Uses of biomass chars – carbon, nutrient and contaminant perspective

Ondřej Mašek
University of Edinburgh, UKBRC

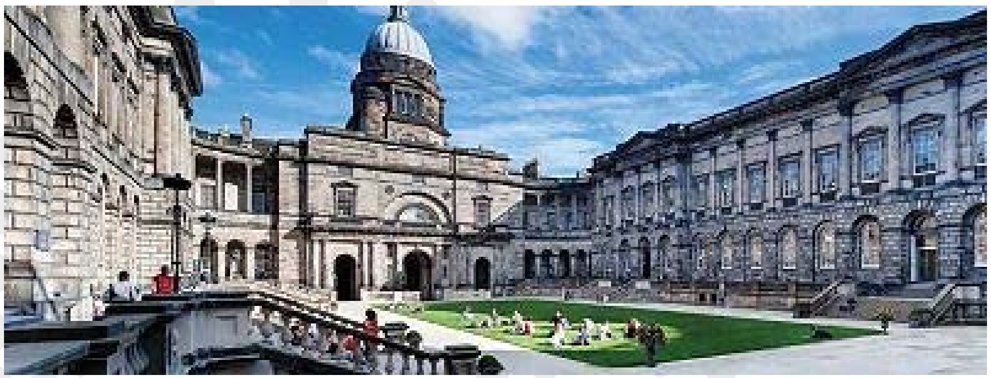
Bolzano/Bozen, 2nd– 3rd December 2016

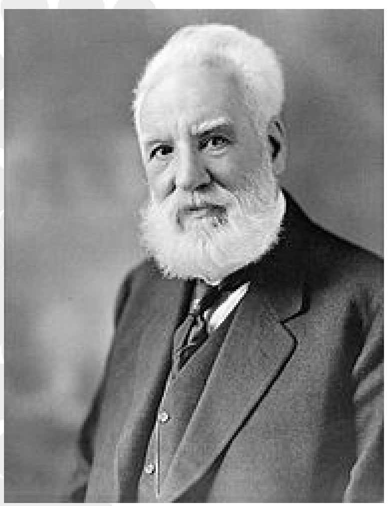
UK Biochar Research Centre

Edinburgh

University of Edinburgh (1583)

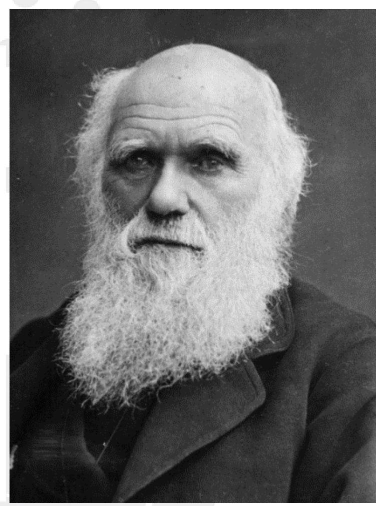
- 33000 students (over 11000 postgraduate)
- Over 6000 academic staff



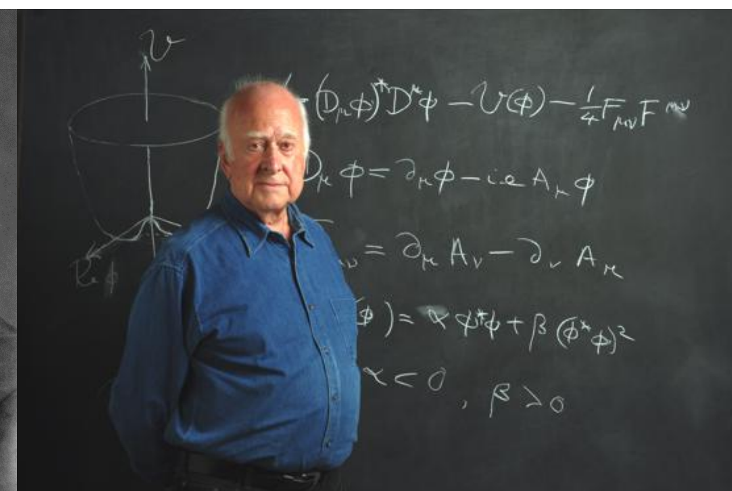


Alexander Graham Bell

James Clark Maxwell



Charles Darwin



Prof. Peter Higgs (2013 Nobel Prize in Physics)

UK Biochar Research Centre (UKBRC)

Multi-disciplinary centre at the University of Edinburgh, based at the School of Geosciences, with activities spanning the Schools of Biology, Chemistry and Engineering. Established in 2009 to complement research on CO_2 capture and sequestration.

Focussed on integration of biochar in bioenergy, agricultural and bio-economy systems.

Key areas of activity:

- Pyrolysis
- Material characterisation
- Soil science
- Environment
- Bioenergy/ bio-refinery
- Biochar matching

Pyrolysis and biochar production research at UKBRC

UKBRC

Scale

STAGE III

Pilot-scale continuous pyrolysis unit with capacity of up to **50 kg/h** of biomass, mean residence time 5-60 min., and temperature range up to 850 °.

STAGE II

Continuous pyrolysis unit with capacity of up to **2 kg/h** of biomass, mean residence time 5-60 min., and temperature range up to 850 °.

STAGE I

Bench-scale batch pyrolysis with capacity of up to **100g**, operating temperature range up to 1100 °C and heating rate from <1°C/min to >100 °C/s.

TGA/ DSC

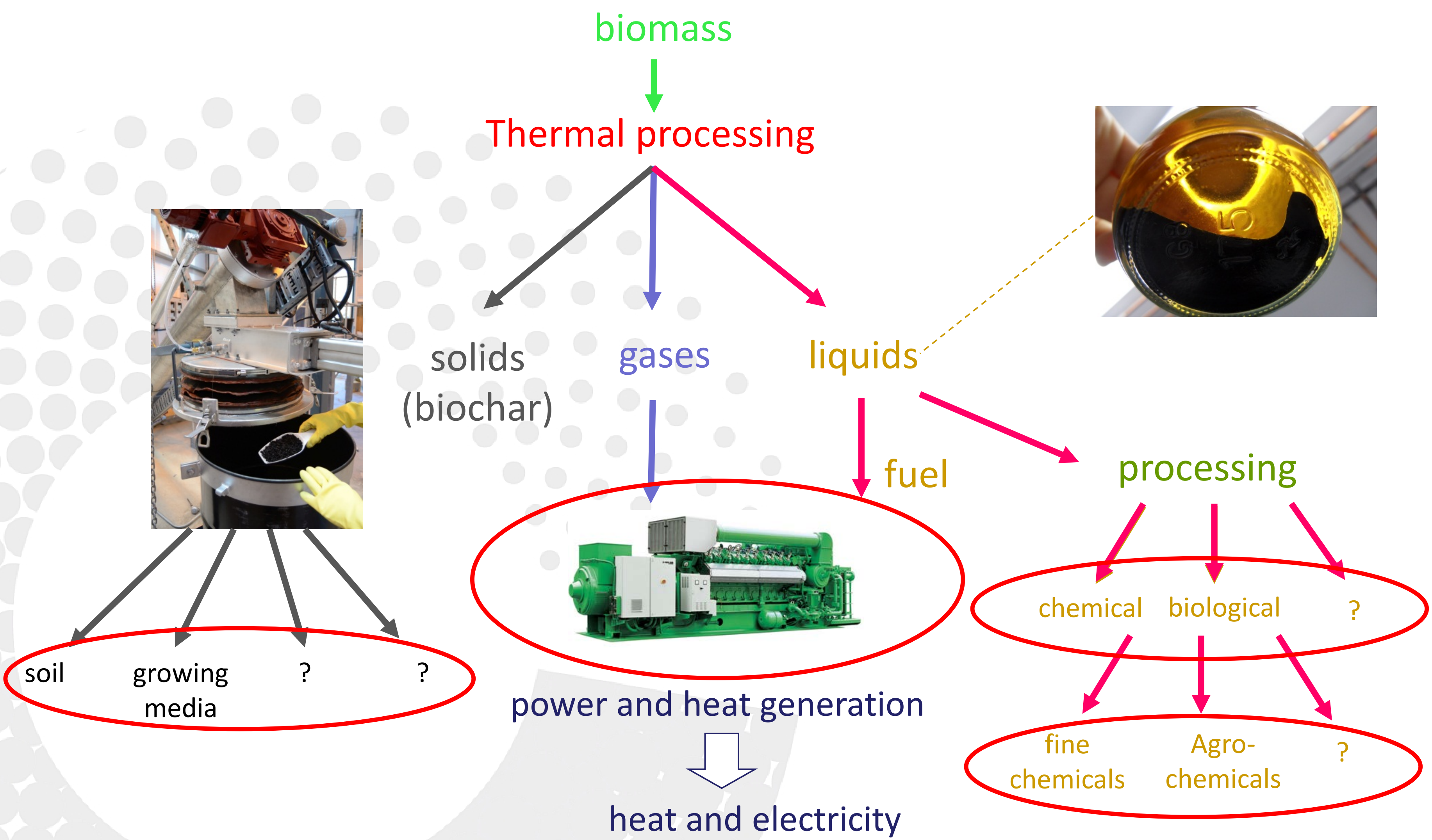
Automated TGA/DSC instrument for biomass pyrolysis and biochar characterisation, capacity up to **5g**.

What is biochar?

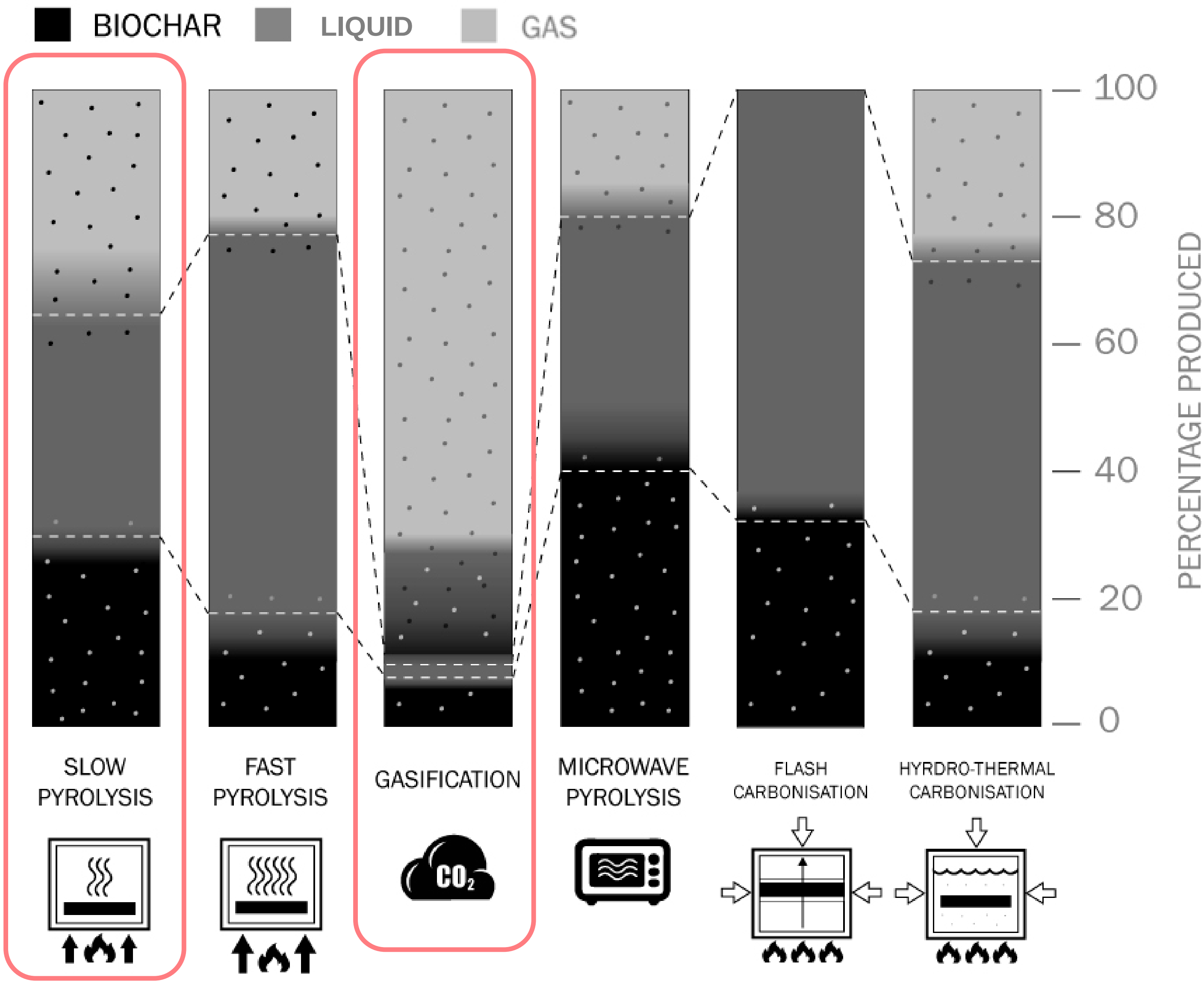
Char made from biomass, ultimately destined for application to soil

may include and outwardly resemble charcoal but can be quite different (functionally) in soil

Thermochemical conversion for carbon bioenergy, carbon sequestration and added-value products

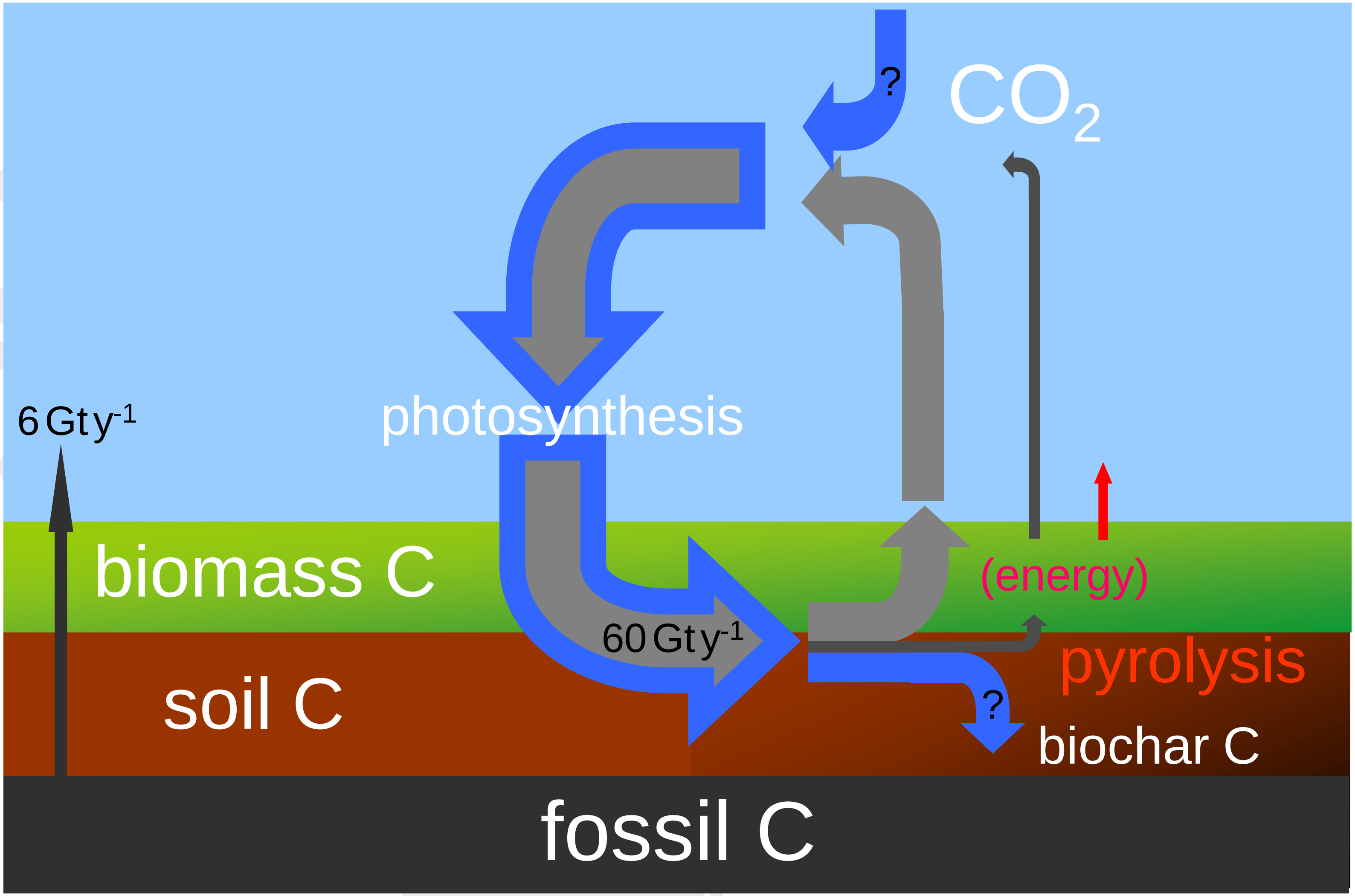


Types of thermochemical conversion



Source: Chapter 2 in Biochar in European Soils and Agriculture, Science and Practice, Routledge (2016)

The pyrolysis-biochar system (PBS)



Source: Saran Sohi, UKBRC

Biochar in bio-energy/ bio-refinery systems

UKBRC

Key contribution of biochar: improved carbon balance and sustainability

Key areas of relevance

Carbon footprint

- From close to carbon-neutral to carbon-negative (across scales, unlike BECCS)

Feedstock supply

- Increased yields
- Reduced input requirements
- Improved environmental performance

Resource use efficiency

- Suitable for poly-generation
- Utilisation of diverse organic residues from different conversion processes

Nutrient cycling

- Return of nutrients removed with harvested biomass
- Improved release dynamics

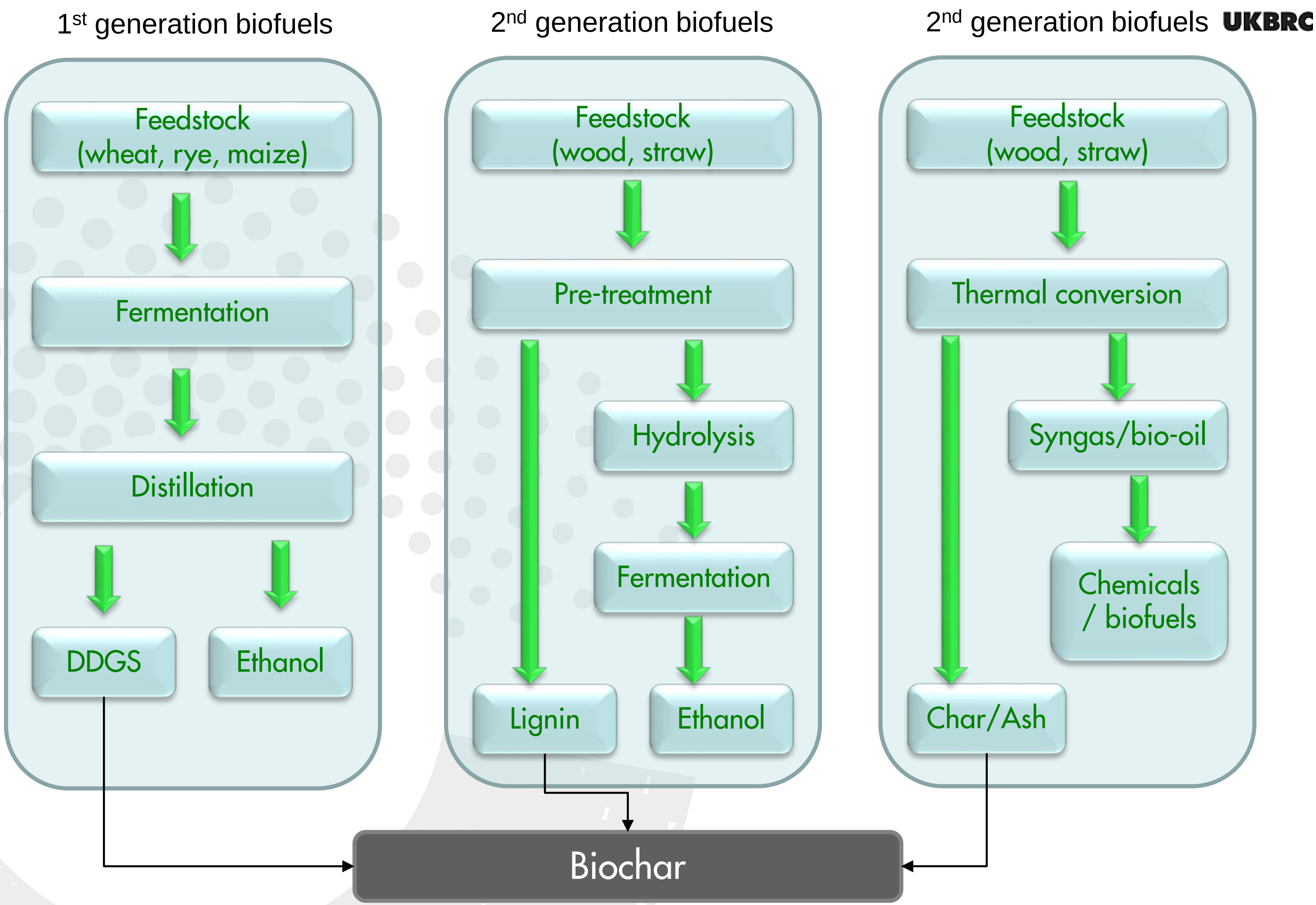
GHG balance

- Reduction of soil GHG emissions
- Reduction of GHG's associated with inputs for biomass production (fertiliser, …)

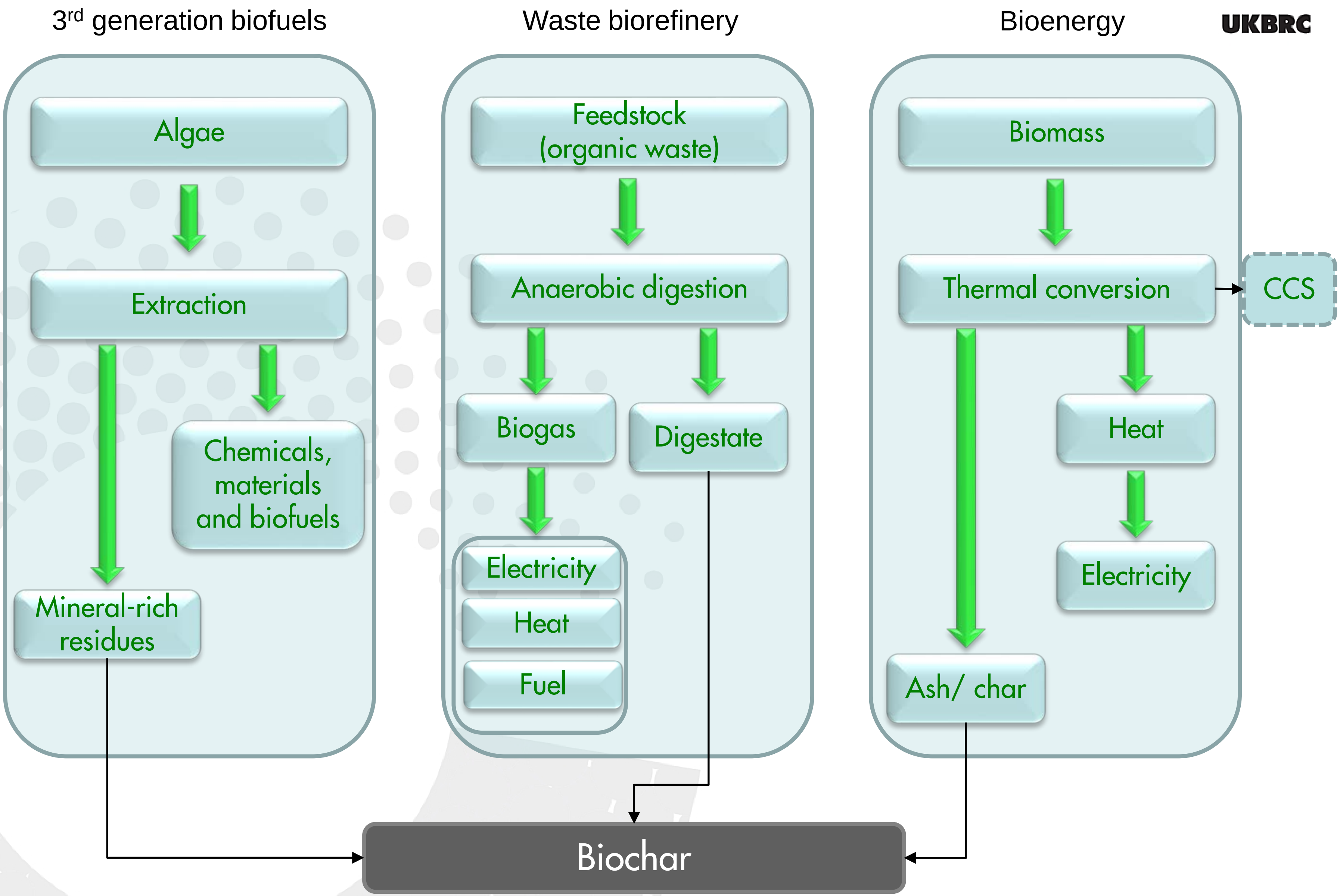
Technical applications

- Catalyst/ catalyst support
- Gas cleaning
- Effluent management

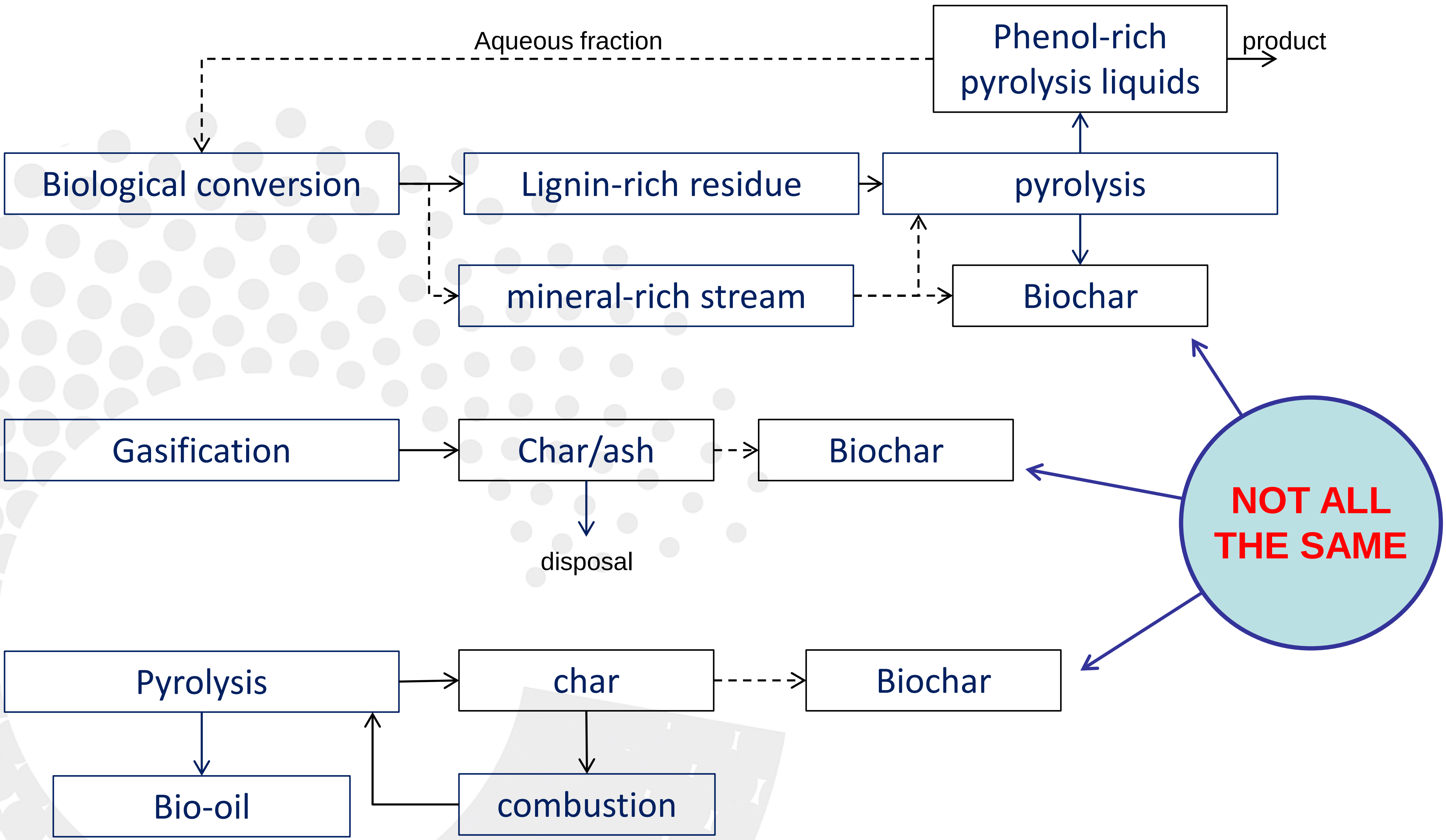
Biorefinery and bioenergy concepts



Biorefinery and bioenergy concepts

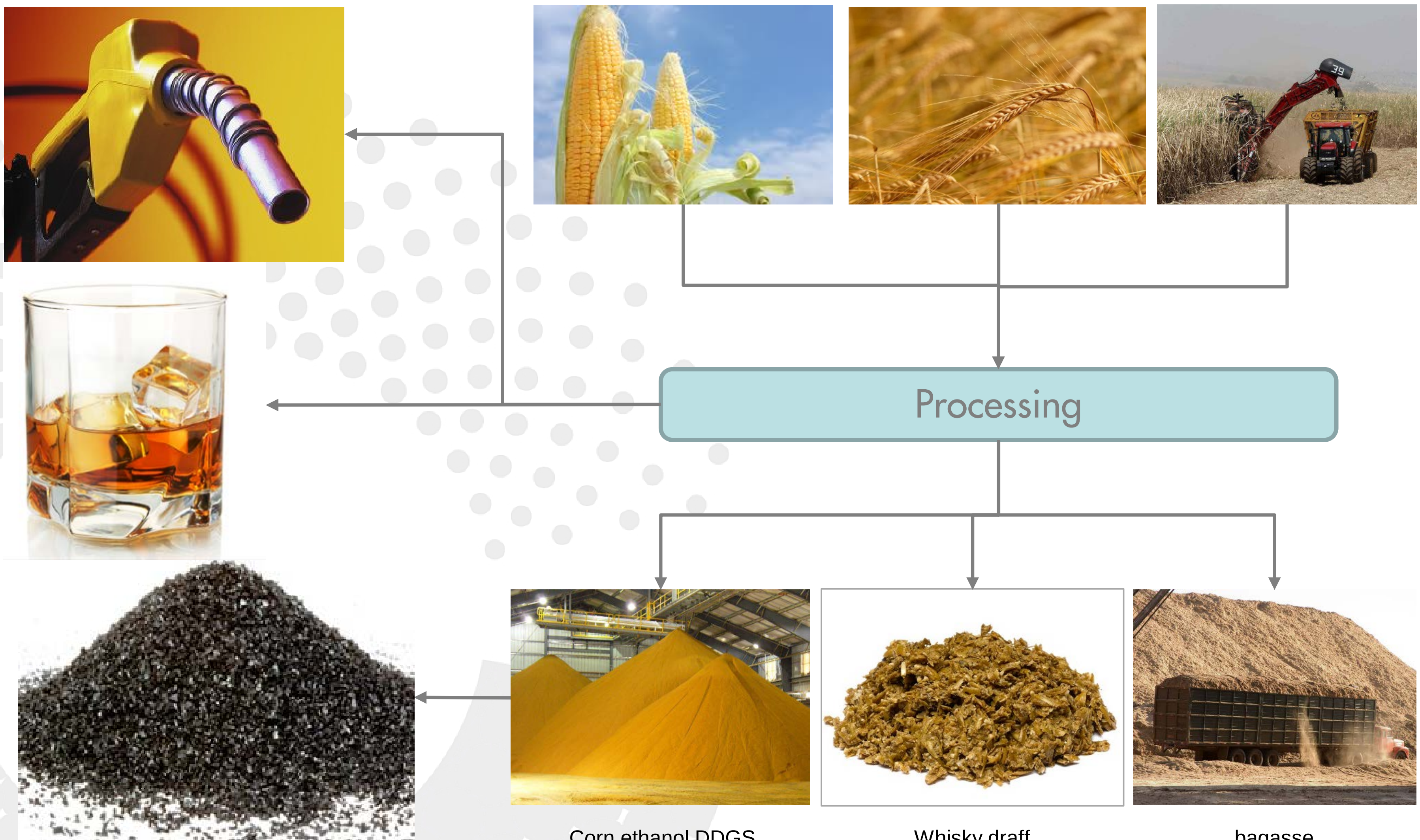


Biochar as a bio-refinery co-product



1st generation biorefinery

- Ethanol production from food crops yields large amount of solid residues



Corn ethanol DDGS

Whisky draff

bagasse

2nd generation biorefinery

- Non-food feedstock can be converted to ethanol or other liquid biofuels, leaving behind lignin-rich and mineral-rich residues that can be utilised in biochar production.

Processing

Lignin

Mineral rich residue

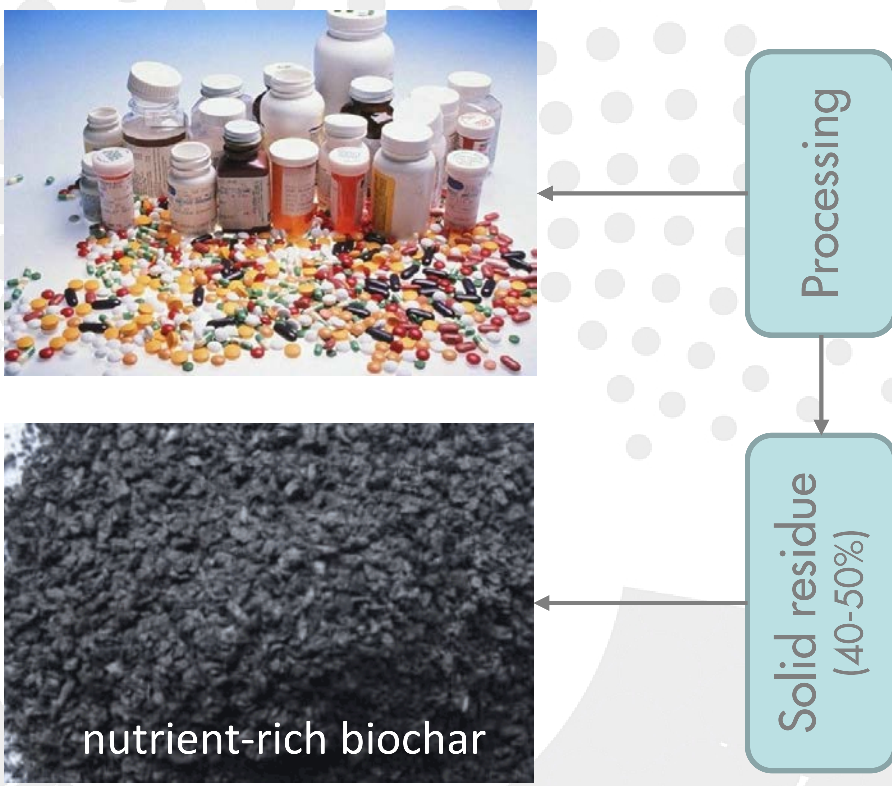
What is lignin?

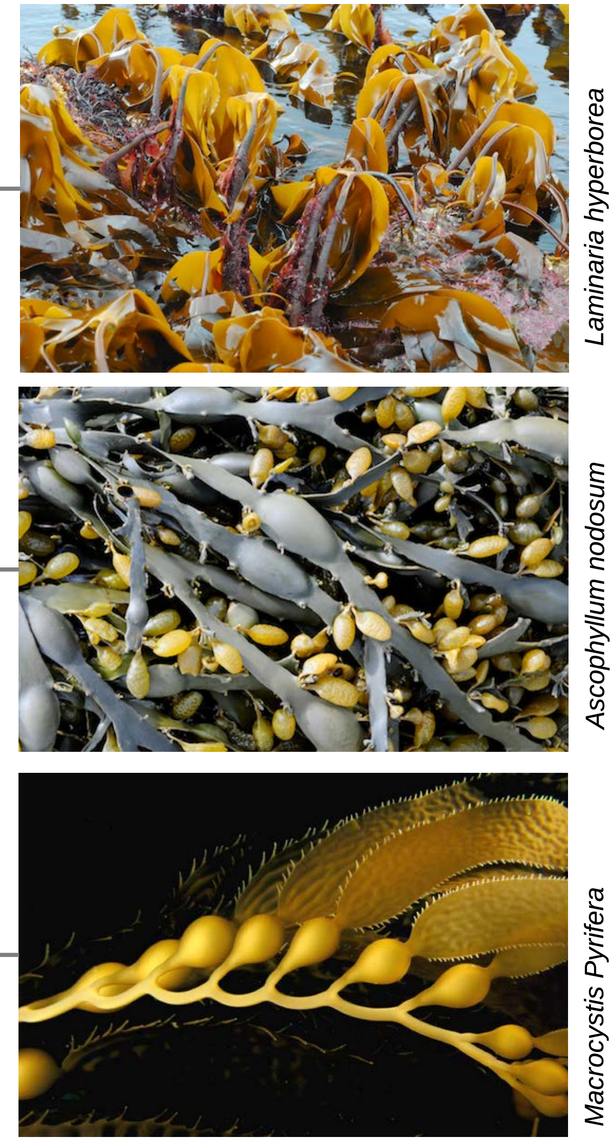
Is it a waste or high value feedstock?

Marine biomass (macro algae) biorefinery

UKBRC

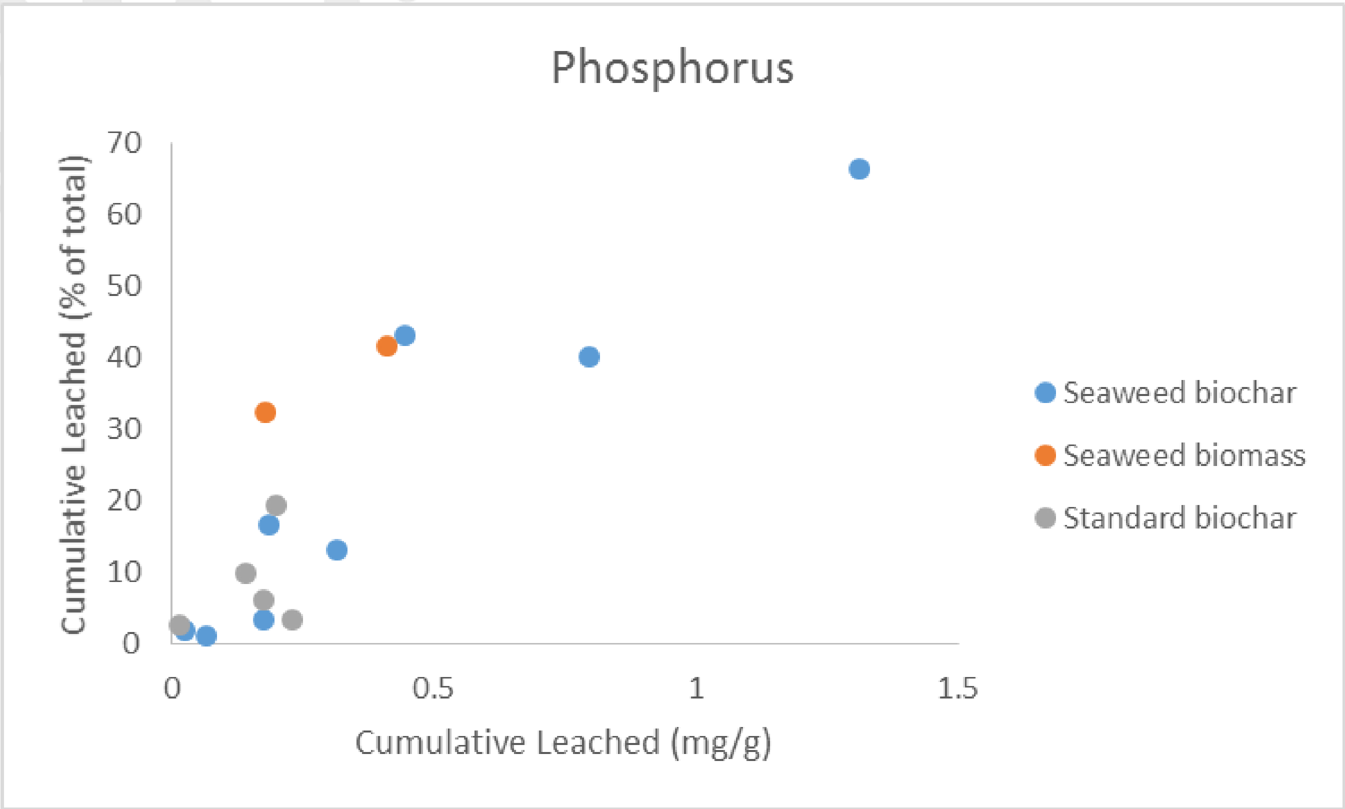
- Macroalgae are a rich source of valuable chemicals and materials, among other alginate
- Mineral rich residues after extraction of compounds of interest
- Very suitable feedstock for production of porous carbons





Release of phosphorus from marine biomass biochar vs. terrestrial biomass

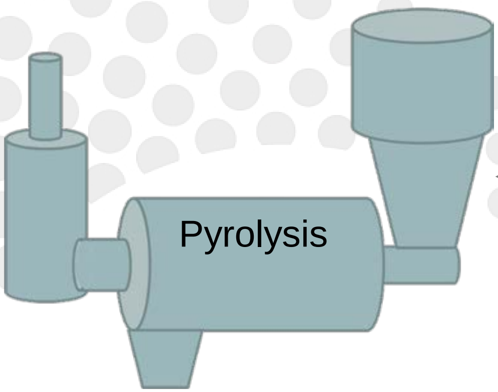
- Pyrolysis increases the availability of phosphorus in marine biomass residues
- The dynamics of release is controlled by the degree of pyrolysis (charring)
- The amount of available phosphorus is comparable to or even higher than that in straw biochar, and much higher than in woody biochar



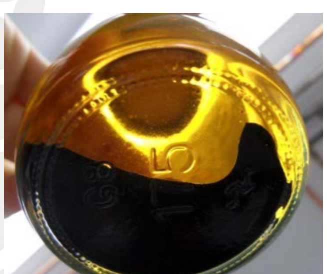
Waste biorefinery

UKBRC

- Organic residues, especially those with high moisture content can be converted to Biogas in anaerobic digestion (AD) systems
- Solid residue (digestate) is a suitable feedstock for thermal conversion, e.g. pyrolysis or HTC, yielding stable, nutrient-rich solid product
- AD offers potential for two-way integration with pyrolysis



Solid residue
(digestate)



Biogas

Chemicals (e.g. VFAs)

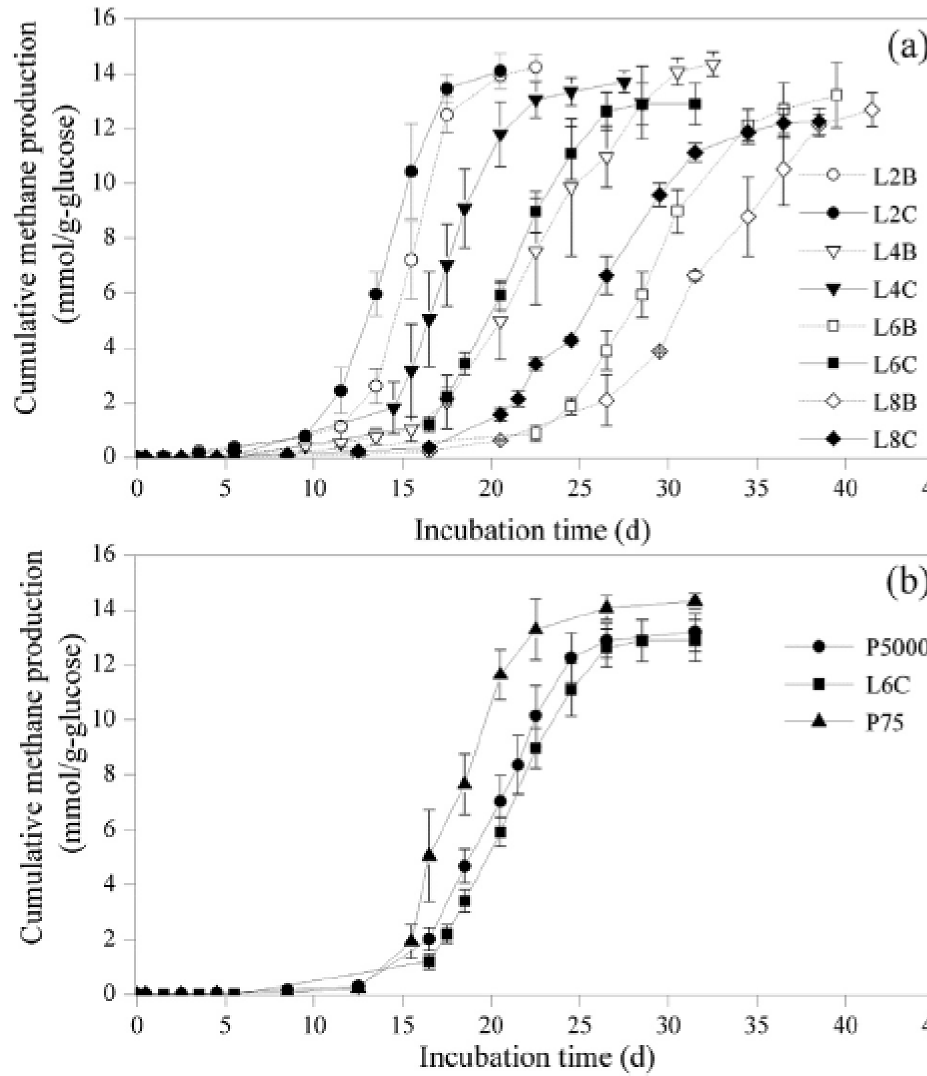
Waste biorefinery
Effect of biochar on AD process

UKBRC

Addition of 0.5-1 mm biochar particles at 10 g/L to mesophilic anaerobic digesters fed with 4, 6 and 8 g/L glucose **shortened the methanogenic lag phase** by 11.4%, 30.3% and 21.6% and **raised the maximum methane production rate** by 86.6%, 21.4% and 5.2%, respectively, compared with the controls without biochar.

Smaller particles performed better.

Addition of biochar affected the composition of microbial communities.



Temporal change in the cumulative methane production per gram glucose. (a) At various glucose concentrations with or without 0.5e1 mm biochar. (b) At glucose concentration of 6 g/L with various particle sizes of biochar.

Source: Luo et al. (Water Resources, 2015)

Waste biorefinery
P recovery by biochar from AD solids

P solution	Ranking		P Sorption (mg P g^{-1})
0.02 g l^{-1}	a	Ochre	1.73 ($\pm 8.93 \times 10^{-3}$)
	b	OCAD550	1.26 ($\pm 4.66 \times 10^{-3}$)
	b	OCAD450	1.24 ($\pm 2.10 \times 10^{-2}$)
	c	AD450	1.06 ($\pm 3.84 \times 10^{-3}$)
	d	AD550	0.986 ($\pm 9.31 \times 10^{-3}$)
	e	Activated carbon	0.884 ($\pm 1.69 \times 10^{-2}$)
	f	Zeolite	0.130 ($\pm 1.05 \times 10^{-2}$)
0.8 g l^{-1}	g	Ochre	14.2 ($\pm$1.77)
	h	Zeolite	11.2 ($\pm$1.46)
	h,i	OCAD550	9.82 ($\pm$2.01)
	h,i	AD450	9.72 ($\pm$0.657)
	i	OCAD450	9.37 ($\pm$0.872)
	i	AD550	9.35 ($\pm$2.21)
	j	Activated carbon	3.47 ($\pm$1.52)
3 g l^{-1}	k	AD450	25.9 ($\pm$5.10)
	k,l	Zeolite	21.5 ($\pm$4.99)
	k.l	OCAD450	20.4 ($\pm$6.35)
	l	Ochre	20.0 ($\pm$5.71)
	l	Activated carbon	15.1 ($\pm$4.35)

Source: Shepherd, J.G., et al. Water Research (2016)

Biochar can effectively remove P from liquid effluents and waste waters and recycle it to soils.

Biochar production

Biochar as the main product

- Slow pyrolysis (biochar yield 20-35 wt.%)

Choice of feedstock and operation conditions can be selected to tune the yield and properties of biochar to suit particular application; also yields other co-products

Most likely to achieve high-grade "engineered" biochar with high-value applications, and predictable function

Biochar as a by-product

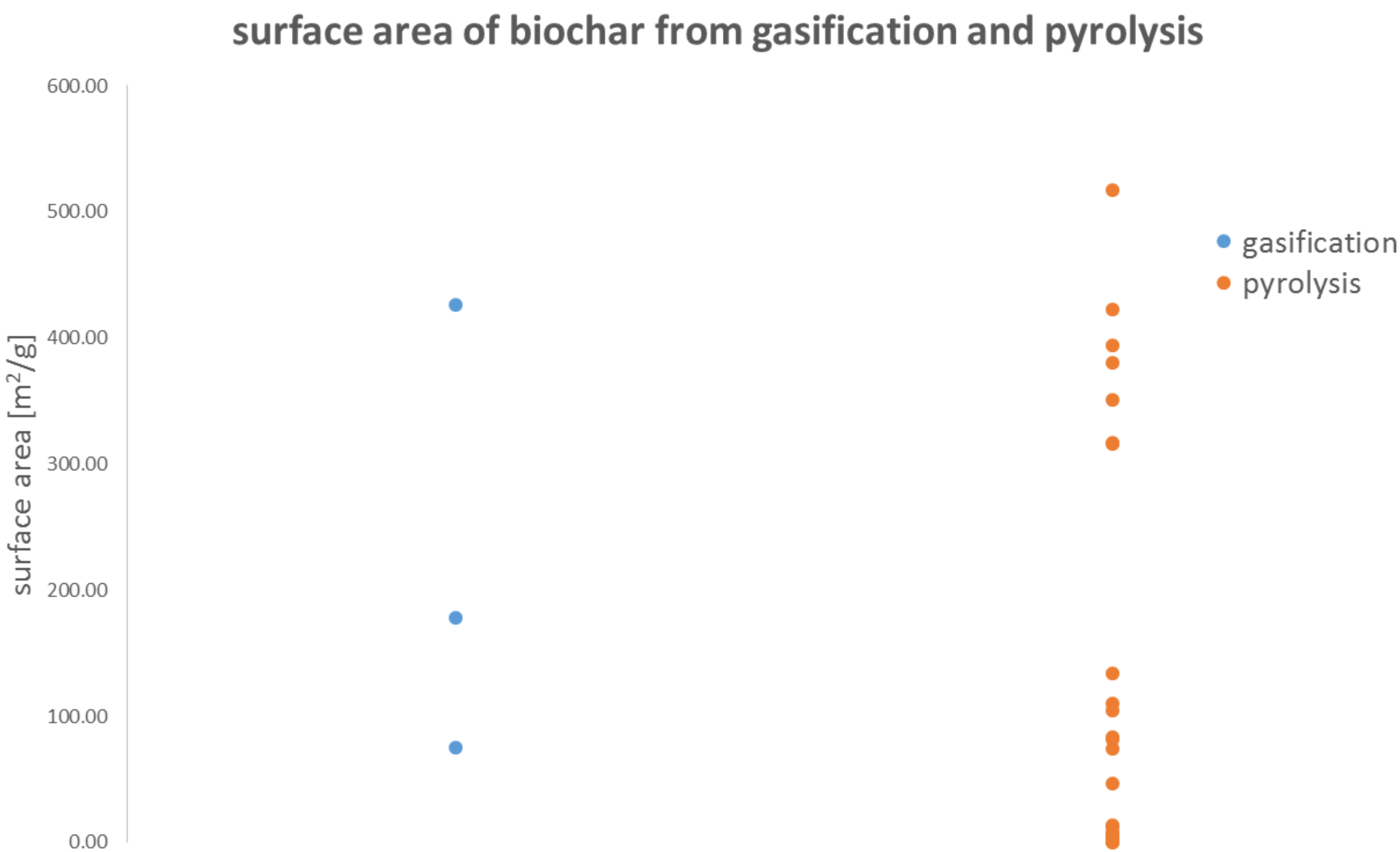
- Fast pyrolysis (biochar yield 10-15 wt.%)
- Gasification (biochar yield <10 wt.%)

Choices of feedstock and operation conditions are dictated by the needs of the main product, i.e. liquids (fast pyrolysis) and gases (gasification)

Mostly use of solid by-products, and therefore the char is unlikely to be engineered for specific application. However, based on understanding of relationships between biochar, soil and crops, its use can be successfully prescribed to achieve safe use and good performance.

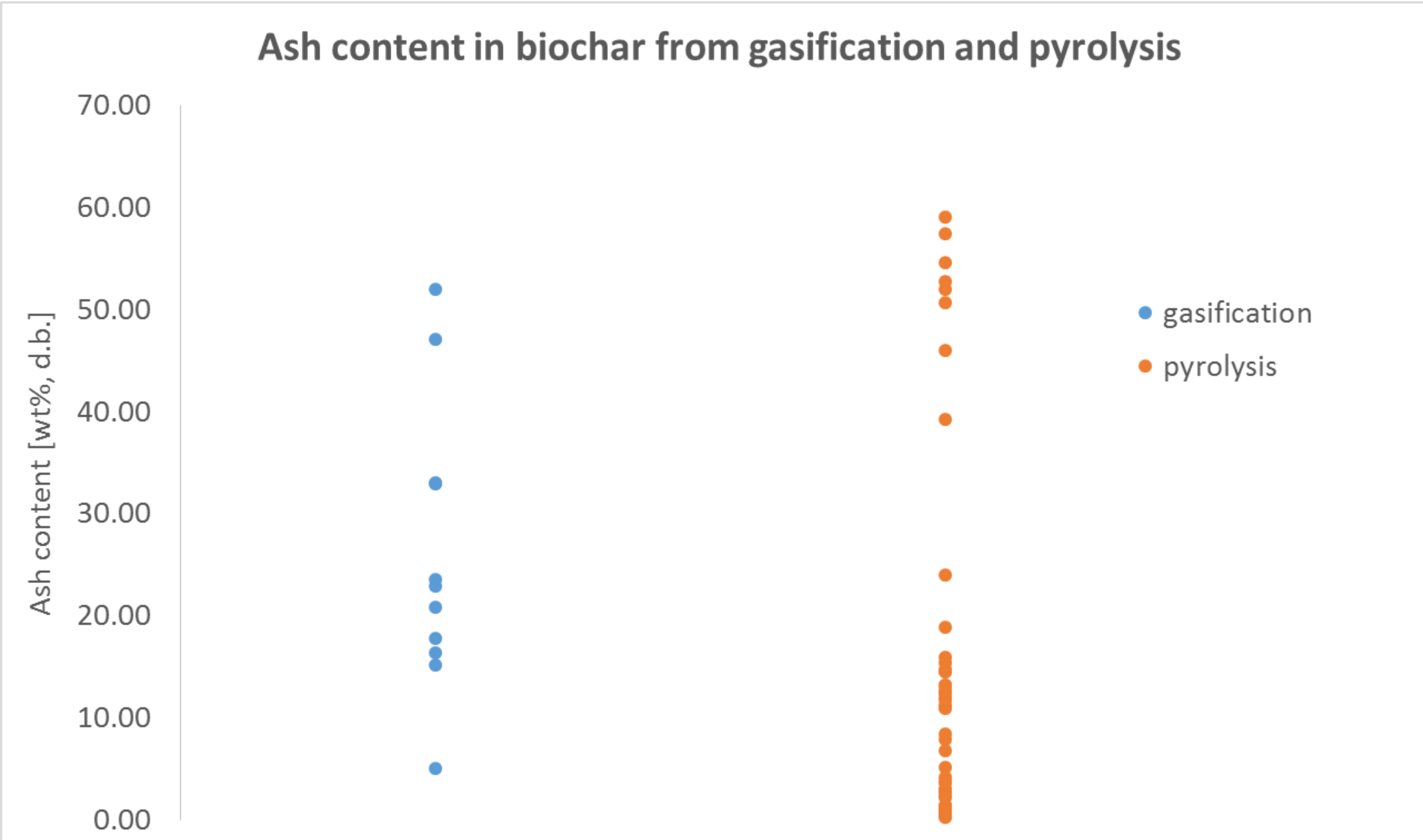
Different sets of opportunities and challenges

Gasification vs pyrolysis biochar physical properties



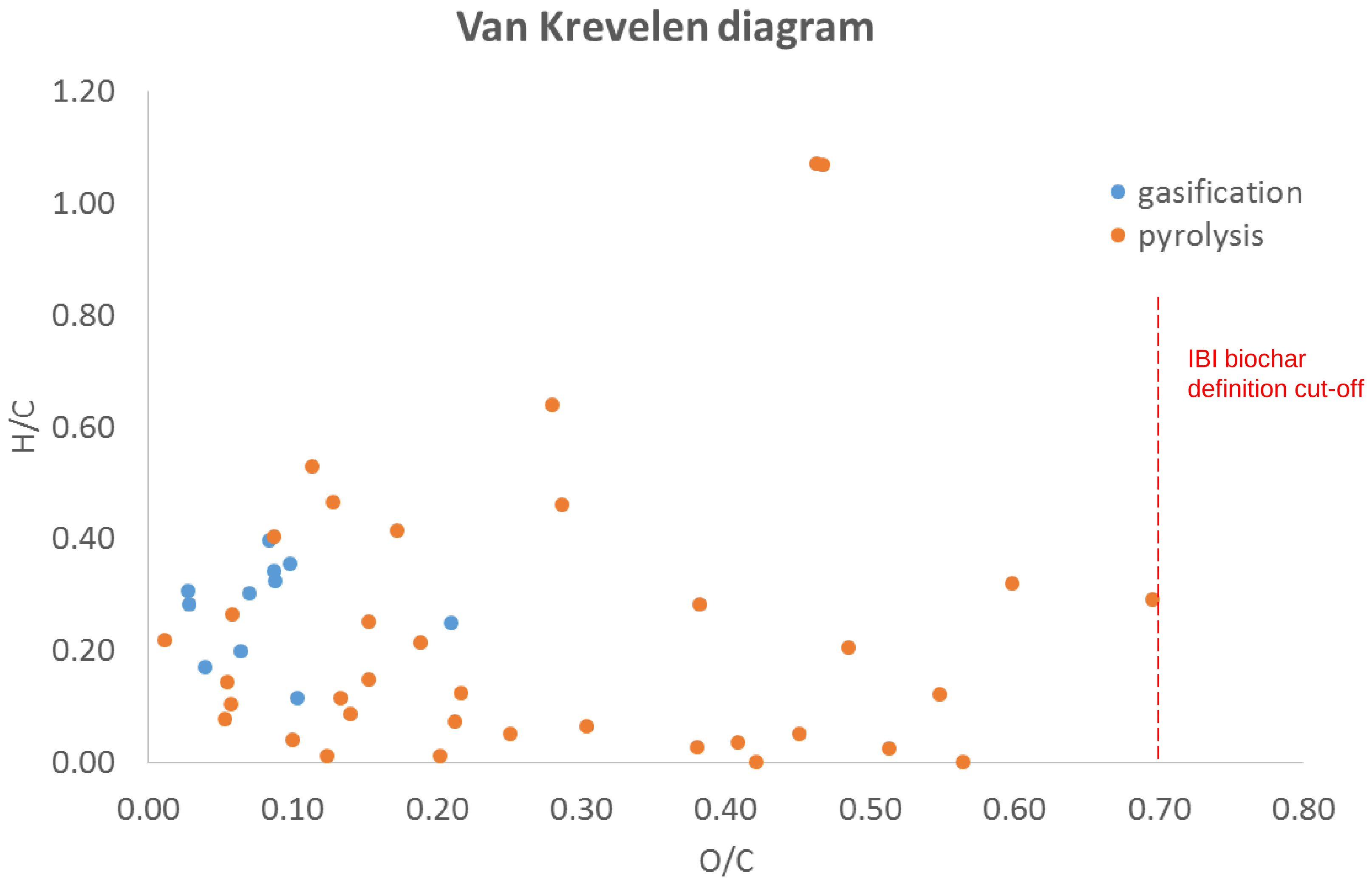
Source: based on data from Mayer et al. (2014), Wiedner et al. (2013), Hansen et al. (2015), and Hale et al. (2012)

Gasification vs pyrolysis biochar chemical properties



Source: based on data from Mayer et al. (2014), Wiedner et al. (2013), Hansen et al. (2015), and Hale et al. (2012)

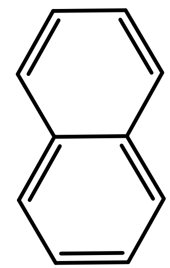
Gasification vs pyrolysis biochar chemical properties



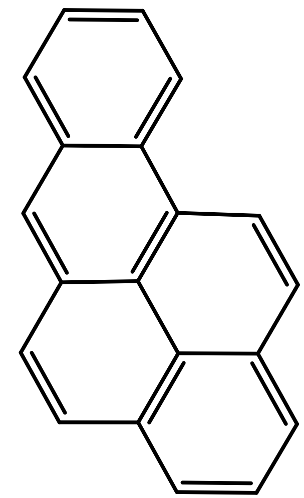
Source: based on data from Mayer et al. (2014), Wiedner et al. (2013), Hansen et al. (2015), and Hale et al. (2012)

Contaminants in biochar

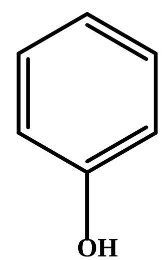
- Potentially toxic elements (PTEs): arsenic, cadmium, cobalt, chromium, copper, mercury, molybdenum, nickel, lead, zinc
  - Indestructible, only transformable
- Polycyclic aromatic hydrocarbons (PAHs)
  - Mobile, little toxic ↔ immobile, strongly toxic
- Volatile organic compounds (VOCs)
  - Mobile → volatile and easily leachable
- Polychlorinated aromatic compounds: not investigated here
  - Biochar production: not favourable conditions for dioxin formation → very low levels found (Granatstein 2009, Hale 2012, Wiedner 2013)



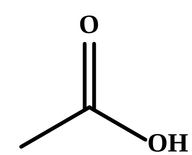
Naphthalene



Benzo(a)pyrene



Phenol

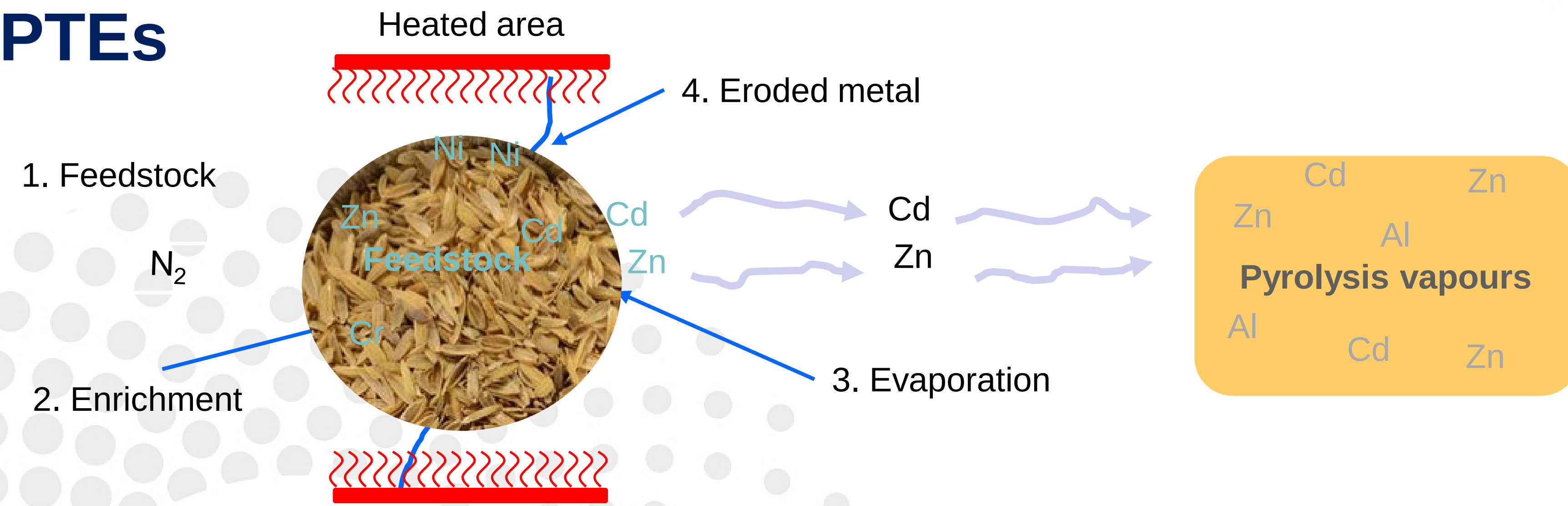


Acetic acid

Source: Wolfram Buss

Contaminants in biochar production

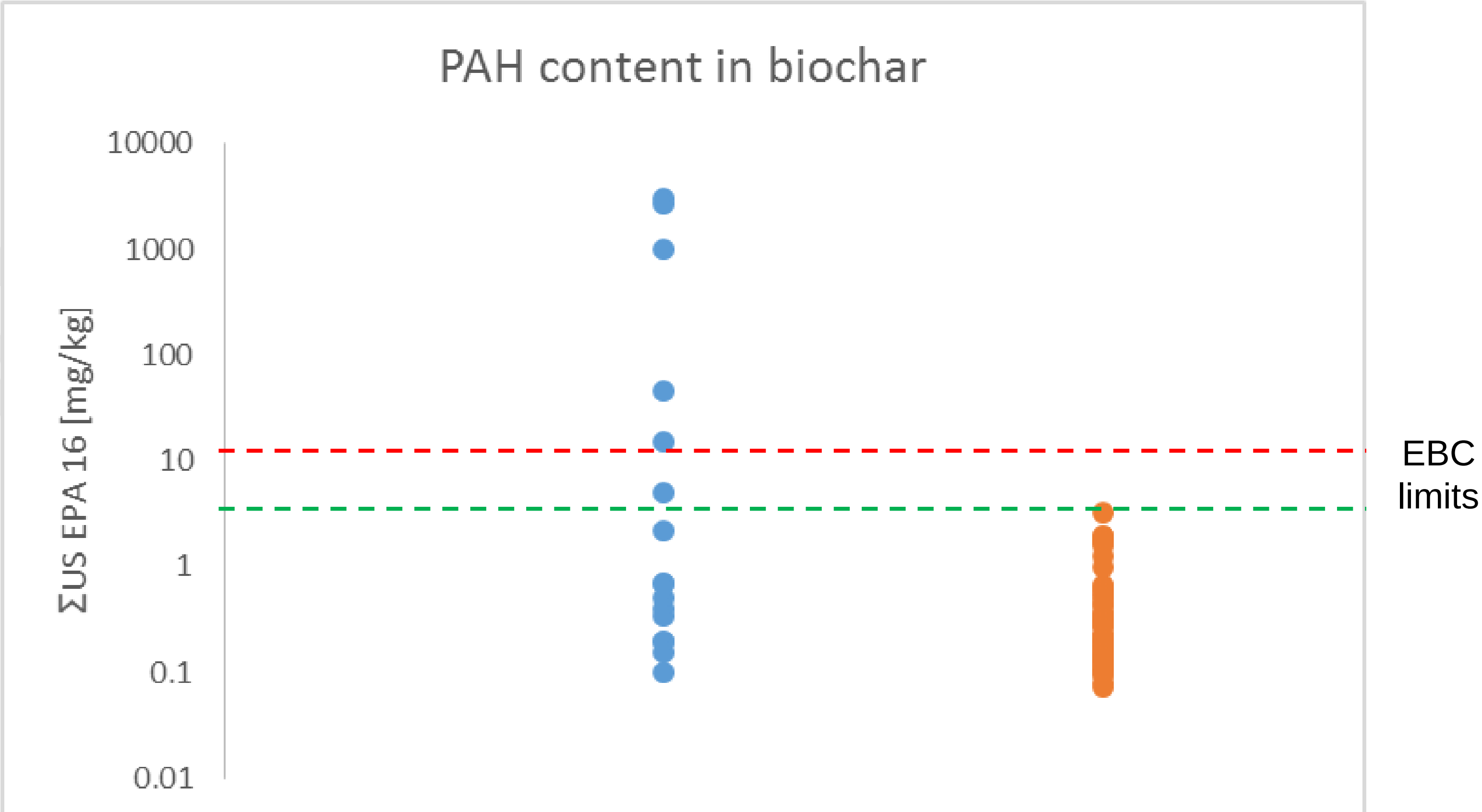
PTEs



Organics

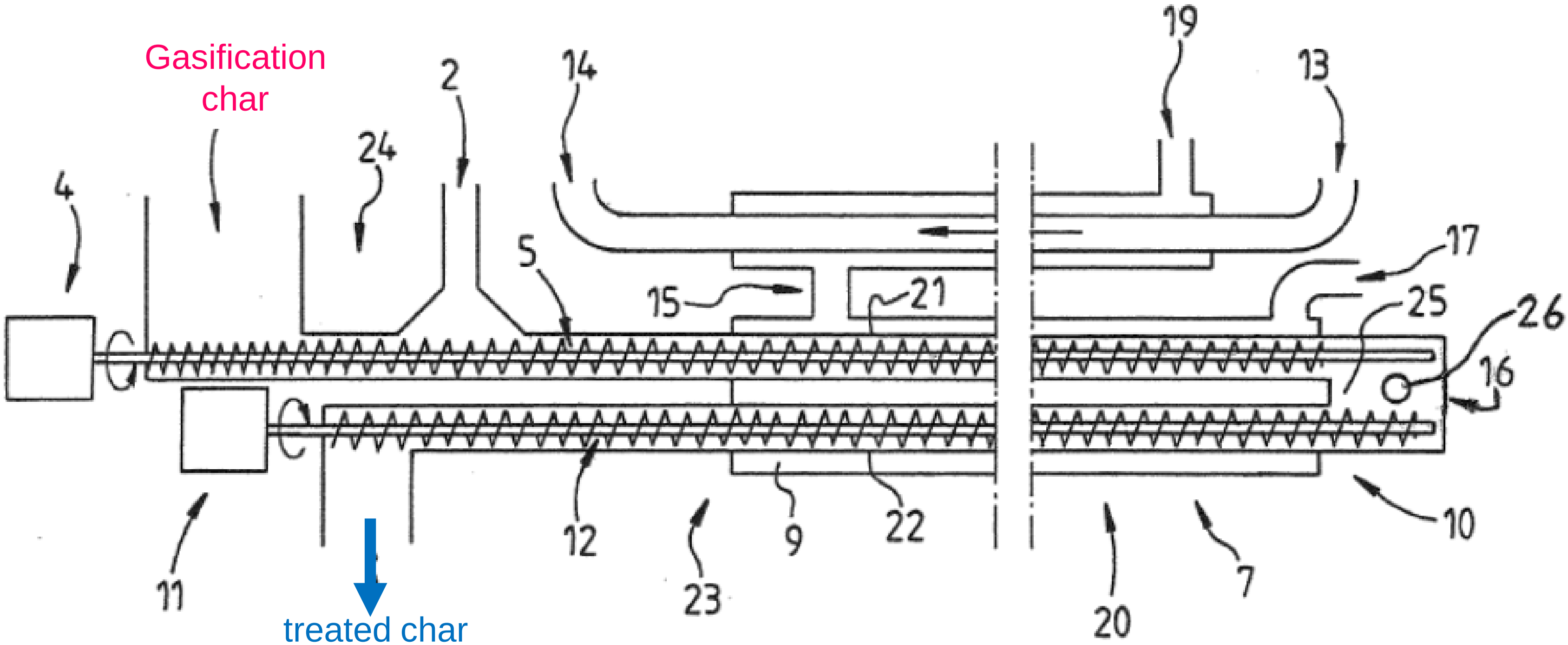
Source: Wolfram Buss

Gasification vs pyrolysis biochar chemical properties – organic contaminants



Source: based on data from Mayer et al. (2014), Wiedner et al. (2013), Hansen et al. (2015), and Hale et al. (2012)

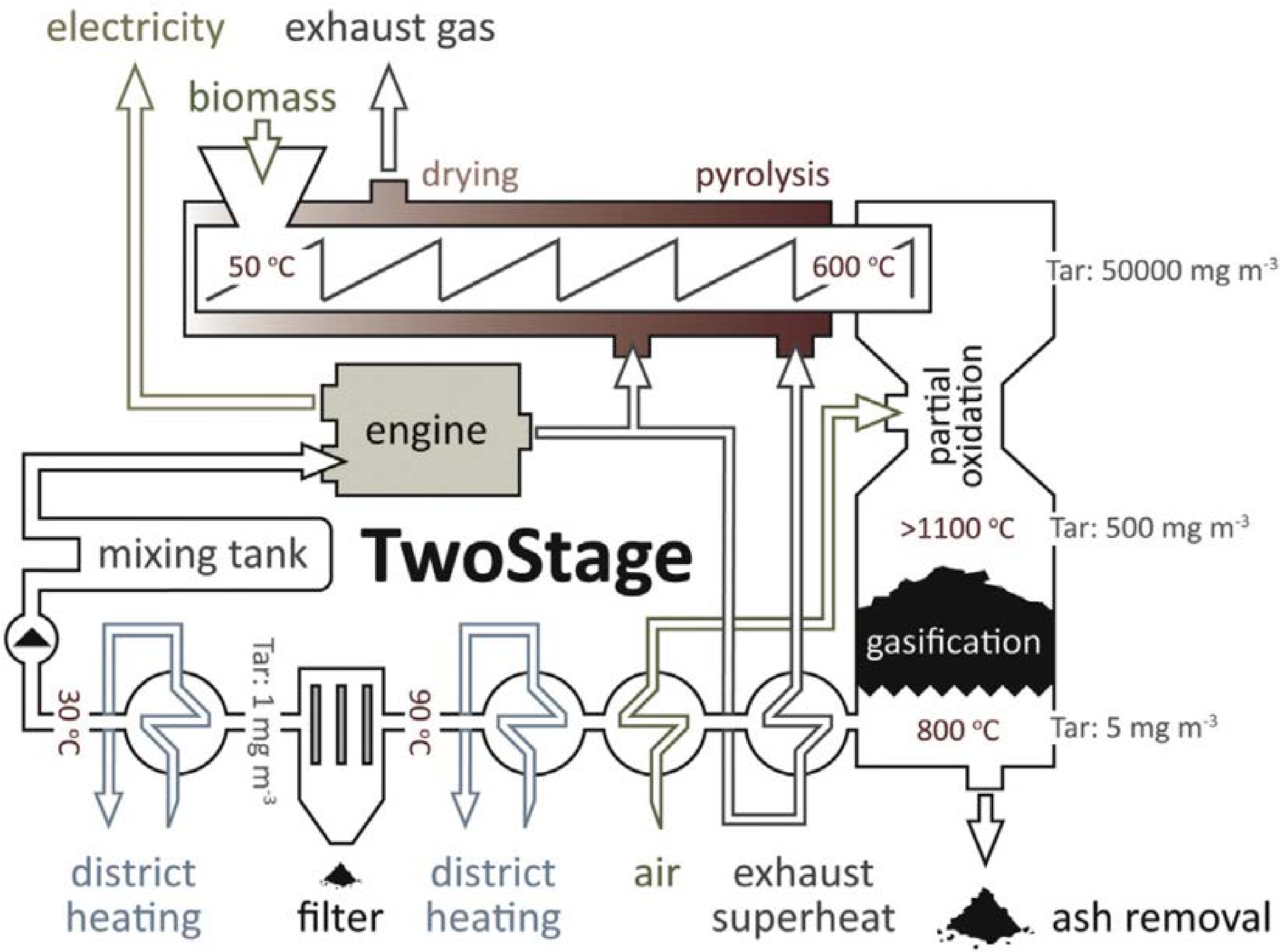
Biochar post-treatment
Thermal removal of PAHs



- reduction of the Σ EPA16 PAH content in gasification residues by 36% to 82% was achieved
- the residual Σ EPA16 PAH content (between 396 and 1,713 mg/kg DM) was still far too high to allow for an agricultural use of the residues
- Laboratory tests showed that post-treatment at higher temperature (650 °C) can yield biochar with sufficiently low Σ EPA16 PAH content
- Extended treatment (24h) even at lower temperatures (200-300 °C) can have similar effect, i.e., remove most PAHs (M. Kołtowski, P. Oleszczuk / Ecological Engineering 75 (2015) 79–85)

Source: Thermal Removal of Polycyclic Aromatic Hydrocarbons from Gasification Biochars
http://dx.doi.org/10.5772/57269

Biochar post-treatment
Thermal removal of PAHs



Source: Gasification biochar as a valuable by-product for carbon sequestration and soil
10.1016/j.biombioe.2014.10.013

From lab to deployment - Key challenges

Two different ways to think about scale-up

1) Move from test tubes and laboratory units to industrial processing

- Energy balance
- Product quality
- Product consistency
- Control and monitoring
- Reliability
- Economics

Mainly technical

2) Move from development and demonstration to wide deployment

- Sustainability (resource use, residues management, etc.)
- Resource use efficiency (there are many uses for biomass beyond heat and electricity)
- Economics (high value co-products vs. relatively low-value co-products)

Mainly non-technical

Conclusions

- A wide range of organic materials can be converted to biochar
- Biochar properties depend on the feedstock and conversion process used, and can be very different in nature
- Properties of biochar can be tuned to suit its application, e.g. nutrient release dynamics, physical structure

Acknowledgements

SCOTTISH biofuel PROGRAMME
UK Biochar Research Centre
EPSRC Engineering and Physical Science Research Council
Scottish Funding Council Promoting further and higher education

Thank you!

Dr. Ondřej Mašek

Tel. +44 131 650 5095

Skype: ondrej.masek-ukbrc

Email: ondrej.masek@ed.ac.uk

Web: http://www.geos.ed.ac.uk/homes/omasek

Web: www.biochar.ac.uk

Standard biochar

Purpose:

Provide a systematic set of affordable research-grade biochar.

Advantages:

A set of research grade biochars used across a number of scientific and engineering disciplines offers a number of benefits:

- To compare alternative measures of key functions of biochar independent of soil and soil science methods (characterisation)
- To have material in common between different real-time experiments (alongside context-specific biochar types)
- To compare consistency in application of new methods between labs (reference materials)
- Connect parallel international initiatives, e.g. COST Action with IBI "biochar carbon stability" initiative

Ongoing detailed advanced characterisation of standard biochar set by international users will deepen understanding of the materials and assist in interpreting soil/plant/water effects. (published data will be made continuously available via an online biochar database "CHARCHIVE" so that any user of standard biochar can keep up to date with new data and findings)

Standard biochar

A set of research grade biochars

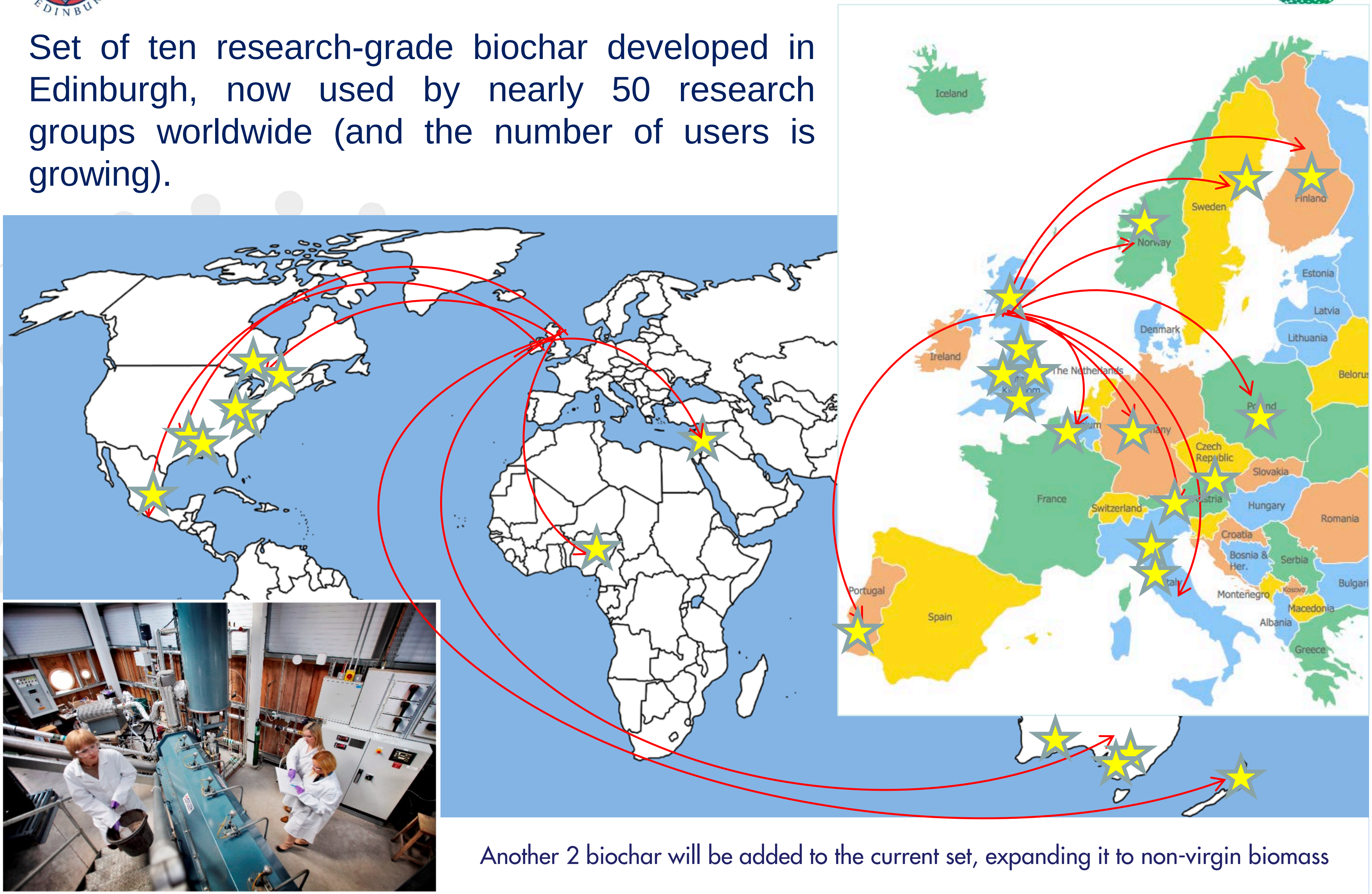
700 °C

550 °C

Rice husk	Wheat straw	Softwood	Oilseed rape straw	Miscanthus straw

UKBRC Standard Biochar

Set of ten research-grade biochar developed in Edinburgh, now used by nearly 50 research groups worldwide (and the number of users is growing).



Another 2 biochar will be added to the current set, expanding it to non-virgin biomass