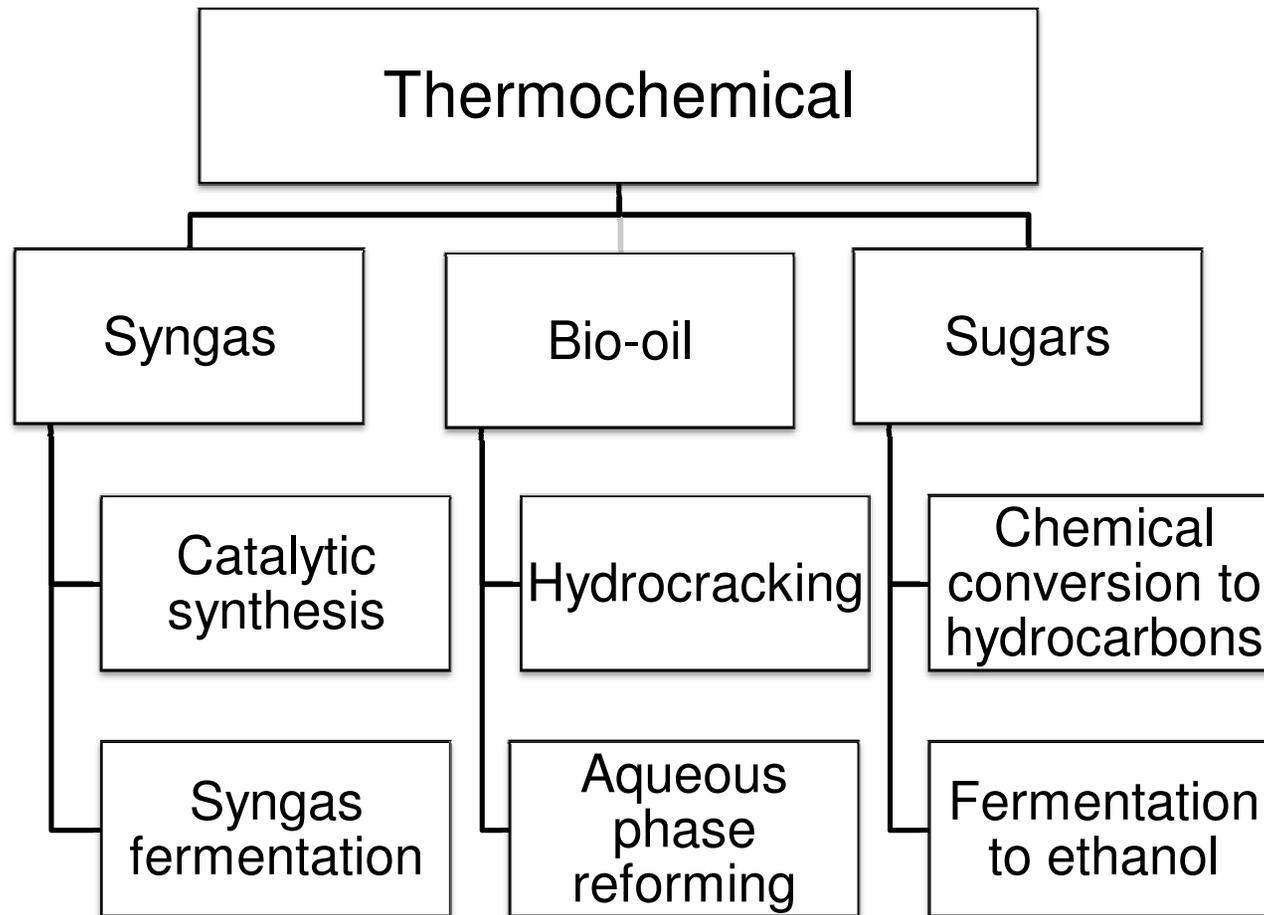
# Renewable Fuels Technologies



# Generalized Thermochemical Process



# Thermolytic Substrates



# Definition

Pyrolysis – thermal decomposition of carbonaceous material in the absence of oxygen

# Py Products

- Gas – non-condensable gases like carbon dioxide, carbon monoxide, hydrogen
- Solid – mixture of inorganic compounds (ash) and carbonaceous materials (charcoal)
- Liquid – mixture of water and organic compounds known as *bio-oil* recovered from pyrolysis vapors and aerosols (smoke)



# The many faces of pyrolysis

Technology	Residence Time	Heating Rate	Temperature (C)	Predominate Products
carbonization	days	very low	400	charcoal
conventional	5-30 min	low	600	oil, gas, char
gasification	0.5-5 min	moderate	>700	gas
Fast pyrolysis	0.5-5 s	very high	650	oil
flash-liquid	<1 s	high	<650	oil
flash-gas	<1 s	high	<650	chemicals, gas
ultra	<0.5 s	very high	1000	chemicals, gas
vacuum	2-30s	high	<500	oil
hydro-pyrolysis	<10s	high	<500	oil
methano-pyrolysis	<10s	high	<700	chemicals

Mohan D., Pittman C. U. Jr., and Steele P. H. "Pyrolysis of Wood/Biomass for Bio-oil: A Critical Review" Energy & Fuels, 20, 848-889 (2006)

# Carbonization (slow pyrolysis)

- Charcoal is the carbonaceous residue obtained from heating biomass under oxygen-starved conditions.
- Charcoal word origin - “the making of coal.”
- Geological processes that make coal are quite different from those that produce charcoal and properties are quite different.
- Charcoal contains 65% to 90% carbon with the balance being volatile matter and mineral matter (ash).
- Antal, Jr., M. J. and Gronli, M. (2003) The Art, Science, and Technology of Charcoal Production, Ind. Eng. Chem. Res. 42, 1619-1640



Charcoal yields (dry weight basis) for different kinds of batch kilns

<b>Kiln Type</b>	<b>Charcoal Yield</b>
Pit	12.5-30
Mound	2-42
Brick	12.5-33
Portable Steel (TPI)	18.9-31.4
Concrete (Missouri)	33

Kammen, D. M., and Lew, D. J. (2005) Review of technologies for the production and use of charcoal, Renewable and Appropriate Energy Laboratory, Berkeley University, March 1, <http://rael.berkeley.edu/files/2005/Kammen-Lew-Charcoal-2005.pdf>, accessed November 17, 2007.

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# Fast Pyrolysis

Fast pyrolysis - rapid thermal decomposition of organic compounds in the absence of oxygen to produce predominately liquid product



Biochar

# Fast Pyrolysis

- Dry feedstock: <10%
- Small particles: <3 mm
- Moderate temperatures (400-500 °C)
- Short residence times: 0.5 - 2 s
- Rapid quenching at the end of the process
- Typical yields
  - Oil: 60 - 70%
  - Char: 12 -15%
  - Gas: 13 - 25%

# Fast Pyrolysis

- Advantages
  - Operates at atmospheric pressure and modest temperatures (450 C)
  - Yields of bio-oil can exceed 70 wt-%
- Disadvantages
  - High oxygen and water content of pyrolysis liquids makes them inferior to conventional hydrocarbon fuels
  - Phase-separation and polymerization of the liquids and corrosion of containers make storage of these liquids difficult

# Differences between Bio-Oil and Heavy Fuel Oil

property	pyrolysis oil	heavy fuel oil
moisture content, wt %	15–30	0.1
pH	2.5	
specific gravity	1.2	0.94
elemental composition, wt %		
carbon	54–58	85
hydrogen	5.5–7.0	11
oxygen	35–40	1.0
nitrogen	0–0.2	0.3
ash	0–0.2	0.1
higher heating value, MJ/kg	16–19	40
viscosity (50°C), cP	40–100	180
solids, wt %	0.2–1	1
distillation residue, wt %	up to 50	1

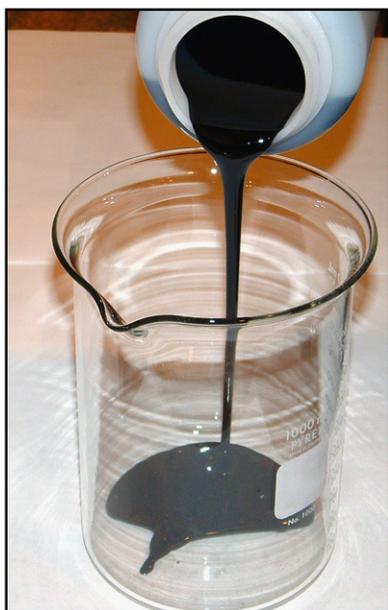
Source: Huber et al. (2006) Chem. Rev. 106, 4044-4098

# Typical Properties of Bio-Oil

Property	Characteristics
Appearance	Black or dark red-brown to dark green
Miscibility	Water content from 15 wt% to upper limit of 30-50 wt%; phase separation occurs with water addition; miscible in polar solvents but immiscible in petro fuels;
Density	1.2 kg/L
Viscosity	25 – 1000 cSt @ 40 C depending upon water and light volatiles content and aging
Distillation	About 50% of liquid cannot be vaporized due to polymerization
Storage	Chemically unstable over time especially at elevated temperatures: volatility reduction, polymerization, gum deposition, and phase separation; high acidity causes storage tank corrosion.

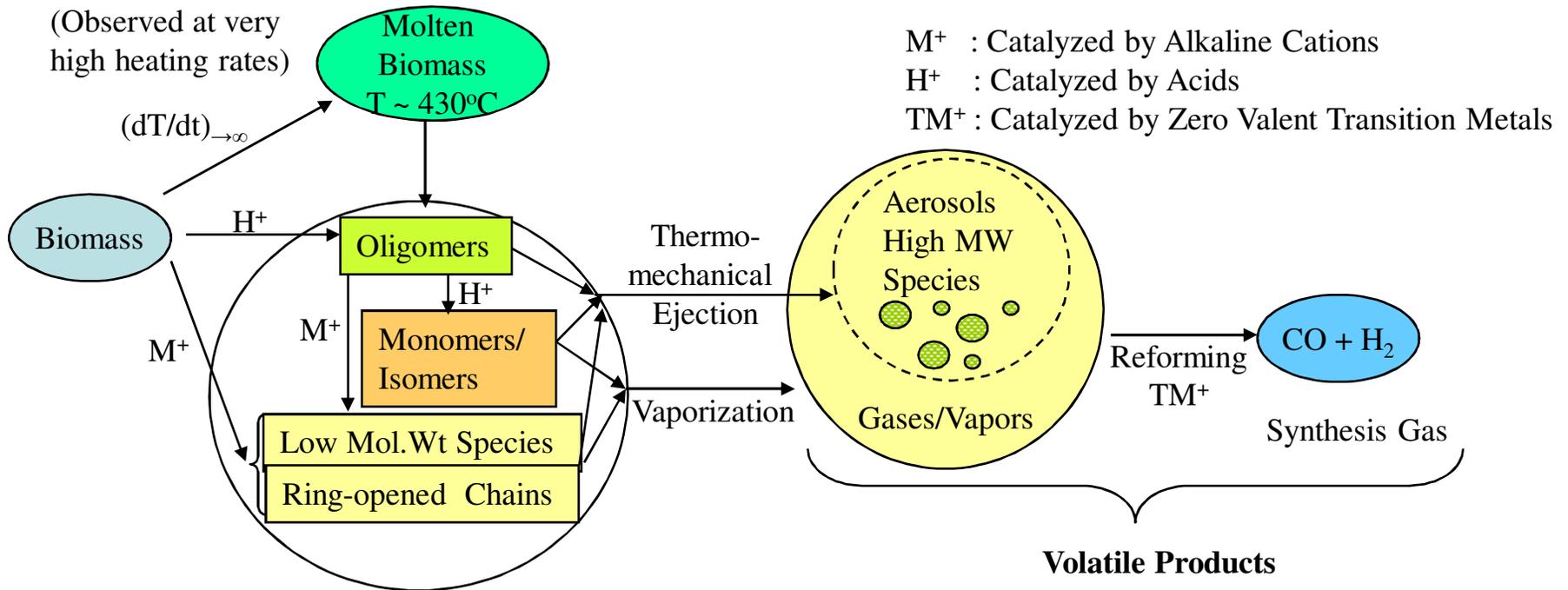
# Bio-Oil

Pyrolysis liquid (bio-oil) from flash pyrolysis is a low viscosity, dark-brown fluid with up to 15 to 20% water



Source: Piskorz, J., et al. (1988)	White Spruce	Poplar
Moisture content, wt%	7.0	3.3
Particle size, $\mu\text{m}$ (max)	1000	590
Temperature	500	497
Apparent residence time	0.65	0.48
<b>Bio-oil composition, wt %, m.f.</b>		
Saccharides	3.3	2.4
Anhydrosugars	6.5	6.8
Aldehydes	10.1	14.0
Furans	0.35	--
Ketones	1.24	1.4
Alcohols	2.0	1.2
Carboxylic acids	11.0	8.5
Water-Soluble – Total Above	34.5	34.3
Pyrolytic Lignin	20.6	16.2
Unaccounted fraction	11.4	15.2

# Pyrolysis Pathways



Radlein, D.; in Fast Pyrolysis of Biomass: Handbook Volume 1, A.V. Bridgwater, ed. (1999) 164-188.

# General Mechanism of Pyrolysis

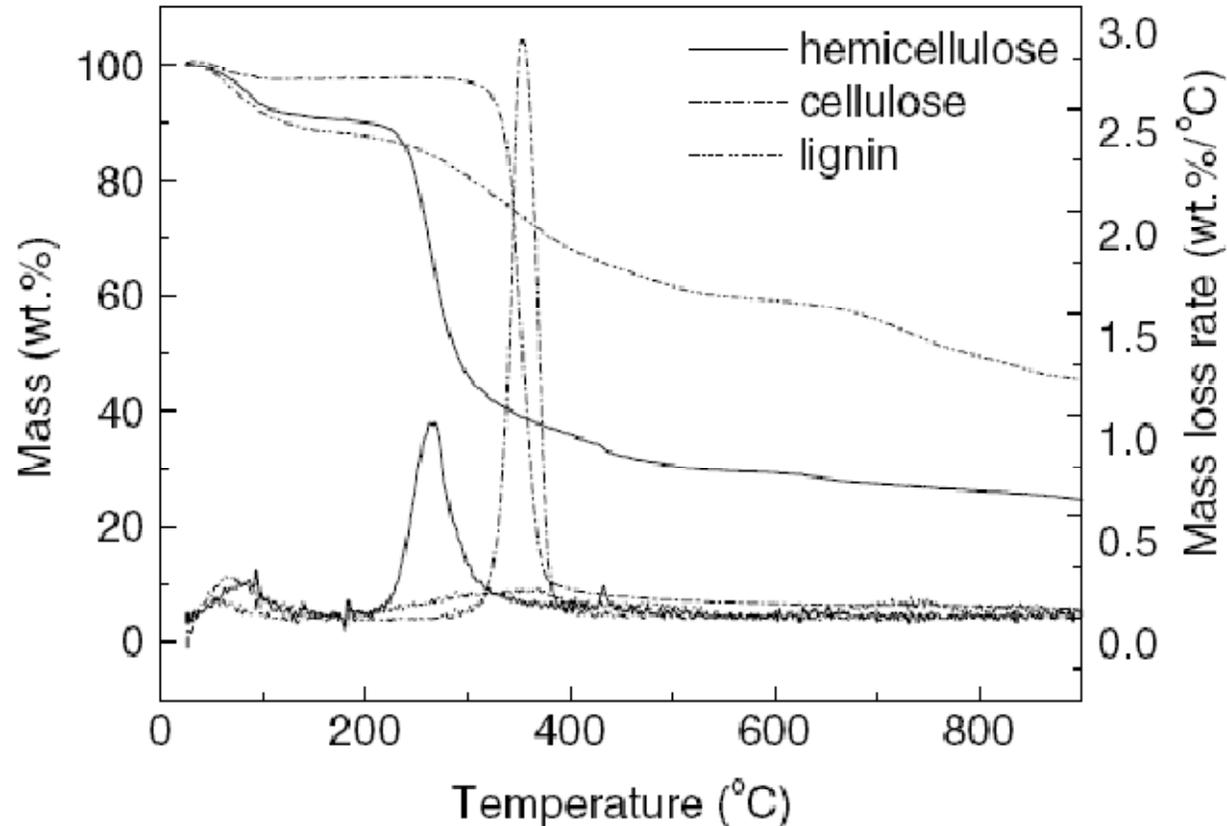
- (1) Heat transfer from a heat source, to increase the temperature inside the fuel;
- (2) The initiation of primary pyrolysis reactions at this higher temperature releases volatiles and forms char;
- (3) The flow of hot volatiles toward cooler solids results in heat transfer between hot volatiles and cooler unpyrolyzed fuel;
- (4) Condensation of some of the volatiles in the cooler parts of the fuel, followed by secondary reactions, can produce tar;
- (5) Autocatalytic secondary pyrolysis reactions proceed while primary pyrolytic reactions (item 2, above) simultaneously occur in competition; and
- (6) Further thermal decomposition, reforming, water gas shift reactions, radicals recombination, and dehydrations can also occur, which are a function of the process's residence time/temperature/pressure profile.

# Primary and Secondary Charcoal

- Primary Charcoal: Arises from solid-phase reactions in which devolatilized biomass leaves behind a carbonaceous residue
  - Endothermic reaction
- Secondary Charcoal: Formed by decomposition of organic vapors (tars) on primary charcoal (coking)
  - Exothermic
  - Likely to be catalyzed by primary charcoal
- Low charcoal yields can result if vapors and gases are removed from the reaction zone before thermodynamic equilibrium can be attained.

Antal, Jr., M. J. and Gronli, M. (2003) The Art, Science, and Technology of Charcoal Production, Ind. Eng. Chem. Res. 42, 1619-1640

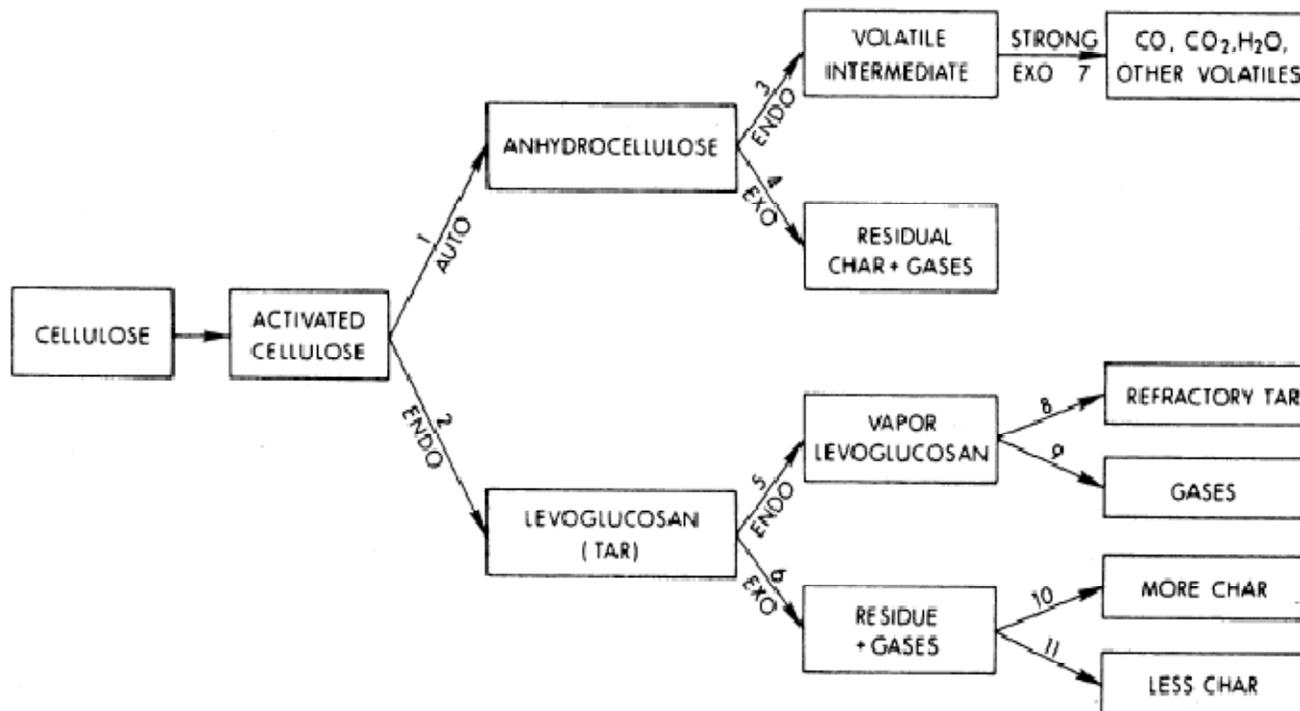
# Thermal Decomposition of Lignocellulose



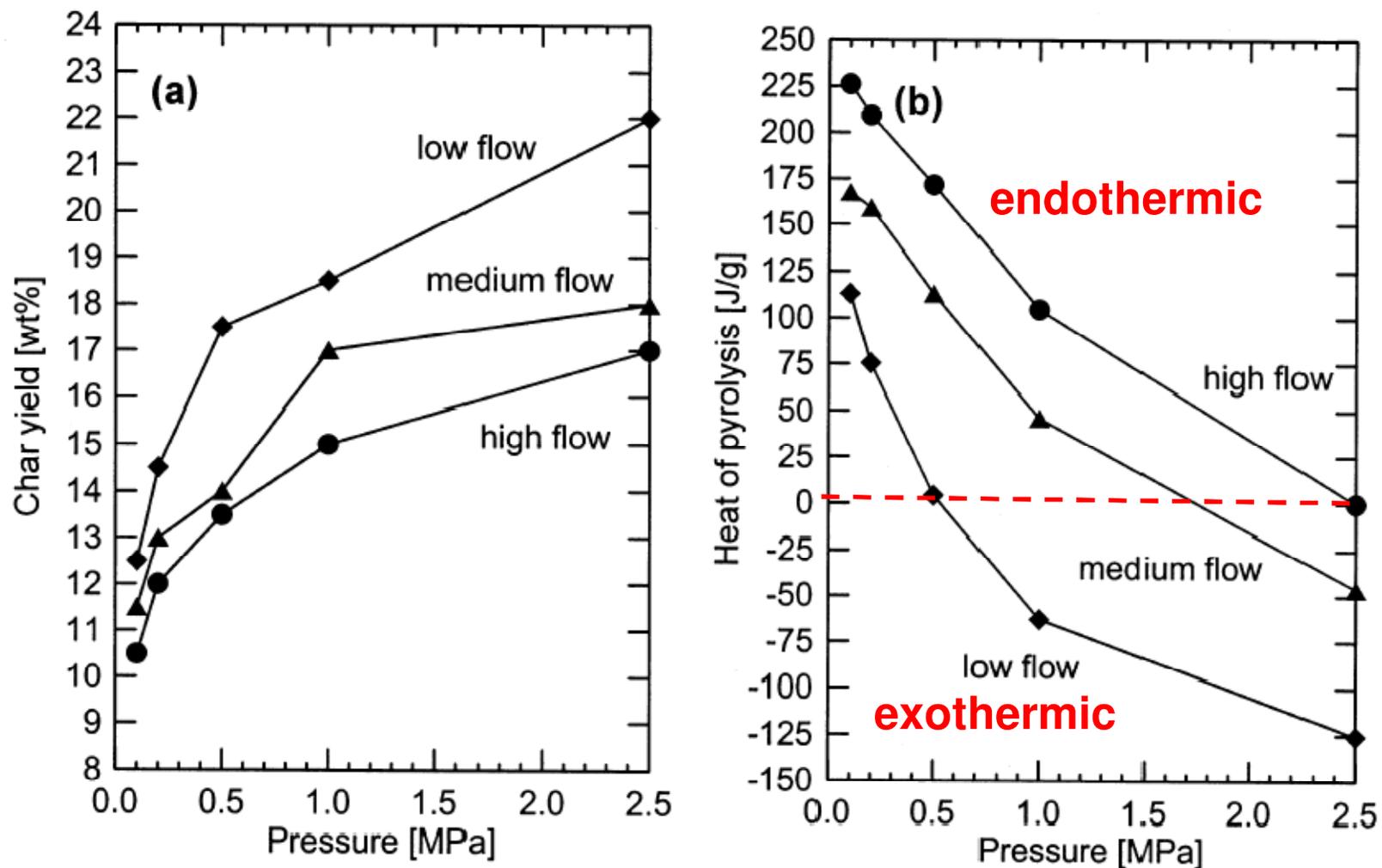
Thermogravimetric analysis of the pyrolysis of cellulose, hemicellulose (xylan), and lignin at constant heating rate ( $10^{\circ}\text{C}/\text{min}$ ) with nitrogen sweep gas at  $120\text{ ml}/\text{min}$  (Rutherford, D. W., Wershaw, R. L., and Cox, L. G. (2004) Changes in Composition and Porosity Occurring During the Thermal Degradation of Wood and Wood Components, U.S. Geological Survey, Scientific Investigation Report 2004-5292)

# Cellulose Decomposition

- Includes both an exothermic pathway via anhydrocellulose and an endothermic pathway via levoglucosan.
  - anhydrocellulose pathway yields charcoal and non-condensable gases in a process that is overall exothermic but it occurs at extremely slow heating rates making this pathway of little practical importance
  - The levoglucosan (anhydroglucose) pathway is an endothermic devolatilization process that can lead to either predominately tarry vapors or charcoal as the final product.



# Effect of Char-Tar Contacting Time

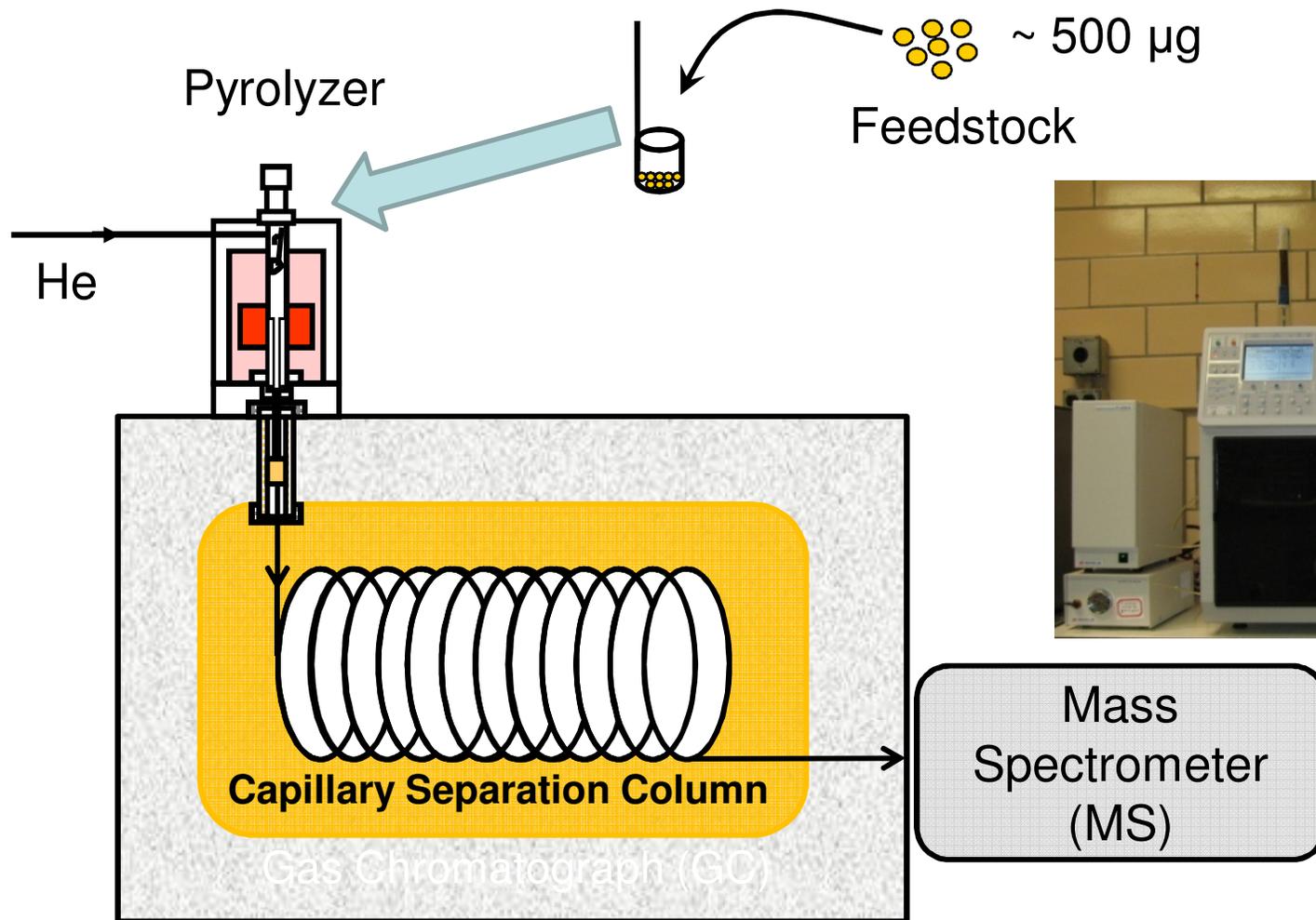


Mok, W. S. L.; Antal, M. J. Effects of Pressure on Biomass Pyrolysis. II. Heats of Reaction of Cellulose Pyrolysis. *Thermochim. Acta* 1983, 68, 165.

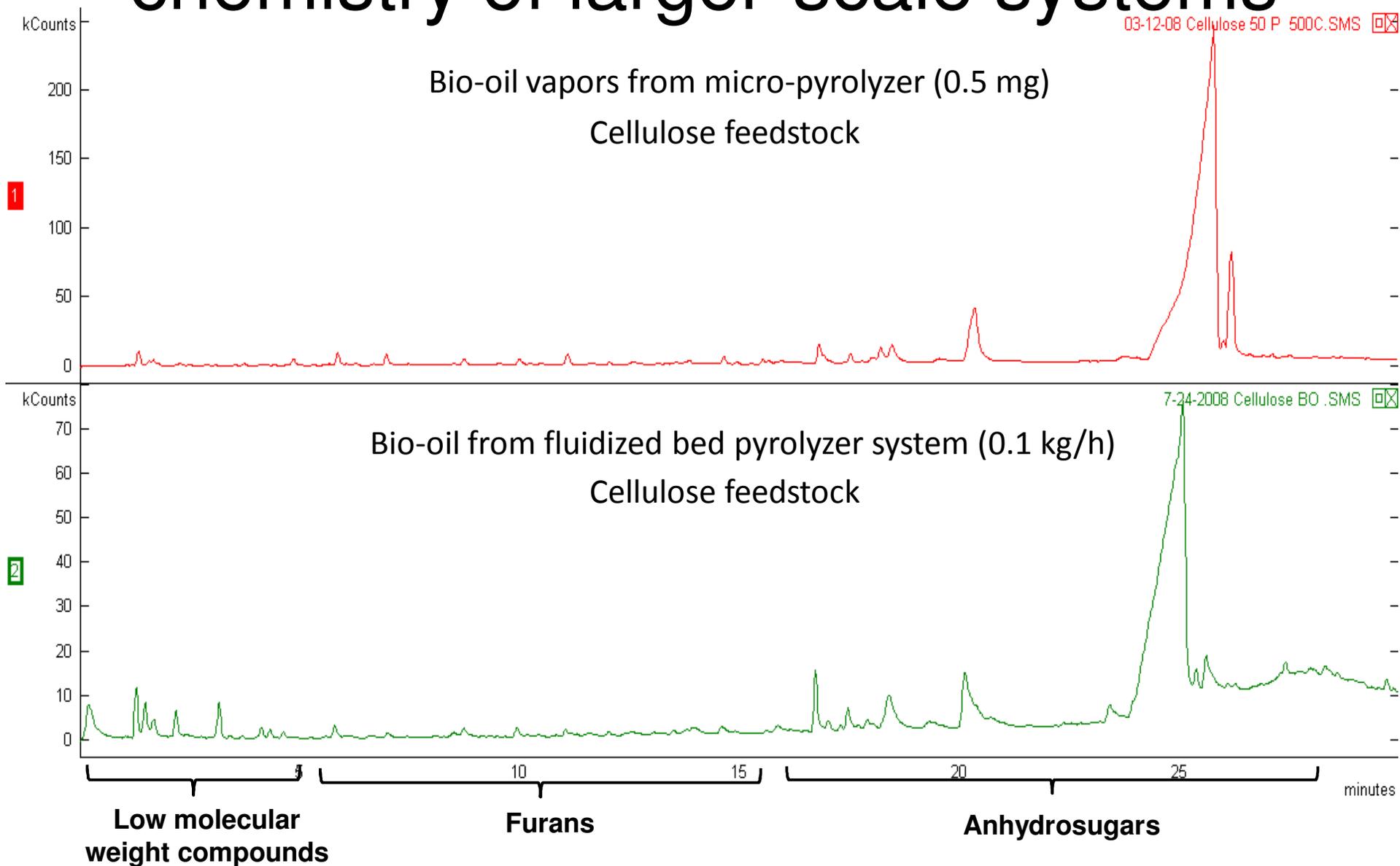
# Demonstration of Secondary Char Formation



# Fundamental studies with micro-pyrolyzer coupled to GC/MS



# Micro-pyrolyzer captures important chemistry of larger-scale systems

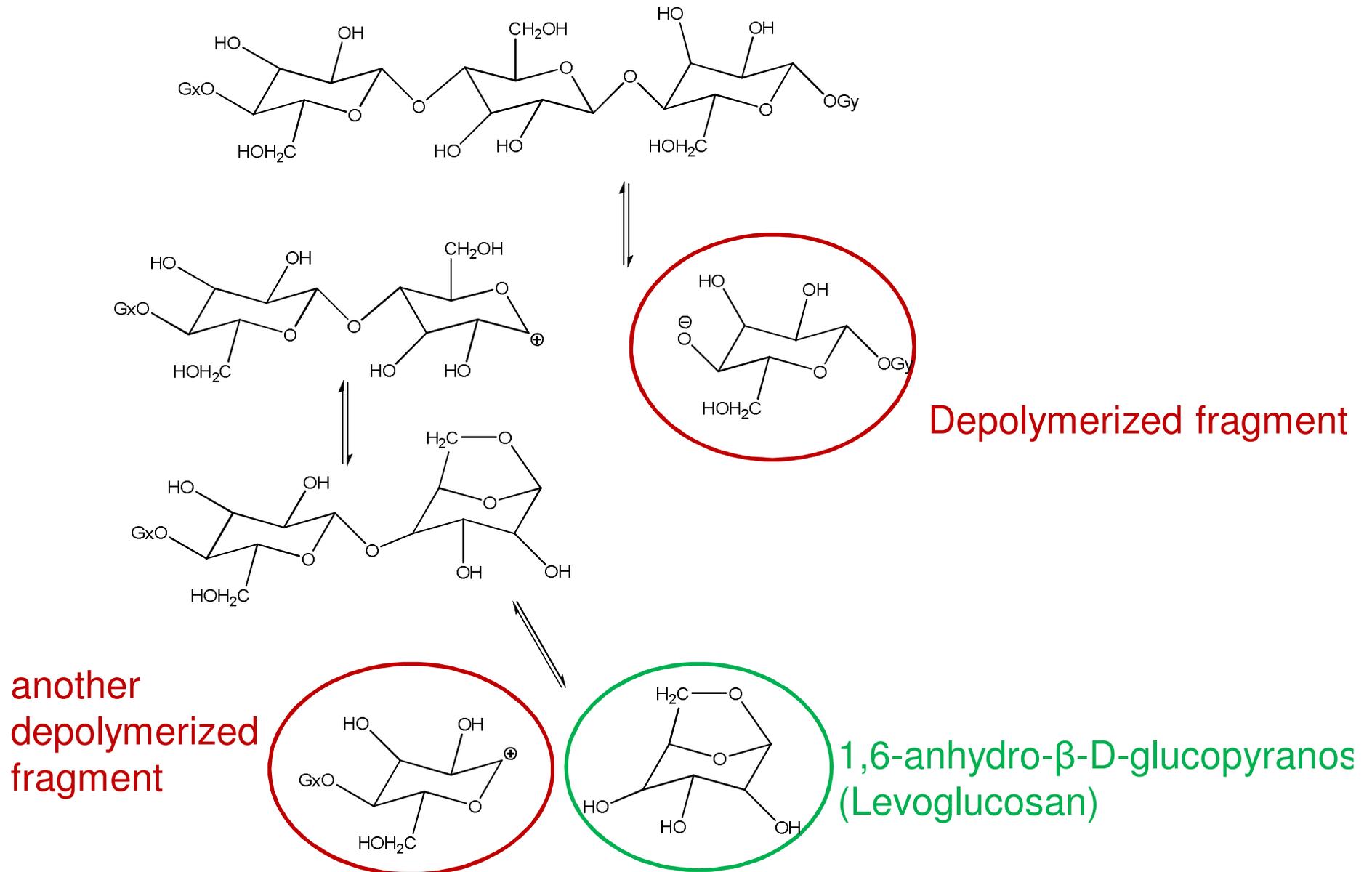


# Effect of Chain Link

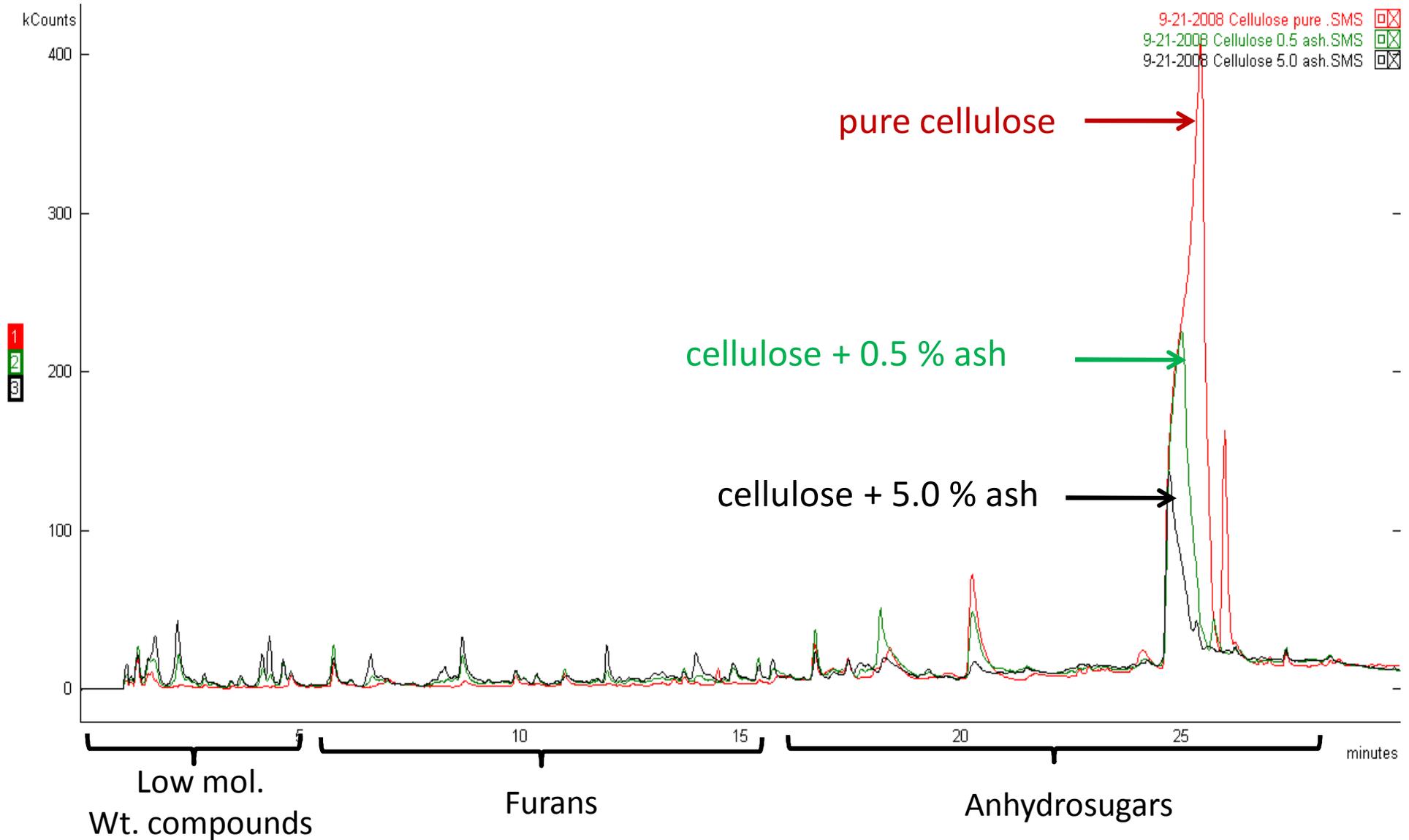
Compound	Glucose	Cellobiose	Cellulose
acetone	0.50	0.82	0.51
acetic acid	0.34	0.46	0.24
acetol	6.26	5.15	0.00
2-methyl furan	5.34	5.48	1.00
furfural	1.85	2.22	0.37
furfuryl alcohol	0.79	2.58	0.00
3-furan methanol	0.27	0.39	0.25
methyl furfural	0.11	0.19	0.09
5-hydroxymethyl furfural	6.00	9.11	2.76
2-hydroxy-3- methyl 2-cyclopentanone	0.04	0.08	0.05
Levoglucozan	17.22	32.91	73.38
Other anhydrosugar	20.92	9.18	12.44
TOTAL	61.59	71.56	91.09

- Glucose produces more low molecular weight compounds
- Cellobiose yields more furan derivatives
- Cellulose degrades mainly into anhydro sugars

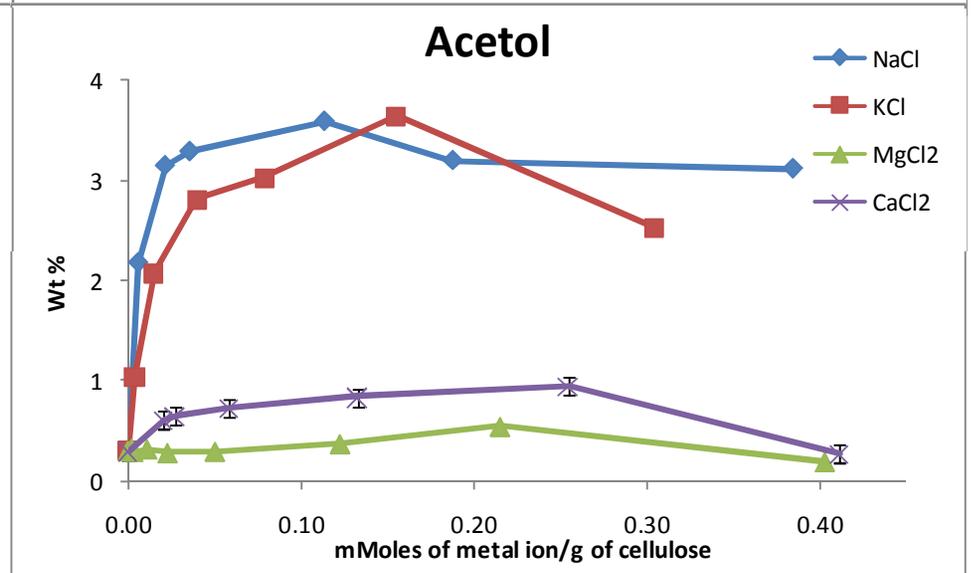
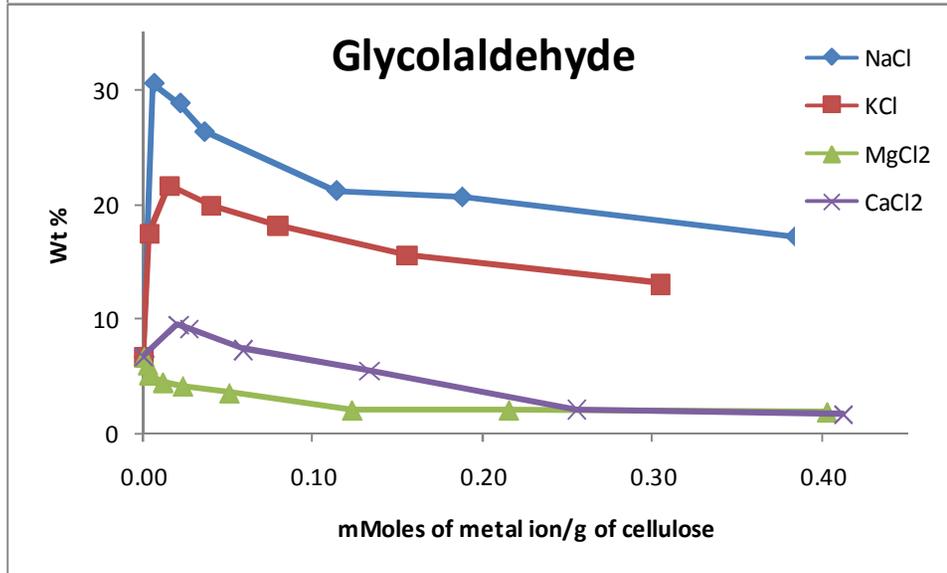
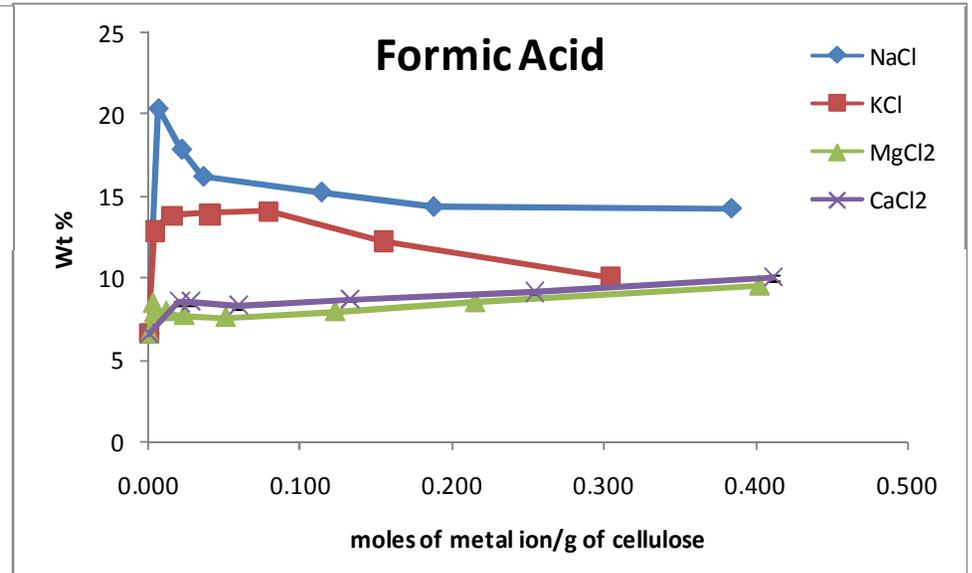
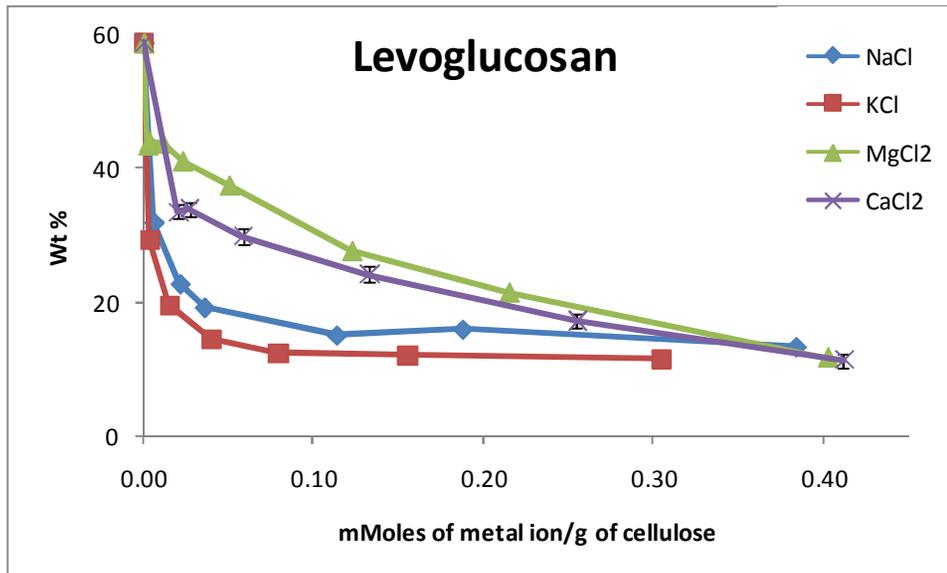
# Mechanism of Levoglucosan Formation\*



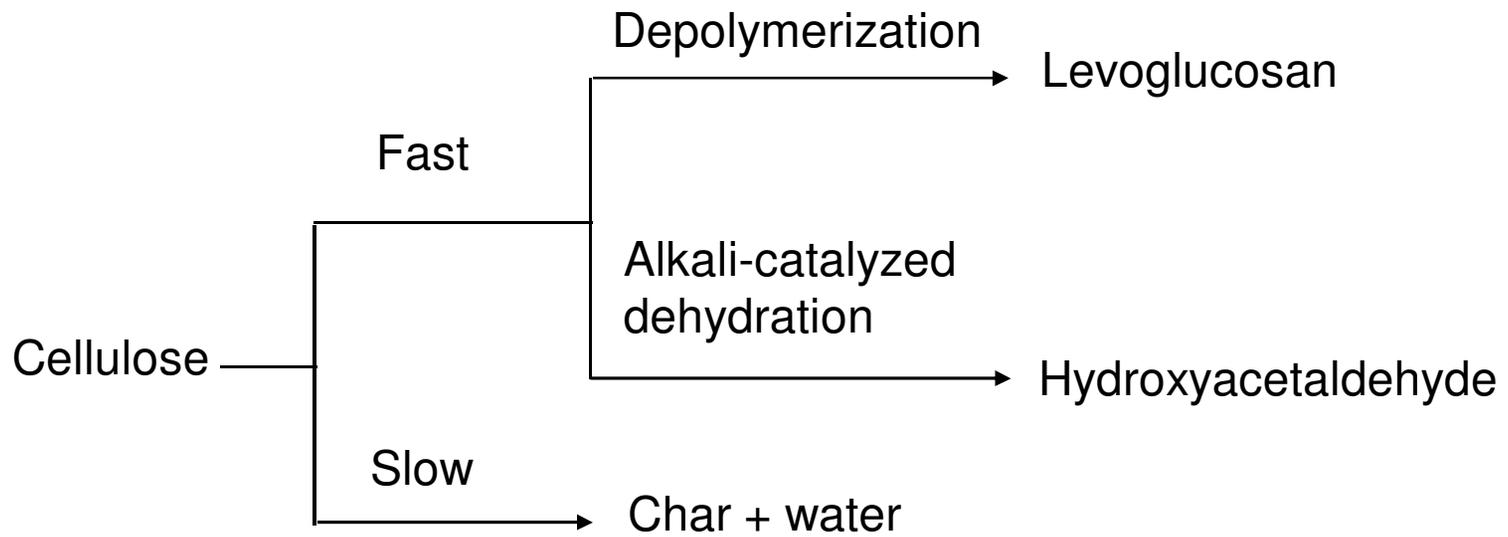
# Addition of switchgrass ash to cellulose prior to pyrolysis



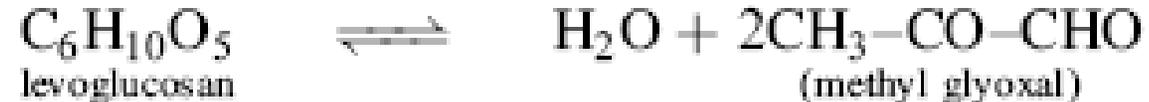
# Effect of Cations



# Cellulose Degradation

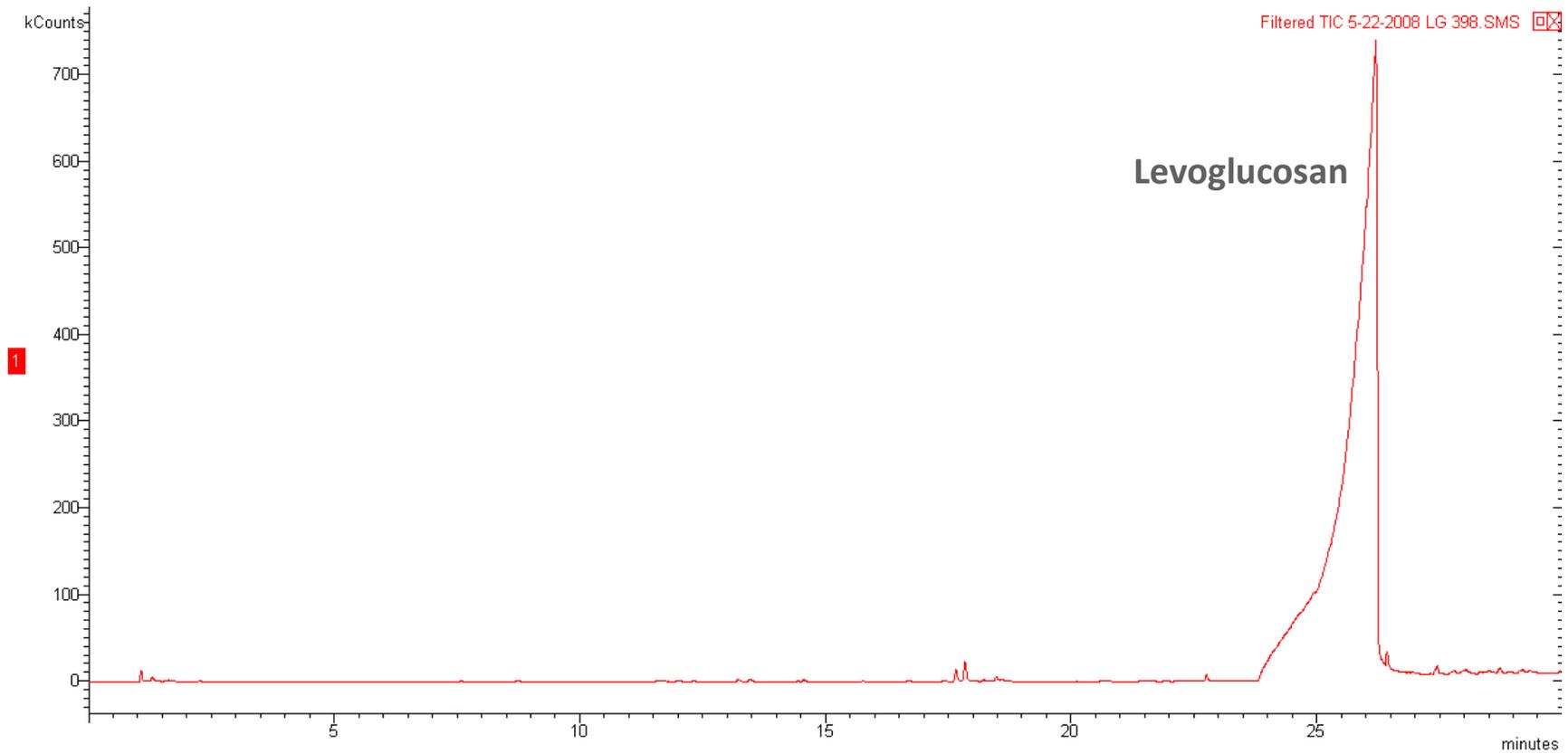


# Levoglucosan Decomposition?



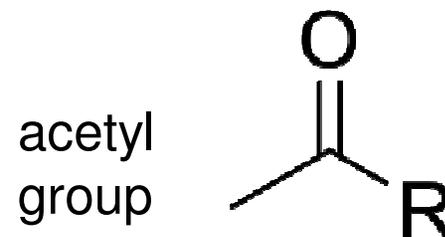
Demirbas, A., (2000) Energy Conversion Management , 41, 633-646.

# Proof Otherwise: Pyrolysis of levoglucosan at 500 °C yields...levoglucosan



# Pyrolysis of Hemicellulose

- Pyrolysis products of hemicellulose include non-condensable gases (primarily CO, CO<sub>2</sub>, H<sub>2</sub>, and CH<sub>4</sub>), low molecular weight organic compounds (carboxylic acids, aldehydes, alkanes, and ethers), and some water.
- Much of the acetic acid liberated from wood is attributed to deacetylation of the hemicellulose.
- Most hemicelluloses do not yield significant amounts of levoglucosan.
- Heavy molecular weight (tarry) compounds are produced in relatively small amounts compared to pyrolysis of cellulose and lignin.



# Pyrolysis of Lignin

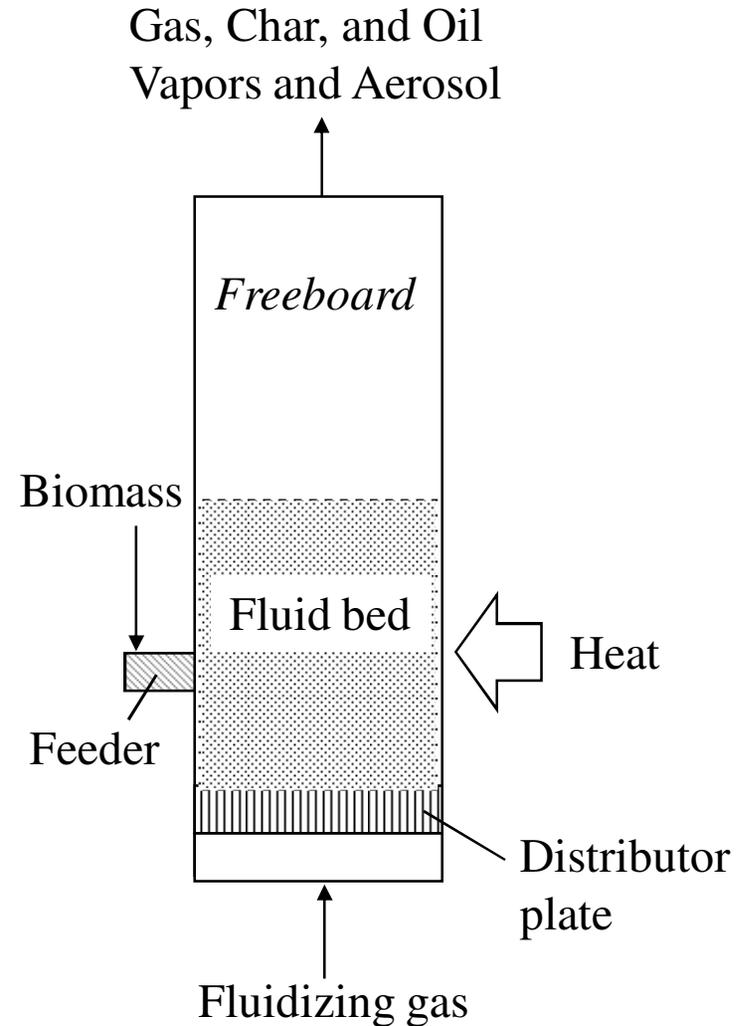
- Pyrolysis of lignin yields non-condensable gases, condensable vapors and liquid aerosols, and charcoal.
- The non-condensable gases, representing about 10 wt-% of the original lignin, consist of CO, CH<sub>4</sub>, and C<sub>2</sub>H<sub>4</sub>.
- Lignin pyrolysis yields phenols via the cleavage of ether and carbon-carbon linkages.
- Lignin pyrolysis produces more residual char than does the pyrolysis of cellulose.
- Condensable vapors and liquid aerosols are recovered as pyroligneous acid and non-soluble tar.
  - Pyroligneous acid is an aqueous phase of methanol, acetic acid, acetone, and soluble tar.
  - Non-soluble tar contains homologous phenolic compounds derived from cleavage of ether and carbon-carbon bonds

# Several Kinds of Fast Pyrolysis Reactors

- Bubbling fluidized bed
- Circulating fluidized beds/transport reactor
- Rotating cone pyrolyzer
- Ablative pyrolyzer
- Vacuum pyrolysis
- Auger reactor

# Bubbling Fluidized Bed

- Heat supplied externally to bed
- Good mass & heat transfer
- Gas residence times shorter than char residence times

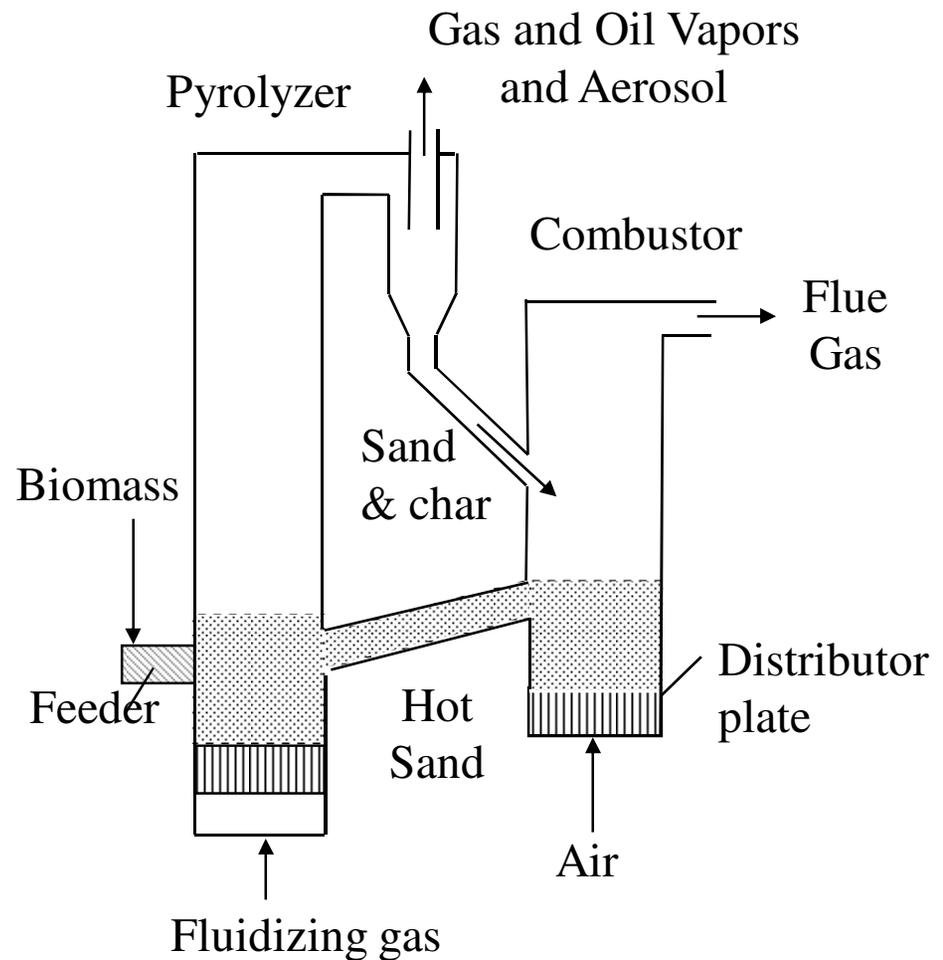


# Bubbling Fluidized Beds

- Small particle sizes of less than 2-3 mm are needed
- Shallow beds and/or a high gas flow rates are needed to achieve short volatiles residence times
- The high gas-to-biomass fed ratio results in a lowering of the thermal efficiency (which is typically 60-70%)

# Circulating Fluidized Bed/Transport Reactor

- Hot sand circulated between combustor and pyrolyzer
- Heat supplied from burning char
- High throughputs

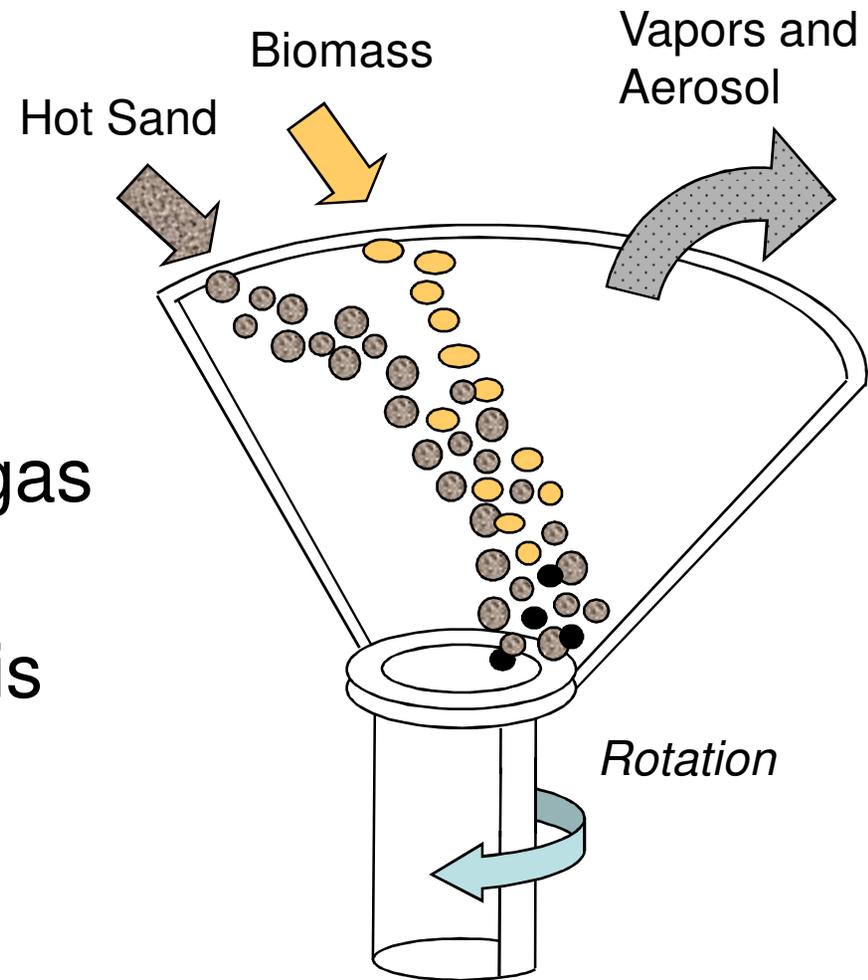


# Circulating Fluidized Bed/Transport Reactor

- Char and gas residence times are similar
- Hydrodynamics are complex
- High char attrition

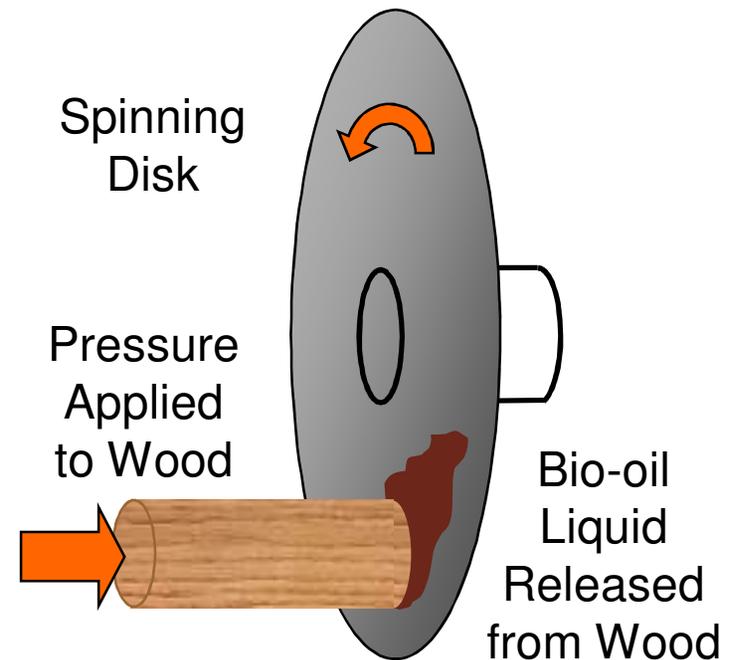
# Rotating Cone Pyrolyzer

- Sand and biomass brought into contact within rotating cone
- Compact design and does not need carrier gas
- Requires very small biomass particles and is hard to scale-up



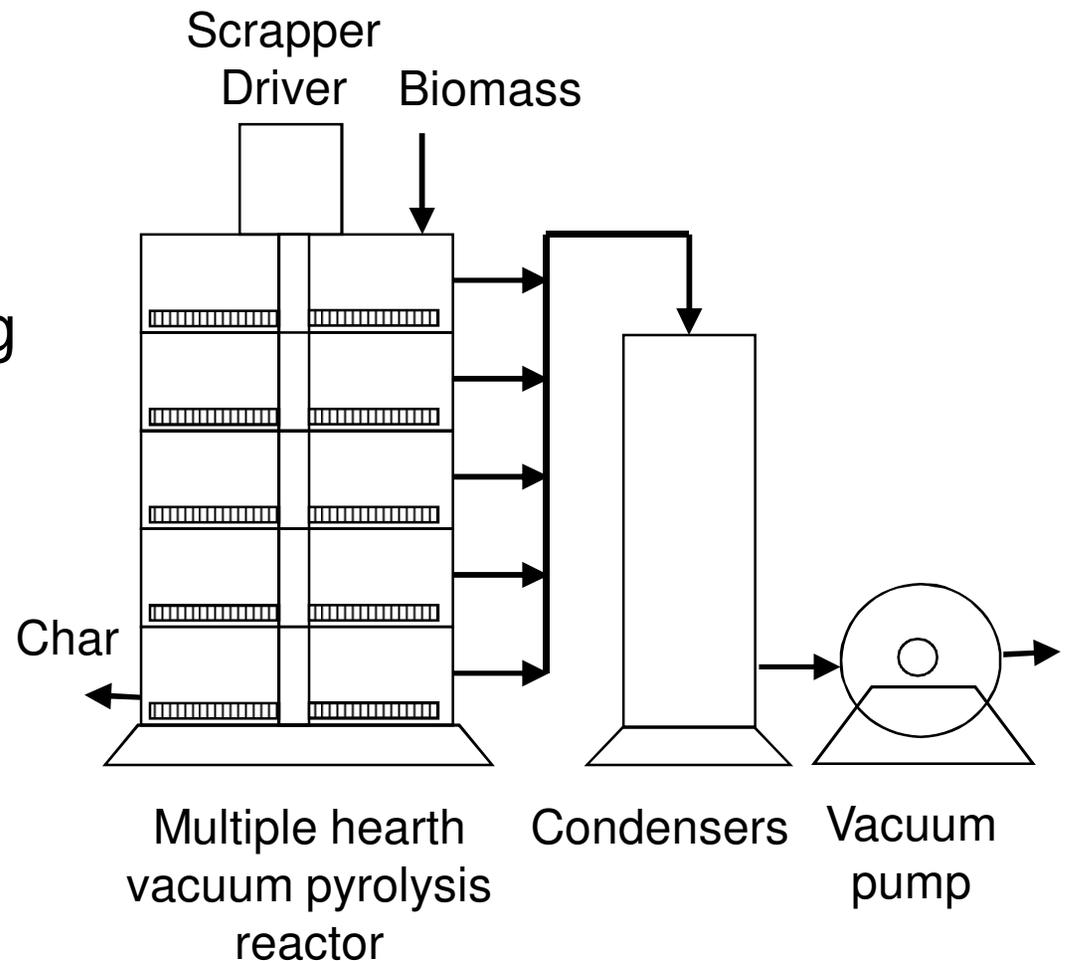
# Ablative Pyrolyzer

- High pressure of particle on hot reactor wall achieved by centrifugal or mechanical motion
- Can use large particles and does not require carrier gas
- Complex and does not scale well



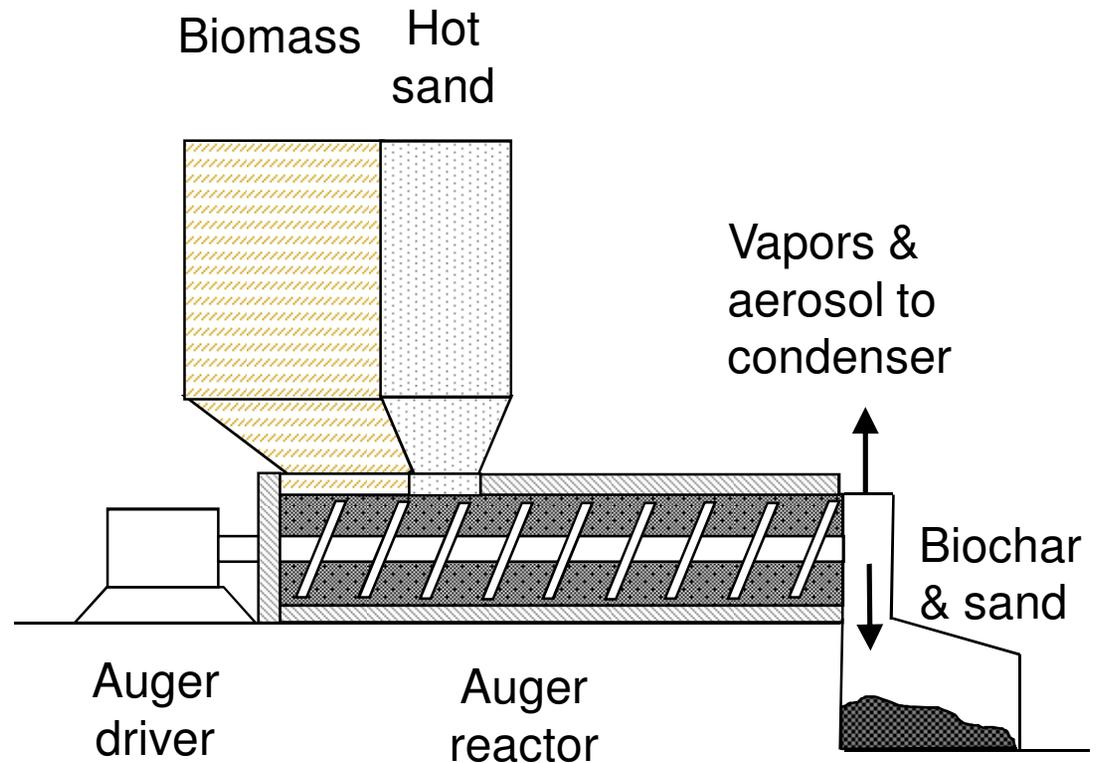
# Vacuum Pyrolysis

- Biomass moved by gravity and rotating scrappers through multiple hearth pyrolyzer with temperature increasing from 200 C to 400 C
- Can use larger particles and employs little carrier gas
- Expensive vacuum pump and difficult to scale-up



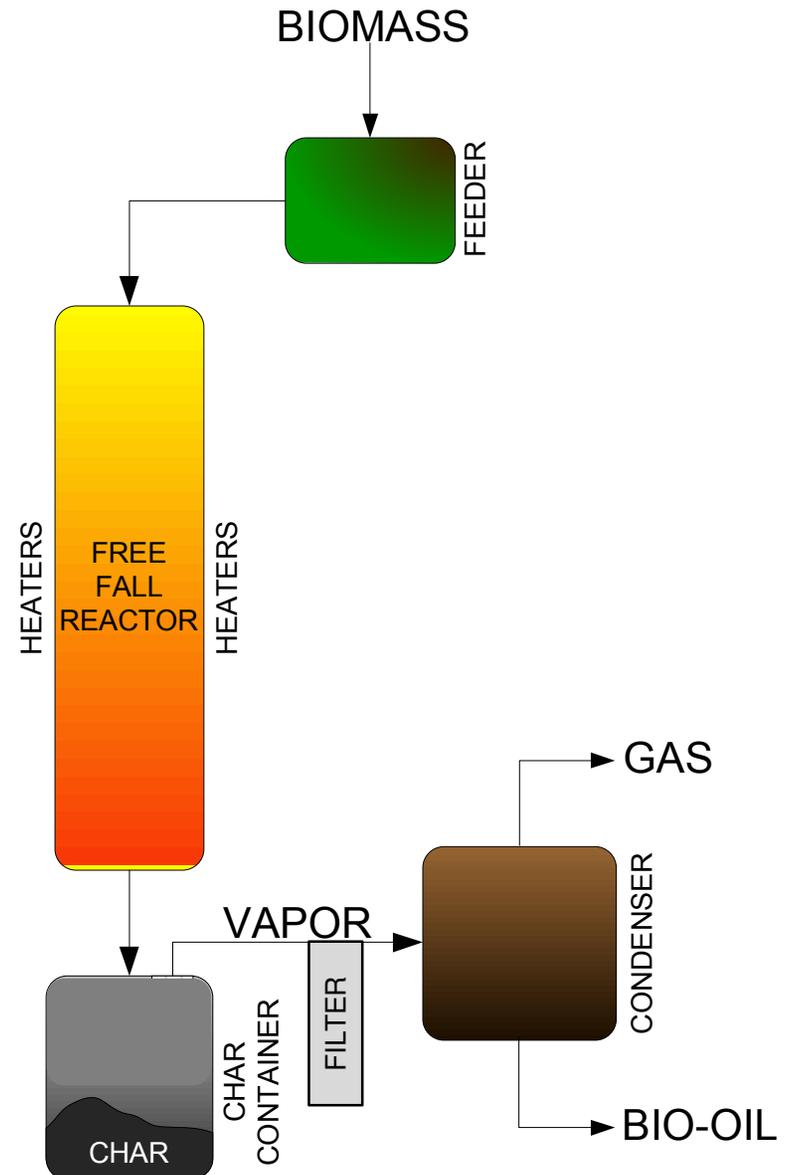
# Auger Reactor

- Hot sand and biomass mixed by auger
- Suitable for small scale
- Requires hot sand heating and circulation system



# Free Fall Reactor

- No heat carrier
- Little to no carrier gas
- Simple design –no moving parts
- Requires small biomass particles
- May be suitable for distributed pyrolysis operations and small scale

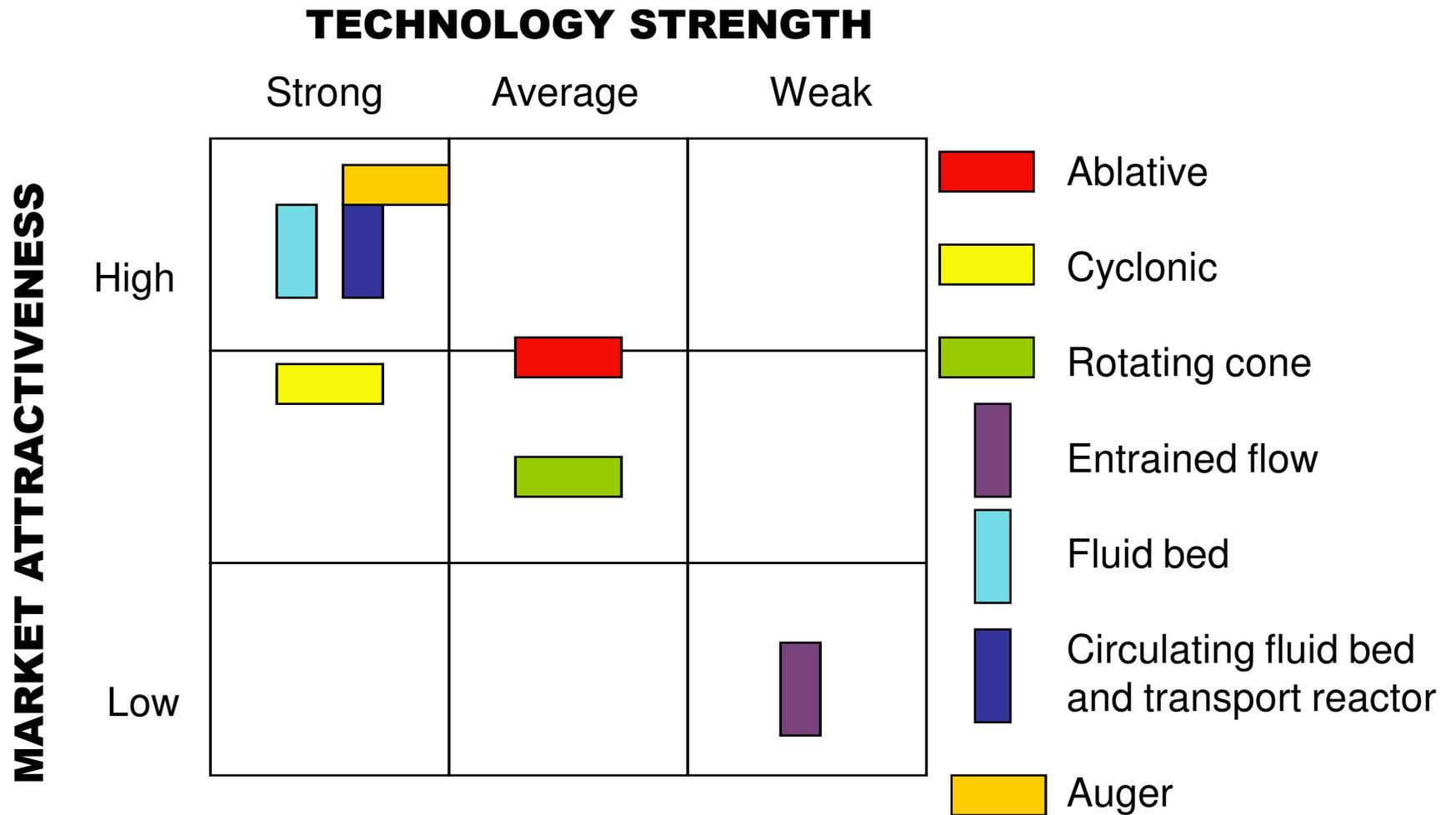


# Relative Merits of Various Reactors

Property	Status	Bio-oil wt%	Complexity	Feed size	Inert gas need	Specific size	Scale up
Fluid bed	Demo	75	Medium	Small	High	Medium	Easy
CFB	Pilot	75	High	Medium	High	Large	Easy
Entrained	None	65	High	Small	High	Large	Easy
Rotating cone	Pilot	65	High	V small	Low	Small	Hard
Ablative	Lab	75	High	Large	Low	Small	Hard
Auger	Lab	65	Low	Small	Low	Medium	Easy
Vacuum	Demo	60	High	Large	Low	Large	Hard
The darker the cell color, the less desirable the process.				Lab: 1 – 20 kg h <sup>-1</sup> Pilot: 20 – 200 kg h <sup>-1</sup> Demo: 200 – 2000 kg h <sup>-1</sup>			

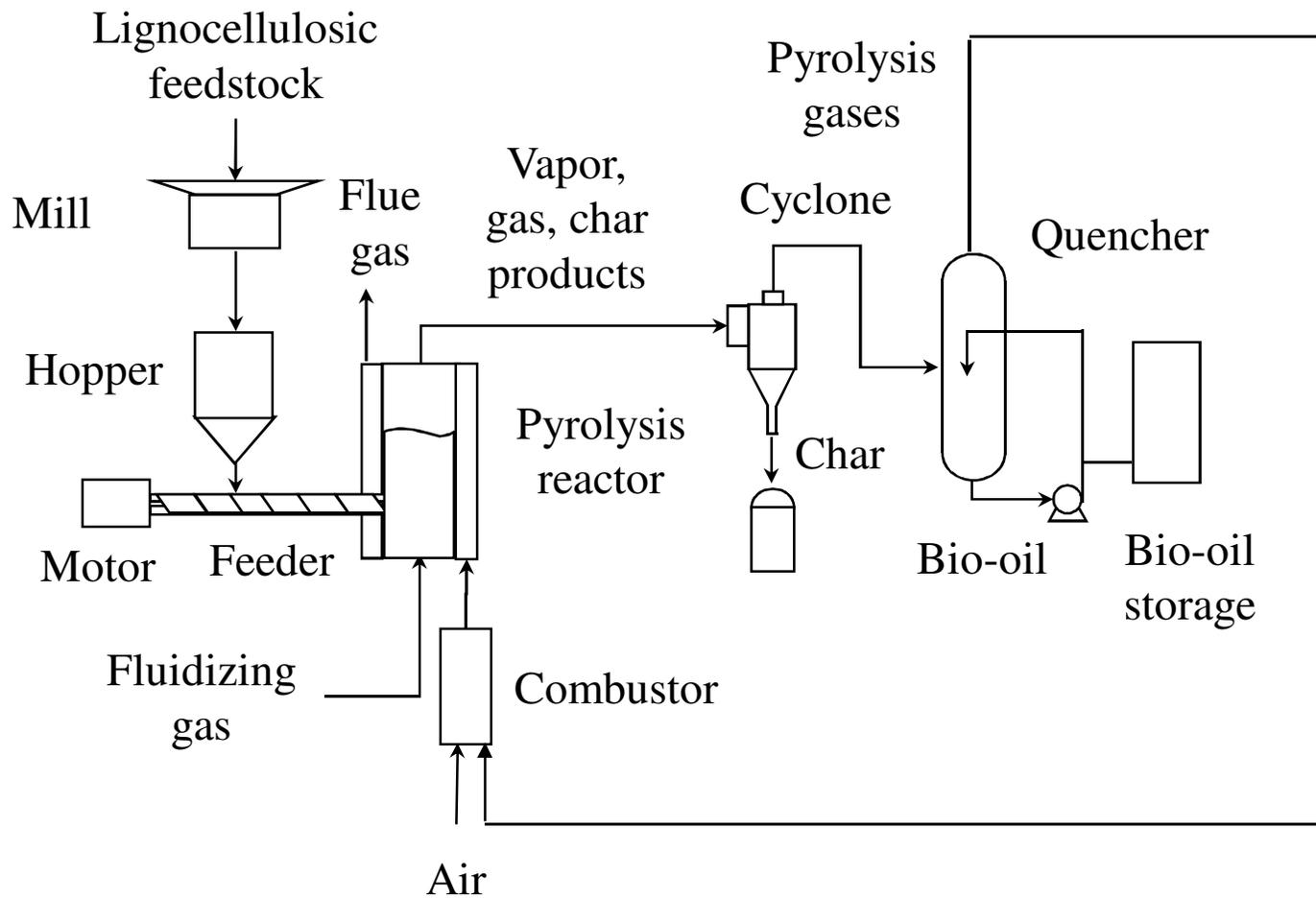
Adapted from PYNE IEA Bioenergy <http://www.pyne.co.uk>

# Which will dominate?



Adapted from PYNE IEA Bioenergy <http://www.pyne.co.uk>

# Fast Pyrolysis System



# Energy Efficiency

- Conversion to 75 wt-% bio-oil translates to energy efficiency of 70%
- If carbon used for energy source (process heat or slurried with liquid) then efficiency approaches 94%

Source: <http://www.ensyn.com/info/23102000.htm>

# Suitable Feedstocks

- Wide variety of feedstocks can be used
- Fibrous biomass usually employed
- Wood higher yielding than herbaceous biomass

# Storage & Transportation

- Distributed preprocessing allows transport and storage as liquid
- High acidity requires storage in stainless steel or plastic
- Stability problems need to be solved

# Quality Assurance

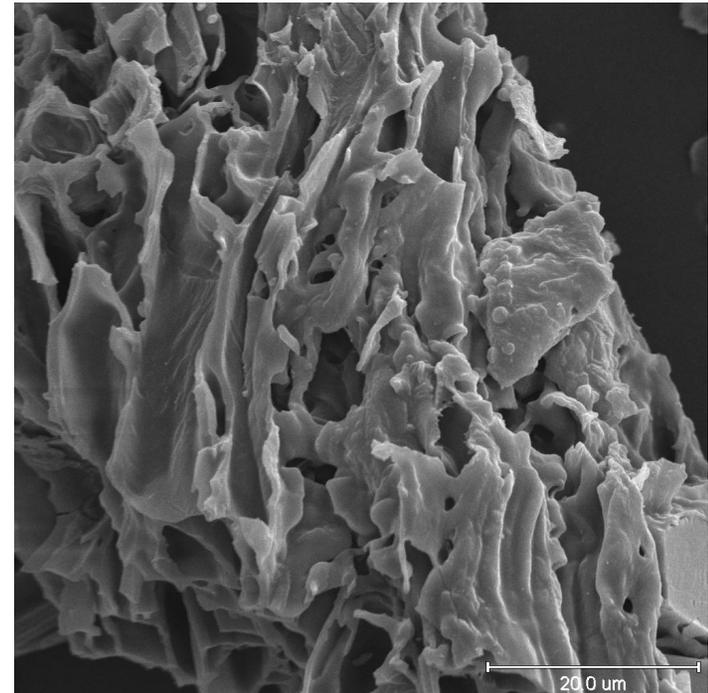
- Bio-oil quality issues:
  - Moisture content
  - Acidity
  - Particulate matter content
  - Stability over time
  - Sulfur and nitrogen content
  - Molecular weight of lignin oligomers

# Technical Barriers

- Preparing dry, finely divided biomass particles
- Maintaining high bio-oil yields
- Improving bio-oil stability
- Determining optimal scale of facility

# Co-Products

- Gas (CO, H<sub>2</sub>, light hydrocarbons)
  - Can be used to heat pyrolysis reactor
- Char: Several potential applications
  - Process heat
  - Activated carbon
  - Soil amendment



# Bio-char: Soil amendment and carbon sequestration agent

SEQUESTRATION NEWS FEATURE

NATURE | Vol. 442 | 10 August 2006



## Black is the new green

In 1879, the explorer Herbert Smith led the readers of *The Times* "with tales of the Amazon, covering everything from the fastness of tapirs to the extraordinary fecundity of the sugar plantations." The case-fact detail? He wrote of one rum-making operation: "is a splendid sight; the stalks ten feet high in many places and as big as one's wrist." His secret, he went on, was "the rich terra preta, black land, the best on the Amazon. It is a fine dark loam, a foot, and often two feet thick."

Last month the hero to Smith's enthusiasm met in a hotel room in Philadelphia, Pennsylvania, during the World Congress of Soil Science. Their agenda was to take terra preta from the annals of history and the backwaters

of the Amazon into the twenty-first century world of carbon sequestration and biofuels. They want to follow what the green revolution did for the developing world: plants with a black revolution for the world's soils. They are aware that this is a tough sell, not least because hardly anyone outside the room has heard of their product. But that does not dissuade them: more than one eye in the room had a strictly evangelical gleam.

The soil scientists, archaeologists, geographers, agronomists, and anthropologists who study terra preta now agree that the Amazon's dark earths, terra preta do Indio, were made by the river basin's original human residents, who were much more numerous than formerly supposed. The darkest patches correspond to the

Drop of the black stuff: terra preta contrasts strongly with normal soil in colour (left) and produces much more vigorous crops (below).

remains of settlements and are littered with cross-sections of broken pottery. The larger patches were once agricultural areas that the farmers enriched with charred trash of all sorts. Some soils are thought to be 7,000 years old. Compared with the surrounding soil, terra preta can contain three times as much phosphorus and nitrogen. And as its colour indicates, it contains far more carbon. In samples taken in Brazil by Wilian Viçosa, an expert in soil nutrient elements at the University of Karlsruher, the terra preta was up to 90% carbon, compared with 5% for plain soil from places nearby.

From Smith's time onwards, the sparse scholarly discussion of terra preta was focused mainly on the question of whether 'savages' could have been as clever as to enhance their land's fertility. But Woods' case makes the biology of the system the subject: now double in size every decade. About 40% of the paper's contents were published in the past six years.

### Loam ranger

The main stimulus for this interest was the work of Wim Sombroek, who died in 2003 and is still mourned in the field. Sombroek was born in the Netherlands in 1924 and lived through the Dutch famine of 1944 — the *Hongerwinter*. He finally lost body and soul together with the help of a small plot of land, made rich and dark by generations of laborious fertilization. Sombroek later improved the land in part by storing it with the ash and cinders from their home. When, in the 50s, Sombroek came across terra preta in the Amazon, it reminded him of that life-giving 'pluggen' soil, and he more or less fell in love. His 1966 book *Amazon Soils* began the scientific study of terra preta.

Since that tidal affair trial with crop after crop has shown how remarkably fertile the terra preta

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SEQUESTRATION NEWS FEATURE

ic Bruno Glaser, of the University of Bayreuth, Germany, a sometime collaborator of Sombroek, estimates that productivity of crops in terra preta is twice that of crops grown in nearby soil. But it is easier to measure the effect than explain it through detailed analysis.

Everyone agrees that the explanation lies in large part with the char (or biochar) that gives the soil its darkness. This char is made when organic matter smolders in an oxygen-poor environment, rather than burns. The particles of char produced this way are somehow able to gather up nutrients and water that might otherwise be washed down below the reach of roots. They become homes for populations of microorganisms that turn the soil into a spongy, fragrant, calc material that gardeners everywhere love to plunge their hands into. The char is not at all the good stuff: terra preta — as distinct from an excrement and bone probably play a role too — but it is the most important factor.

Leaving aside the subtleties of how char particles improve fertility, the sheer amount of carbon they can stash away is phenomenal. In 1982, Sombroek published his first work on the potential of terra preta as a soil for carbon sequestration. According to Glaser's research, a hectare of nine-deep terra preta can contain 250 tonnes of carbon, as opposed to 100 tonnes in unimproved soil from similar parent material. The extra carbon is not just in the char — it's also in the organic carbon and enhanced microbial biomass that the char sustains.

### Ground control

That difference of 150 tonnes is greater than the amount of carbon in a hectare's worth of plants. That means turning an improved soil into terra preta can store away more carbon than growing a tropical forest. For a start, on the same piece of land, before you've started to make use of it, manure and fertility. Johannes Lehmann of Cornell University in Ithaca, New

York, has studied with Glaser and worked with Sombroek. He estimates that by the end of this century terra preta schemes, in combination with biofuel programmes, could store up to 5.5 billion tonnes of carbon a year — more than is emitted by all today's fossil-fuel use.

### Mad pack

The year before he died, Sombroek helped to round up like-minded colleagues into the Terra Preta Now group, which looks at the usefulness of using char in large-scale farming and as a carbon sink. The group was well represented at the Philadelphia meeting, although Glaser was not there. Their aim is to move beyond the small projects in which many of them are involved and find ways of integrating char into agribusiness. After all, who ever there is bio-fuels that farmers want to get rid of, that no one can eat, char is a possibility. That means there are a lot of possibilities.

One problem is that there is a new competitor for farm waste. Plant are largely made up of cellulose, indigestible material in cell walls. Recent technological advances make it likely that quantities of that cellulose might be turned into biofuel. At the moment, ethanol is made from corn in the United States and from sugar in Brazil; if it were made directly from cellulose, producers could work with a wider range of cheaper biomass. Given the choice of turning waste material into fuel or into charcoal, farmers might be expected to go for fuel, especially if that is the way that policy-makers are pushing them. US President George W. Bush promised \$150 million for work on cellulosic ethanol in his 2006 state of the union speech.

But Lehmann and his colleagues don't see biofuel as an alternative to char — they see the two developing hand in hand. Take the work of Danny Day, the founder of Eprida. This "for-profit social-purpose enterprise" in Athens, Georgia, builds contraptions that farmers can use to turn farm waste into biofuel while making char. Farm waste (or a crop designed for biofuel use) is shredded — pyrolysed, in the jargon — and this process gives off volatile organic molecules, which can be used as a basis for biodiesel or turned into hydrogen with the help of steam. After the pyrolysis, half of the starting material will be used up and half will be char. That can then be put back on the fields, where it will sequester carbon and help get will be used up.

### Negative thinking

The remarkable thing about this process is that, even after the fuel has been burned, more carbon dioxide is removed from the atmosphere than is put back. Traditional biofuels claim to be carbon neutral because the carbon dioxide assimilated by the growing biomass makes up for the carbon dioxide given off by the burning of the fuel. But as Lehmann points out, systems such as Day's go one step further: "They are the only way to make a fuel that is actually carbon negative."



Slow burn: the idea of using charcoal to sequester carbon may take awhile to catch on.

Day's pilot plant processes 10 to 25 kg of Georgia pecan hulls and pine pellets every hour. From 100 kg of biomass, the group gets 40 kg of carbon — half as char — and around 5 kg of hydrogen enough to go 500 kilometers in a hydrogen-fuel cell car (not that there are many around yet). Originally, Day was mostly interested in making biofuel; the char was just something he threw out, or used to make carbon filters. Then he discovered that his employees were reaping the culinary benefits of the enormous turkeys that had sprung up on the piles of char lying around at the plant. Combining this char with ammonium bicarbonate, made using steam-recovered hydrogen, creates a soil additive that is now one of his process's selling points: the ammonium bicarbonate is a nitrogen-based fertilizer.

"We don't maximize for hydrogen, we don't maximize for biofuel, we don't maximize for char," says Day. "By being a little bit inefficient with each, we approximate nature and get a completely efficient cycle." Robert Storer, an engineer at Iowa State University in Ames, has a \$1.8-million grant from the United States Department of Agriculture (USDA) to finance similar technology, although being in Iowa, he uses corn stalks not pecan hulls.

"We are trying an integrated approach, we are trying to evaluate the agronomic value, the sequestration value, the economic value, the engineering," he says.

Brown thinks a 200-hectare farm on a char-and-ammonium-bicarbonate system can sequester 1,900 tonnes of carbon a year. A crude calcu-



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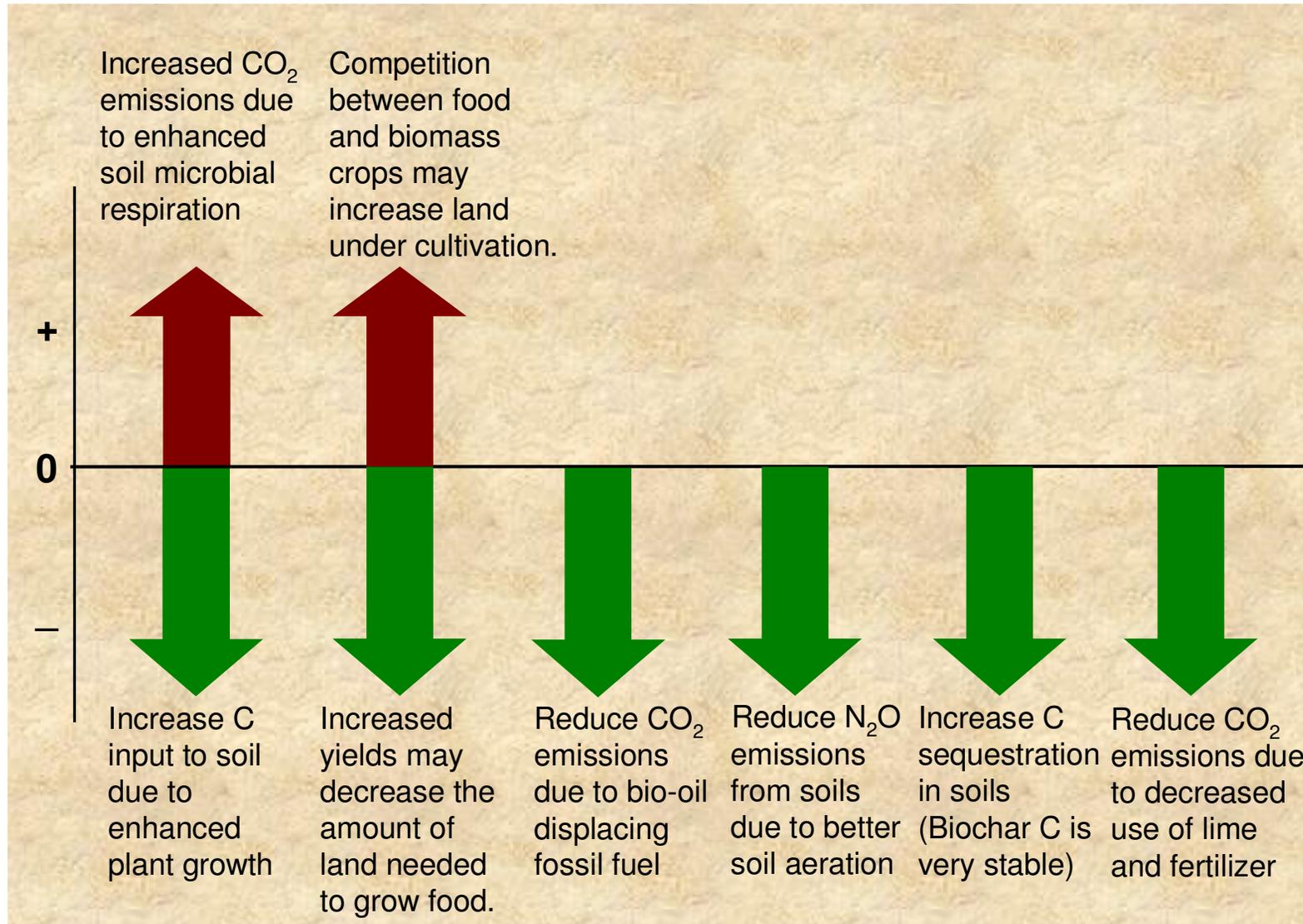
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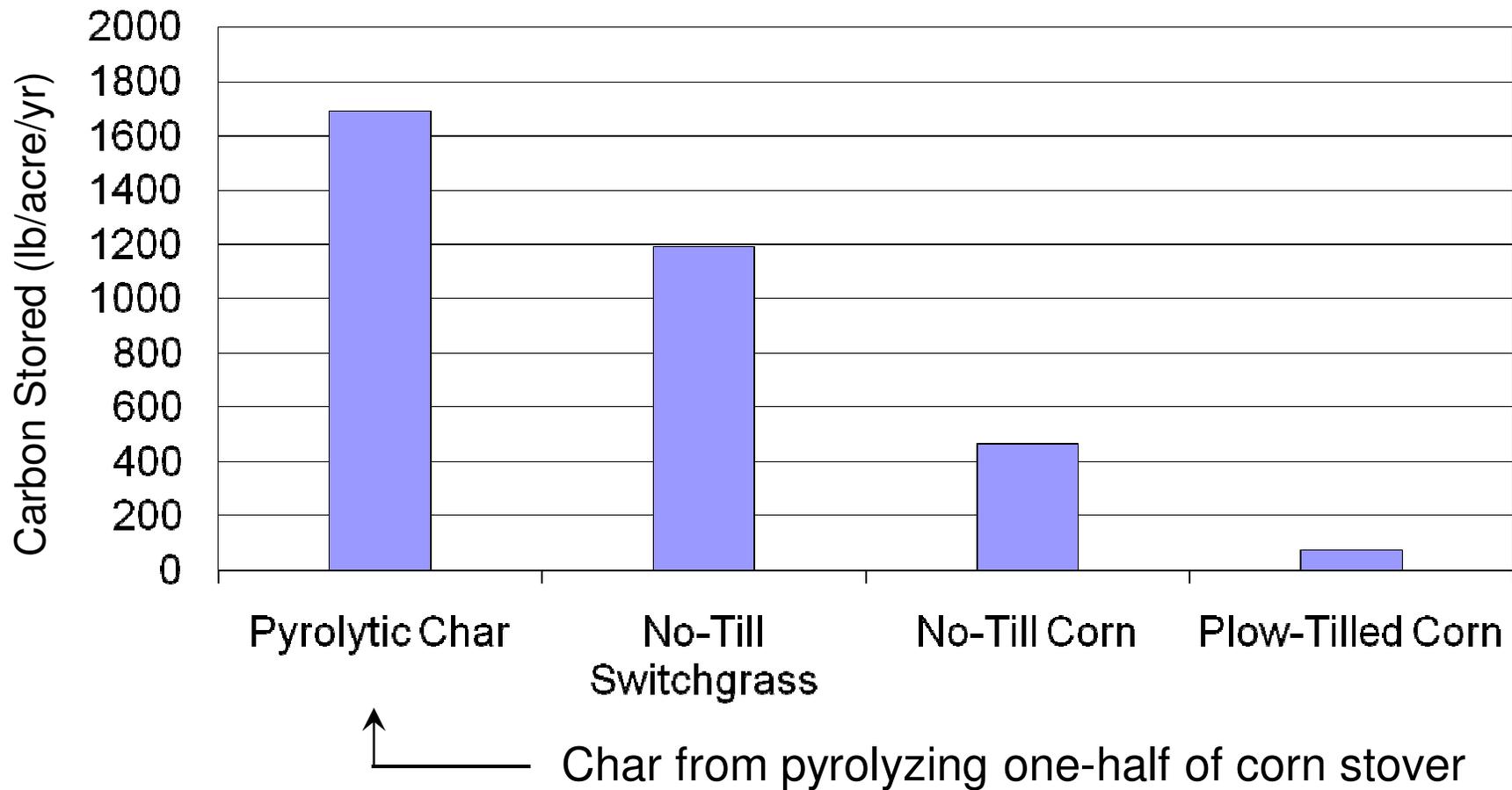
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# GHG Impacts of Soil Application of Biochar



# Greenhouse gases reduced by carbon storage in agricultural soils



# Lovelock on Biochar

“There is one way we could save ourselves and that is through the massive burial of charcoal. It would mean farmers turning all their agricultural waste...into non-biodegradable charcoal, and burying it in the soil.”



James Lovelock in an otherwise pessimistic interview with New Scientist Magazine (January 2009) on our prospects for halting global climate change

# Proof-of-Concept: Terra Preta in Brazil

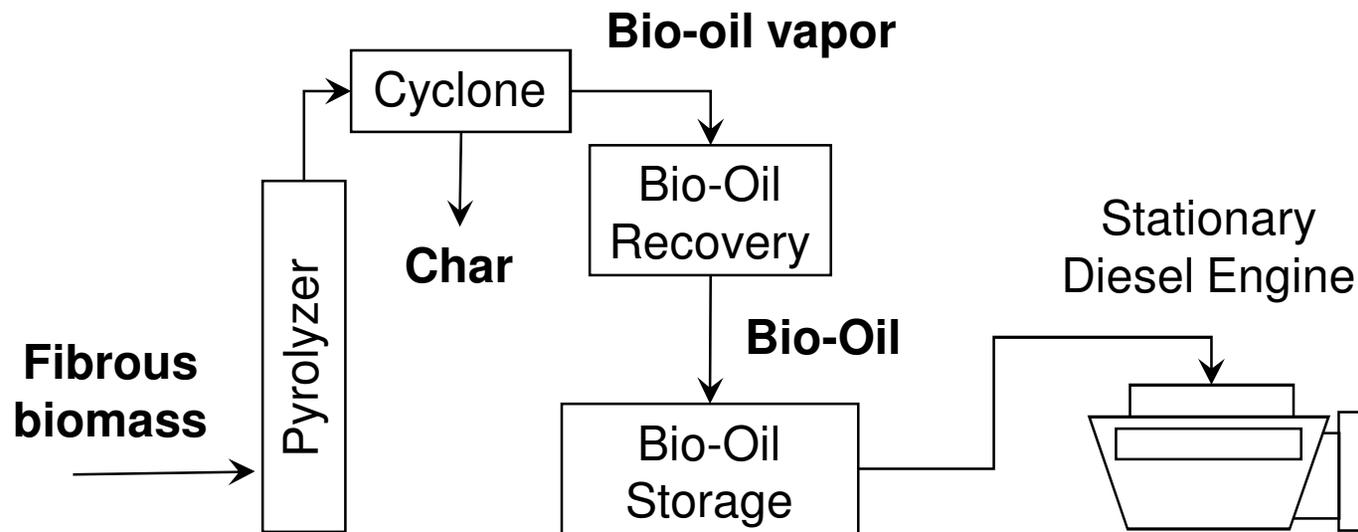


# Applications of Bio-Oil

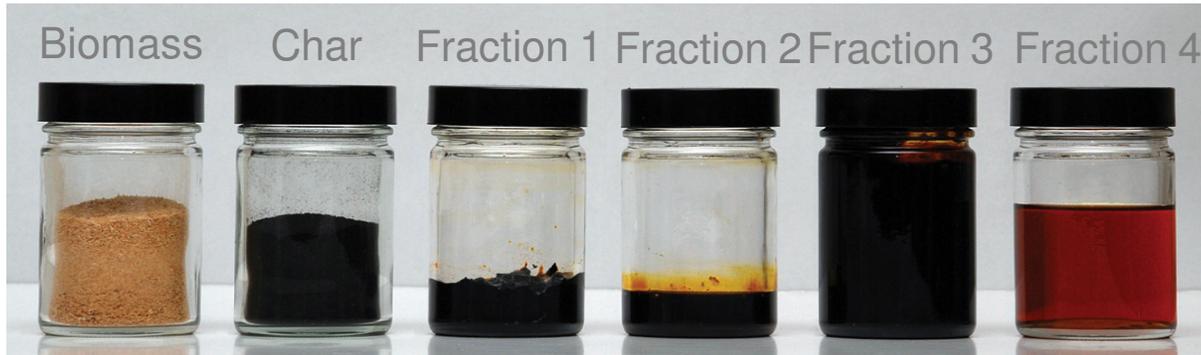
- Stationary Power
- Commodity Chemicals
- Transportation Fuels (requires upgrading)
  - Gasification
  - Hydrocracking
  - Fermentation

# Stationary Power

- Substitutes directly for natural gas, heavy fuel oil, or coal
  - Boilers
  - Diesel engines
  - Gas turbines



# Commodity Chemicals

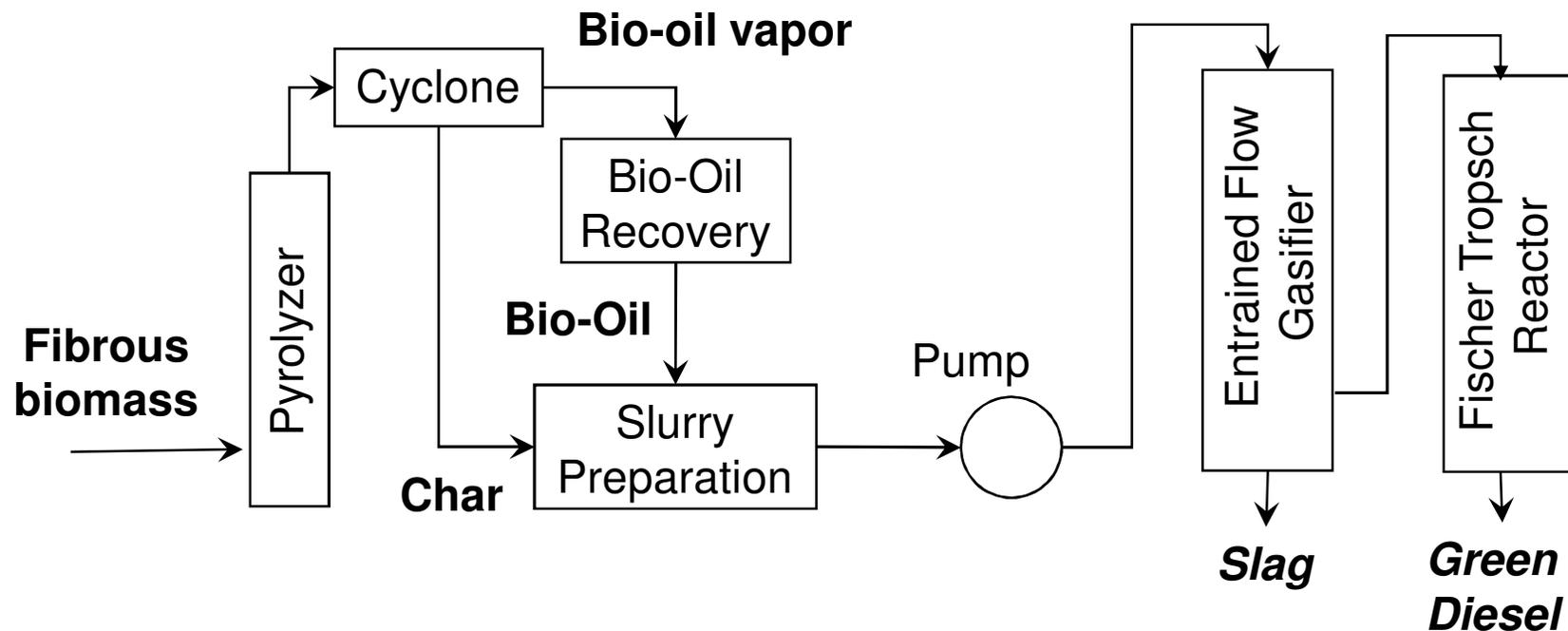


- Bio-oil contains many commercially valuable chemicals (carboxylic acids, phenols, aldehydes, carbohydrates, furans, lignin oligomers)
- Barrier is economical recovery
- Currently only two commercial products
  - Liquid smoke
  - Browning agents



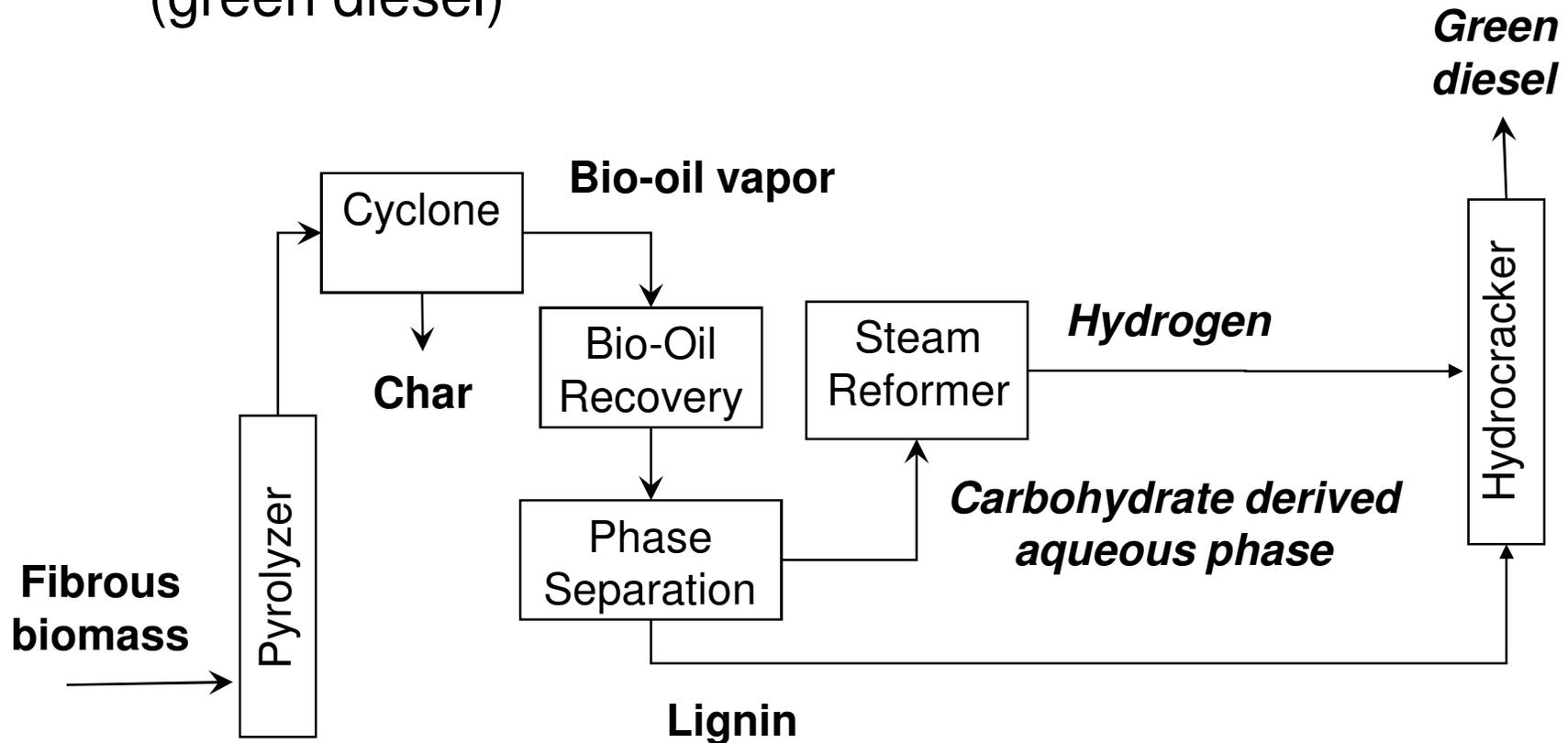
# Bio-Oil Gasification

- Bio-oil and char slurried together to recover 90% of the original biomass energy
- Slurry transported to central processing site where it is gasified in an entrained flow gasifier to syngas
- Syngas is catalytic processed into green diesel (F-T liquids)

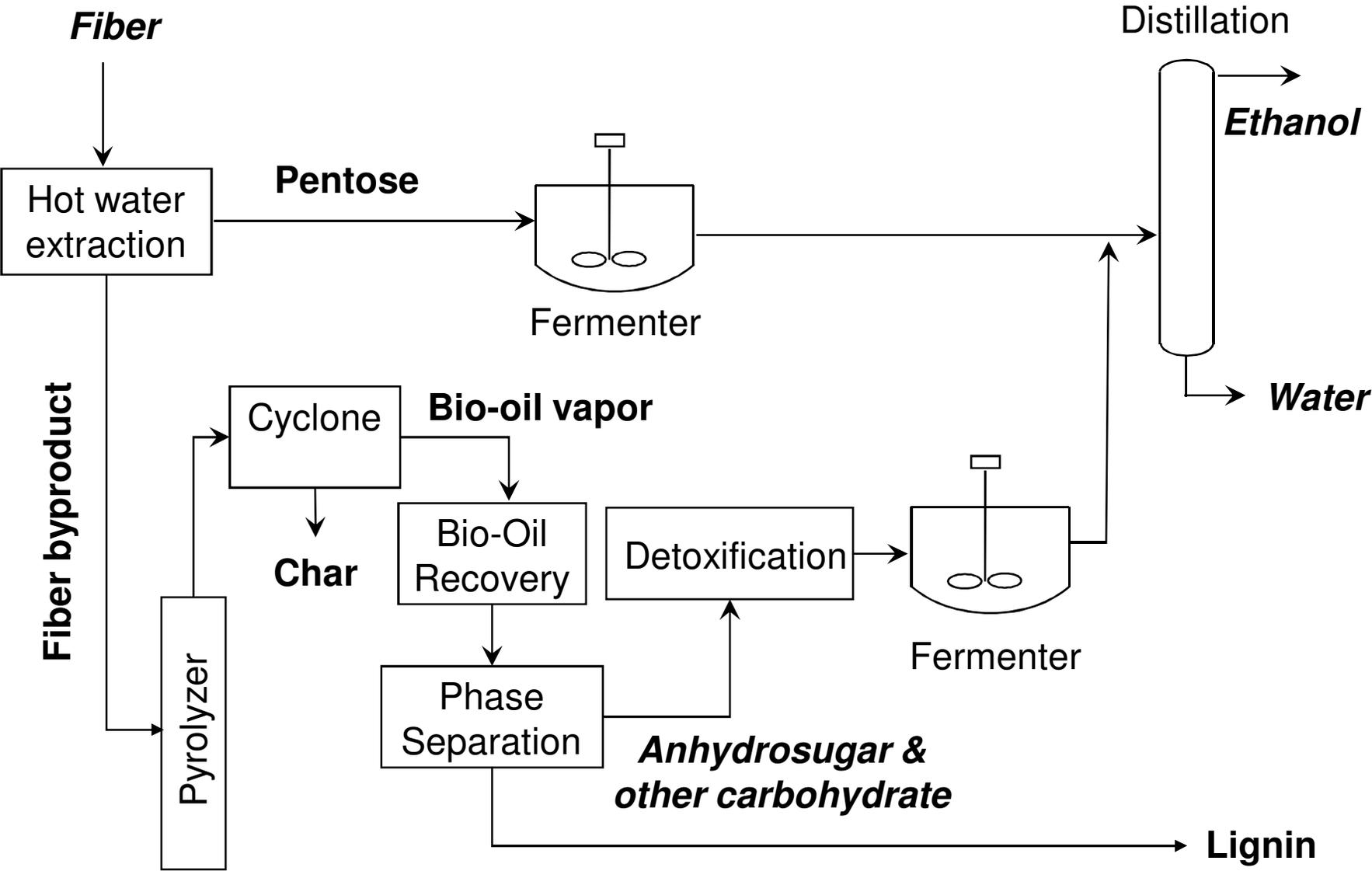


# Bio-Oil Hydrocracking

- Directly converts biomass into liquid bio-oil (lignin, carbohydrate derivatives, and water) and char
- Bio-oil catalytically converted into hydrocarbon fuel (green diesel)



# Bio-Oil Fermentation



Questions?

Does slow pyrolysis only  
generate charcoal?

Why does fast pyrolysis  
generate more bio-oil than  
does fast pyrolysis?

How is bio-oil different from  
crude oil?

What do all fast pyrolysis reactors have in common in terms of their operating conditions?