Sent: Wednesday, 18 September 2024 9:42 AM
To: State Development
Cc: 'Scott Fairbairn'; 'Anthony Reid'; 'Russ Martin'
Subject: Email 1 of 3 - RE: Inquiry into post-mining land use – Post-hearing responses – 12 August 2024
Attachments: 1. Transcript - HIGHLIGHTED FOR QON - State Development - Post Mining – 12 August 2024_RM and CB responses - Copy.pdf; 2a. Aust Technologies for Renewable Energy & Biochar_ANZBIG Tas Forum_Fnl2_CBagnall.pdf

Thank you again for the extension to provide this, it was very much appreciated and apologies for the delay. As requested, please find attached the following, split over 3 emails due to file sizes:

1. **My comments on the Transcript with corrections in comments as noted**
    - FYI I have added these to Russ's version for ease of reference, and renamed the file.
2. **Further supporting Information/Evidence for the Committee as discussed (including items "taken on notice"):**
    a) **Negative Emissions Technologies (NETs) (carbon-negative) for Biochar Carbon Dioxide Removal (BCR)** - as taken on notice on **page 54** of the Transcript. *(see attached to email 1)*
        - Please find attached copy of presentation by Craig Bagnall in May 2024 at the *Tasmanian Forum* for the Australian Biochar Industry 2030 Roadmap state forums entitled: ***"Australian Technologies for Renewable Energy and Biochar Carbon Removal".***
        - This also includes some selected information on technologies from overseas too. It also explains why and how BCR contributes as an Negative Emissions technology.
        - If there are any queries on this presentation for BCR technologies or any further information is required, this can be provided upon request.

    b) **Copy of a global meta-analysis on decades of Biochar research** (Joseph et al 2021) as mentioned in my testimony on **page 55** of the Transcript. *(see email 2)*
        - ***"How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar",*** prepared by some of the world's most renowned biochar and soil scientists.

    c) **V2.0 of the Australian Biochar Industry 2030 Roadmap** (just released) *(see email 3)*
        - This version **includes important government policy alignments** at a national level to address key challenges including Climate Change/Net Zero, Sustainability and Circular Economy, Agriculture, Water/Drought Resilience, Energy / Storage, Employment & Regional Resilience. I would imagine these alignments would be of significant interest to the Committee.

    d) **Copy of presentation I gave last week on behalf of the ANZ Biochar Industry Group to the *Australian Bioeconomy Conference:*** *(see email 3)*
        - *"**Circular and Regenerative Bioenergy:** Pathways for CO_2 Removal and Renewable Energy for Net Zero, via the Australian Biochar Industry 2030 Roadmap"*

As also mentioned in the transcript SEATA would like to extend an invitation to any/all members of the Committee to visit SEATA's new pilot plant at our ***"Clean Energy & Carbon Sequestration R&D Centre"*** located in Glen Innes NSW (New England Renewable Energy Zone). Please advise if there may be interest from the committee to see it. 😊

Additionally, I note that on page 60 of the Transcript Russ noted that he is currently working on a ***'policy paper'*** regarding decoupling pyrolysis and gasification to produce biochar <*to separate*> from linear combustion technologies. We can confirm this work is underway and a draft is currently being finalised for review by the *Policy & Regulatory Working Group* of the ANZ Biochar Industry Group. As soon as it is publicly available (following approval by that working group and the Technical Advisory Board and Executive Board) it will be provided to the Committee. We see that as a pivotal document for guiding climate-positive change by government across Australia.

I trust this meets your needs, but if you have any queries at all please don't hesitate to call. I am in a meeting this morning but am free afterwards if needed.

Thanks again for the opportunity to contribute to this important inquiry, very much appreciated.

Kind regards,

Craig

Craig Bagnall
BE(Env)(Hons), CEnvP(IA Specialist)
Director, Environment and Regulatory

W www.seatagroup.com.au

SEATA
Deconstructing the world's problems
to create carbon negative solutions

Recent estimates indicate that biochar could mitigate up to 6.6 Billion tonnes of CO_{2e} globally per year by 2050[1]. This is indicatively equivalent to the USA's annual GHG emissions (1990-2019)[2].

(1) IPCC 6th Assessment Report, March 2022;
(2)UNEP Emissions Gap Report, 2020.

Australian Technologies for Renewable Energy *and* Biochar Carbon Removal:

"Having your cake and eating it too"

Navigating available thermal technologies for biochar and renewable energy

ANZBIG Tasmanian Forum
May 2024

Craig Bagnall
Director, Partner – Catalyst Environmental Management
Director Environment & Regulatory, SEATA Group

Presentation Outline

- **Why Biochar *and* Bioenergy?** *(several slides for those new to biochar)*
- **How? - Biochar Bioenergy projects & technologies – *Starting with the End in Mind***
  - **What is the market gap/problem needing to be solved?**
- **What/Which/When? Horses and Courses – Thermal Treatment Technologies Typically Used for Biochar**
  - *Pyrolysis*
  - *Gasification*
- **Who?...Example Australian Technologies** – *Some example ANZBIG Member Technologies and OS Counterparts*
- **Next Generation Technologies**
  - **Beyond Syngas for Energy – *Secondary Derivatives for Hydrogen, Biofuels and biochemicals.***
  - **Why Biohydrogen?**

> *“ If your house is on fire, you don’t tell the fireman to just let it simmer, you want to put the fire **out** ..we need carbon **removal** that actually **keeps the carbon out afterwards** ”*
>
> *Albert Bates*

Why bioenergy *and* biochar?

Q: Is there a way to produce **sustainable** energy *and* **remove** excess carbon from the sky that is causing climate change, ***at the same time***?

A: **Yes**, and the answer comes from nature….

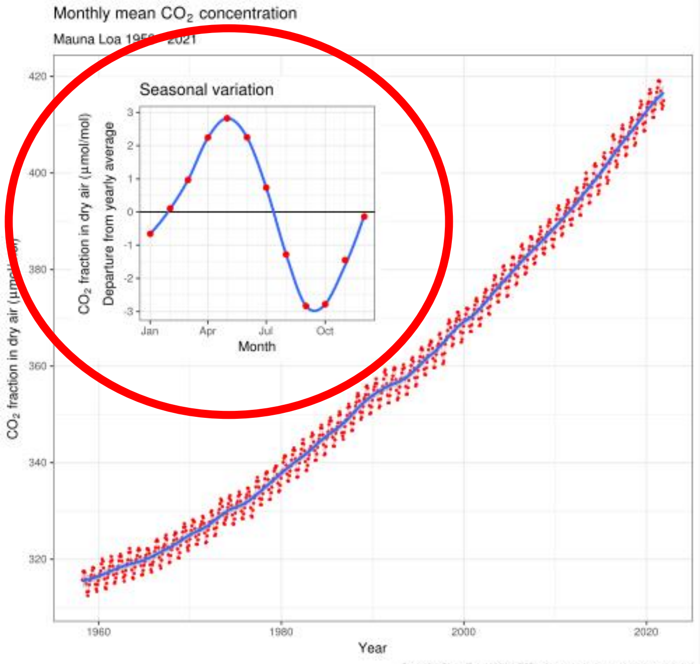
The Need for Carbon *Removal*

- Anthropogenic CO_2 added to the atmosphere lasts between **300 to 1000 years**
- Even if **all emissions stopped** immediately, the earth is expected to continue to heat for decades, and would take **thousands of years to cool to pre-industrial levels**. *(Source: Royal Society, March 2020)*
- Target limit 1.5 degrees by 2100 via Net Zero 2050, with **half the reductions required by 2030**

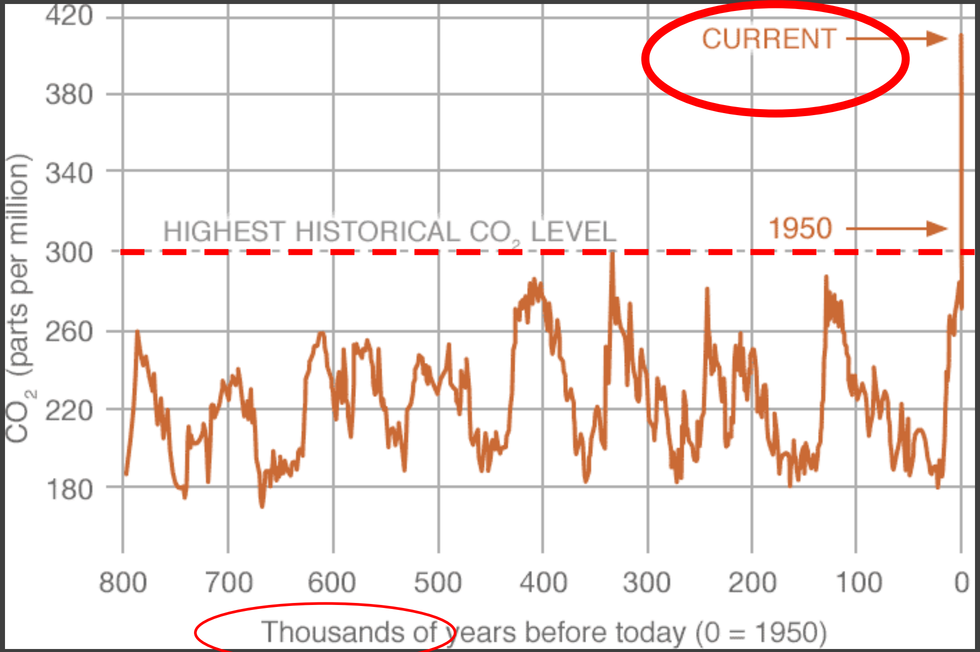
  BUT we're **currently tracking well above worst case modelling, potentially >>3.2 degrees**

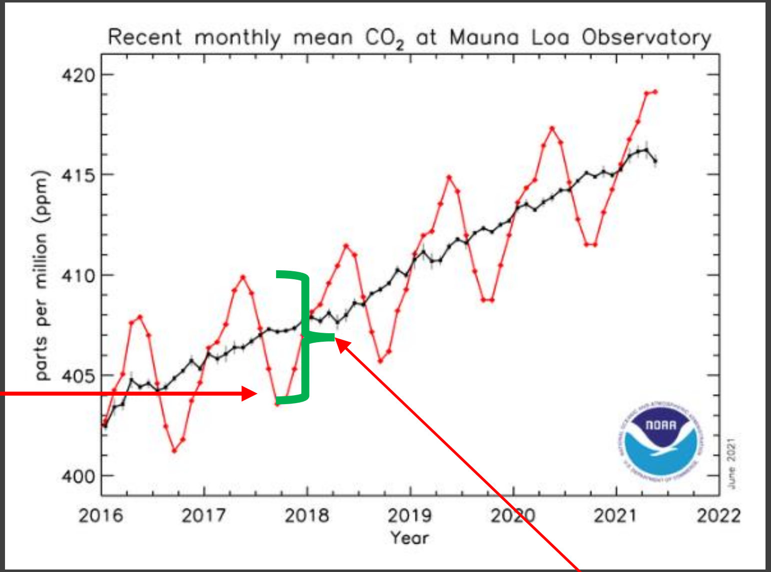
➔ Carbon *removal* is urgently needed in addition to emissions reduction

➔ Nature's existing carbon sinks need "turbo-charging" – **nature already indicates ways to do it**



Data : Dr. Pieter Tans, NOAA/ESRL (https://gml.noaa.gov/ccgg/trends/) and Dr. Ralph Keeling, Scripps Institution of Oceanography (https://scrippsco2.ucsd.edu/). Accessed 2021-12-16 https://w.wiki/4ZWn





Large annual variations are due to seasonal Photosynthesis

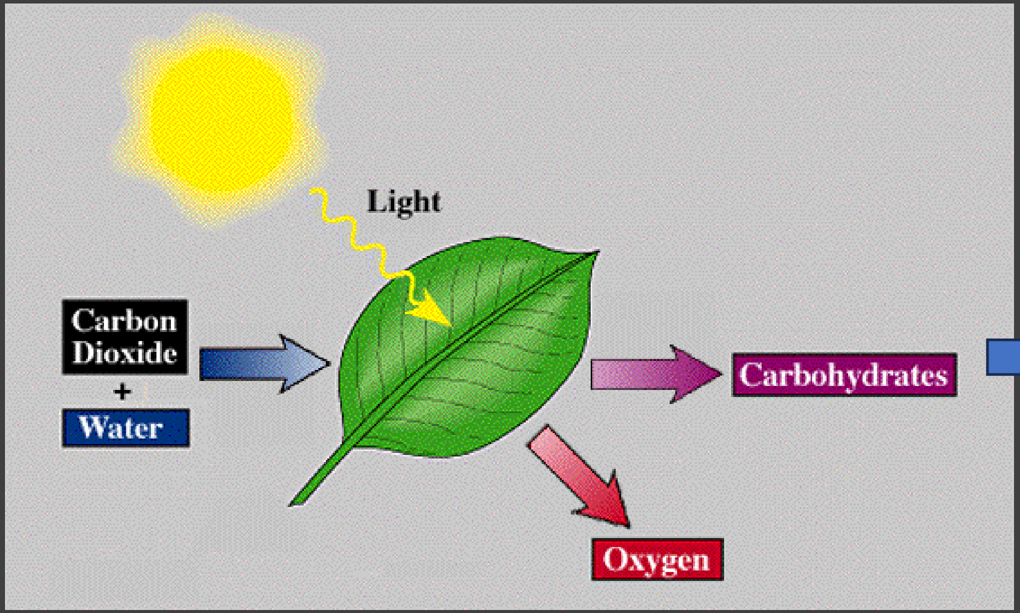
The very definition of *sustainable* energy

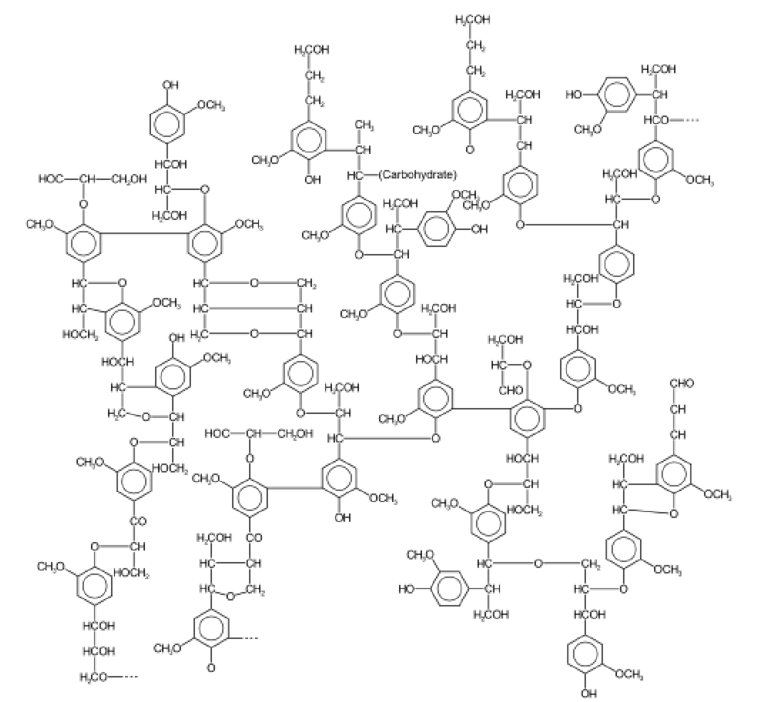
….. >3 Billion years of photosynthesis, C & H cycles…

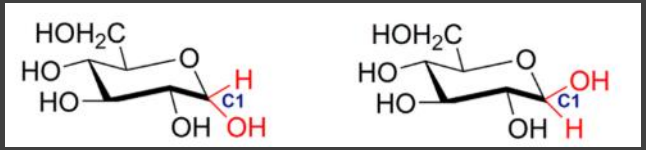
➔ Takes CO_2 out of the atmosphere and combines it with hydrogen & oxygen to make carbohydrates (sugar building blocks) for plant growth

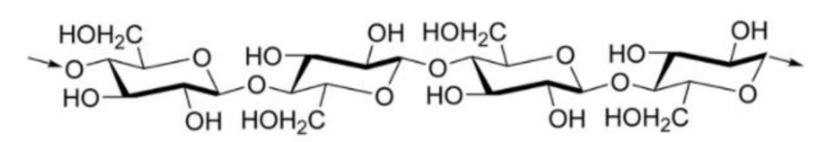
$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

- *Photosynthesis*



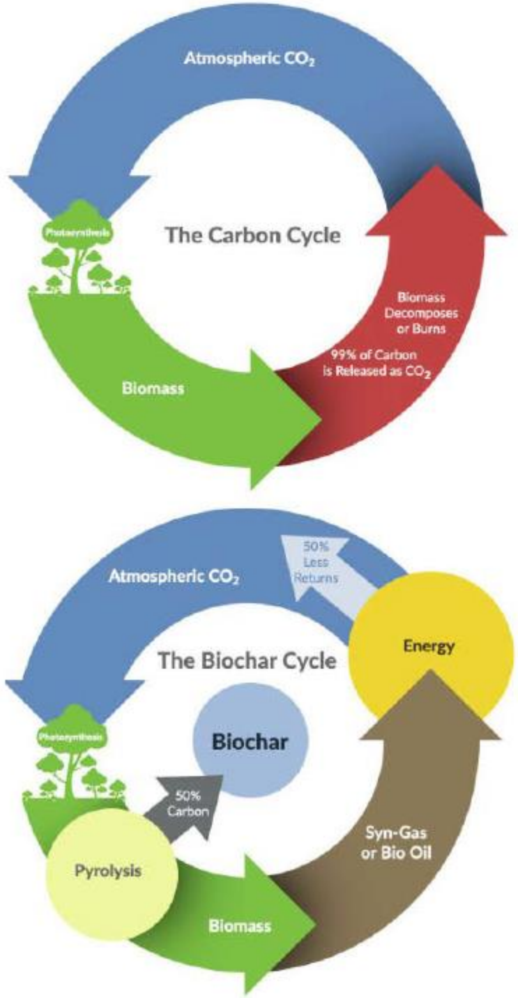






- Glucose
- Cellulose
- Lignin

Biochar CO_2 Removal – priority climate action



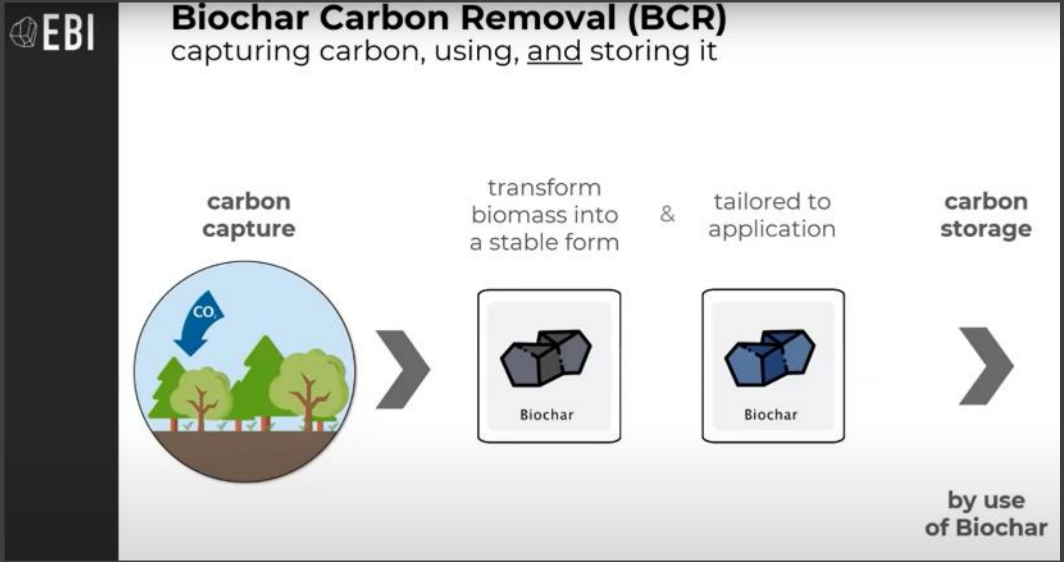
Over 99% of CO_2 captured by biomass re-enters our atmosphere as part of the natural carbon cycle.

Pyrolysing wasted plant biomass into biochar **intercepts the cycle** and converts carbon into a form that is typically stable for **centuries to millennia**.

Recent estimates indicate that biochar could mitigate up to 6.6 Billion tonnes of $CO_{2}e$ globally per year by 2050[1]. This is indicatively equivalent to the USA's annual GHG emissions (1990-2019)[2].

(1) IPCC 6th Assessment Report, March 2022;
(2)UNEP Emissions Gap Report, 2020.

> *"The **deployment of CDR** to counterbalance hard to abate residual emissions is **unavoidable if net zero** (CO_2 and total GHG) **is to be achieved**."*
>
> IPCC 6th Assessment Report April 2022



Biochar Carbon Removal (BCR)
capturing carbon, using, and storing it

ANZ BIOCHAR INDUSTRY GROUP

Biomass Feedstocks: Sustainable, Regenerative, Gt-Scale Drawdown



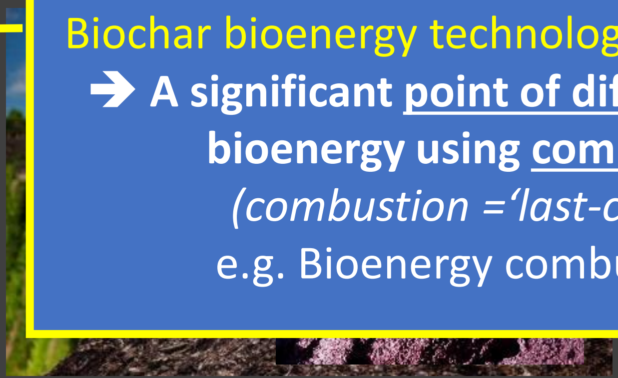
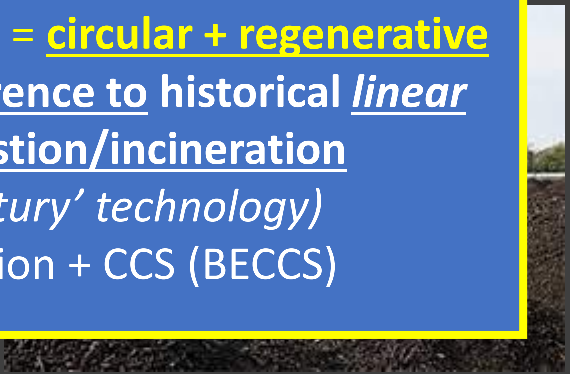

Global biochar CDR potential up to 6.6 Gt CO$_2$e/y (up to 1.8Gt/y at <USD$100/tCO$_2$e) (IPCC, 2022)

>> 50 Mtpa biomass is burned or landfilled in Australia alone (ANZBIG 2022)

(up to 80-110 Mtpa of biomass sustainably available, CSIRO 2016)

Biochar = Enhanced food production and security



Biochar bioenergy technologies = **circular + regenerative**

➔ A significant point of difference to historical *linear* bioenergy using combustion/incineration

(combustion ='last-century' technology)

e.g. Bioenergy combustion + CCS (BECCS)

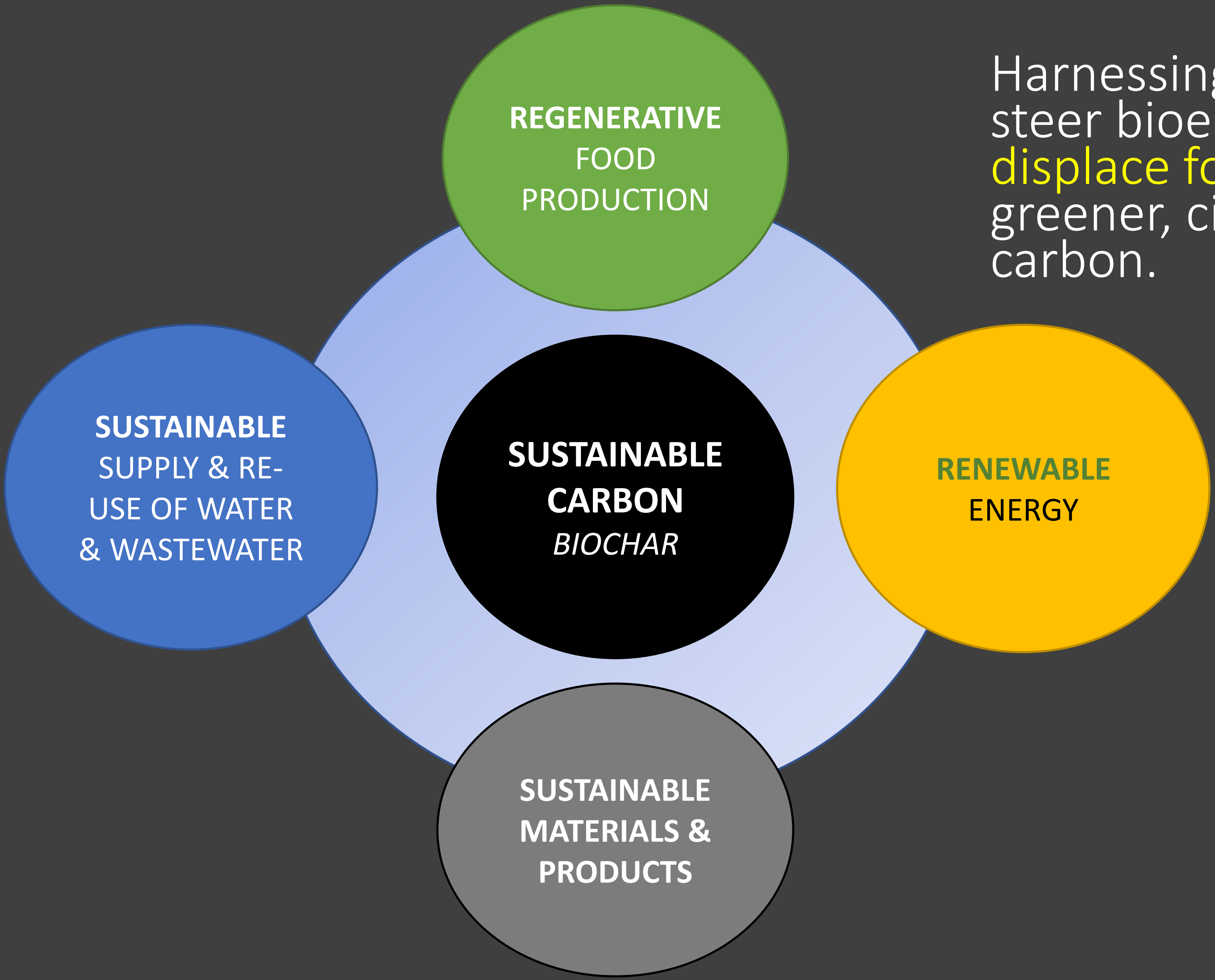
Re-thinking Carbon, Waste to Value – ‘Upcycling’

“Waste is a waste”

***Upcycling** is the process of transforming waste materials into products of better quality or for better environmental value*

Upcycling otherwise wasted biomass resources into biochar can provide a source of non-fossil carbon (with multiple co-benefits) for many sectors of the economy….

Carbon plays a key role in the food-energy-water nexus…



REGENERATIVE FOOD PRODUCTION

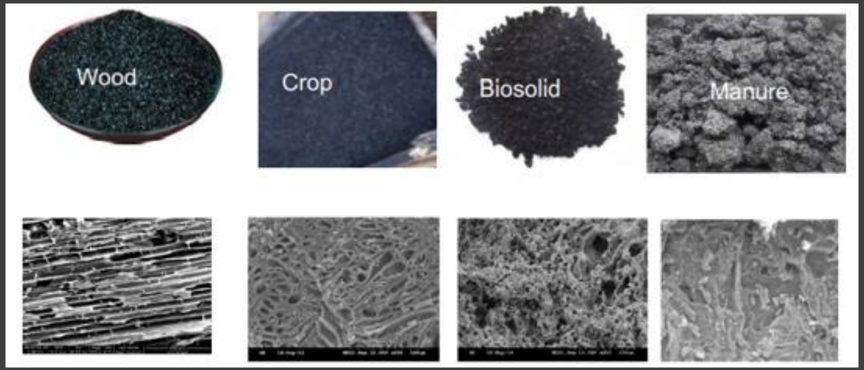
SUSTAINABLE SUPPLY & RE-USE OF WATER & WASTEWATER

SUSTAINABLE CARBON *BIOCHAR*

RENEWABLE ENERGY

SUSTAINABLE MATERIALS & PRODUCTS

Harnessing this fact can help steer bioenergy projects to displace fossil carbon with greener, circular, regenerative carbon.



Credit: Dr G.Pan, 2020

Starting with the End in Mind…
"Chars ain't chars"

Identify target **market/application needs** in order to **engineer biochar properties** to meet them, and **which technologies/treatments achieve this**

- Biochar properties dictate (and limit) its potential uses
- **Biochar properties** are primarily a result of **feed type(s)**, **processing conditions** (temp, RT/HR) and **Treatments** (pre/post; physical, chemical and biological)
- *Co-pyrolysis* and/or *blending* to customise properties

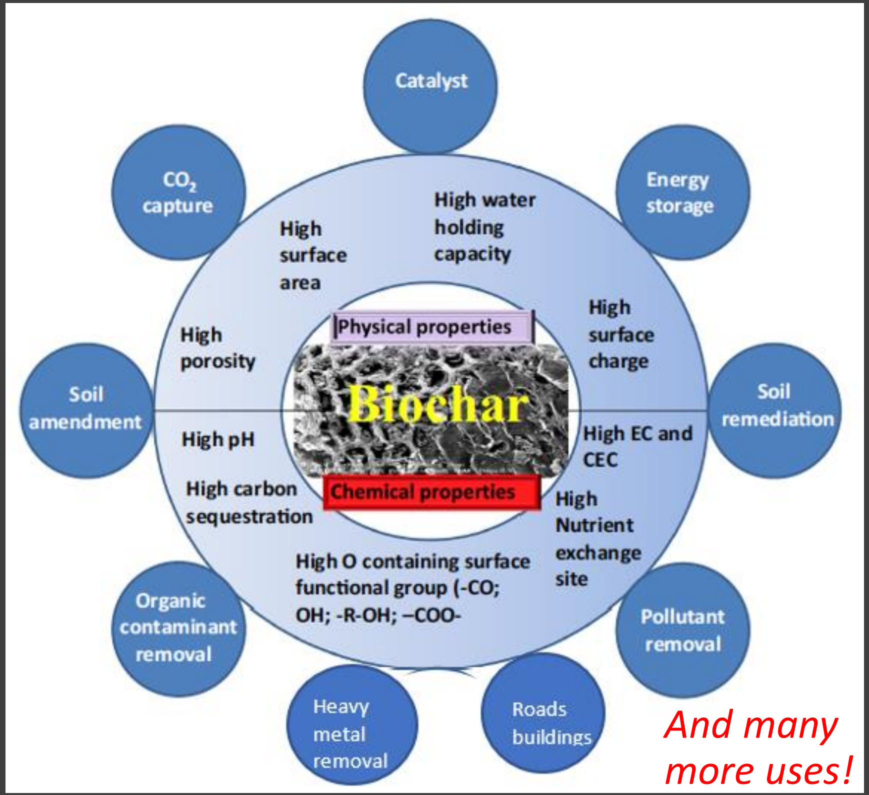
➔ i.e. **biochars can be designed and engineered**

Fit For Purpose biochars are designed for intended applications

" Horses for Courses "

➔ ANZBIG has established a Code of Practice (2021)

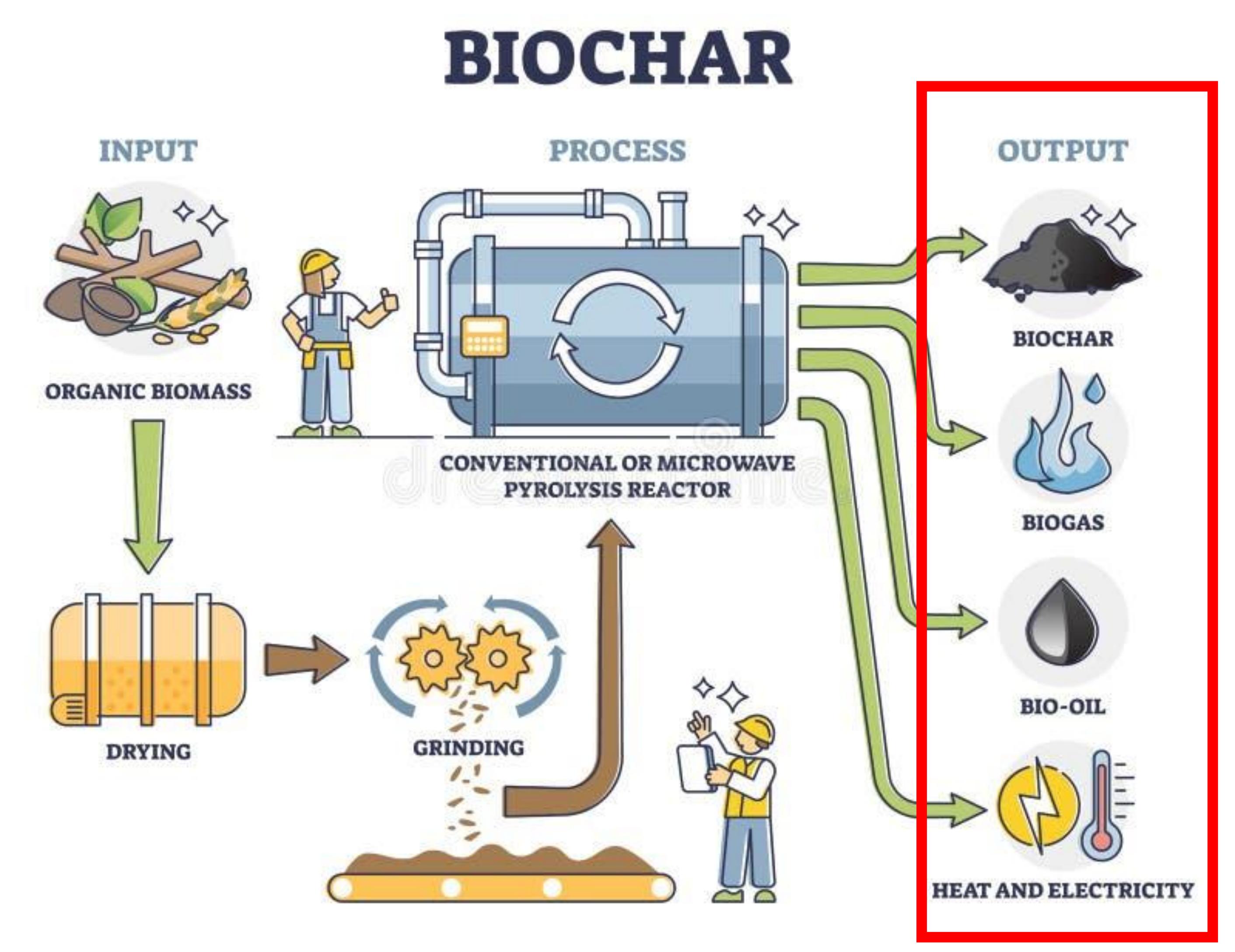
Which classifies 3x Grades of biochars to be fit for purpose….



And many more uses!

Adapted from Patel et al 2020

Common commercial *pyrolysis* outputs



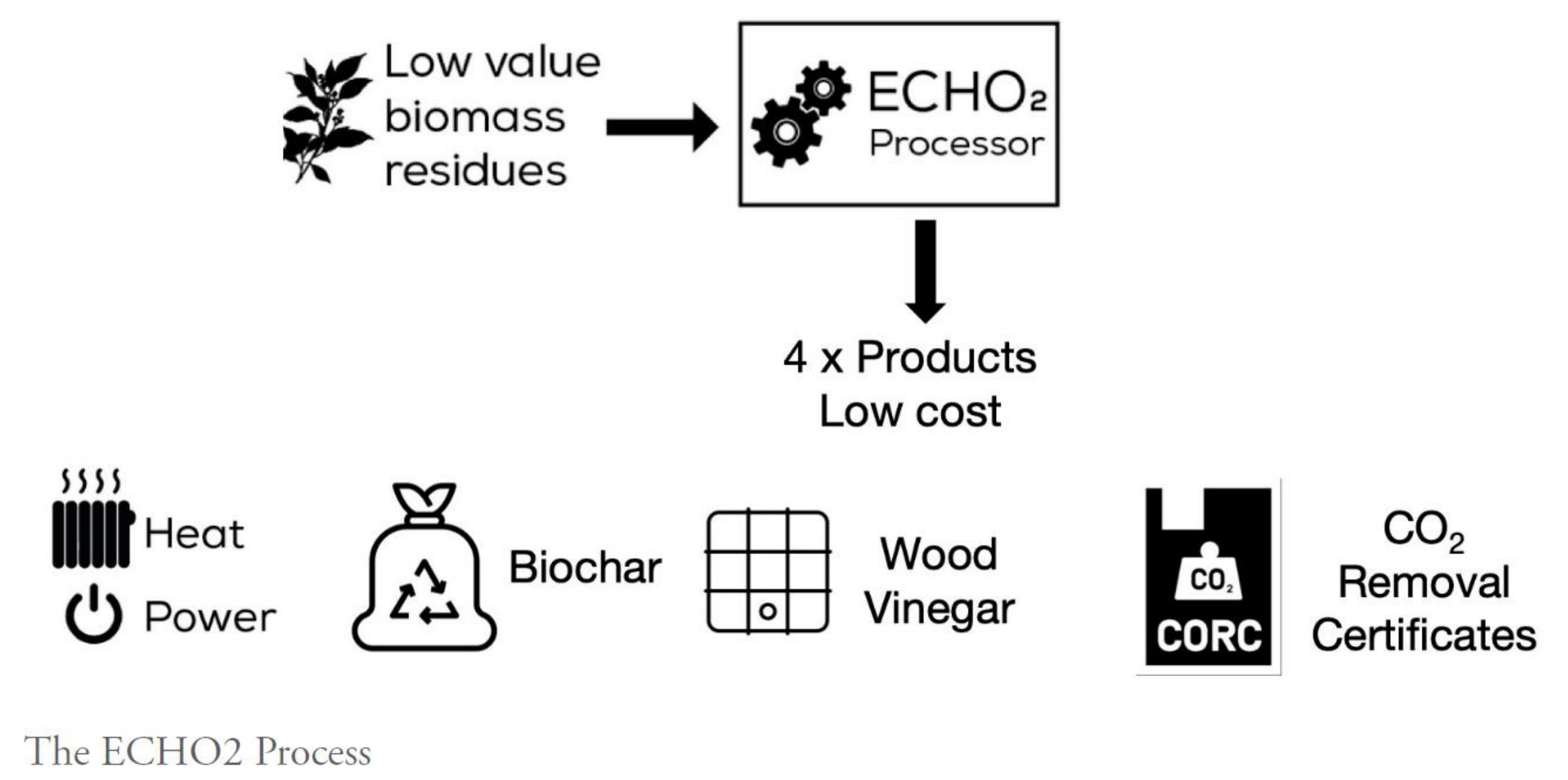
SOLID

GAS

LIQUID

HEAT

Modern systems can also achieve *additional* revenue streams via carbon credits



The ECHO2 Process

Which Horse for the Course?

Choosing a suitable thermal technology

- **Scale / Capacity?** 100’s, 1000’s, 10,000’s, 100,000’s tpa?
- **Mobile or Stationary?**
- **Batch or Continuous? Manual / Automated?**
- **Pyrolysis / Gasification / Other Thermal**
- **Moisture - Wet or dry feedstock? Or Both? (co-feeds)**
- **What Primary Output(s) do you need? – biochar, bio-oils, syngas, heat?**
- **Thermal Efficiency**
  - **Mass & Energy Balance (MEB)** performance
  - **Indirect Heating vs Direct Heating**
  - **Do you need additional external energy (beyond startup)?**
- **Materials Handling (sizing/pre-treatments/post-treatments) eg shredding, pelletisation?**

Which Horse for the Course?

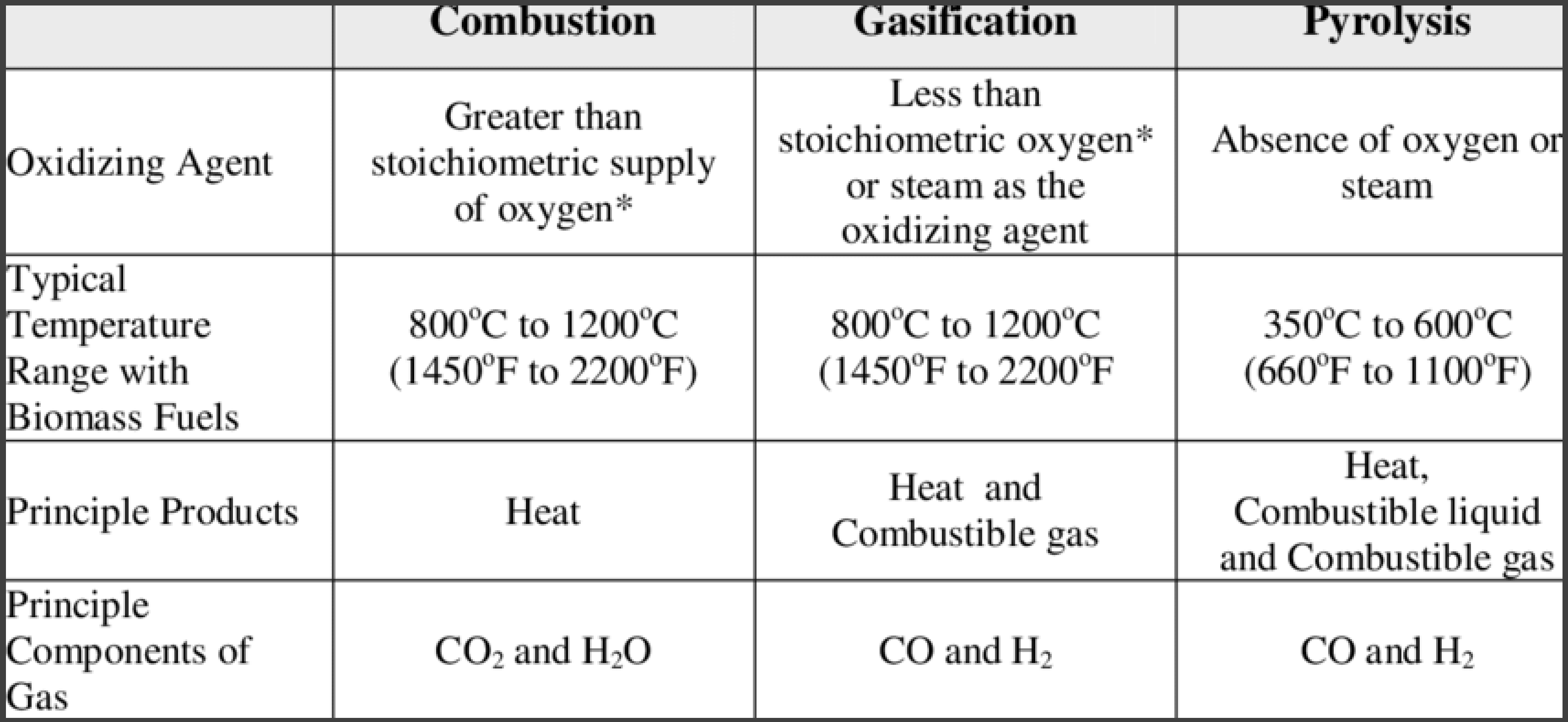
Choosing a suitable thermal technology

- **Temperature Needs - high/low? heating rate?** (flash/fast/slow)
- **Location –** rural/remote or "next door to a Child Care Centre"? (e.g. emissions control contexts) , **Climate** (**cold/wet** vs hot/dry)
- **Project Duration** – days, weeks or years/decades?
- **Maintenance** – commercial 'up time' (%/hrs per year)
- **Ancilliary needs - Water consumption?**
- **Wastes produced – (S/L/G emissions) – eg air emissions, scrubber water wastes, oils. Particulates, D's, F's etc.**
- **Applicable Regulatory Frameworks - where/which state are you operating AND where selling to? E.g. Emission control requirements and <u>much</u> more**

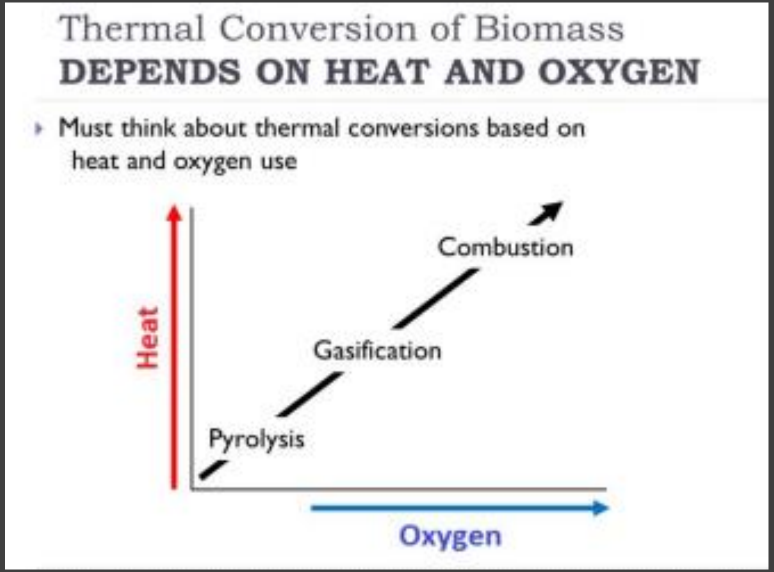
➔ **<u>Bottom line</u>: Choose '*fit for purpose'* tech to do *your* specific job, with an end-use/market focus ('demand-pull'). After all you are *recycling carbon*, and there is *"no point recycling if you are not buying recycled"***

Thermal Treatment / Conversion Technologies:

Incineration Vs Gasification Vs Pyrolysis



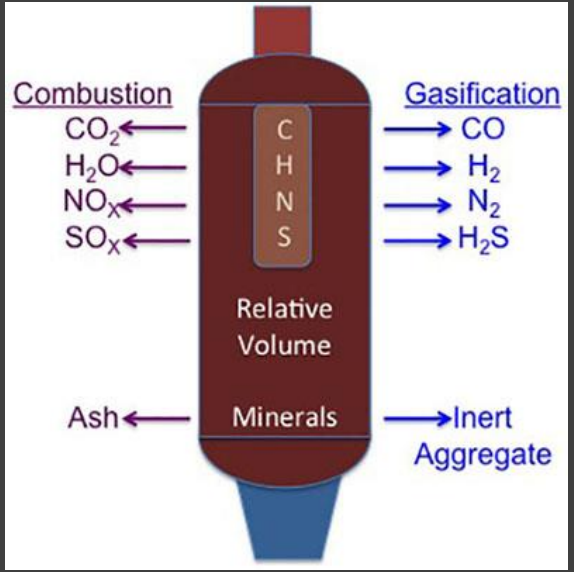
	Combustion	Gasification	Pyrolysis
Oxidizing Agent	Greater than stoichiometric supply of oxygen*	Less than stoichiometric oxygen* or steam as the oxidizing agent	Absence of oxygen or steam
Typical Temperature Range with Biomass Fuels	800°C to 1200°C (1450°F to 2200°F)	800°C to 1200°C (1450°F to 2200°F	350°C to 600°C (660°F to 1100°F)
Principle Products	Heat	Heat and Combustible gas	Heat, Combustible liquid and Combustible gas
Principle Components of Gas	CO_2 and H_2O	CO and H_2	CO and H_2



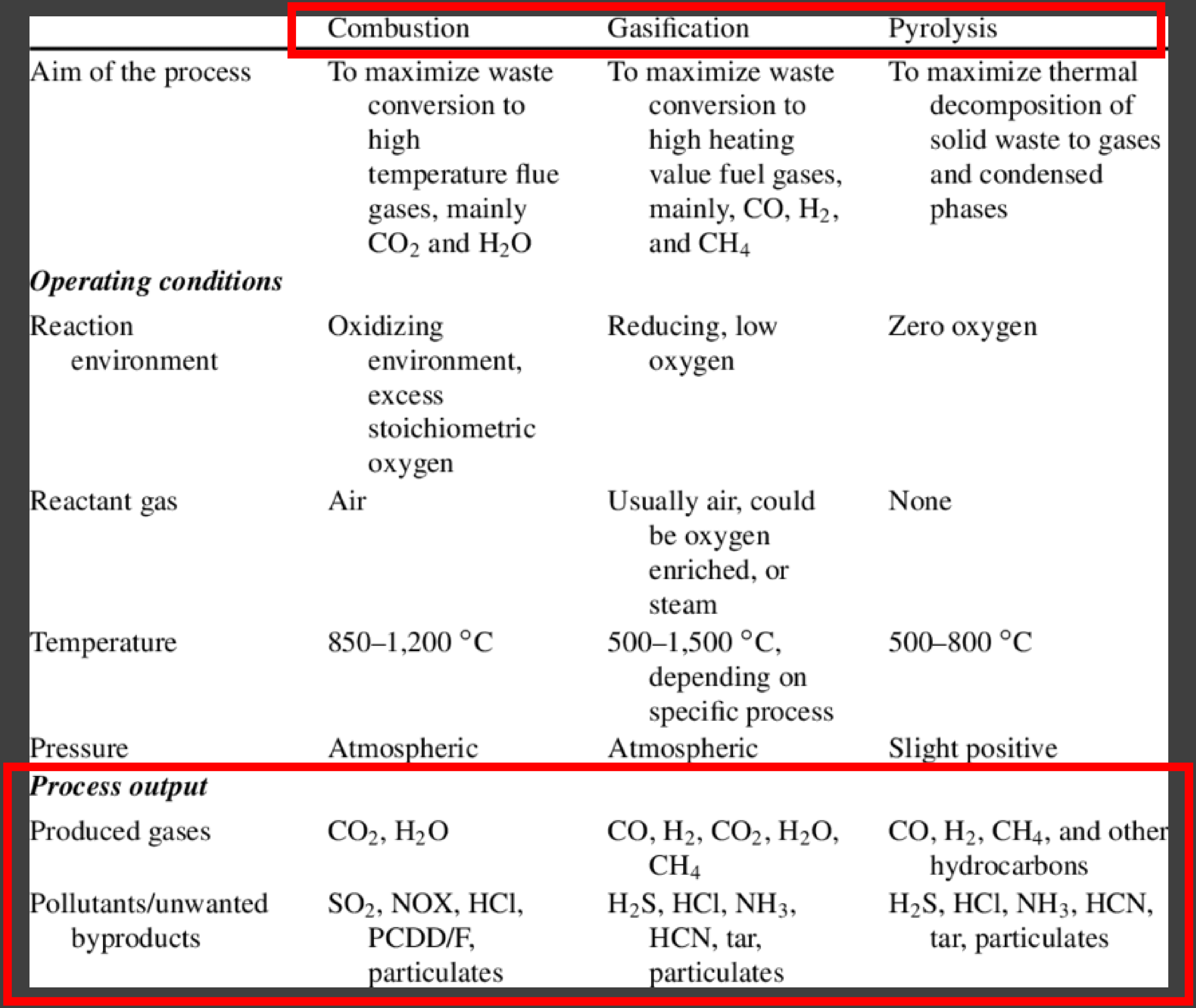
Thermal Conversion of Biomass

DEPENDS ON HEAT AND OXYGEN

- Must think about thermal conversions based on heat and oxygen use



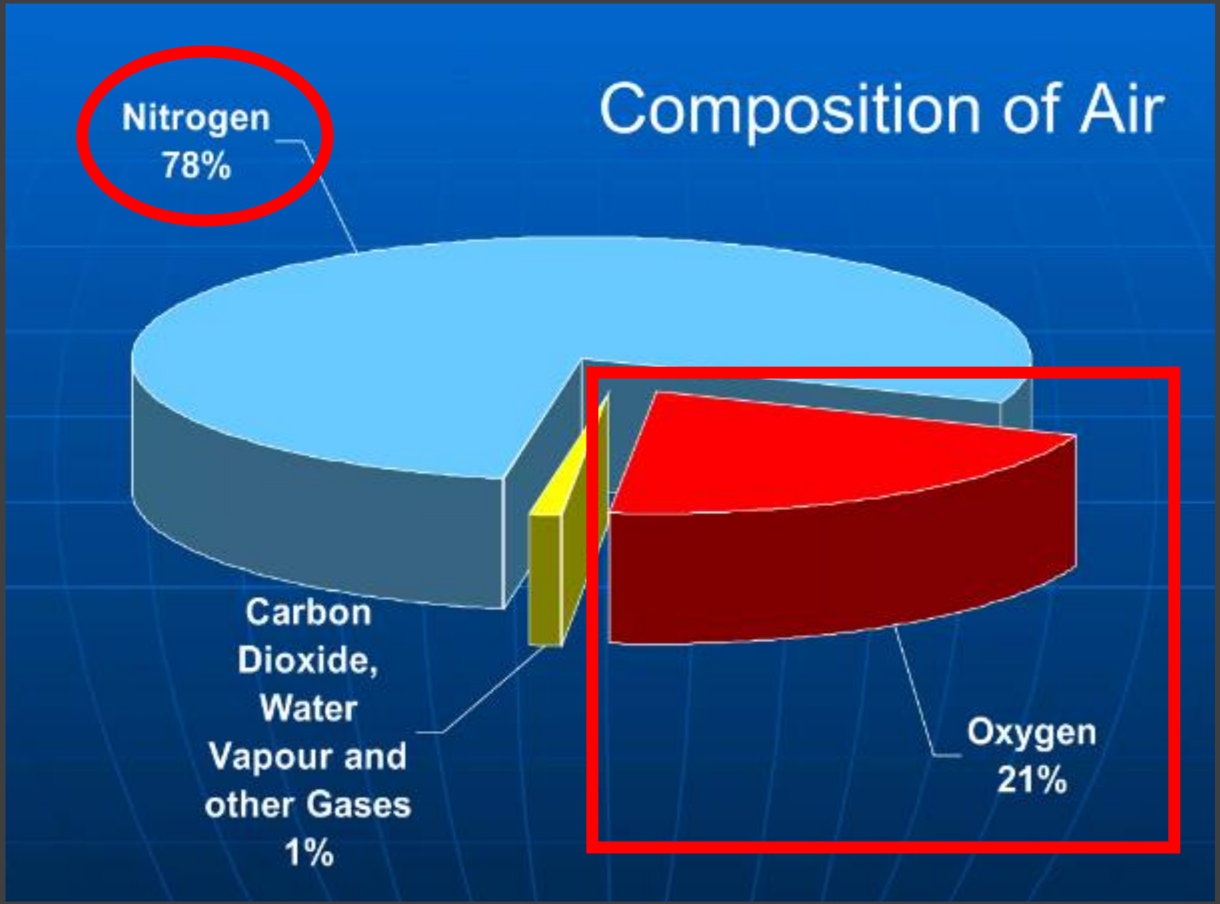
Thermal Conversion:

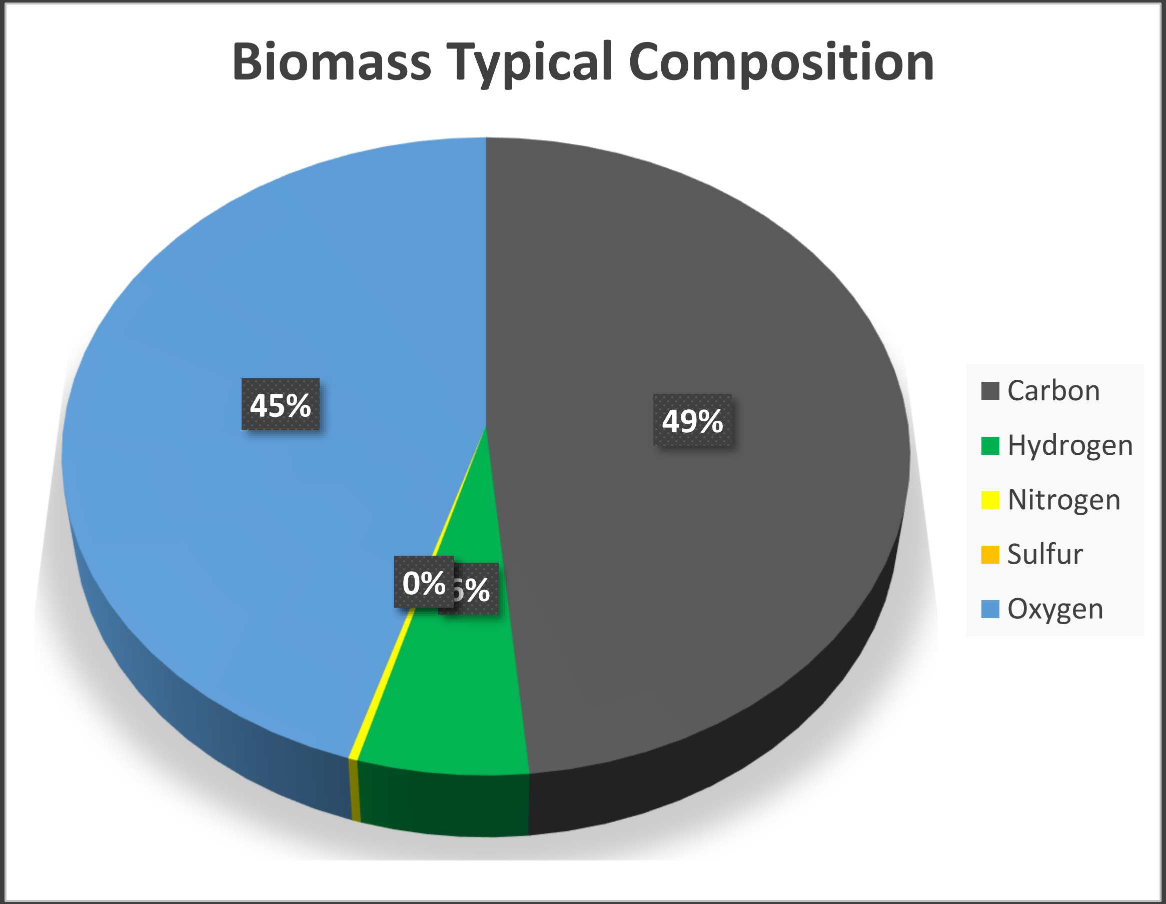


	Combustion	Gasification	Pyrolysis
Aim of the process	To maximize waste conversion to high temperature flue gases, mainly CO_2 and H_2O	To maximize waste conversion to high heating value fuel gases, mainly, CO, H_2, and CH_4	To maximize thermal decomposition of solid waste to gases and condensed phases
Operating conditions			
Reaction environment	Oxidizing environment, excess stoichiometric oxygen	Reducing, low oxygen	Zero oxygen
Reactant gas	Air	Usually air, could be oxygen enriched, or steam	None
Temperature	850–1,200 °C	500–1,500 °C, depending on specific process	500–800 °C
Pressure	Atmospheric	Atmospheric	Slight positive
Process output			
Produced gases	CO_2, H_2O	CO, H_2, CO_2, H_2O, CH_4	CO, H_2, CH_4, and other hydrocarbons
Pollutants/unwanted byproducts	SO_2, NOX, HCl, PCDD/F, particulates	H_2S, HCl, NH_3, HCN, tar, particulates	H_2S, HCl, NH_3, HCN, tar, particulates

Incineration Vs Gasification Vs Pyrolysis

NB: More gas = higher energy recovery but more cleanup / emissions control *(significant)*

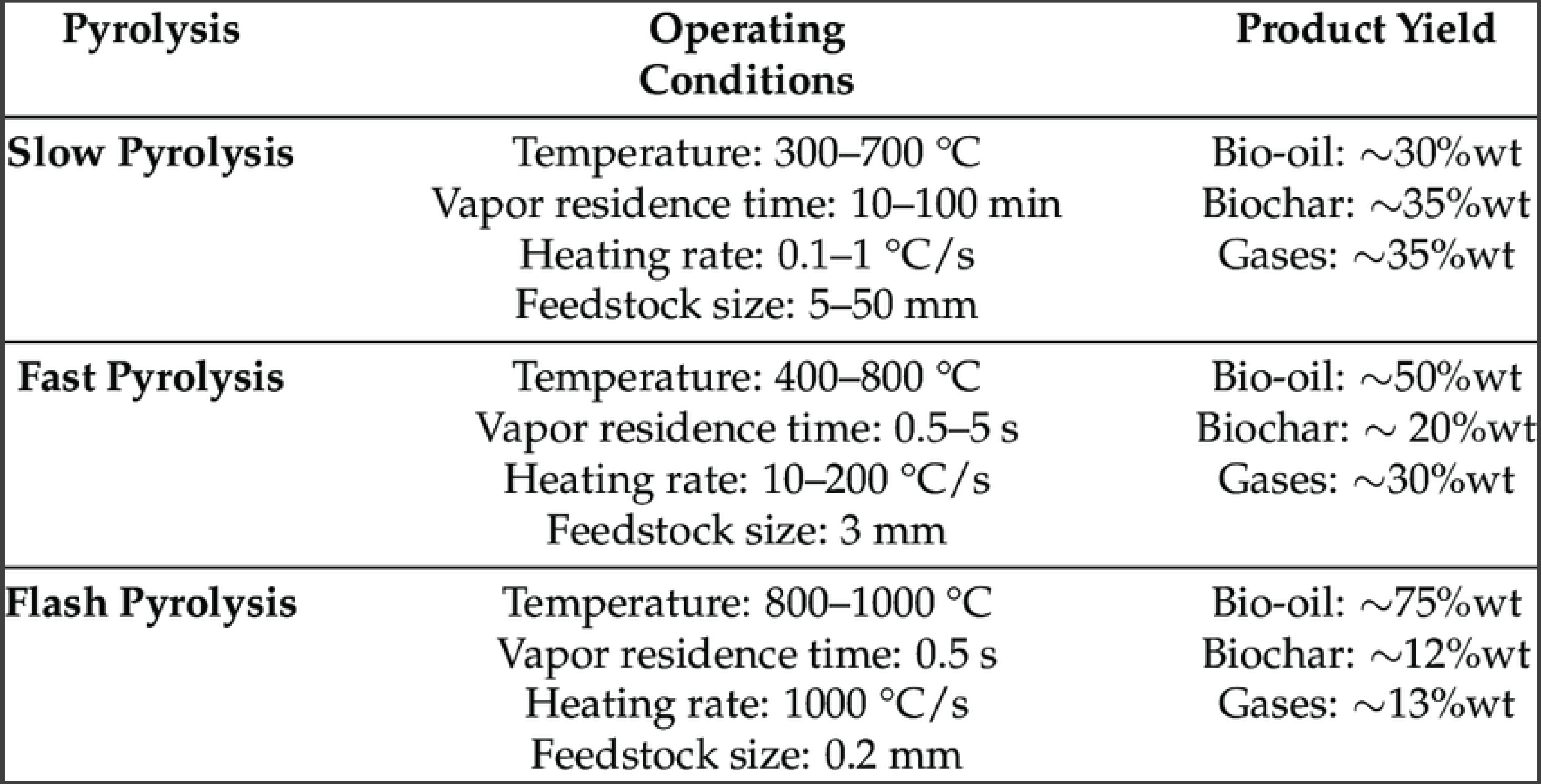




Using Air to get Oxygen = ~80% waste (nitrogen!)
i.e. air = signif. more emission control costs (CAPEX)

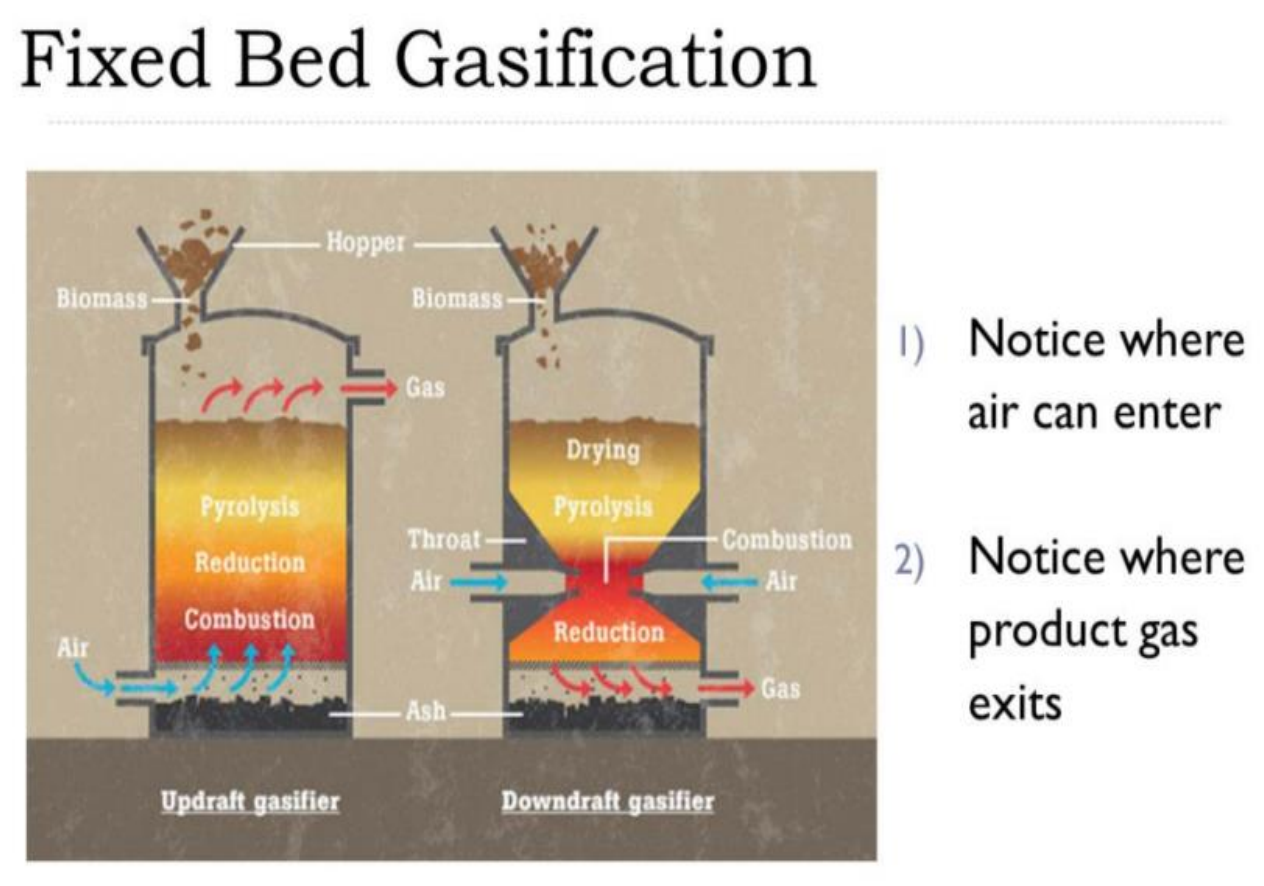
Types of Pyrolysis

Slow, Fast, Flash Pyrolysis – ‘common’ characteristics



Pyrolysis	Operating Conditions	Product Yield
Slow Pyrolysis	Temperature: 300–700 °C Vapor residence time: 10–100 min Heating rate: 0.1–1 °C/s Feedstock size: 5–50 mm	Bio-oil: ∼30%wt Biochar: ∼35%wt Gases: ∼35%wt
Fast Pyrolysis	Temperature: 400–800 °C Vapor residence time: 0.5–5 s Heating rate: 10–200 °C/s Feedstock size: 3 mm	Bio-oil: ∼50%wt Biochar: ∼ 20%wt Gases: ∼30%wt
Flash Pyrolysis	Temperature: 800–1000 °C Vapor residence time: 0.5 s Heating rate: 1000 °C/s Feedstock size: 0.2 mm	Bio-oil: ∼75%wt Biochar: ∼12%wt Gases: ∼13%wt

Gasification – Fixed Bed (Updraft & Downdraft)



Fixed Bed Gasification

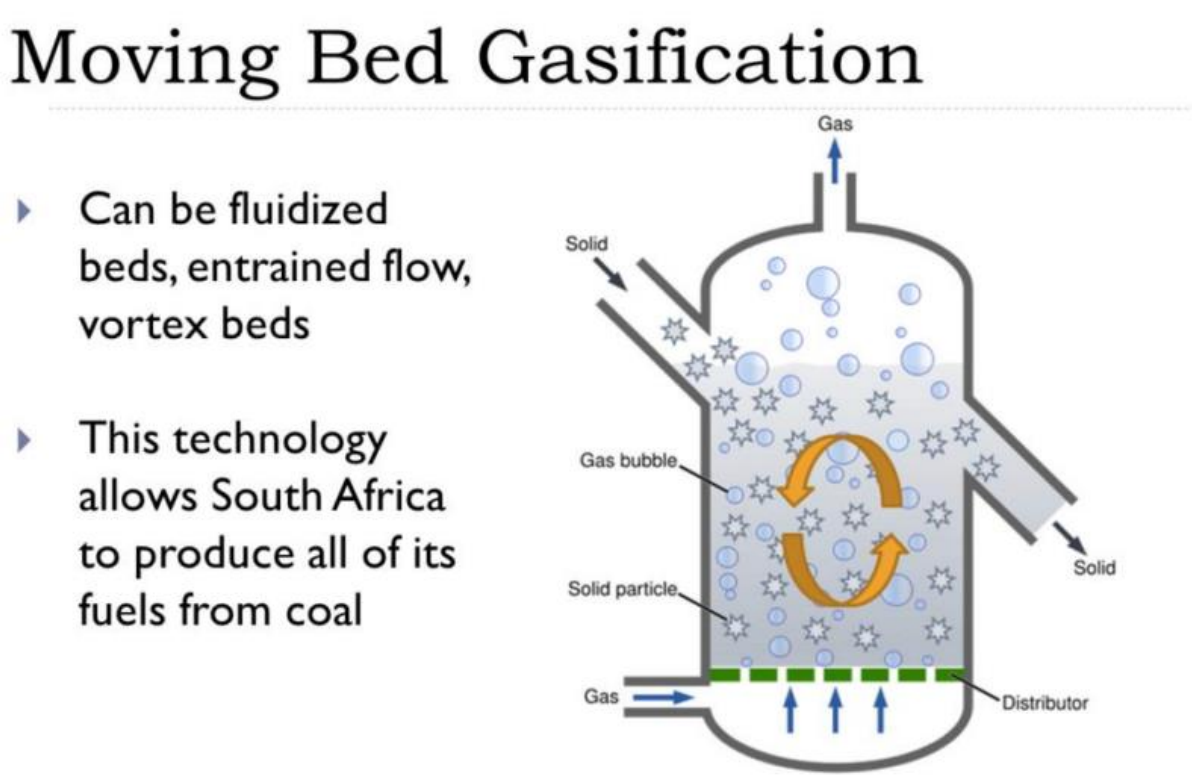
1) Notice where air can enter

2) Notice where product gas exits

- **Many kinds but updraft & downdraft most common due to simplicity.**
- **Bottom-up conversion = updraft**
- **Top-down conversion = downdraft**
- **Updraft can convert wetter feeds but typically lower quality syngas (higher pyrolysis vapour content)**
- **Downdraft needs drier fuels but makes a better quality syngas**
- **Emission control considerations (TO, Scrubbers)**

➔ Choice of gasifier depends on biomass type and product needs.

Gasification –Moving/Fluidised Beds



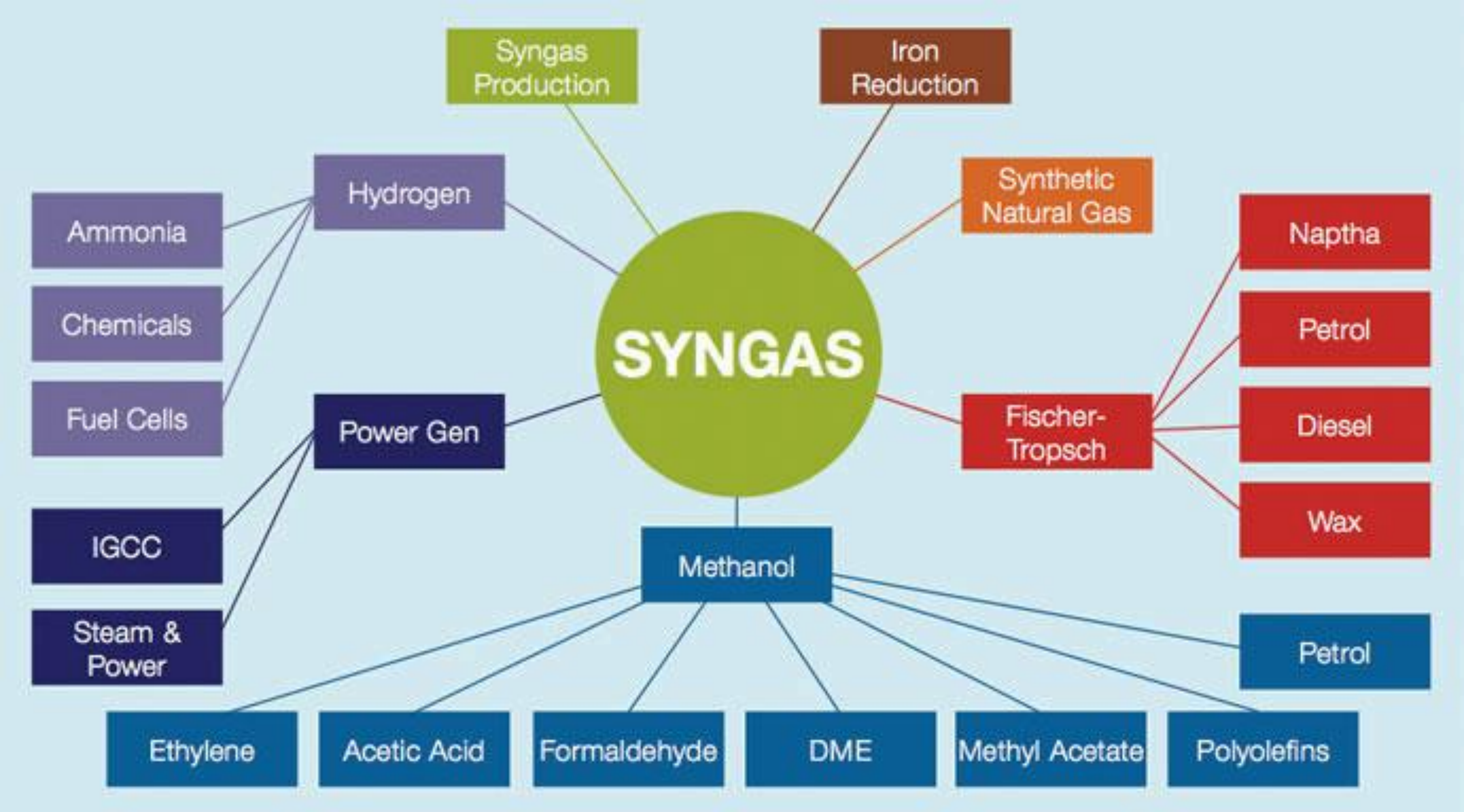
Moving Bed Gasification

- Can be fluidized beds, entrained flow, vortex beds
- This technology allows South Africa to produce all of its fuels from coal

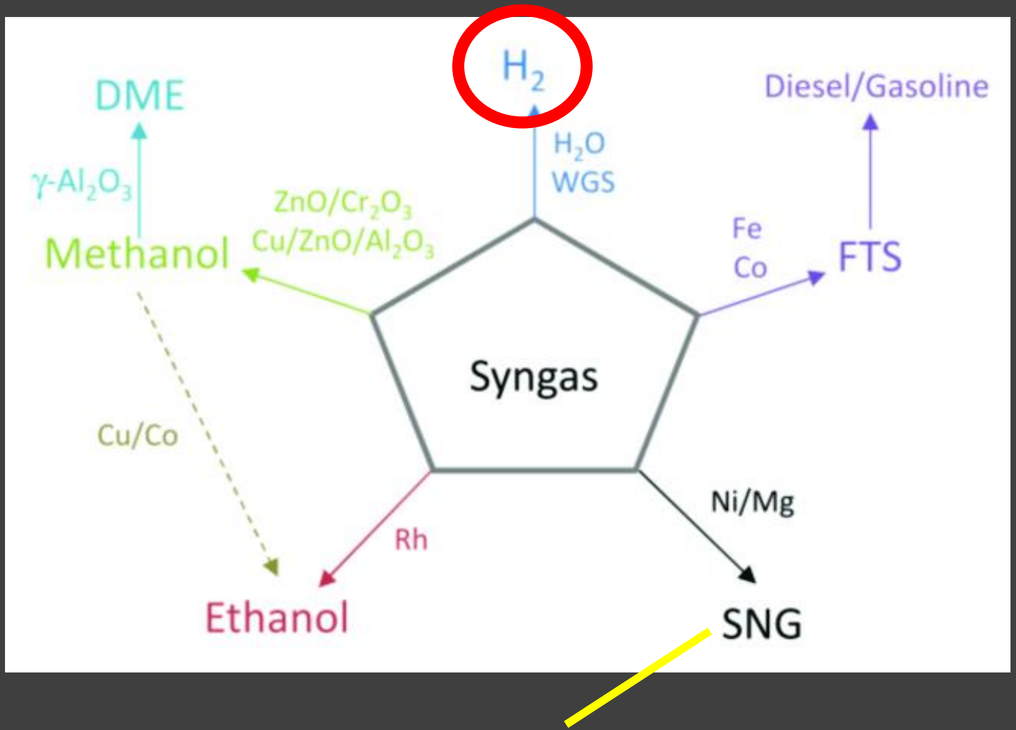
- **Far more efficient biomass carbon conversion** than fixed bed
- **Higher quality syngas**
- **More scalable** than fixed bed
- Typically more complex (than fixed)

- *Like all bioenergy technologies there are **tradeoffs** depending on size and type of biomass resources and amount and type/quality of product required*

Syngas Uses - Bioenergy (electricity) *and much more*



Syngas to Biohydrogen and Biofuels (incl rNG)



- **(rNG – Renewable Natural Gas / biomethane)**

- **Hydrogen and Carbon = chemical building blocks of MANY other derivatives** (biofuels, bioplastics / olefins etc)
- **H:C ratios important for scale up** (typically need 2:1, leaving carbon behind in solid char helps this)
- **Historically, syngas cleanup required**

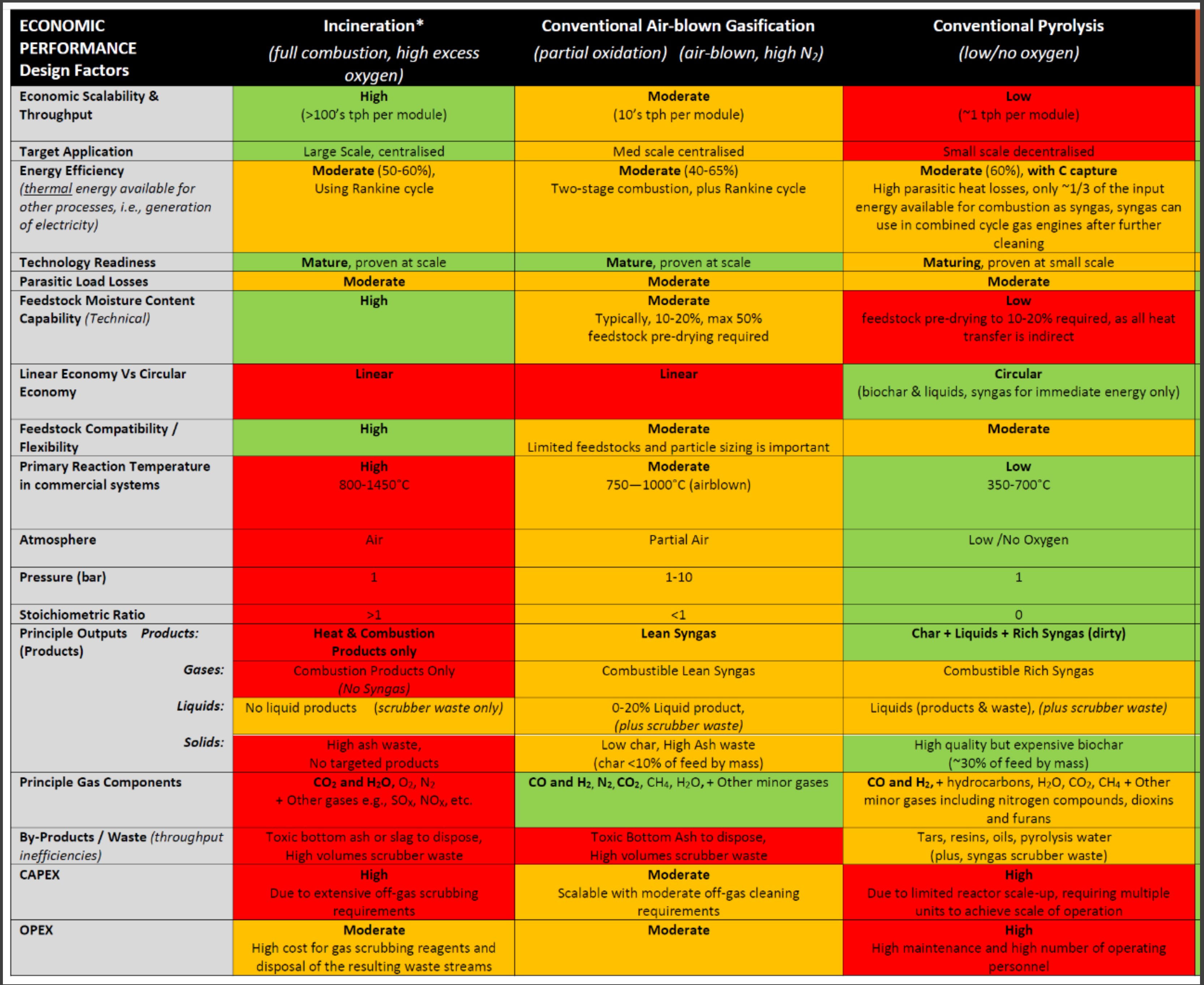
➔ Clean/concentrated syngas helps facilitate scale

- **Hydrogen** separation via PSA (or WSR at scale)

Thermal Treatment:

Incineration vs Gasification Vs Pyrolysis

Economic Performance

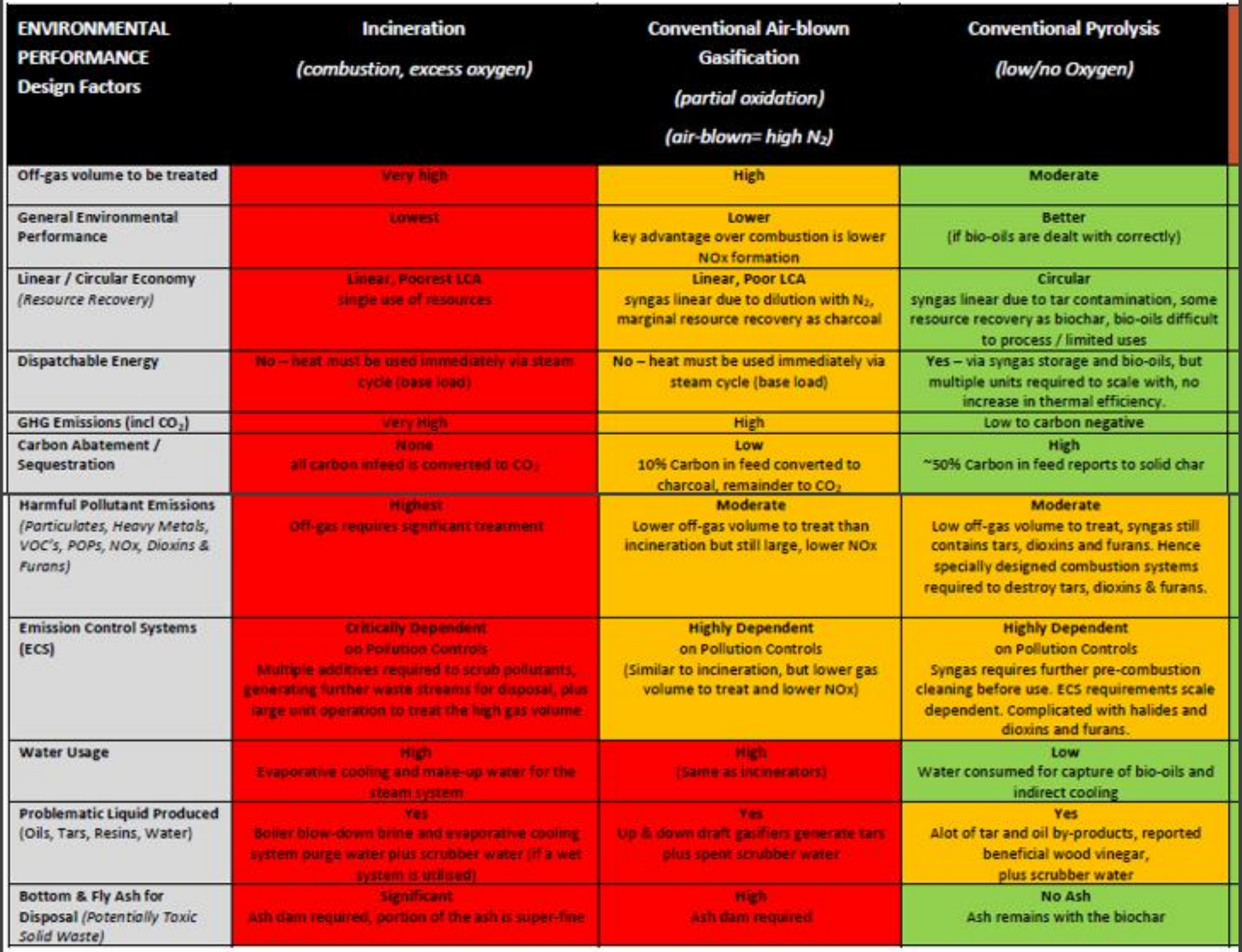


ECONOMIC PERFORMANCE Design Factors	**Incineration*** *(full combustion, high excess oxygen)*	**Conventional Air-blown Gasification** *(partial oxidation) (air-blown, high N_2)*	**Conventional Pyrolysis** *(low/no oxygen)*
Economic Scalability & Throughput	**High** (>100's tph per module)	**Moderate** (10's tph per module)	**Low** (~1 tph per module)
Target Application	Large Scale, centralised	Med scale centralised	Small scale decentralised
Energy Efficiency *(thermal energy available for other processes, i.e., generation of electricity)*	**Moderate** (50-60%), Using Rankine cycle	**Moderate** (40-65%) Two-stage combustion, plus Rankine cycle	**Moderate** (60%), **with C capture** High parasitic heat losses, only ~1/3 of the input energy available for combustion as syngas, syngas can use in combined cycle gas engines after further cleaning
Technology Readiness	**Mature**, proven at scale	**Mature**, proven at scale	**Maturing**, proven at small scale
Parasitic Load Losses	**Moderate**	**Moderate**	**Moderate**
Feedstock Moisture Content Capability *(Technical)*	**High**	**Moderate** Typically, 10-20%, max 50% feedstock pre-drying required	**Low** feedstock pre-drying to 10-20% required, as all heat transfer is indirect
Linear Economy Vs Circular Economy	**Linear**	**Linear**	**Circular** (biochar & liquids, syngas for immediate energy only)
Feedstock Compatibility / Flexibility	**High**	**Moderate** Limited feedstocks and particle sizing is important	**Moderate**
Primary Reaction Temperature in commercial systems	**High** 800-1450°C	**Moderate** 750—1000°C (airblown)	**Low** 350-700°C
Atmosphere	Air	Partial Air	Low /No Oxygen
Pressure (bar)	1	1-10	1
Stoichiometric Ratio	>1	<1	0
Principle Outputs (Products) ***Products:***	**Heat & Combustion Products only**	**Lean Syngas**	**Char + Liquids + Rich Syngas (dirty)**
Gases:	Combustion Products Only *(No Syngas)*	Combustible Lean Syngas	Combustible Rich Syngas
Liquids:	No liquid products *(scrubber waste only)*	0-20% Liquid product, *(plus scrubber waste)*	Liquids (products & waste), *(plus scrubber waste)*
Solids:	High ash waste, No targeted products	Low char, High Ash waste (char <10% of feed by mass)	High quality but expensive biochar (~30% of feed by mass)
Principle Gas Components	**CO_2 and H_2O,** O_2, N_2 + Other gases e.g., SO_x, NO_x, etc.	**CO and H_2, N_2, CO_2**, CH_4, H_2O, + Other minor gases	**CO and H_2**, + hydrocarbons, H_2O, CO_2, CH_4 + Other minor gases including nitrogen compounds, dioxins and furans
By-Products / Waste *(throughput inefficiencies)*	Toxic bottom ash or slag to dispose, High volumes scrubber waste	Toxic Bottom Ash to dispose, High volumes scrubber waste	Tars, resins, oils, pyrolysis water (plus, syngas scrubber waste)
CAPEX	**High** Due to extensive off-gas scrubbing requirements	**Moderate** Scalable with moderate off-gas cleaning requirements	**High** Due to limited reactor scale-up, requiring multiple units to achieve scale of operation
OPEX	**Moderate** High cost for gas scrubbing reagents and disposal of the resulting waste streams	**Moderate**	**High** High maintenance and high number of operating personnel

Thermal Treatment:

Incineration vs Gasification Vs Pyrolysis

Environmental Performance



ENVIRONMENTAL PERFORMANCE Design Factors	Incineration *(combustion, excess oxygen)*	Conventional Air-blown Gasification *(partial oxidation)* *(air-blown= high N_2)*	Conventional Pyrolysis *(low/no Oxygen)*
Off-gas volume to be treated	Very high	High	Moderate
General Environmental Performance	Lowest	Lower key advantage over combustion is lower NOx formation	Better (if bio-oils are dealt with correctly)
Linear / Circular Economy *(Resource Recovery)*	Linear, Poorest LCA single use of resources	Linear, Poor LCA syngas linear due to dilution with N_2, marginal resource recovery as charcoal	Circular syngas linear due to tar contamination, some resource recovery as biochar, bio-oils difficult to process / limited uses
Dispatchable Energy	No – heat must be used immediately via steam cycle (base load)	No – heat must be used immediately via steam cycle (base load)	Yes – via syngas storage and bio-oils, but multiple units required to scale with, no increase in thermal efficiency.
GHG Emissions (incl CO_2)	Very High	High	Low to carbon negative
Carbon Abatement / Sequestration	None all carbon infeed is converted to CO_2	Low 10% Carbon in feed converted to charcoal, remainder to CO_2	High ~50% Carbon in feed reports to solid char
Harmful Pollutant Emissions *(Particulates, Heavy Metals, VOC's, POPs, NOx, Dioxins & Furans)*	Highest Off-gas requires significant treatment	Moderate Lower off-gas volume to treat than incineration but still large, lower NOx	Moderate Low off-gas volume to treat, syngas still contains tars, dioxins and furans. Hence specially designed combustion systems required to destroy tars, dioxins & furans.
Emission Control Systems (ECS)	Critically Dependent on Pollution Controls Multiple additives required to scrub pollutants, generating further waste streams for disposal, plus large unit operation to treat the high gas volume	Highly Dependent on Pollution Controls (Similar to incineration, but lower gas volume to treat and lower NOx)	Highly Dependent on Pollution Controls Syngas requires further pre-combustion cleaning before use. ECS requirements scale dependent. Complicated with halides and dioxins and furans.
Water Usage	High Evaporative cooling and make-up water for the steam system	High (Same as incinerators)	Low Water consumed for capture of bio-oils and indirect cooling
Problematic Liquid Produced (Oils, Tars, Resins, Water)	Yes Boiler blow-down brine and evaporative cooling system purge water plus scrubber water (if a wet system is utilised)	Yes Up & down draft gasifiers generate tars plus spent scrubber water	Yes Alot of tar and oil by-products, reported beneficial wood vinegar, plus scrubber water
Bottom & Fly Ash for Disposal *(Potentially Toxic Solid Waste)*	Significant Ash dam required, portion of the ash is super-fine	High Ash dam required	No Ash Ash remains with the biochar

Comparing options and technologies – how can you compare the “apples, pears and bananas” out there?

1. **Consult an expert**

2. RMIT BTAS Tool (under development) – designed primarily for water utilities and councils for biosolids/co-feeds (FOGO etc)

Australian Pyrolysis and Gasification Technologies

commonly used for making *biochar:*

Some example ANZBIG members (and few from OS)

Available technologies – High level overview

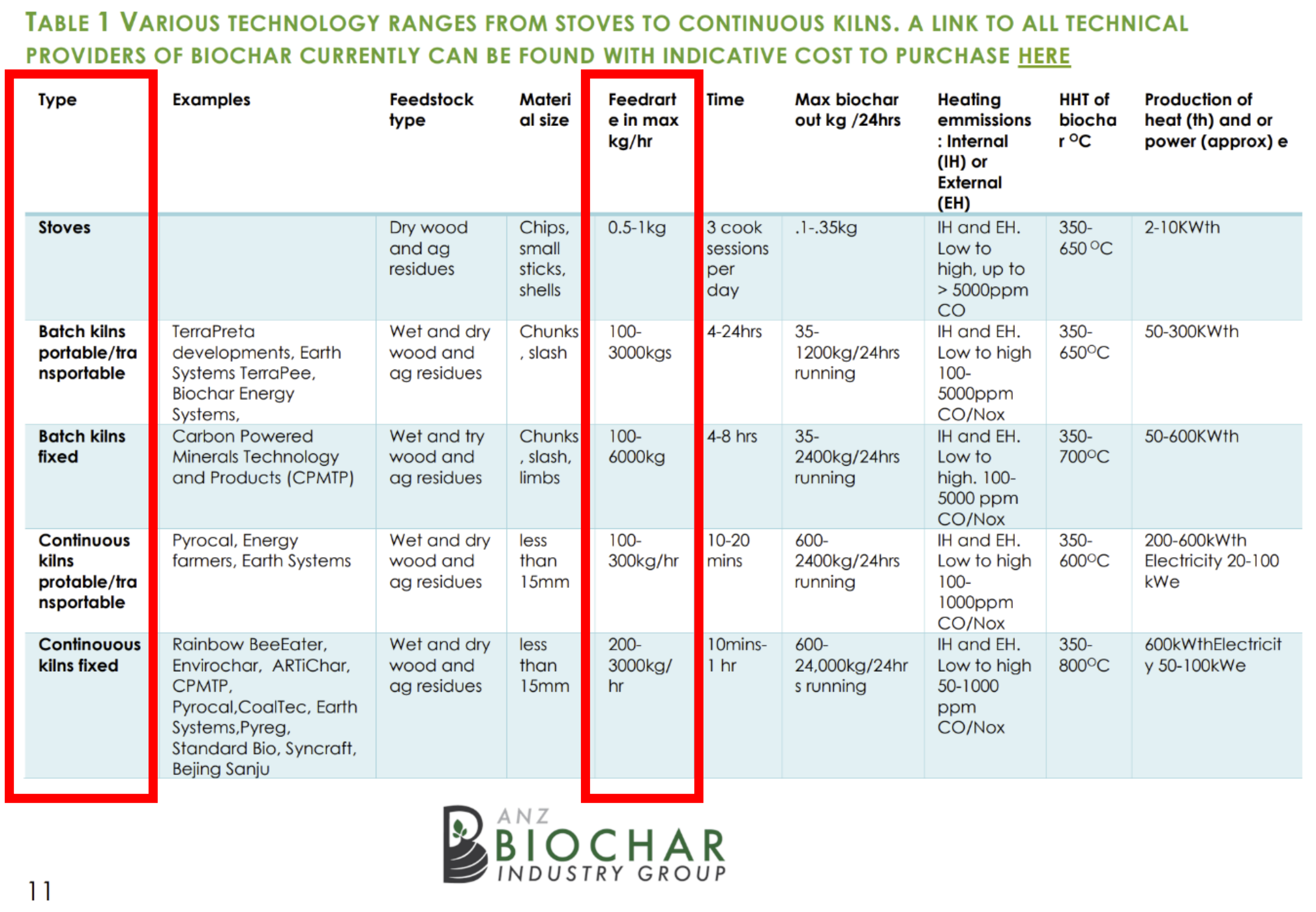


TABLE 1 VARIOUS TECHNOLOGY RANGES FROM STOVES TO CONTINUOUS KILNS. A LINK TO ALL TECHNICAL PROVIDERS OF BIOCHAR CURRENTLY CAN BE FOUND WITH INDICATIVE COST TO PURCHASE HERE

Type	Examples	Feedstock type	Material size	Feedrarte in max kg/hr	Time	Max biochar out kg /24hrs	Heating emmissions : Internal (IH) or External (EH)	HHT of biochar °C	Production of heat (th) and or power (approx) e
Stoves		Dry wood and ag residues	Chips, small sticks, shells	0.5-1kg	3 cook sessions per day	.1-.35kg	IH and EH. Low to high, up to > 5000ppm CO	350-650 °C	2-10KWth
Batch kilns portable/transportable	TerraPreta developments, Earth Systems TerraPee, Biochar Energy Systems,	Wet and dry wood and ag residues	Chunks, slash	100-3000kgs	4-24hrs	35-1200kg/24hrs running	IH and EH. Low to high 100-5000ppm CO/Nox	350-650°C	50-300KWth
Batch kilns fixed	Carbon Powered Minerals Technology and Products (CPMTP)	Wet and try wood and ag residues	Chunks, slash, limbs	100-6000kg	4-8 hrs	35-2400kg/24hrs running	IH and EH. Low to high. 100-5000 ppm CO/Nox	350-700°C	50-600KWth
Continuous kilns protable/transportable	Pyrocal, Energy farmers, Earth Systems	Wet and dry wood and ag residues	less than 15mm	100-300kg/hr	10-20 mins	600-2400kg/24hrs running	IH and EH. Low to high 100-1000ppm CO/Nox	350-600°C	200-600kWth Electricity 20-100 kWe
Continouous kilns fixed	Rainbow BeeEater, Envirochar, ARTiChar, CPMTP, Pyrocal,CoalTec, Earth Systems,Pyreg, Standard Bio, Syncraft, Bejing Sanju	Wet and dry wood and ag residues	less than 15mm	200-3000kg/hr	10mins-1 hr	600-24,000kg/24hrs running	IH and EH. Low to high 50-1000 ppm CO/Nox	350-800°C	600kWthElectricity 50-100kWe

ANZ BIOCHAR INDUSTRY GROUP

- More info via ANZBIG members resources webpage

www.anzbig.org

#1. (very) **Small-Scale, Low Cost S**ystems

(commonly biochar only, no/limited co-recovery of other products)

Typically batch, but new 'continuous' systems emerging

2. **Mobile batch** systems – air curtains

(typically biochar only, waste management focus, no/limited co-recovery of other products (syngas/wood vinegar)

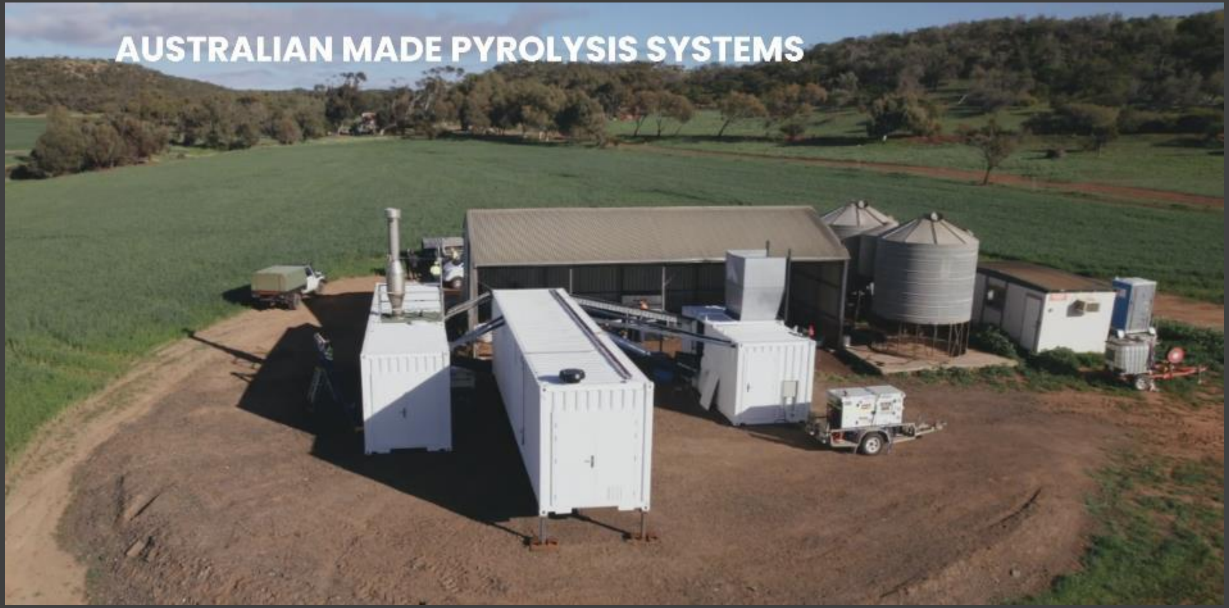
Available technologies – Australian commercial systems

EARTH SYSTEMS
Environment | Water | Sustainability

FIGURE 13 CHARMAKER CONTINUOUS TECHNOLOGY DESIGNED AND BUILT BY EARTH SYSTEMS PROCESSES A RANGE OF FEEDSTOCKS.

Available technologies – Australian commercial systems

Mobile and Stationary systems



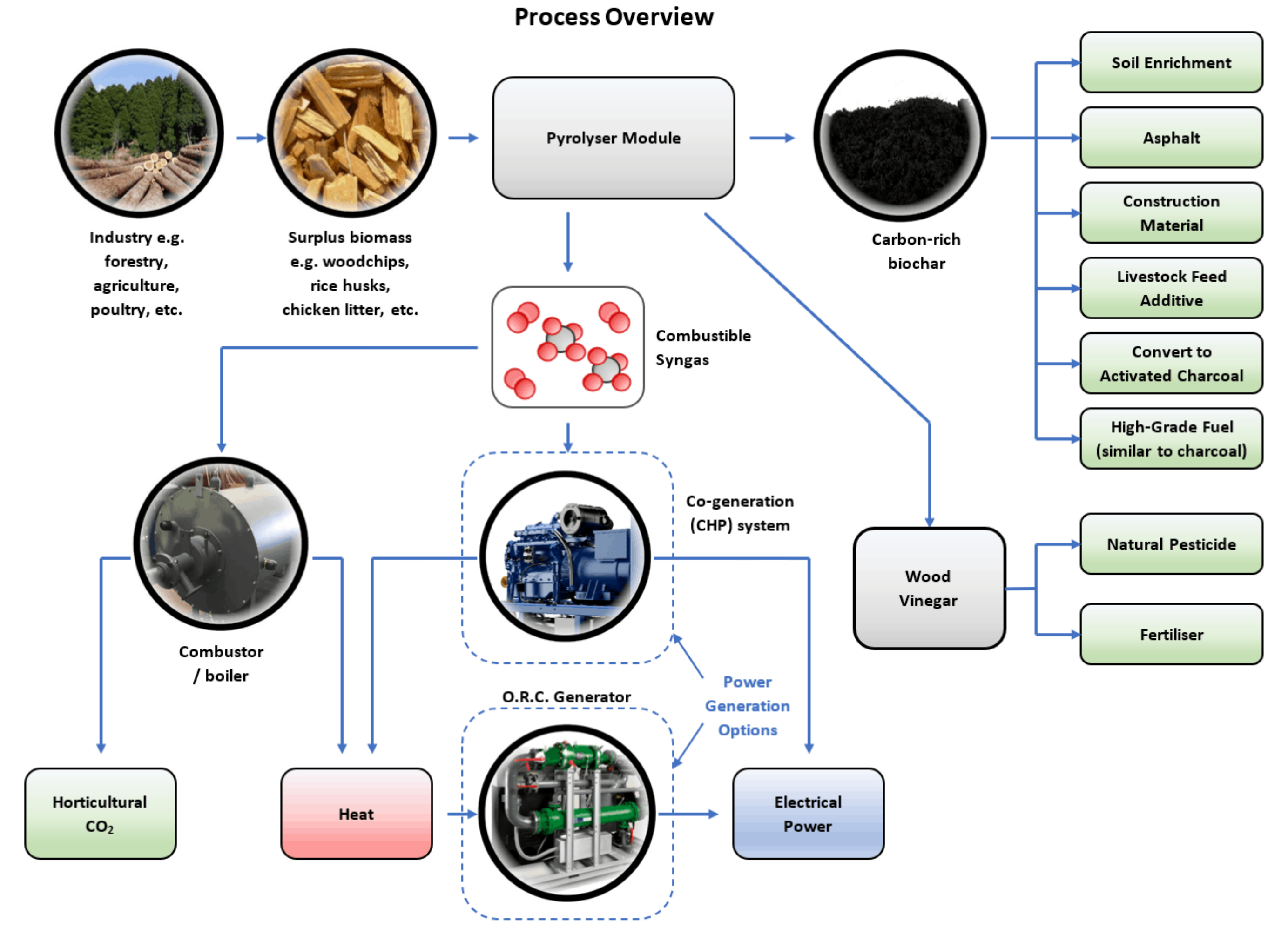
Energy Farmers AUSTRALIA

Available technologies – Australian commercial systems

FIGURE 14 CARBON POWERED MINERAL COMPLEX FACTORY. LARGER SYSTEM SET UP ALSO NOW DEPLOYED.

CPMTP
Carbon Powered Mineral Technology & Products

Available technologies – Australian commercial systems



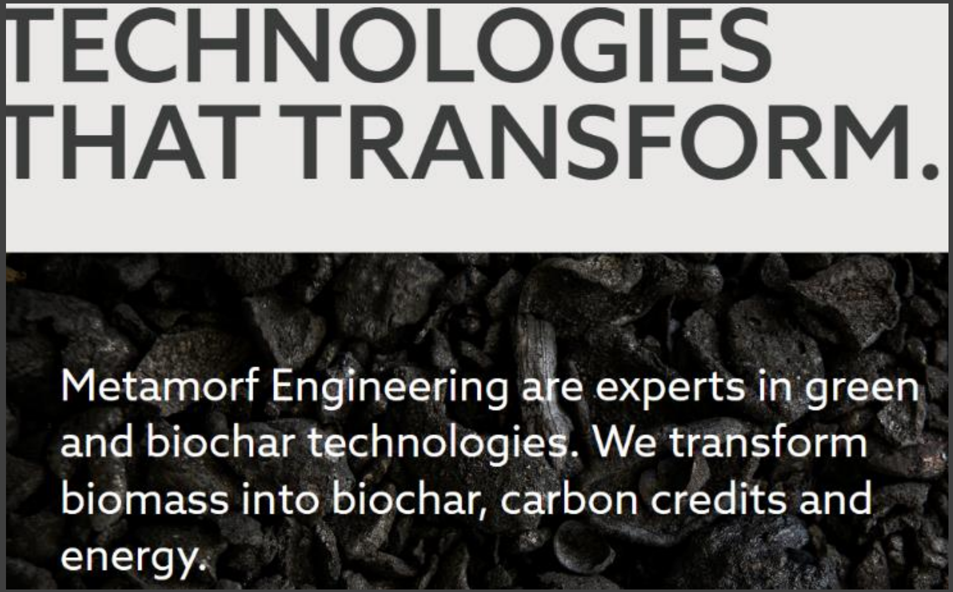
SDA Engineering

Available technologies – Australian commercial systems

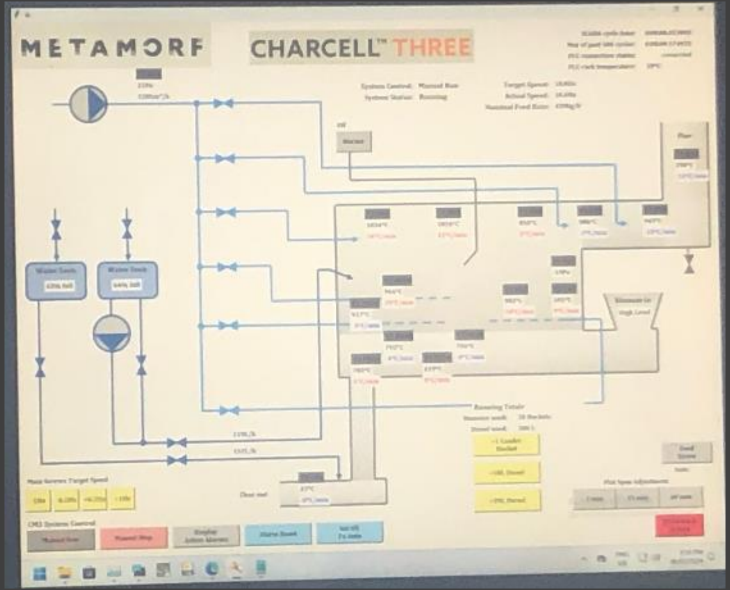
METAMORF™

Metamorf Engineering
[Incorporating SDA Engineering]

SDA Engineering


TECHNOLOGIES THAT TRANSFORM.

Metamorf Engineering are experts in green and biochar technologies. We transform biomass into biochar, carbon credits and energy.



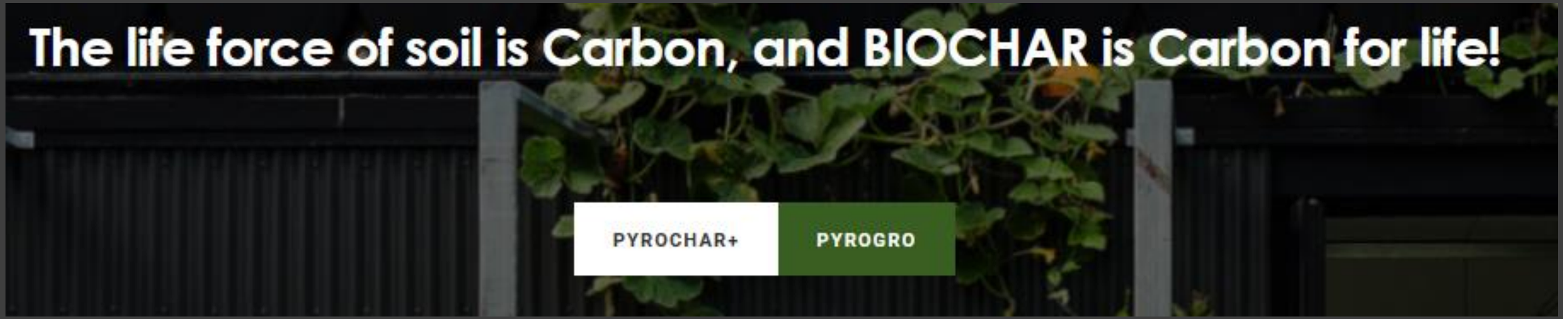
Available technologies – Australian commercial systems

ALL THINGS BIOCHAR
+
futurefoodsystem

Russell Burnett – All Things Biochar

(ANZBIG Biochar Hall of Fame)

Elmore Victoria



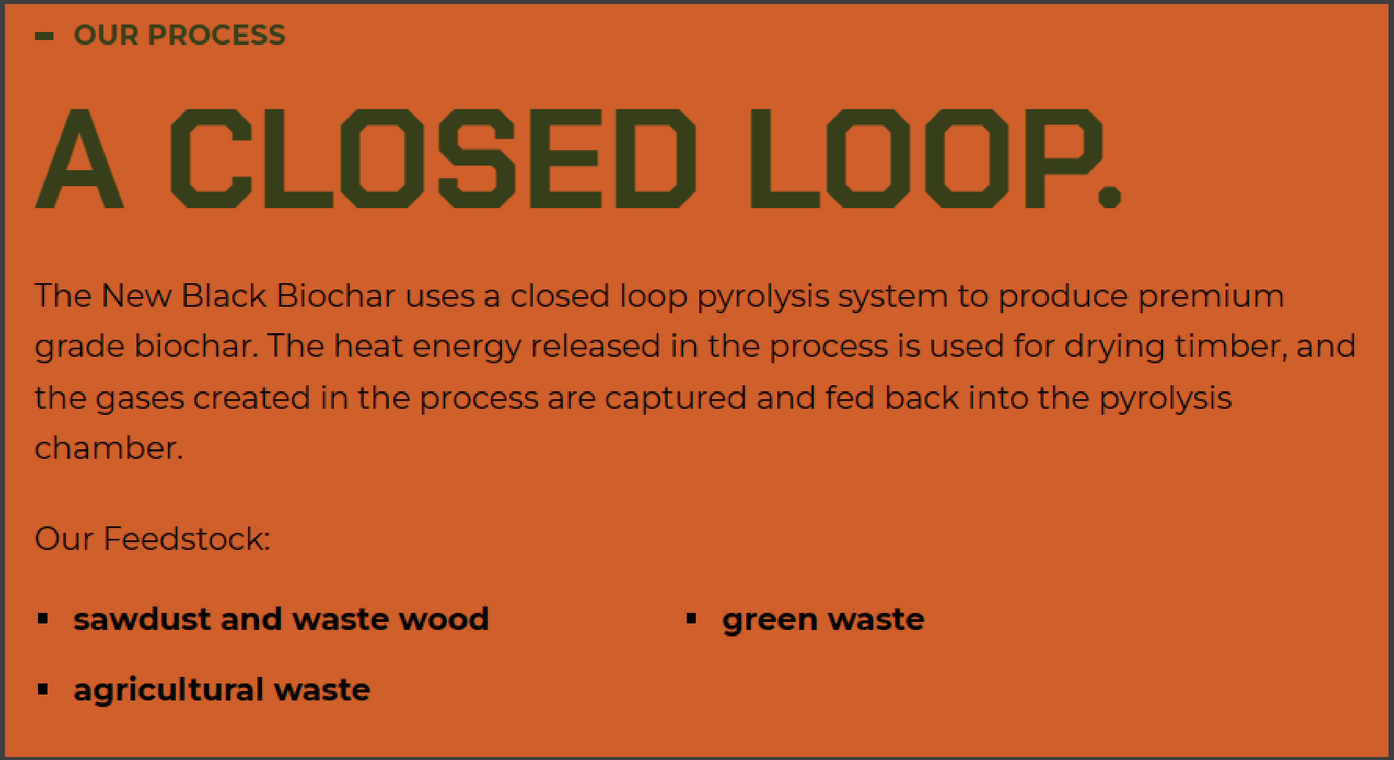
The life force of soil is Carbon, and BIOCHAR is Carbon for life!

Australian Technologies: The New Black, Glen Huon Tasmania

THE
NEW
BLACK

WE STABILISE & STORE CARBON.

We transform waste organic material into a valuable resource, while sequestering carbon for the long term.



OUR PROCESS

A CLOSED LOOP.

The New Black Biochar uses a closed loop pyrolysis system to produce premium grade biochar. The heat energy released in the process is used for drying timber, and the gases created in the process are captured and fed back into the pyrolysis chamber.

Our Feedstock:

- **sawdust and waste wood**
- **agricultural waste**
- **green waste**

Available technologies – Australian commercial systems

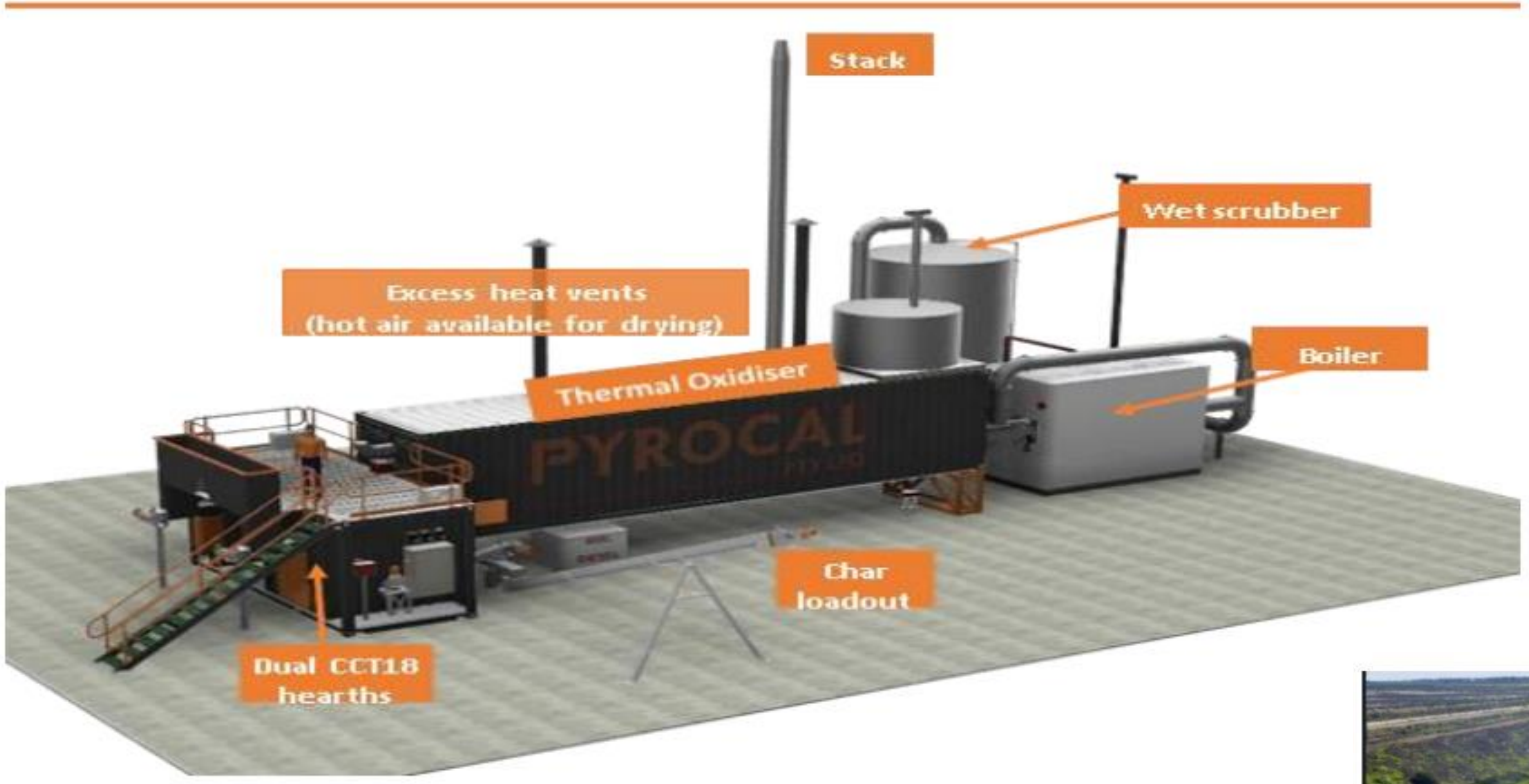


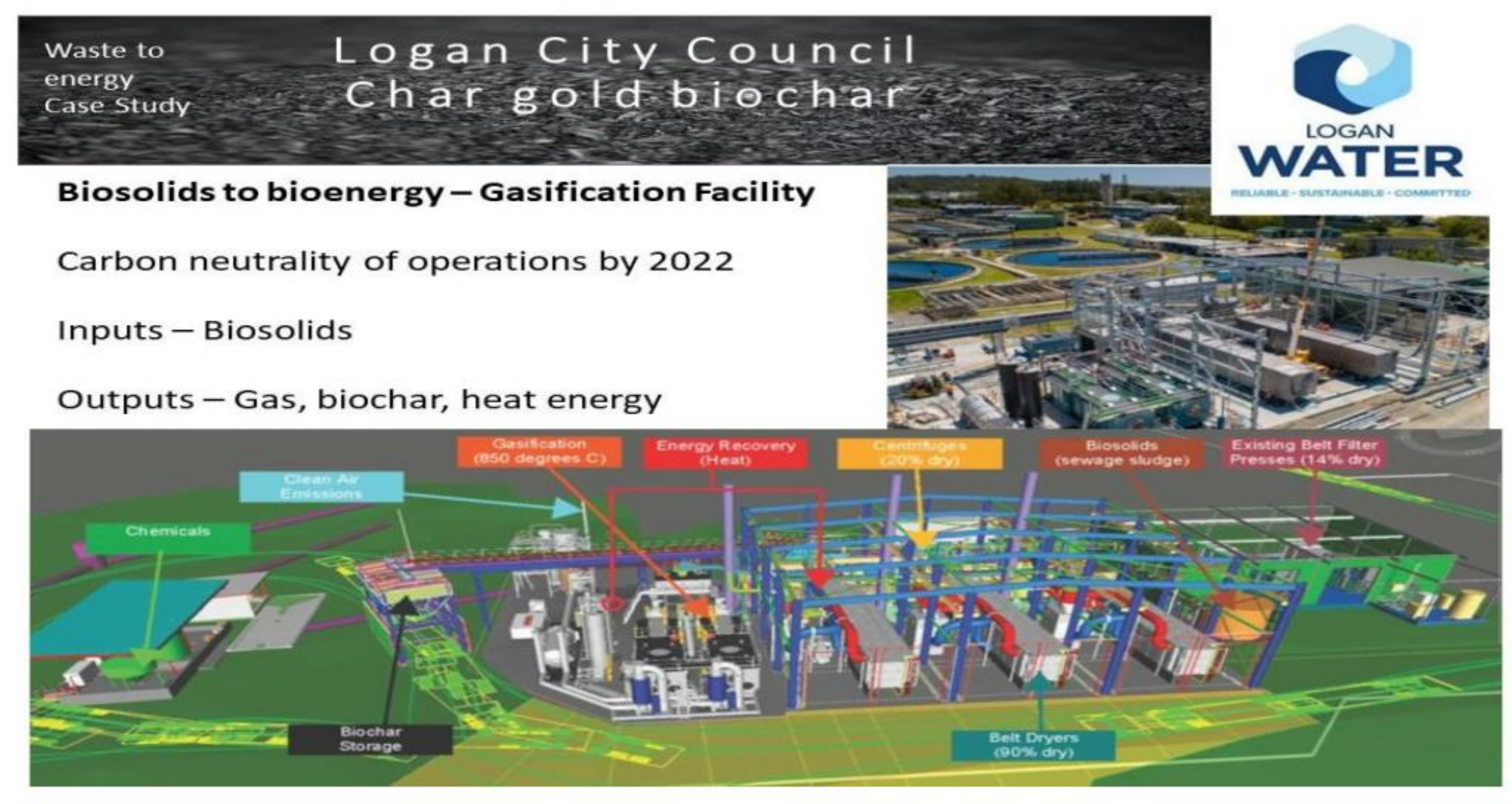
FIGURE 9 DESIGN OF JEFFRIES COMPOST – PYROCAL CCT TWIN SYSTEM (EXTRACTED FROM PRESE
ANZBC18)

PYROCAL PTY LTD

FIGURE 8JEFFRIES PYROCAL SYSTEM OPERATING IN 2022

Pyrocal – Jeffries (SA) – design for 3000 tpa biochar

Available technologies – Australian commercial systems



Waste to
energy
Case Study

Logan City Council
Char gold biochar

LOGAN
WATER
RELIABLE · SUSTAINABLE · COMMITTED

Biosolids to bioenergy – Gasification Facility

Carbon neutrality of operations by 2022

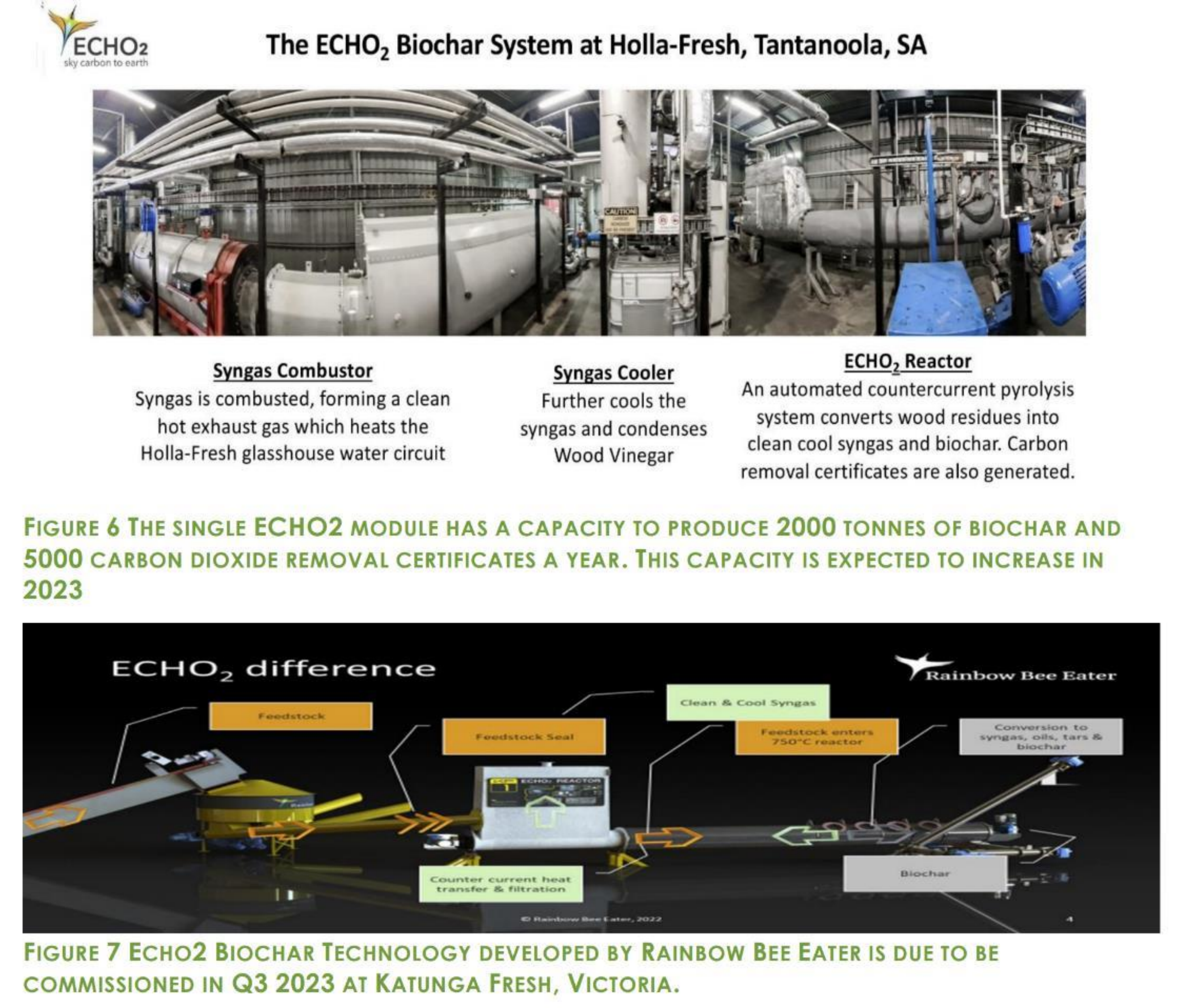
Inputs – Biosolids

Outputs – Gas, biochar, heat energy

PYROCAL
PTY LTD

Pyrocal / Downer EDI –
Logan Water biosolids project
(an ARENA project)

Available technologies – Advanced commercial systems



ECHO2
sky carbon to earth

The ECHO$_2$ Biochar System at Holla-Fresh, Tantanoola, SA

Syngas Combustor
Syngas is combusted, forming a clean hot exhaust gas which heats the Holla-Fresh glasshouse water circuit

Syngas Cooler
Further cools the syngas and condenses Wood Vinegar

ECHO$_2$ Reactor
An automated countercurrent pyrolysis system converts wood residues into clean cool syngas and biochar. Carbon removal certificates are also generated.

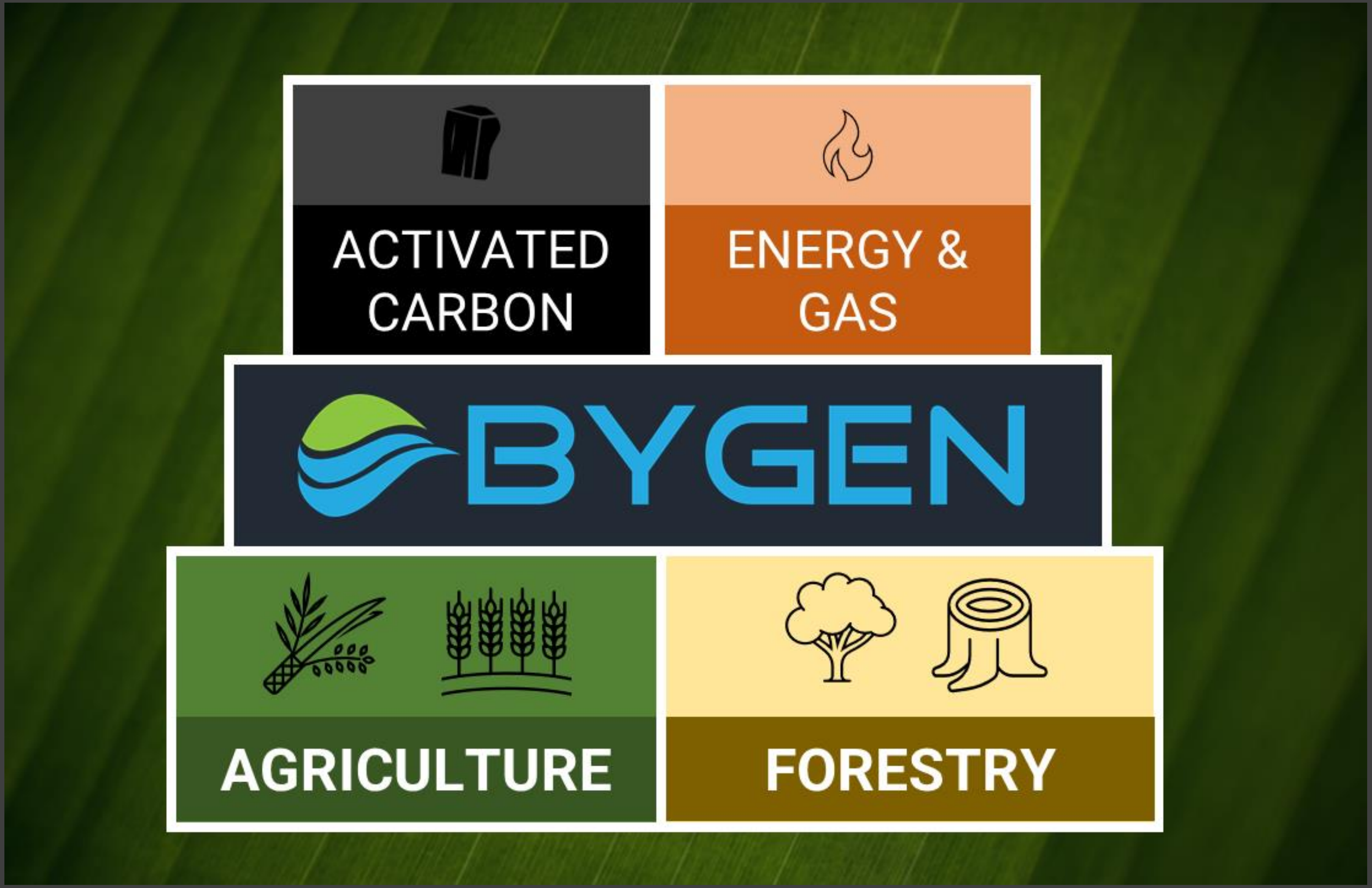
FIGURE 6 THE SINGLE ECHO2 MODULE HAS A CAPACITY TO PRODUCE 2000 TONNES OF BIOCHAR AND 5000 CARBON DIOXIDE REMOVAL CERTIFICATES A YEAR. THIS CAPACITY IS EXPECTED TO INCREASE IN 2023

FIGURE 7 ECHO2 BIOCHAR TECHNOLOGY DEVELOPED BY RAINBOW BEE EATER IS DUE TO BE COMMISSIONED IN Q3 2023 AT KATUNGA FRESH, VICTORIA.

Rainbow Bee Eater

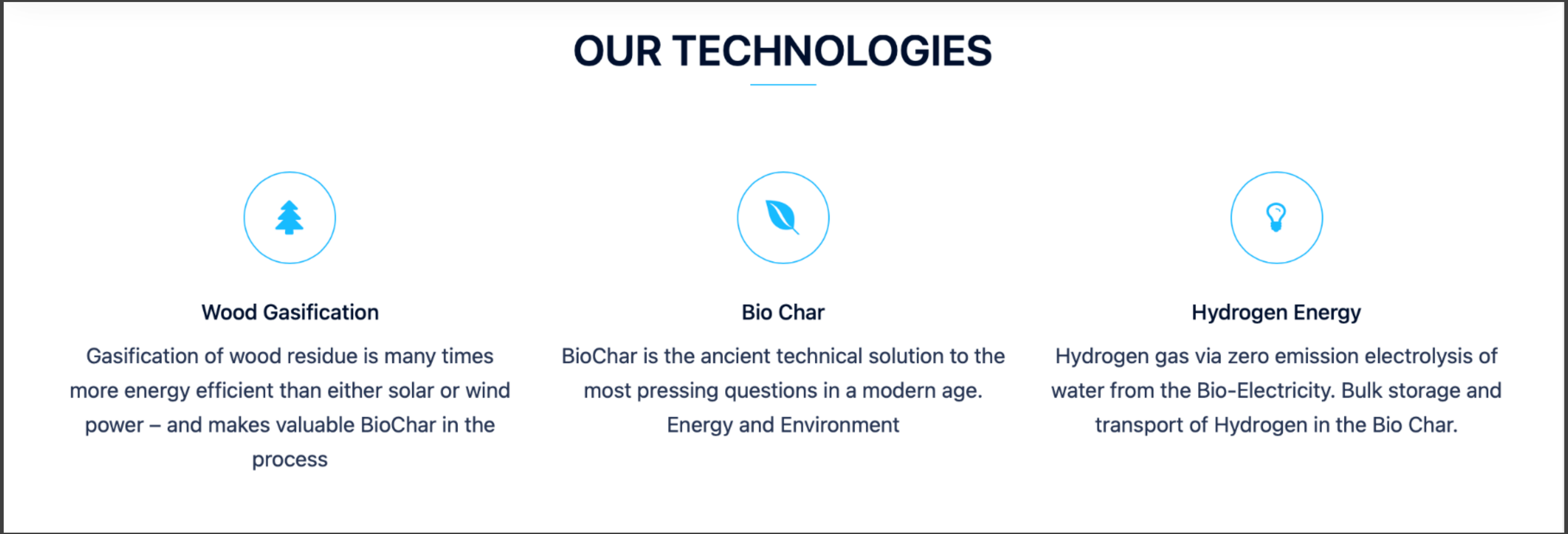
OPTIMAL

Available technologies – Australian commercial systems



Low Temperature Activation (LTA) Process

Available technologies – Australian commercial systems



OUR TECHNOLOGIES

Wood Gasification

Gasification of wood residue is many times more energy efficient than either solar or wind power – and makes valuable BioChar in the process

Bio Char

BioChar is the ancient technical solution to the most pressing questions in a modern age. Energy and Environment

Hydrogen Energy

Hydrogen gas via zero emission electrolysis of water from the Bio-Electricity. Bulk storage and transport of Hydrogen in the Bio Char.

H2BIOGEN
Our Renewable Future

Available technologies – Chartech (NZ)

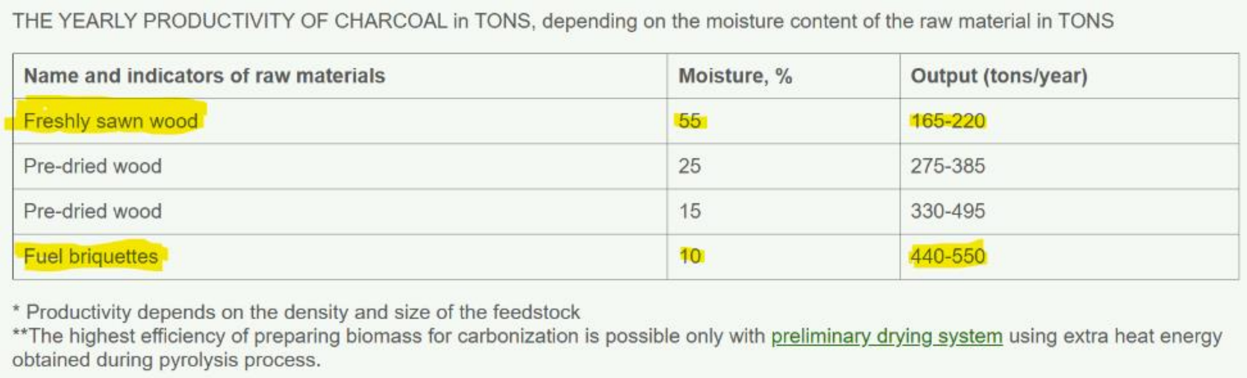
CharTech

EKKO Carbonization Furnace

An environmentally friendly furnace for carbonization of raw materials, using low speed pyrolysis, to produce high-grade charcoal. Extra heat can be used for preliminary drying of the raw material or for other purposes.

- ultra-high temperature
- Automated control systems
- Highly Efficient
- Low electricity consumption

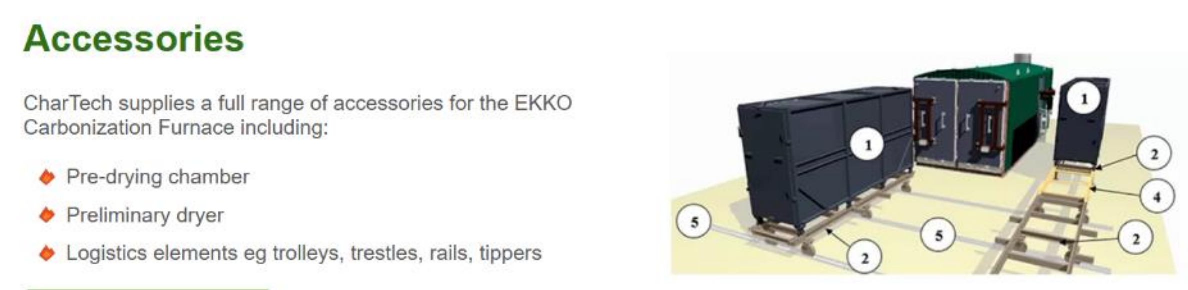
Product Details



THE YEARLY PRODUCTIVITY OF CHARCOAL in TONS, depending on the moisture content of the raw material in TONS

Name and indicators of raw materials	Moisture, %	Output (tons/year)
Freshly sawn wood	55	165-220
Pre-dried wood	25	275-385
Pre-dried wood	15	330-495
Fuel briquettes	10	440-550

* Productivity depends on the density and size of the feedstock
**The highest efficiency of preparing biomass for carbonization is possible only with preliminary drying system using extra heat energy obtained during pyrolysis process.



Accessories

CharTech supplies a full range of accessories for the EKKO Carbonization Furnace including:

- Pre-drying chamber
- Preliminary dryer
- Logistics elements eg trolleys, trestles, rails, tippers

Some examples from Europe & US
(a few are now available here)

Available technologies – Some examples from Europe

Biochar manufacturing equipment

Examples for industrial equipment producing Biochar in EBC quality

Biochar manufacturing equipment

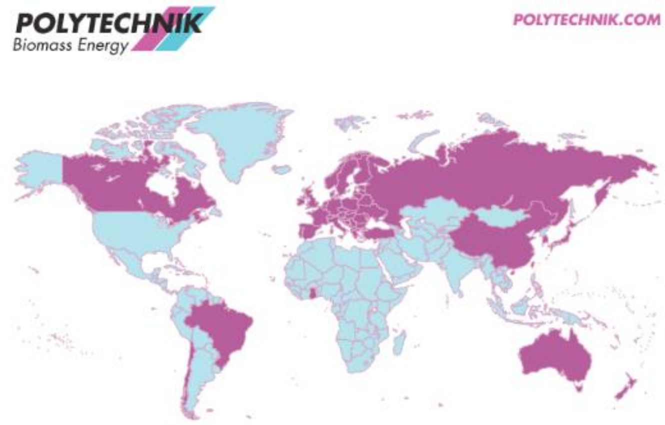
Further examples for industrial equipment producing Biochar in EBC quality

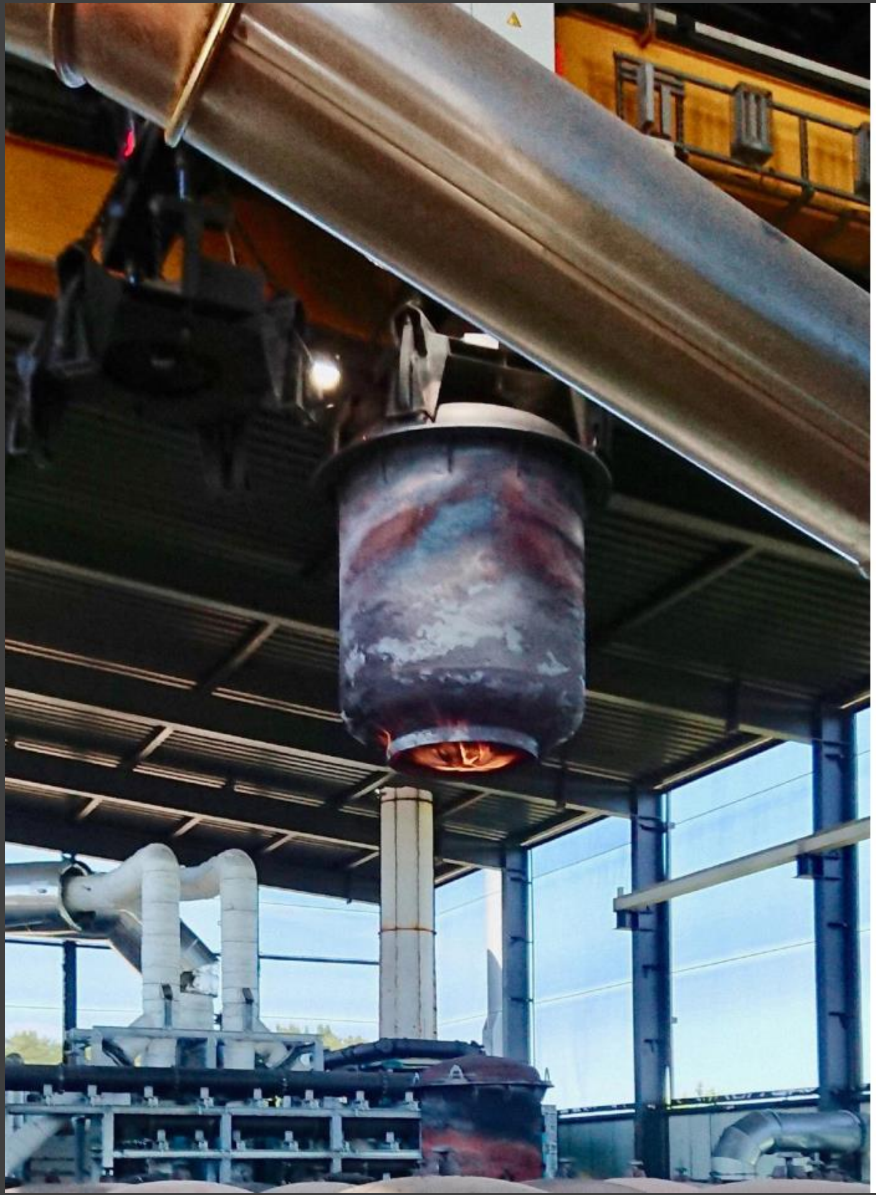
More info:

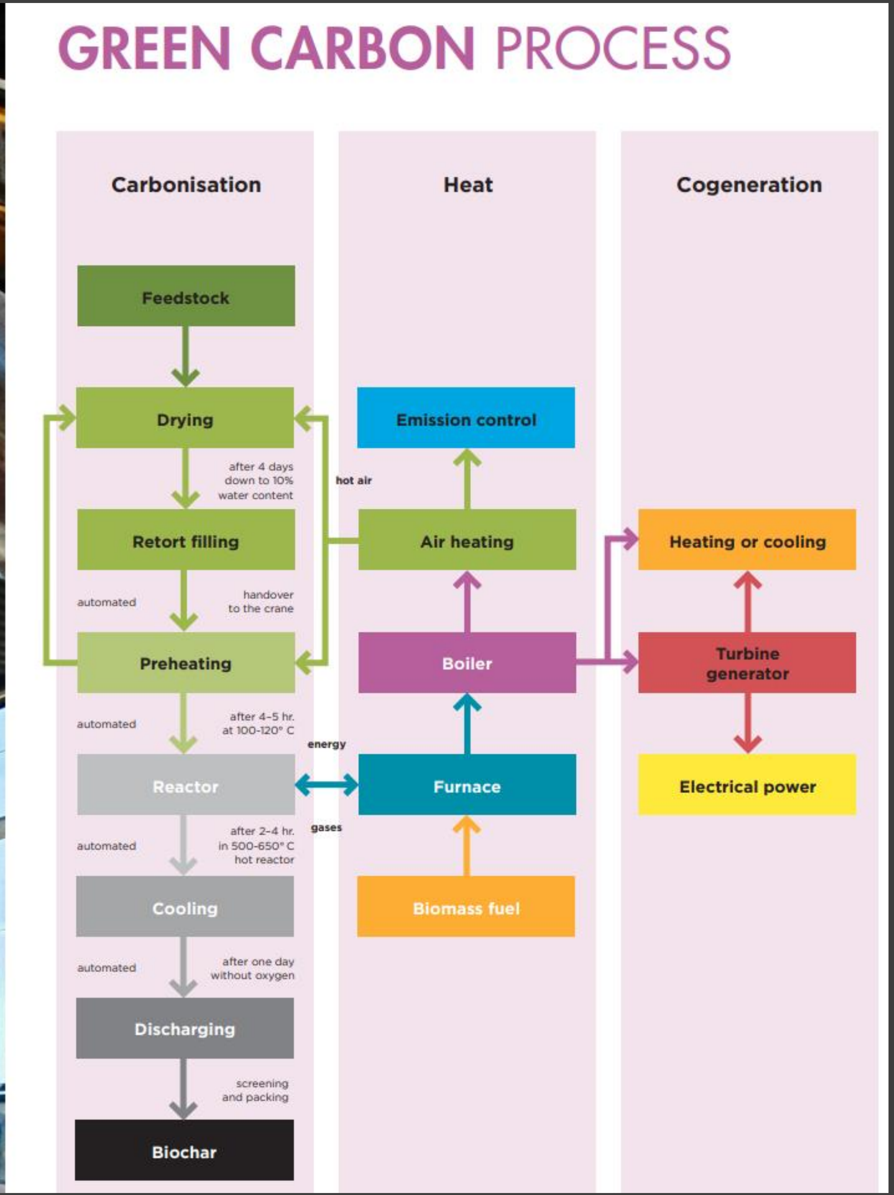
EBIC (European Biochar Industry Consortium)

Available technologies (OS) – **Polytechnik** (Global, Austrian Base, NZ)

POLYTECHNIK
Biomass Energy







GREEN CARBON PROCESS

Carbonisation

Feedstock

Drying

after 4 days down to 10% water content

Retort filling

automated

handover to the crane

Preheating

automated

after 4-5 hr. at 100-120° C

Reactor

automated

after 2-4 hr. in 500-650° C hot reactor

Cooling

automated

after one day without oxygen

Discharging

screening and packing

Biochar

hot air

energy

gases

Heat

Emission control

Air heating

Boiler

Furnace

Biomass fuel

Cogeneration

Heating or cooling

Turbine generator

Electrical power

Available technologies (OS) – **Polytechnik** (Austria, NZ base)

HIGH-TECH PYROLYSIS PLANT

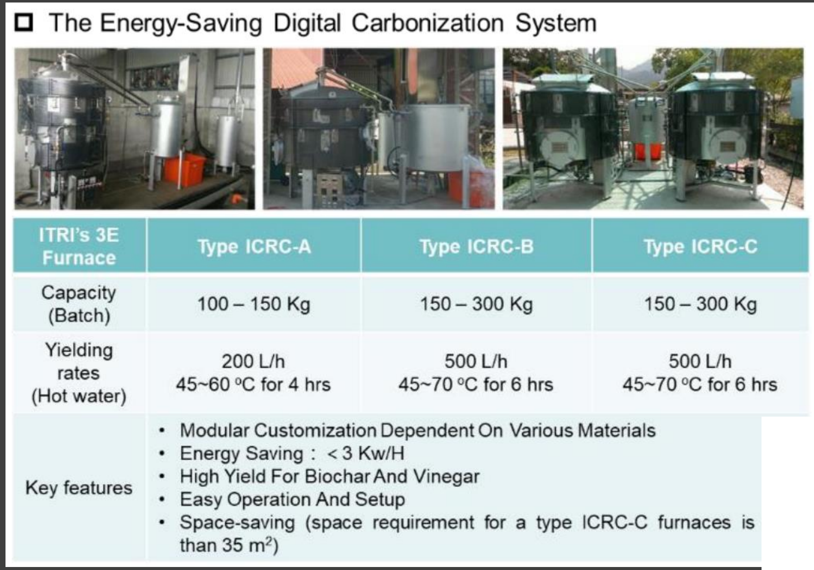
Polytechnik's pyrolysis plants offer great flexibility — different types of feedstock can be used to produce large amounts of high-quality charcoal products. At the same time, the plant also produces carbon-neutral heat and power (CHP).

The world's first fully automated pyrolysis plant not only produces high-quality and certified carbon products from biomass waste, but it also produces energy with emissions well below the European Union's strict limits. One possible technology that can be combined with the Green Carbon process is Polytechnik's ORC (Organic Rankine Cycle) plant.

The CHP plant includes fully automated fuel storage and handling systems that feed the combustion system of the plant with biomass. The biomass is completely incinerated and the energy released is used to heat the heat transfer medium (thermal oil), which supplies high-temperature energy to an ORC unit. The electricity produced by the ORC unit can then be fed into the local grid and the thermal oil/hot water can be used for heating. The entire process is fully automated and can be controlled remotely by both operators and Polytechnik service experts.

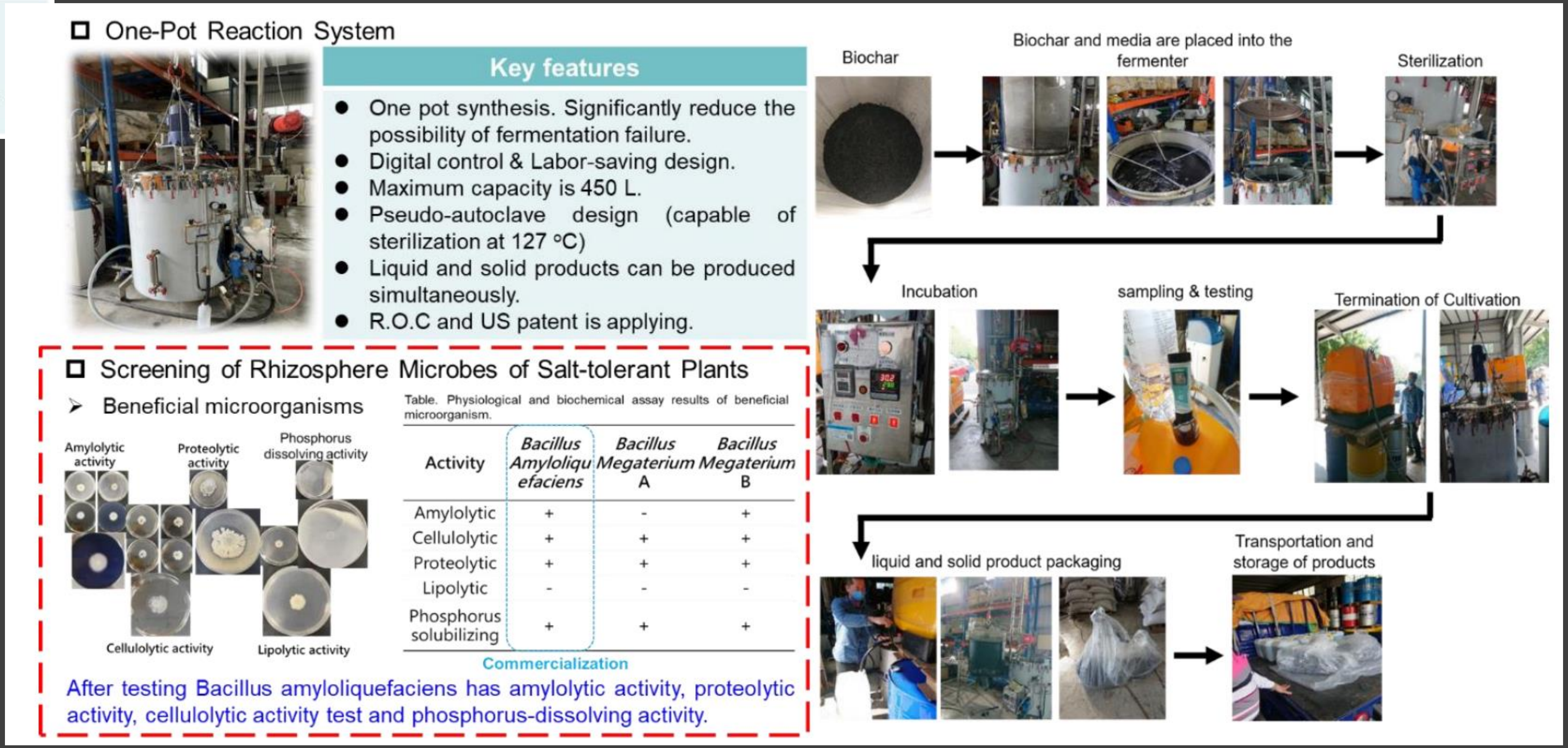
POLYTECHNIK
Biomass Energy

Available technologies (OS) – IRTC (Taiwan)



☐ The Energy-Saving Digital Carbonization System

ITRI's 3E Furnace	Type ICRC-A	Type ICRC-B	Type ICRC-C
Capacity (Batch)	100 – 150 Kg	150 – 300 Kg	150 – 300 Kg
Yielding rates (Hot water)	200 L/h 45~60 °C for 4 hrs	500 L/h 45~70 °C for 6 hrs	500 L/h 45~70 °C for 6 hrs
Key features	• Modular Customization Dependent On Various Materials • Energy Saving : < 3 Kw/H • High Yield For Biochar And Vinegar • Easy Operation And Setup • Space-saving (space requirement for a type ICRC-C furnaces is than 35 m^2)		



☐ One-Pot Reaction System

Key features

- One pot synthesis. Significantly reduce the possibility of fermentation failure.
- Digital control & Labor-saving design.
- Maximum capacity is 450 L.
- Pseudo-autoclave design (capable of sterilization at 127 °C)
- Liquid and solid products can be produced simultaneously.
- R.O.C and US patent is applying.

☐ Screening of Rhizosphere Microbes of Salt-tolerant Plants

➢ Beneficial microorganisms

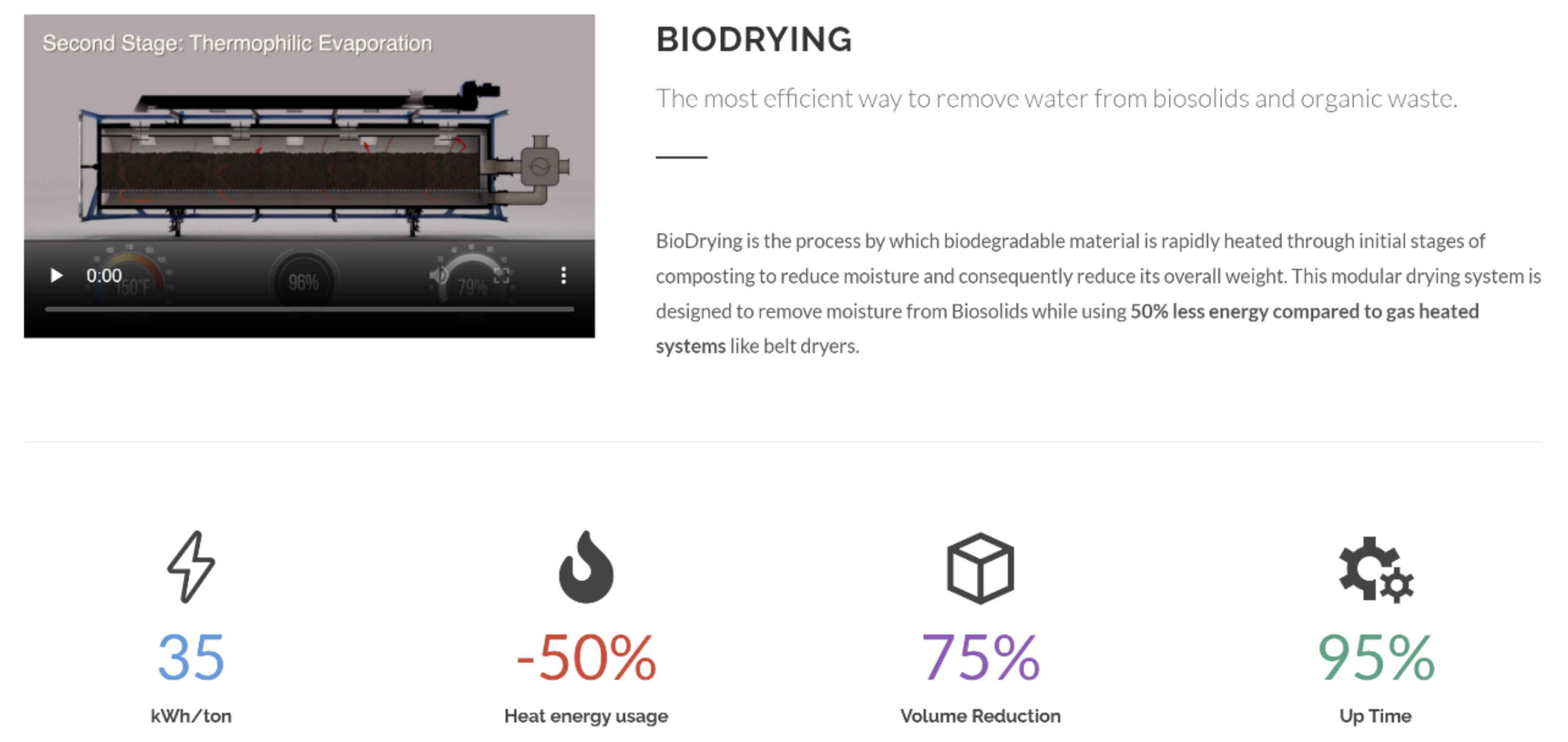
Table. Physiological and biochemical assay results of beneficial microorganism.

Activity	*Bacillus Amyloliquefaciens*	*Bacillus Megaterium* A	*Bacillus Megaterium* B
Amylolytic	+	-	+
Cellulolytic	+	+	+
Proteolytic	+	+	+
Lipolytic	-	-	-
Phosphorus solubilizing	+	+	+

Commercialization

After testing Bacillus amyloliquefaciens has amylolytic activity, proteolytic activity, cellulolytic activity test and phosphorus-dissolving activity.

Drying technologies – Biodrying



BIODRYING

The most efficient way to remove water from biosolids and organic waste.

BioDrying is the process by which biodegradable material is rapidly heated through initial stages of composting to reduce moisture and consequently reduce its overall weight. This modular drying system is designed to remove moisture from Biosolids while using **50% less energy compared to gas heated systems** like belt dryers.

35
kWh/ton

-50%
Heat energy usage

75%
Volume Reduction

95%
Up Time

BIOFORCETECH
Corporation

Bioforcetech (USA)


Installation at Redwood City, CA

Emerging Australian Technologies

What's next?

Emerging Technologies in Rapidly Changing Times…

~30 years ago (1994)

- Nokia
- Motorola etc

✗

2024

+30 Years (2054)

??

.....Markets reward *capability to adapt* to disruptive changes and add *value*

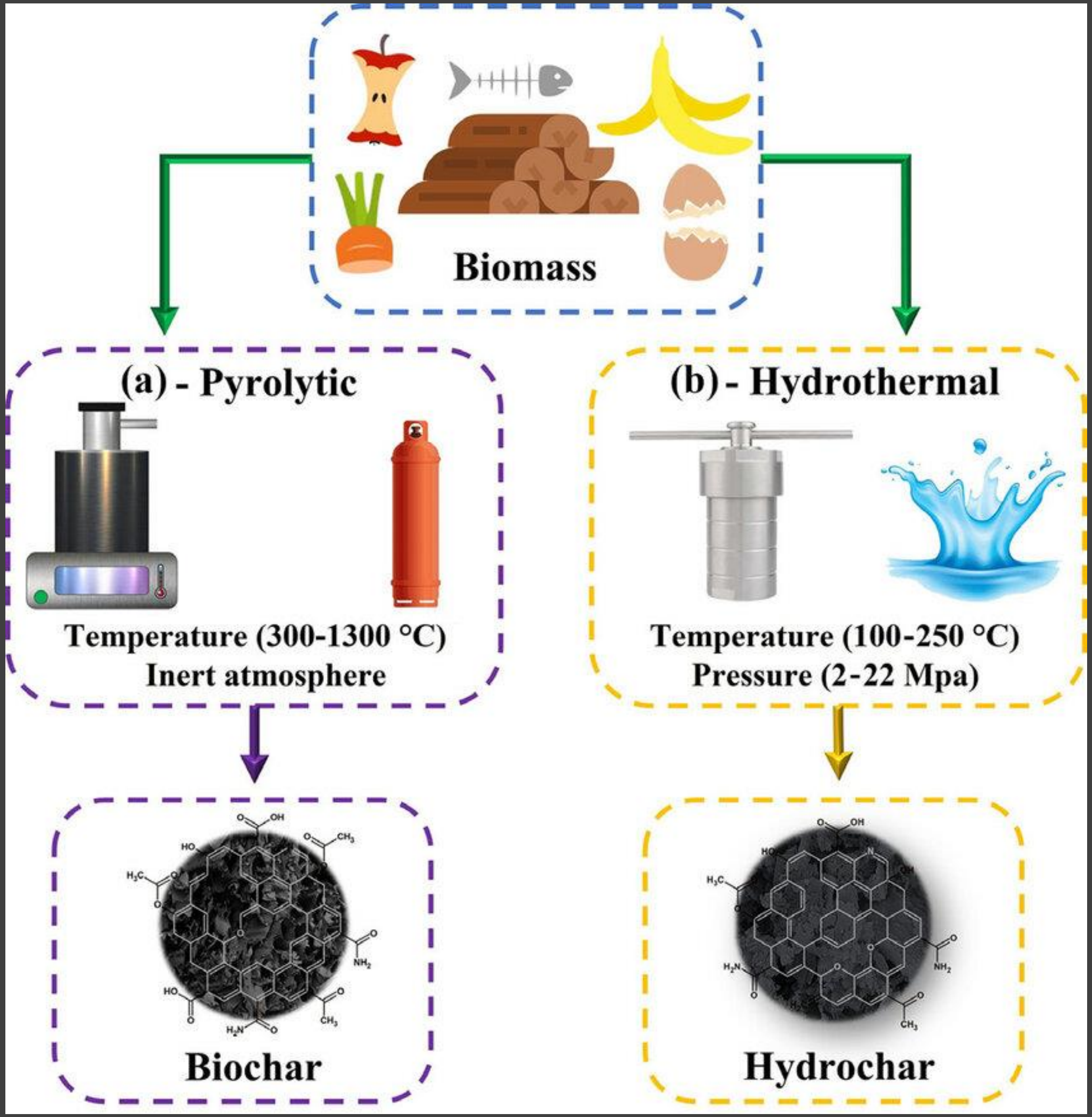
Emerging technologies – Pyroco (Biosolids / Co-feeds)

“Pyroco’ Technology being commercialized by RMIT in partnership with Victorian Water Utilities

RMIT UNIVERSITY

South East Water

Hydrothermal (‘wet’ pyrolysis) systems – HTC/HTL



‘Wet’ Wastes → ***“hydrochars”***

High char yield

High pressure (scale challenges?)

Lower temp

Lower stability (short term)

Yet to be significantly commercialized

Potential synergies with conventional thermal pyrolysis fro sludges/wet wastes (pre-step?)

Emerging Australian technologies: SEATA Group

Energy and beyond – Advanced systems for syngas derivatives including hydrogen, biofuels, biochemicals, bioplastics etc.

SEATA

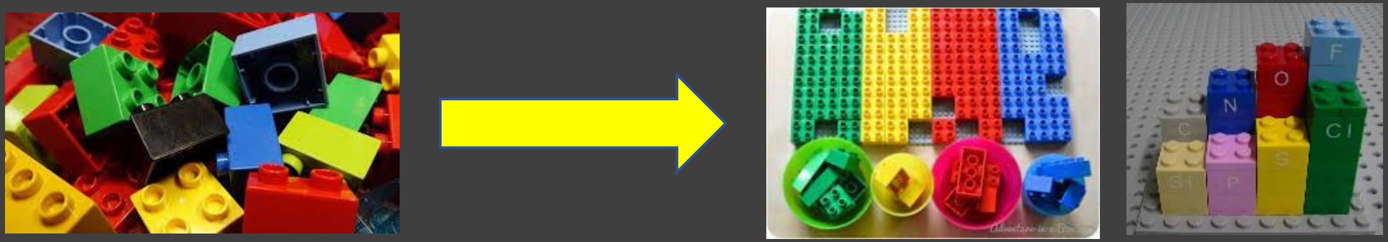
Deconstructing the world's problems
to create carbon negative solutions

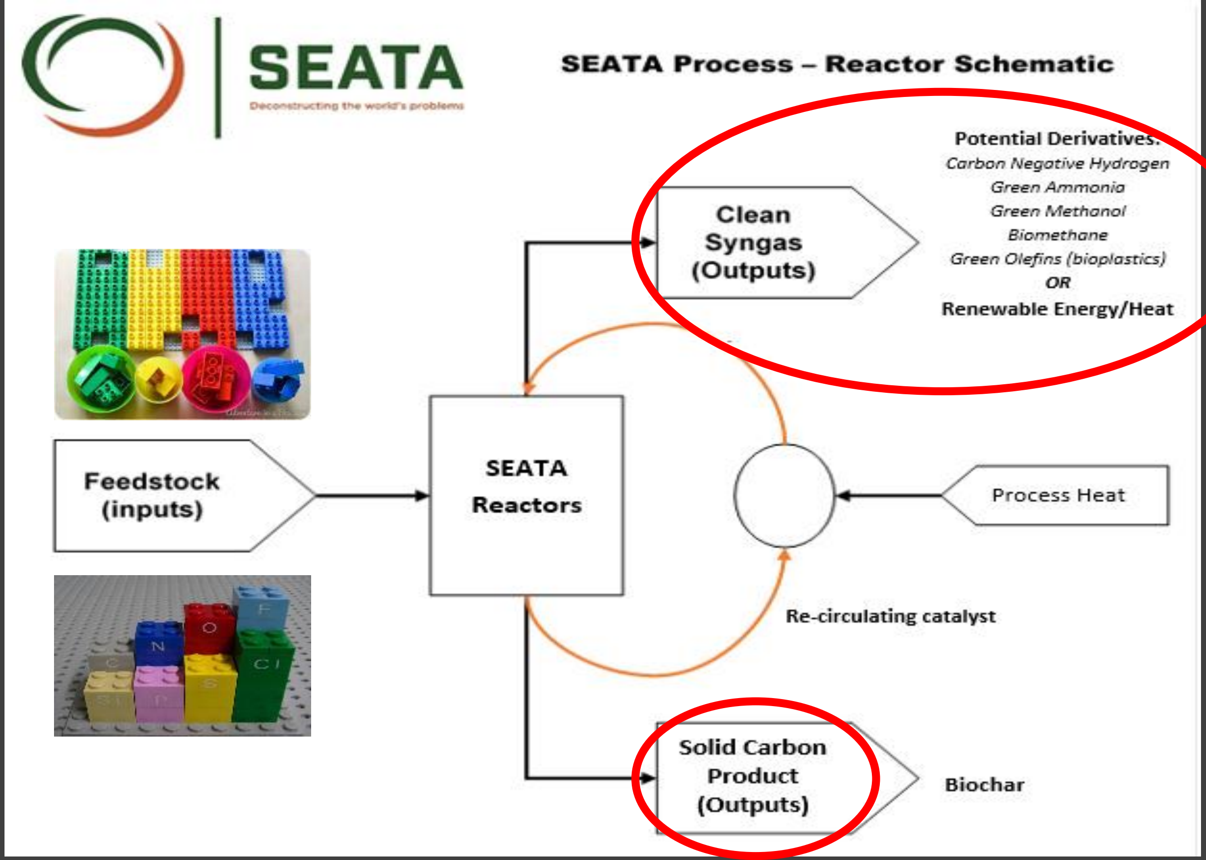
The next generation:

Chemical & Thermal Looping (CTL) – Pyrolysis + Partial Gasification

Going beyond burning syngas for heat and energy…..for industrial scale

We **deconstruct** wasted biomass and other carbon sources into valuable chemical **building blocks for circular fuels, chemicals and materials**



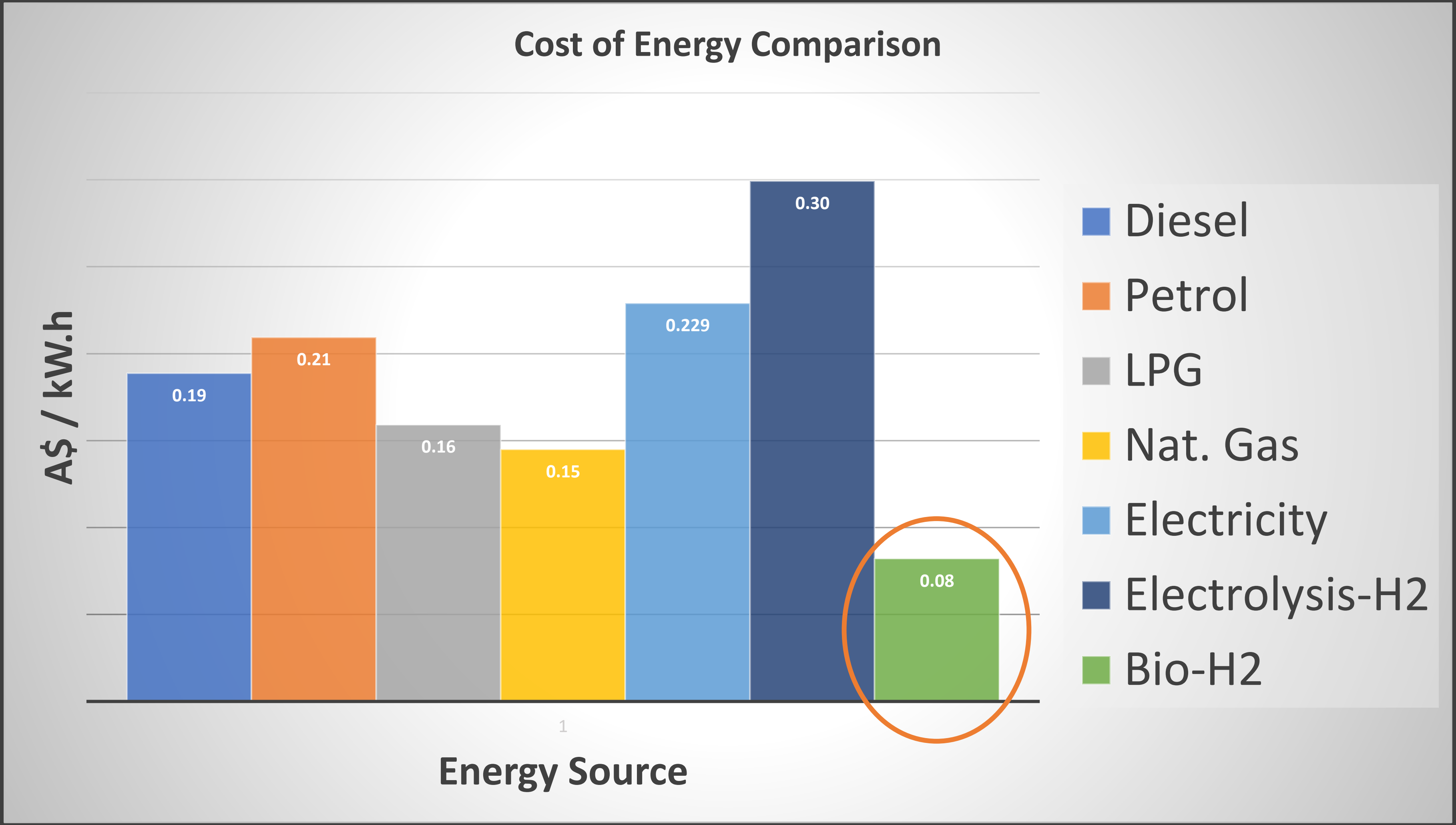


- **Concentrated syngas undiluted by atmospheric Nitrogen** = economically separable constituents (e.g. hydrogen via PSA/WSR)
- **HYDROGEN RICH -** typically >50% by Volume, separable to high purity. Remainder is mainly high purity CO, plus methane and water vapour.
- Clean syngas also suitable for direct use in gas engines with min cleanup
- Suitable H:C ratios in syngas for making chemical building blocks for many biofuels & bioplastics
- Direct heat transfer (very high thermal efficiencency)
- Industrial Sscalable design – scales by volume not by surface area,

  designed 5 – 40tph

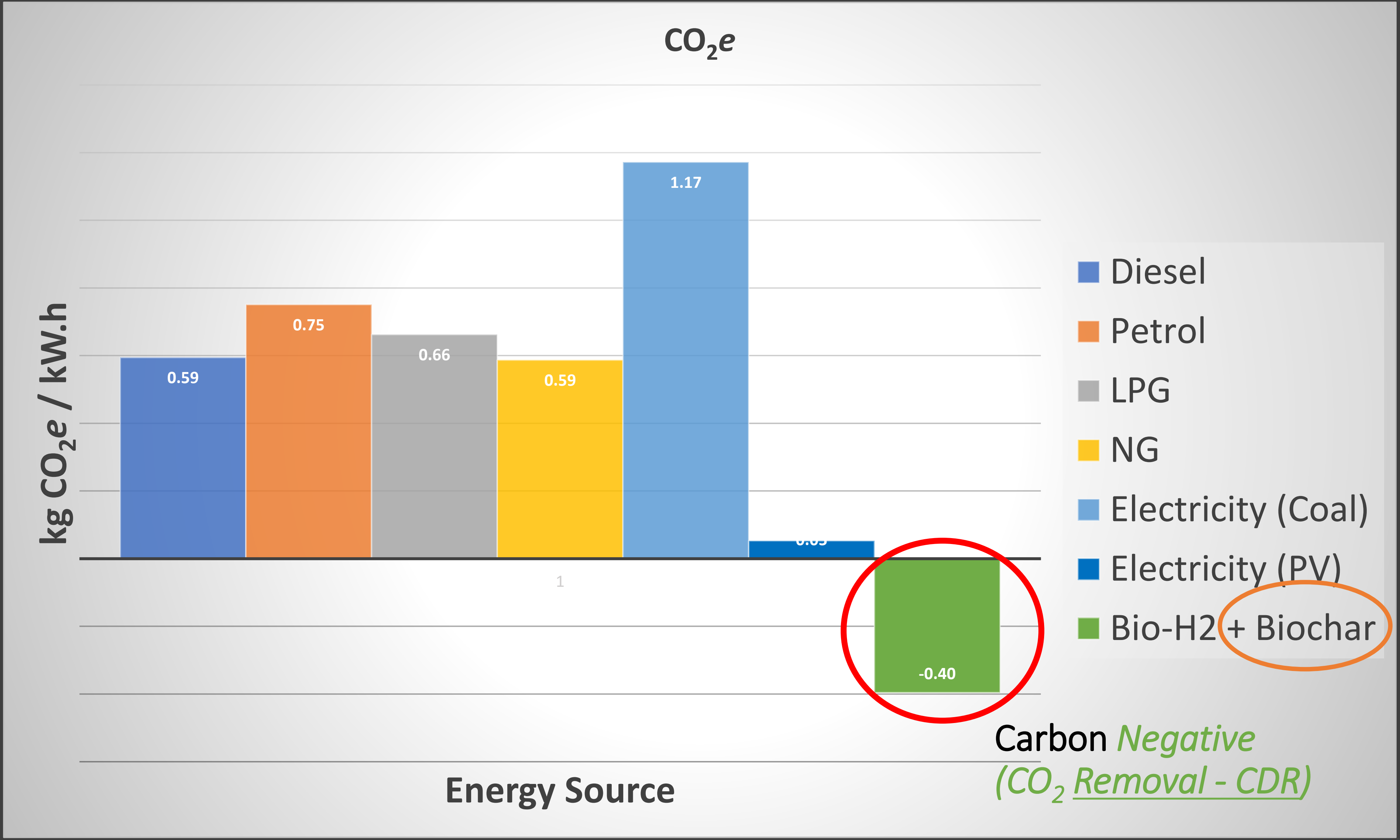
- **CARBON –** typically ~50% by mass reports into solid biochar/biocarbon.

Why Bio-Hydrogen?



Ref: GlobalPetrolPrices.com, 23 Jan 2023.

‘Greener than Green’ - carbon *negative* hydrogen



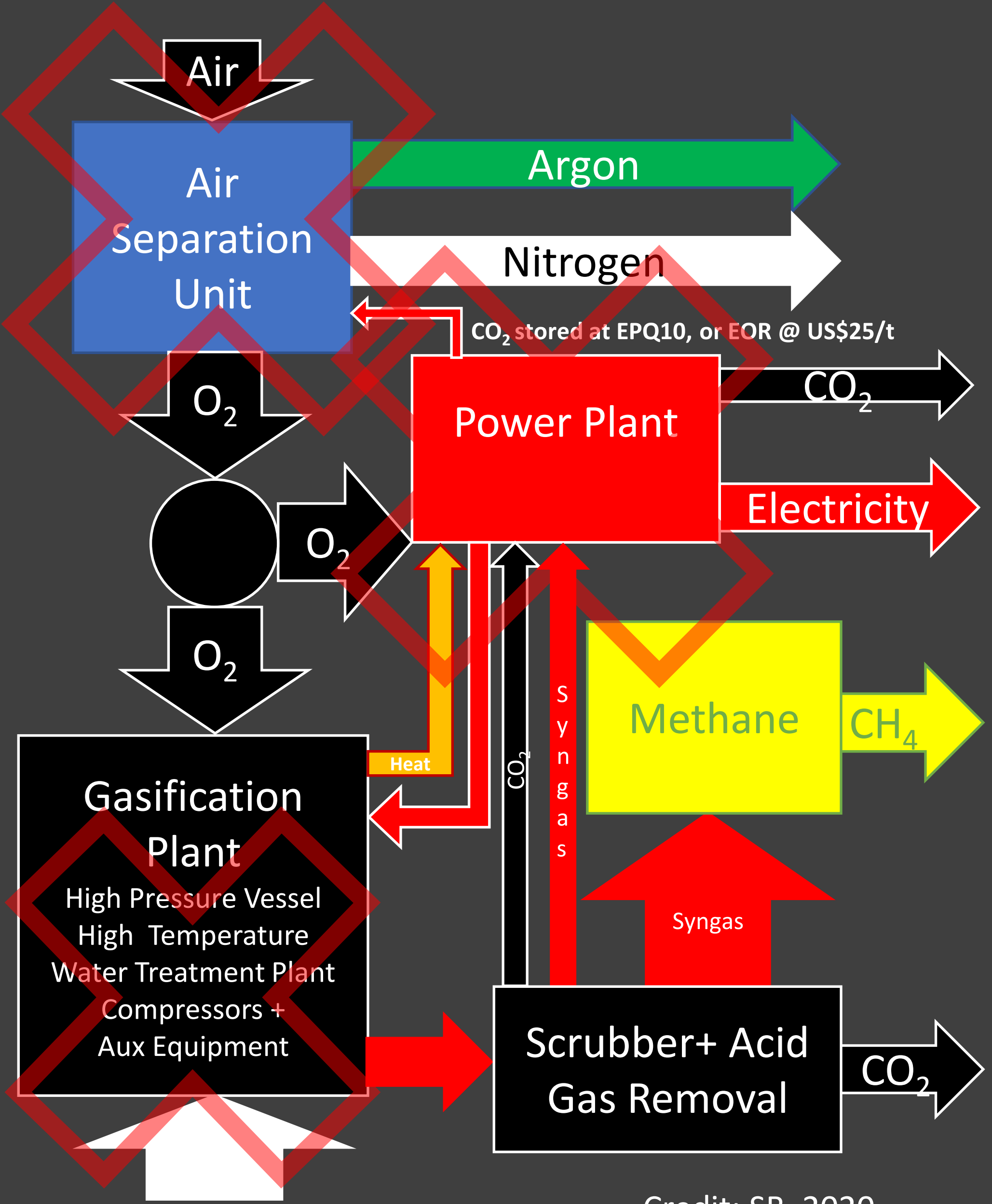
Carbon *Negative*
(CO_2 Removal - CDR)

SEATA vs Conventional Industrial-Scale Gasification Plants (including Methanation)

No expensive ASU + No Power Plant + No High Pressure

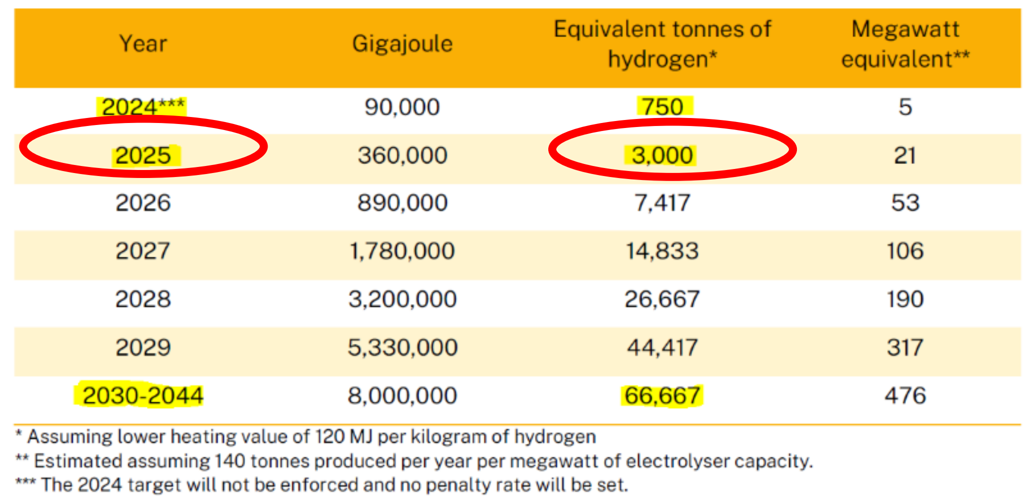
Chemical looping simplifies gasification

- Reduced Thermal Process Energy Losses
- No Air Separation Unit (ASU) - $$$ very high CAPEX
- No High Pressure Compressors
  - SEATA at atmospheric pressure
- No slag water quenching
  - No wastewater ('black water') treatment plant
- No Power Units
  - Low power consumption
  - Co-generation plant unnecessary



Credit: SB, 2020

Hydrogen Production Potential: Comparison with NSW targets



Year	Gigajoule	Equivalent tonnes of hydrogen*	Megawatt equivalent**
2024***	90,000	750	5
2025	360,000	3,000	21
2026	890,000	7,417	53
2027	1,780,000	14,833	106
2028	3,200,000	26,667	190
2029	5,330,000	44,417	317
2030-2044	8,000,000	66,667	476

* Assuming lower heating value of 120 MJ per kilogram of hydrogen

** Estimated assuming 140 tonnes produced per year per megawatt of electrolyser capacity.

*** The 2024 target will not be enforced and no penalty rate will be set.

NSW Hydrogen Production Targets & Timing

(OECC, NSW Treasury 2023)

Plant Infeed Size (DM):	**RDSM Pilot <300 kg/h**	**5 tph Infeed Commercial Plant**	**Up to 40 tph Infeed Industrial Scale Plant**
Locations	*SEATA R&D Centre, Glen Innes NSW, Australia*	C&I Site **(Elsewhere)** (interstate?) (TBC)	Industrial Site **(TBC)**
Potential Design Infeeds (DM) *(@7,500 hrs/yr, ~85% use)*	2,250 tpa	37,500 tpa	300,000 tpa
Potential Carbon Yield *(@~25% yield per tonne of infeed)* *(can customize to <10 to >35%)*	~560 tpa	Up to ~9,400 tpa	75,000 tpa *(current total Aust production <20,000 tpa)*
Indicative Drawdown Via Biochar *(using plant biomass feeds only)* *(+ ~25% more if CO_2 gas also sunk into CCUS (commercial scale)*	**~1,400t** CO_2e/yr *(assuming net ~2.5 tCO_2e per tonne of biochar after LCA)*	Up to **23,500t** CO_2e/yr *(assuming net ~2.5 tCO_2e per tonne of biochar)*	Up to **187,500t** CO_2e/yr *(assuming net ~2.5 tCO_2e per tonne of biochar)*
Design H_2 Yield (as % of infeed)	Flared Initially, (expected ~7% by mass)	7-10% by mass (recovery via PSA or WSR)	**10% by mass** (Recovery eg via WSR)
Potential Annual H_2 Yield *(tpa, uncompressed)*	Nil (no energy recovery)	**2625 – 3750 tpa**	**30,000 tpa**

- **SEATA technology has potential to remove CO_2 from the atmosphere at very significant rates to combat climate change whilst *concurrently* also significantly reducing/avoiding new emissions by assisting energy and fuel transition.**
- Scenarios are theoretical potential pending approvals, funding and successful deployments. Bankable Feasibility Studies to be completed following pilot trials, ahead of commercial plant.

Direct Air Capture + CCS (DACCS) Context:
Project Orca Iceland (operational) = 4,000 tpa (8 x 500 tpa units)
Project Mammoth (const) = 36,000 tpa (72 x 500 tpa units)

SEATA Technology - Potential Hydrogen Production

Based on designs and piloting to demonstrate:

- **2025 NSW total H_2 production target** could potentially be met by a *single* 5 tonne per hour SEATA plant.
- **2030-2044 NSW annual production target (66,667 tonnes H_2)** could potentially be met by around two 40tph SEATA plants (or multiple distributed smaller plants).
- When run on plant wastes (green waste, agricultural residues etc), concurrent potential to provide ***very significant*** **CO_2 Removal** toward genuine Net Zero targets (cheaper and far more per unit than DACCS).

Complementary/Synergistic with Conventional Technologies:
Green & Blue Hydrogen & Conventional Renewables (solar/wind etc)

- **"Nature's Battery" - Night-time/dispatchable generation** optimizes CAPEX for integrated systems for **24/7 continuous generation**
- **CO_2 Removal** to assist genuine Net Zero for integrated systems with positive footprints.
- **Feedstock carbon for battery storage technologies** to support solar/wind renewables
  - **Sodium-Carbon Batteries –** potential to help turn desal brine wastes into *resources* to avoid ocean disposal ***(Zero Liquid Discharge)***
- **Biochar/H_2 to Enhance rNG/Biomethane production from Anaerobic Digestion (AD)**
- Potential to **further assist blue and grey hydrogen** (no $$ ASU unit needed, high purity CO_2 facilitates CCUS applications)
- **Additional Revenue streams** from co-benefit markets (carbon commodities & removal credits) to optimize CAPEX and OPEX
- **Potential for further secondary sequestration via sinking high-grade CO_2 into emerging CCUS applications** (in addition to providing carbon dioxide removal (CDR) credits via biochar.)
- Provide additional "green" jobs, notably in rural and regional areas

SEATA Clean Energy & Carbon Sequestration R&D Centre – Glen Innes NSW (New England REZ)

Field Pilot Demonstration Plant:

- ~1/10th commercial scale continuous run pilot *R&D Scale Model (RDSM)*
- **Objective**: Provide high quality field data for client-commissioned feedstocks enabling genuine bankable feasibility for commercial deployment elsewhere.
- Operates on 'campaign' commission basis (24/7 when testing).
- **Fully approved** (planning consent and EPA Licenced), commencing Q1 2024.
- Approved for infeed up to **300 kg/hr**, including co-feeds
- **Approved range of 'clean' Biomass and Biosolids Feedstocks** (no plastics etc)
- Feeds from within NSW only, outside the 'Waste Levy Area'
- **NSW EfW Policy compliance** required syngas characterization then **flared** at this stage (pilot proof of concept). Future mod required to recover energy onsite.

- **Next Steps**:
  - Commence *detailed* testing campaigns of clean feed(s)
  - Obtain engagement for **commercial 5tph Plant(s)**
  - **Dirty Feeds R&D Plant / Commercial Plant** *(concurrent with above)*
  - Approval modification to recover energy onsite at Glen Innes as soon as innovation pathways established for such (*concurrent with above)*.

Thankyou. Questions?

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SEATA
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to create carbon negative solutions

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"Wartime" investment in carbon capture must start now, researchers say

What could wartime levels of emergency funding buy us in the fight against global warming?

> *"During WWII no-one asked, 'Can we afford to fight the war?' We could not afford **not** to fight it. The same goes for the climate crisis."*
>
> Joseph Stiglitz, 2019

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RESEARCH REVIEW

How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar

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Abstract

We synthesized 20 years of research to explain the interrelated processes that determine soil and plant responses to biochar. The properties of biochar and its effects within agricultural ecosystems largely depend on feedstock and pyrolysis conditions. We describe three stages of reactions of biochar in soil: dissolution (1–3 weeks); reactive surface development (1–6 months); and aging (beyond 6 months). As biochar ages, it is incorporated into soil aggregates, protecting the biochar carbon and promoting the stabilization of rhizodeposits and microbial products. Biochar carbon persists in soil for hundreds to thousands of years. By increasing pH, porosity, and water availability, biochars can create favorable conditions for root development and microbial functions. Biochars can catalyze biotic and abiotic reactions, particularly in the rhizosphere, that increase nutrient supply and uptake by plants, reduce phytotoxins, stimulate plant development, and increase resilience to disease and environmental stressors. Meta-analyses found that, on average, biochars increase P availability by a factor of 4.6; decrease plant tissue concentration of heavy metals by 17%–39%; build soil organic carbon through negative priming by 3.8% (range −21% to +20%); and reduce non-CO_2 greenhouse gas emissions from soil by 12%–50%. Meta-analyses show average crop yield increases of 10%–42% with biochar addition, with greatest increases in low-nutrient P-sorbing acidic soils (common in the tropics), and in sandy soils in drylands due to increase in nutrient retention and water holding capacity. Studies report a wide range of plant responses to biochars due to the diversity of biochars and contexts in which biochars have been applied. Crop yields increase strongly if site-specific soil constraints and nutrient and water limitations are mitigated by appropriate biochar formulations. Biochars can be tailored to address site constraints through feedstock selection, by modifying pyrolysis conditions, through pre- or post-production treatments, or co-application with organic or mineral fertilizers. We demonstrate how, when used wisely, biochar mitigates climate change and supports food security and the circular economy.

KEYWORDS
carbon sequestration, GHG mitigation, heavy metals, priming effect, resilience, rhizosphere processes, soil carbon

1 | INTRODUCTION

Biochar is produced by thermal transformation of organic matter in an oxygen-limited environment. Research interest in biochar has grown markedly since 2000 (Figure S1), stimulated by early studies of Terra Preta soils in the Amazon that indicated potential for biochar amendment to simultaneously improve a broad range of soil properties and thus increase agricultural yields, while also contributing to climate change mitigation (Glaser et al., 2002; Lehmann et al., 2006).

A wide range of biochar types produced from feedstocks including woody residues, crop straw, animal manures, sewage sludge, and food wastes are pyrolyzed at temperatures (highest treatment temperature, HTT) ranging from around 350°C to over 750°C. Biochar properties vary widely, determined largely by feedstock, HTT, and residence time at HTT, as well as treatments applied before and after pyrolysis (Schimmelpfennig & Glaser, 2012). A review of 5400 studies (Ippolito et al., 2020) found that wood-based feedstocks generally produced biochars with the highest surface area, straw-based feedstocks gave the highest cation exchange capacity (CEC), and manure feedstocks produced biochars with the highest N and P content. HTTs above 500°C produced biochars that were more persistent in soil, with higher ash contents and pHs.

Biochar trials have used a wide range of application rates and formulations (Text S1; Table S1; Figure S2; Figure S3). Higher rates (10–50 Mg ha^{-1}) have commonly been applied where low-nutrient biochar is used as a soil conditioner to improve bulk soil chemical and physical properties, while lower rates (<1 Mg ha^{-1}) have been used as a nutrient carrier to increase fertilizer use efficiency and decrease nutrient losses, and in mechanized planting (Table S1). Economic analyses suggest that formulations combining biochar with fertilizer (biochar compound fertilizer [BCF]), applied at low rates, are likely to be the most cost-effective approach for broadacre cropping in higher income countries (Robb et al., 2020).

Studies report a wide range of effects of biochars on physical, biological, and chemical soil properties and functions, and on plant growth. Reviews and meta-analyses show that biochar generally lowers soil acidity and increases buffering capacity; increases dissolved and total organic C, CEC, available nutrients, water retention, and aggregate stability; and reduces bulk density (El-Naggar et al., 2019; Lehmann & Joseph, 2015). Biochar can increase microbial activity, accelerate nutrient cycling, and reduce leaching and volatilization of nitrogen (Lehmann & Joseph, 2015).

In terms of plant performance, biochars can affect seed germination, plant growth, flowering, resistance to disease, and acclimation to abiotic stresses. Many studies report that biochar increases plant productivity, with an average yield increase of 10%–42% (Table 1), although negative effects have also been recorded (Jeffery et al., 2017; Macdonald et al., 2014; Ye et al., 2020). Studies reporting positive responses have commonly used biochar application rates of 5–20 Mg ha^{-1} (Table 1); however, applications of biochar–fertilizer mixes at low rates (<1 Mg ha^{-1} biochar) have also increased yields, particularly when applied as a band near the seed (Table S1). The effects of biochar on crop yields are discussed further in Section 4.

Besides agronomic benefits, biochar contributes to climate change mitigation: Biochar C persists in soil for one to two orders of magnitude longer than unpyrolyzed organic residues, providing long-term C sequestration when applied to soil. In addition, biochar can increase soil C levels by decreasing mineralization of existing soil organic matter (SOM; Wang et al., 2016) and newly added plant C (Weng et al., 2017). Furthermore, biochar can reduce emissions of the greenhouse gases (GHGs), nitrous oxide and methane (Van Zwieten, Kammann, et al., 2015).

The large body of literature that has accumulated over the last two decades has greatly increased our observational database of the effects biochar can have on soil properties and crop performance. In-depth mechanistic studies have brought focus to the importance of the rhizosphere in these effects. The objectives of this review are to synthesize the last 20 years of research on biochar to elucidate the underlying biochar–soil–plant processes, and mechanisms that lead to plant responses to biochar, and to provide recommendations for optimizing the use of biochar to increase plant yield, soil health, and climate change mitigation.

We first describe biochar–soil–plant interaction mechanisms, focusing on rhizosphere processes and implications for plant growth, concentrating on biochar applied to annual crops. Use of biochar in annual crops has been the most commonly studied application to date and is anticipated to be the most widespread future application of biochar. Subsequent sections review the implications of biochar for food security, climate change mitigation, and the role of biochar in the circular economy. We conclude with a summary of key processes, knowledge gaps, and recommendations for optimal biochar use.

2 | MECHANISMS OF BIOCHAR EFFECTS ON SOIL AND PLANTS

We consider the interactions between biochar, soil and plants in the context of the annual crop cycle:

- Stage 1: Short-term (1–3 weeks) reactions of biochar in soil, and effects on seed germination and seedlings
- Stage 2: Medium-term (1–6 months) creation of reactive surfaces on biochar, effects on plant growth and yield from seedling to harvest
- Stage 3: Long-term (>6 months) interactions as biochar "ages" in soil, and its effect on subsequent crop cycles.

Biochar is commonly applied at sowing or 1–3 weeks before sowing. Mechanisms involved when biochar is applied in conjunction with mineral and/or organic fertilizers, and as a BCF comprising biochar, fertilizer, minerals (e.g., gypsum, dolomite, diatomite, rock phosphate) and binder (e.g., clay, starch) are examined.

2.1 | Stage 1: Short-term reactions (1–3 weeks)

2.1.1 | Biochar reactions in soil

Chemical effects

The general properties of biochars are described in Text S2. After application to soil, water entering biochar pores dissolves soluble organic and mineral compounds on biochar outer and inner surfaces (Figure 1). These solutes increase dissolved organic carbon (DOC), cations, and anions in the soil solution (Silber et al., 2010), which increases the electrical conductivity and pH and reduces Eh (Joseph et al., 2015) The extent of changes in soil solution composition depends on the specific biochar and soil (Mukherjee & Zimmerman, 2013; Schreiter et al., 2020). Release of DOC and nutrient ions from biochar (Kim et al., 2013) is rapid over the first week and much slower over the following

TABLE 1 Summary of meta-analyses of yield response to biochar, and synthesis of findings

Study	Number of studies included	Notes	Biochar dose giving optimal response (t/ha)	Crop factor reported	Grand mean change %	Synthesis of key findings
Jeffery et al. (2011)	23	First meta-analysis of biochar effects on yield, using pot and field studies.	100	Crop yield	10	• Greatest benefit in acidic and pH neutral soils suggesting liming effect as key driver • Greater effect in coarse-textured soils suggesting improved water and nutrient availability • Poultry litter feedstock showed the greatest positive benefit
Biederman and Harpole (2013)	114	Yield response presented for fertilized biochar treatment vs. fertilized control	ns	Crop yield	42	• Improved plant tissue P and K concentrations compared to fertilizer alone • Grass and manure feedstocks most effective especially at higher temperatures due to increased liming effect • Application rate was not a good predictor due to variable responses arising from different interactions
Crane-Droesch et al. (2013)	84	Predicted yield response based on the application of 3 Mg ha^{-1} biochar	3	Crop yield	10	• Soil CEC and SOC content are predictors of yield response • Greatest benefits in lowest-potential agricultural areas, which are predominantly found in the humid tropics • Benefits to yield increased yearly up until year 4 after application
Liu et al. (2013)	103		<10–20	Crop yield	11	• Greatest benefit in acidic soils ($pH < 5$) • Greatest benefit in sandy soils, followed by clay, then silt or loam-textured soils • Manure feedstock generally most effective, followed by wood, then crop residue
Thomas and Gale (2015)	17	Study focused on responses of trees	NA	Tree biomass	41	• Greater positive effect in tropical than in temperate systems, and in angiosperms than conifers • Limited number of studies exist but authors suggest significant opportunities during reforestation
Jeffery et al. (2017)	111		NA	Crop yield	13	• An average 25% yield increase in the tropics with liming effect and fertilizer value as the key driver • Biochars containing higher nutrient contents had greater benefit to yield than lower nutrient biochars • The authors stressed the need to understand the constraint that is being addressed by biochar

TABLE 1 (Continued)

Study	Number of studies included	Notes	Biochar dose giving optimal response (t/ha)	Crop factor reported	Grand mean change %	Synthesis of key findings
Xiang et al. (2017)	136	Analysis focused on below ground effects	NA	Root biomass	32	• No change in root N concentration but significantly increased root P concentration • Benefits were greater for legumes and resulted in increased nodulation • Higher temperature biochars had a greater effect and HTT was a more important indicator than feedstock type
Awad et al. (2018)	50	Study focuses on rice production	1–10	Crop yield	16	• Greatest benefits observed in very acidic soil • No significant differences in effects with biochar rate • Soil texture did not have a major role in determining yield effect
Dai et al. (2020)	153		NA	Crop yield	16	• Liming, improved soil physical properties, and increased nutrient use efficiency were key mechanisms resulting in positive effects • Interactions between soil properties and biochar properties were key to delivering positive effects • Biochars with high ash content (e.g., higher nutrient content) applied into sandy and/or acidic soils likely to give greatest benefits.
Ye et al. (2020)	56	Comparison with unfertilized control	<5	Crop yield	30	• The study separately assessed biochar response in comparison with fertilized and unfertilized controls, and showed that benefits to yield are additive to the fertilizer effect • Soils with CEC < 100 $\text{mmol}_c\ \text{kg}^{-1}$ showed the greatest positive response • Soils with SOC ≤ 20 g kg^{-1} showed the greatest positive response • Crops grown on soils with pH ≤ 6.5 always had a positive yield response to biochar addition
		Comparison with fertilized control	5–10	Crop yield	10	

Abbreviations: CEC, cation exchange capacity; NA, not applicable/ not investigated; ns, no response detected; SOC, soil organic carbon.

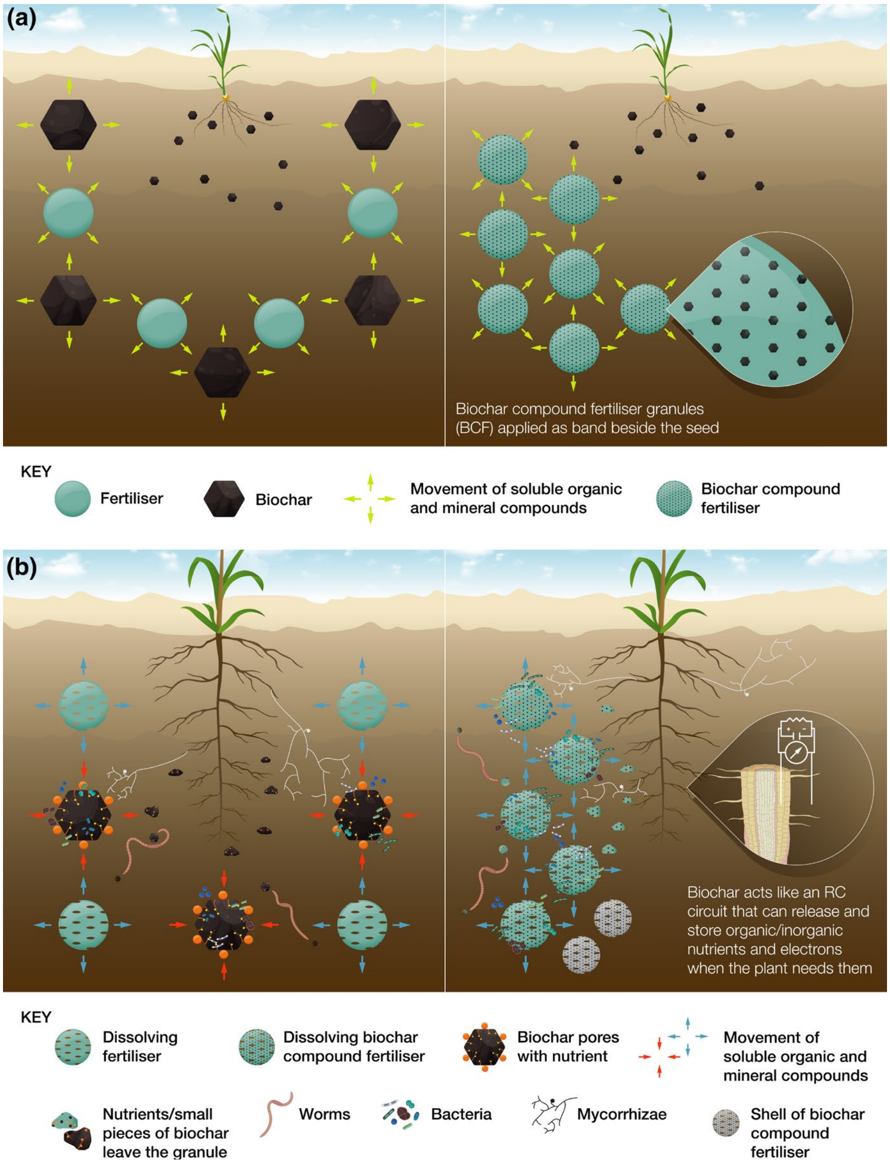

FIGURE 1 Summary of the processes that occur when biochar is applied to soil, based on two modes of application: (left) biochar and fertilizer applied together and incorporated through the soil prior to sowing, and (right) biochar compound fertilizer (BCF) comprising biochar mixed with fertilizer, minerals and a binder, granulated, applied to the soil as a band near the seed. (a) Stage 1: dissolution of biochar, interactions with seedlings; (b) Stage 2: reactive surface development on biochar, interactions with growing plants. RC, resistor and capacitor in parallel

weeks (Mukherjee & Zimmerman, 2013). Initial rapid dissolution can occur via dissolution of salts, ion exchange, submicrometer particle detachment, and preferential dissolution at crystal imperfections (Wang et al., 2020). After the initial rapid dissolution stage, continued dissolution is faster in acidic (Silber et al., 2010) and low-nutrient soils (Wang et al., 2020).

When biochar is applied in the form of BCF that combines biochar, minerals, and N and P compounds (e.g., urea, ammonium sulfate, diammonium phosphate), the physical and chemical reactions that occur during the production of the granules slow the rate and extent of dissolution of N compounds compared with dissolution of mineral fertilizers (Chen et al., 2017; Shi et al., 2020).

Fresh biochar typically has a low CEC, as the high temperatures during pyrolysis reduce the concentration of functional groups (e.g., –OH, –COOH, –CH, and –C=O). CEC of biochar is more difficult to measure than CEC of soils, due to its pH-dependent variable charge properties and the presence of soluble salts (Graber et al., 2017; Munera-Echeverri et al., 2018). Using methods considered suitable for biochar, CEC ranges from approximately 50 to 200 mmol kg^{-1} (Graber et al., 2017; Mitchell et al., 2013), and anion exchange capacity (AEC) is typically also less than 200 mmol kg^{-1} (Lawrinenko et al., 2017). As CEC of fresh biochar is relatively low compared with CEC of many soil components, applying biochar typically does not increase the soil CEC immediately (Kharel et al., 2019). However, the CEC and

AEC of biochar increase over time as additional functional groups form on biochar surfaces (see Section 2.3), increasing its ability to sorb and retain cations and anions (Hagemann, Joseph, et al., 2017; Hagemann et al., 2017; Rechberger et al., 2017; de la Rosa et al., 2018; Wang et al., 2019).

Low-temperature biochars (HTT < 450°C) and biochars produced in facilities with incomplete separation of pyrolysis vapors (Buss & Mašek, 2014; Buss et al., 2015) generally have higher contents of water-soluble organic compounds, particularly low molecular weight neutrals (alcohols, aldehydes, ketones, phenolics, karrikins), polyphenols/polyphenolic acids, and complex macromolecules, whereas high-temperature biochars (HTT >450°C) have relatively lower levels of water-soluble compounds that are dominated by low-molecular weight acids and low-molecular weight neutrals (Graber et al., 2015; Reynolds et al., 2018; Taherymoosavi et al., 2018). Low-temperature biochars can be hydrophobic initially due to accumulation of aliphatic compounds in pores and on the surface; such compounds are usually lost during pyrolysis at higher temperatures. Hydrophobicity can inhibit water uptake by biochar particles (Gray et al., 2014), but this effect dissipates over time.

Most biochars are alkaline, with acid-neutralizing capacity up to 33% of agricultural lime (Van Zwieten, Kimber, Morris, Chan, et al., 2010) due to their carbonate, oxide, and hydroxide content. Biochar is a reductant, and therefore lowers soil redox potential (Joseph et al., 2015). An exception is flooded rice soils, where biochar application can increase Eh due to the release of O_2 from roots. Chew et al. (2020), Joseph et al. (2015), and Pignatello et al. (2017) detail the range of reactions that can take place on the external surfaces and in the pores of biochar (see also Section 2.2). Except in flooded soils, oxygen will diffuse into the pores and react with redox-active organic molecules (e.g., quinones; Yu & Kuzyakov, 2021) and minerals, particularly Fe and Mn. In acid soils, excess H^+ reacts with basic minerals such as calcite and dolomite present within the C lattice of the biochar (Amonette & Joseph, 2009).

Biochars (especially those made at >400°C) can have a high content of free radicals, which can lead to the formation of reactive oxygen species (Pignatello et al., 2017; Ruan et al., 2019; Yu & Kuzyakov, 2021) and strongly accelerate oxidation reactions. This acceleration leads to oxidation not only of biochar itself but also of SOM and plant residues (Du et al., 2020) and is especially intensive in soils with fluctuating water level (Merino et al., 2020) or with high content of iron (oxyhydr)oxides (Merino et al., 2020; Yu & Kuzyakov, 2021).

Physical effects

Biochars commonly increase soil water holding capacity, particularly in coarse-textured soils, decrease bulk density, and increase porosity, with greater effects observed at rates exceeding 40 Mg ha^{-1} (see Section 3; Quin et al., 2014). Biochar can also impact water infiltration into soils, for example, moderating the reduction in infiltration rate that occurs during high-intensity rainstorms in soils prone to surface sealing, as seen at 2% w/w by Abrol et al. (2016). Reduced sealing leads to lower runoff and erosion rates. The effects were attributed to a biochar-related increase in soil solution Ca and decrease in Na, leading to decreased sodium adsorption ratio (Abrol et al., 2016).

Biochar particles have low density and are easily crushed (Abdullah & Wu, 2009). Cultivation and ingestion by soil fauna result in fragmentation and fracturing, creating very small particles (approximately <100 μm). These small particles are more mobile and can have higher reactivity, surface charge, radical content (Das et al., 2020; Yu & Kuzyakov, 2021) and surface area than larger particles (Yang et al., 2020), which can increase reactivity and nutrient availability (Wang et al., 2020). High mineral ash biochars and engineered biochars used in BCF generally contain high quantities of small mineral particles <100 μm (especially silica, alumina, Fe/O and $CaCO_3$, $CaHPO_4$, and Mg compounds) in or on the C matrix that are easily fragmented from the biochar and are mobile in soil.

2.1.2 | Effects on seed germination and early seedling growth

Reported impacts of biochar on germination and seedling growth range from inhibition to stimulation. Hormesis is commonly observed, that is, high rates of biochar can have a detrimental effect, while low rates can be stimulatory. Below we discuss the mechanisms likely to contribute to the range of effects on seed germination and early seedling development reported in the literature.

Seed germination begins with water imbibition and ends when the radicle emerges from the seed coat. The following are the main factors that determine whether biochar impacts seed germination: (i) release of salts from biochar to the soil solution; (ii) release of phytotoxins; (iii) release of germination-inducing hormones or karrikins; (iv) change in water holding capacity and porosity of the soil. These biochar-related factors are the reason that biochar feedstock, production HTT, and application amount have a range of impacts on germination speed and rate. The specific sensitivity of seeds of different plant species to salinity, toxins, hormone-like compounds and water availability also results in very variable results. For example, wood biochar (HTT 620°C) at 80 Mg ha^{-1} in a pot trial inhibited germination of tomatoes, while biochar made from paper sludge and wheat husk (500°C) or sewage sludge (600°C), and applied at the same rate, had no effect on lentil, tomato, cress, cucumber, and lettuce seeds (Gascó et al., 2016). Other studies that applied a range of woody and manure biochars at rates of 10–40 Mg ha^{-1}

found positive or nil effect on germination (Das et al., 2020; Gascó et al., 2016; Khan et al., 2014; Mete et al., 2015; Van Zwieten, Kimber, Morris, Downie, et al., 2010). Some studies (e.g., Uslu et al., 2020) that reported negative effects of biochar on germination at very high rates (120 Mg ha^{-1}) applied biochar directly to seeds in a petri dish, in the absence of soil or other media, which is unlikely to reflect the effects of biochar in the field environment, where charged clay minerals, microbes, and organic compounds interact with biochar, and are likely to modify and buffer the response. Germination rates were not affected by the addition of BCF at <700 kg ha^{-1} in pot or field trials, while seedling growth was the same or greater than with NPK fertilizer alone (Joseph, Graber, et al., 2013; Liao et al., 2020; Qian et al., 2014; Zheng et al., 2017). Aqueous extracts of some biochars have been found to stimulate germination and seedling growth (Taek–Keun et al., 2012).

Seed germination and early seedling development can be influenced as a result of the effects of biochar on soil physical properties (Section 2.1.1). For instance, by reducing soil bulk density and increasing soil aeration, biochar can provide oxygen for seed germination and improve seedling growth through lower resistance to root penetration and seedling emergence. These effects typically increase with higher biochar rates (Obia et al., 2018).

Chemical impacts of biochar on soils and soil water solution can also affect seed germination and early seedling development. For example, by raising the pH, alkaline biochars alleviate Al and heavy metal toxicity that can reduce root growth in acidic soils (Lauricella et al., 2021; Shetty et al., 2020; Van Zwieten, Rose, et al., 2015). At high application rates, biochars with high levels of soluble salts could inhibit germination and seedling growth through osmotic stress. Certain soluble organic compounds released from biochars can stimulate germination and plant growth (Sun, Drosos, et al., 2017). Kochanek et al. (2016) showed that biochars containing karrikins, a class of water-soluble organic molecules associated with plant response to fire, can accelerate germination and early growth of plants. These authors attributed the response to signaling molecules that stimulate plant development. The quantity of karrikins and germination response varied widely between biochars studied by Kochanek et al. (2016). French and Iyer-Pascuzzi (2018) found evidence that stimulation of the gibberellin pathway contributes to the observed promotion of germination and seedling growth by wood biochar in some tomato genotypes. Similarly, phenols and polyphenols released from biochar (Reynolds et al., 2018) can break seed dormancy, leading to germination, and also promote seedling growth (Mu et al., 2003; Stoms, 1982). Yet, some organic molecules released can be phytotoxic, so applying biochar a few weeks in advance of sowing supports seedling growth through the development of a beneficial rhizosphere microbiome (Jaiswal et al., 2018).

At very high rates of application (>50 Mg ha^{-1}), biochars derived from contaminated sludges or feedstock grown in contaminated soils can release heavy metals that inhibit germination (Das et al., 2020). Biochars contain polycyclic aromatic hydrocarbons (PAHs; Gascó et al., 2016; Weidemann et al., 2018), organic pollutants formed during incomplete combustion, that can inhibit germination at high rates. However, PAHs in biochar are generally of little or no concern for plant growth due to their strong binding by biochar, and furthermore, their concentration is usually below regulatory limits if biochar is made under slow pyrolysis conditions (Buss et al., 2015; Hale et al., 2012; Hilber et al., 2017).

At high biochar application rates in the absence of soil (volumetrically equivalent to >40 Mg ha^{-1}, in a petri dish), free radicals from biochar inhibit germination and seedling growth (Liao et al., 2014). However, at low biochar rates, low levels of free radicals could be beneficial, as reactive oxygen species can interact with plant hormones that trigger germination (Gomes & Garcia, 2013). Furthermore, free radicals associated with biochar have been found to degrade certain organic and inorganic pollutants (Ruan et al., 2019) which in turn could enhance germination and seedling growth. In addition, biochar can lower the production of reactive oxygen species by plants: Natasha et al. (2021) showed that the production of reactive oxygen species was lower, on average, by 33% in plants grown in soils contaminated with trace elements where biochar was applied (2%–10% w/w).

In summary, most biochars and biochar formulations do not inhibit germination and early growth of plants in soil unless applied at very high rates (e.g., >40–50 Mg ha^{-1}), and can promote germination and seedling growth at moderate rates. The mechanisms for the positive effects largely involve water-soluble organic compounds that stimulate germination and seedling growth, or reactions that deactivate inhibitory factors such as heavy metals and phytotoxic organic compounds. These effects vary between biochars: low temperature biochars have a higher content of water-soluble organic molecules that can promote germination and early growth at low application rates; these biochars are also likely to cause inhibition if applied at high rates. Negative effects on germination can result where high rates are applied due to release of soluble salts or phytotoxic levels of organic compounds, where biochar is contaminated, and where soil is absent. Biochars with high levels of soluble mineral compounds can also cause inhibition at high application rates.

2.2 | Stage 2: Medium-term reactions (1–6 months)

The effects of biochar in later periods differ from the first stage which is dominated by dissolution of compounds from biochar. In stage 2, plant roots intercept and interact with biochar. Root hairs enter biochar pores, roots wrap around biochar (Joseph et al., 2010; Prendergast-Miller et al., 2014), and very small biochar particles can attach to root surfaces (Figure 1; Chew et al., 2020). Biochar affects the abundance of specific microorganisms especially in the rhizosphere, and the interactions between biochar, soil, plants, and the microbiome affect plant growth and health (Anderson et al., 2011; Jaiswal et al., 2015).

2.2.1 | Physical and chemical reactions in soil

The physical and chemical properties of biochar surfaces change significantly in Stage 2 through a range of biotic and abiotic processes that take place in the pores exposed after the rapid dissolution phase ends (Joseph et al., 2010). The surface area and porosity increase (Schreiter et al., 2020), and a fine layer of organic matter with a high concentration of C–O and C–N functional groups forms around the external and some of the internal pore surfaces of the biochar and BCF. This fine layer adsorbs cations (including heavy metals), anions, nanoparticulate minerals, and organic compounds through a range of binding mechanisms that include cation and anion exchange, ligand exchange, covalent bonding, complexation, chelation, precipitation, redox, and acid–base reactions, that together result in formation of organo-mineral layers (Hagemann, Joseph, et al., 2017; Joseph, Van Zwieten, et al., 2013). These layers are redox-active and mesoporous. Surfaces in nanopores bind molecules more tightly than larger pores (Pignatello et al., 2017). Some of the nutrients released from fertilizer, especially N and P, can react with the biochar pore surfaces and organo-mineral layers (Haider et al., 2020; Hestrin et al., 2019; Joseph et al., 2018; Kammann et al., 2015). Biochar pores may become filled with organic matter and minerals, protecting organic matter from microbial decomposition (Pignatello et al., 2017) and reduces availability of nutrients.

Microagglomerates that form on internal and external biochar surfaces, consisting of nanoparticulate minerals bound with organic molecules, have a significant concentration of –C–O, –C=O, –COOH, or –NH functional groups (Joseph et al., 2010). Recent research indicates that many of the reactions described above related to biochar occur on or in the microagglomerates.

Gases such as NH_3, N_2O, and CH_4 produced through biotic and abiotic reactions of fertilizers in soils and/or through chemical reactions on the surfaces of the biochar can diffuse into the nanopores (<50 nm), where they can react with oxidants and reductants, especially if the pores contain water, which reduces N loss and GHG emissions (Section 4.3; Chiu & Huang, 2020; Quin et al., 2015).

2.2.2 | Microbial responses

Meta-analyses have shown that biochar increases microbial biomass and activities (Pokharel et al., 2020), particularly in high-N soils (Zhang et al., 2018) and with biochars produced at low temperature from nutrient-rich feedstocks (Li et al., 2020). Biochars, particularly those made at low temperature from crop residues, cause shifts in microbial community composition, increasing the ratios of fungi to bacteria, and gram-positive to gram-negative bacteria (Zhang et al., 2018). The meta-analysis by Pokharel et al. (2020) identified that biochar increased microbial biomass C and the activities of the enzymes urease, alkaline phosphatase, and dehydrogenase by 22%, 23%, 25%, and 20%, respectively, with greatest effects in acidic fine-textured soils. This increase in enzyme activities as well as the shift in microbial community diversity and activity (Jaiswal, Elad, et al., 2018) are directly dependent on (i) pH increase after biochar addition, as soil acidity is the main factor regulating microbial composition (Rousk et al., 2010); (ii) increased aeration, and consequently, better conditions for fungi and aerobic bacteria, as well as oxidative enzymes; (iii) changes in metabolic needs due to the prevalence of large organic compounds, and consequently, shift in the community toward K-strategists (Cui et al., 2020), decrease in gram-negative bacteria, shift toward saprophytic fungi, and increase in peroxidases; and (iv) strong increase in hydrophobic compounds in soil that favors activity of fungi (Deng et al., 2021; Xia et al., 2020).

Li et al. (2020) noted a negative effect of high biochar rates (>50 Mg ha^{-1}) on microbial diversity, and suggested the following potential causes: (i) introduction of toxic components that inhibit some species; (ii) increase in the C:N ratios of SOM that limits microbial C utilization, possibly only in the short term and only to the extent that the organic C is metabolized; and (iii) disruption of microbial microenvironments. Note also that C:N ratio does not influence microbial metabolization of biochars (Torres-Rojas et al., 2020).

Fungi and bacteria inhabit the larger nutrient-rich pores of biochar (>2 μm) where they mine the nutrients in the biochar and those that have been absorbed from fertilizers. The adsorption of root exudates, microbial metabolites, and microbial necromass increases SOM levels and thus increases soil organic carbon (SOC; see Section 4.2). Small biochar particles can migrate to the root surface and can alter the abundance of specific root-associated bacteria (Chew et al., 2020; Kolton et al., 2011).

In low P soils, arbuscular mycorrhizal fungi (AMF) invade the pores of biochar, especially biochars with high P content on the pore surface, which can increase plant P uptake (Gujre et al., 2020; Solaiman et al., 2019; Vanek & Lehmann, 2015). Blackwell et al. (2015) found that a phosphorus-enhanced BCF increased root colonization to 75% compared with 20%

in mineral fertilizer and unfertilized control and increased P uptake efficiency.

Adsorption of microbial signaling molecules (especially acyl-homoserine lactone) on biochar surfaces can disrupt soil microbial communication, which could reduce the effects of pathogens (Gao et al., 2016; Masiello et al., 2013). Biochar can also adsorb pathogenic enzymes and toxic metabolites exuded by soil-borne pathogens, thus reducing the concentration of virulence factors in the root zone and lowering disease severity (Jaiswal et al., 2018).

2.2.3 | Plant responses

Nutrient responses

Much of the N within the biochar C matrix (e.g., heterocyclic-N) is unavailable to plants (Clough et al., 2013; Torres-Rojas et al., 2020), whereas most K in biochar is present in soluble forms, released in the short term after application to soil (Silber et al., 2010), and is readily available to plants. Meta-analyses have found that biochar application commonly increases P availability, particularly when applied to acidic or neutral soils, and for biochar produced from low C:N feedstocks (e.g., manure, crop residues), and produced at low temperatures (Gao et al., 2019; Glaser & Lehr, 2019). However, P availability can be low in Ca-rich and K-poor feedstocks such as sewage sludge (Buss et al., 2018, 2020; Torres-Rojas et al., 2020; Wang et al., 2019) because pyrolysis can convert plant-available organic P into inorganic P that is less available in the short term (Buss et al., 2020; Rose et al., 2019). The opposite has also been observed, with pyrolysis increasing plant-available P although decreasing water-extractable P (Wang et al., 2014; Zwetsloot et al., 2015, 2016). The effect of biochar on P availability is determined by microscale effects on soil pH and soil solution composition, especially Ca content (Buss, Assavavittayanon, et al., 2018; Buss et al., 2018). Biochar can retain nutrients, especially N, released as fertilizers dissolve, and nutrients already present in soil, reducing loss through leaching (Haider et al., 2020). For example, meta-analysis found that biochar reduces N leaching on average by 26%, though it can increase ammonia volatilization at biochar application rates >40 Mg ha^{-1} and with biochar pH > 9 (Haider et al., 2020; Liu, Zhang, et al., 2018). While the stimulation of microbial activity by easily-mineralizable components of biochar can reduce N availability through microbial immobilization (Clough et al., 2013), it also accelerates the mineralization of organic matter and nutrient cycling, and AMF root colonization, which can increase N and P uptake by plants, as discussed above (Solaiman et al., 2019) and can also improve root growth under water stress (Mickan et al., 2016).

Adsorption of root exudates by biochar may cause dissolution of mineral compounds in biochar pores (Wang et al., 2020), which can increase nutrient availability, and can result in additional adsorption sites for organic molecules (Prendergast-Miller et al., 2014).

In flooded paddy soils, biochar and BCF particles can be encapsulated in an organo-mineral layer (Chew et al., 2020) on the root surface. BCF attached to the root or located in the rhizosphere of rice grown in flooded soils was observed to significantly alter the pH and Eh around the root, the root membrane potential (the potential difference between the inside of the root and the soil), and the abundance of specific microorganisms that increase nutrient availability (Chew et al., 2020). Thus, when biochar is in contact with root hairs, in the presence of microbes, it has the capacity to store and release nutrient ions and electrons (Chew et al., 2020; Sun, Levin, et al., 2017). The change in root membrane potential can facilitate uptake of nutrients when required by the plant. Chew et al. (2020) have represented these reactions as an RC circuit (Figure 1). Biochar directly mediates electron transfer by functioning as an electron shuttle and indirectly transfers electrons from the valence band to the conduction band in the Fe minerals by generating electron–hole pairs producing reactive oxygen species ($O_2^{\cdot -}$, H_2O_2, $HO^{\cdot}$) by Fenton and Fenton-like reactions (Yu & Kuzyakov, 2021).

Chemolithotroph bacteria can grow on the surfaces of microagglomerates of clay and Fe nanoparticles and make S and Fe more available to plants (Ye et al., 2017). Microbes can form biofilms on biochar surfaces, and establish corrosion cells that increase the solubility of metal species (e.g., insoluble Al_2O_3 to soluble Al; Joseph, Van Zwieten, et al., 2013).

Effects on heavy metal uptake

Many studies have shown that biochar can reduce uptake of heavy metal(loid)s by plants. A meta-analysis found biochar addition to soils resulted in average decreases in plant tissue concentrations of Cd, Pb, Cu, and Zn by 38%, 39%, 25%, and 17%, respectively (Chen et al., 2018). Studies showing significant reduction in bioavailability of heavy metals have often applied high rates of biochar, in excess of 10 Mg ha^{-1} (Chen et al., 2018; Wang et al., 2020). The surface O-functional groups on biochar can immobilize heavy metals through ion exchange, precipitation, cation and anion metal attraction, reduction, electron shuttling, and physisorption (Figure 2; Ahmad et al., 2014; Ding et al., 2014; Liu, Xu, et al., 2018; Tan et al., 2015; Zheng et al., 2020). Alkalinity from biochar (the liming effect) increases pH of acid soils, increasing the negatively charged exchange sites on clay particles, attracting cationic metals (Figure 1). Manure biochars commonly contain higher Ca than plant-derived biochars, and thus can immobilize cationic heavy metals (e.g., Cd^{2+} and Cu^{2+}) through ion exchange (Lei et al., 2019). Stable precipitates formed in biochars with high P can immobilize Pb through the formation of β-$Pb_9(PO_4)_6$, whereas higher alkalinity and calcite

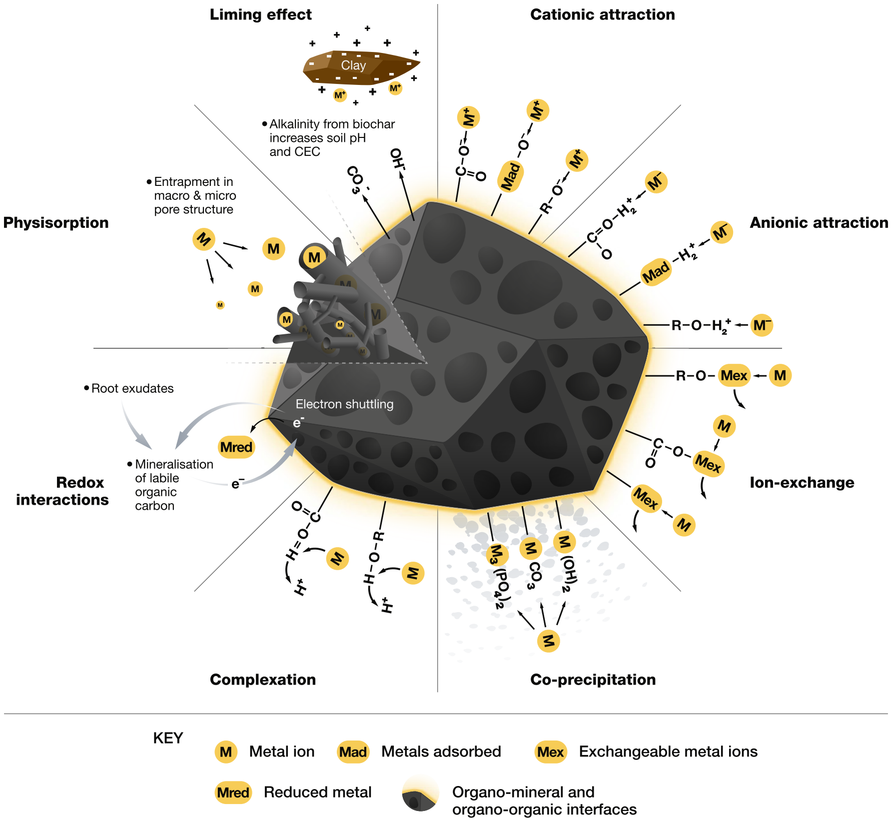

FIGURE 2 Postulated mechanisms of biochar interactions with heavy metals and metalloids (adapted from Ahmad et al., 2014)

in biochar facilitate the formation of insoluble hydrocerussite $Pb_3(CO_3)_2(OH)_2$ (Cao & Harris, 2010; Li et al., 2016). Particles on the surface of biochars consisting of carbon-coated minerals are particularly effective in reducing bioavailability of heavy metals (Kumar & Prasad, 2018). Incorporation into organo-mineral microagglomerates can reduce Cr(VI) to Cr(III) through interaction with reduced Fe, organic compounds, and free radicals (Odinga et al., 2020), including through electron shuttling (Xu et al., 2019), reducing their availability to plants (Kumar, Joseph, et al., 2018; Kumar et al., 2020).

High-temperature willow biochar was found to adsorb heavy metals from sewage sludge through both physisorption and the mechanisms described above (Bogusz et al., 2019). Even feedstocks that contain high contents of heavy metals can reduce the bioavailability of some heavy metals in some soils. For example, sewage sludge biochar decreased the bioaccumulation of As, Cr, Co, Cu, Ni, and Pb, but increased that of Cd and Zn in an acidic paddy soil (Khan et al., 2013).

Biochar can increase the mobility of anionic metalloids such as As (e.g., AsO_4^{3-}, AsO_3^{3-}; Igalavithana et al., 2017) through a decrease in positively charged sites, which decreases the binding sites for As as soil pH increases (Vithanage et al., 2017). Engineering biochars through adding magnetite nanoparticles can increase AEC and thus adsorb As (Wan et al., 2020).

Plant health

Besides the impacts of biochar on plant growth and development, it has been observed in numerous pathosystems that biochar can elicit systemic resistance in plants against diseases (Frenkel et al., 2017). Biochar in the growing medium can "prime" plants (Ton & Maunch-Mani, 2003) for rapid upregulation of defense-related genes (Elad et al., 2010; Jaiswal et al., 2014, 2015, 2017, 2020; Jaiswal, Elad, et al., 2018; Kolton et al., 2017; Kumar et al., 2021; Mehari et al., 2015; Meller Harel et al., 2012). Plants in a primed state display faster and stronger activation of cellular defense responses, such as earlier oxidative burst and stronger upregulation of defense genes, upon encountering biotic stresses (Conrath et al., 2006). This effect has been observed also for abiotic environmental pressures such as salt, heat, cold, toxins, and drought (Ton & Maunch-Mani, 2003).

A range of biochar–rhizosphere mechanisms are potentially responsible for these *in planta* responses (Graber et al., 2014), involving biochar's varied direct and indirect influences on the soil/rhizosphere/pathogen/microbiome/plant system. Some of these include: release of Si from biochar (especially straw and rice husk biochars), reported to increase disease resistance and plant growth (Wang, Wang, et al., 2019) by suppression of initial infection and pathogen access to plant tissues; adsorption by biochar of extracellular pathogenic enzymes and toxins (released by soil pathogens to dissolve and poison roots) lowering their concentrations in the root zone (Jaiswal, Frenkel, et al., 2018); induced systemic acquired resistance through upregulation of genes and pathways associated with plant defense and growth (Jaiswal et al., 2020); and adsorption and deactivation of plant signaling molecules that induce germination of parasitic weed seeds (Eizenberg et al., 2017).

The impact of biochar on plant disease is a function of biochar dose and type (physical/chemical characteristics, as discussed above; Frenkel et al., 2017; Poveda et al., 2021; Rogovska et al., 2017). Generally, no impact is found at low rates (<2 Mg ha^{-1}), positive impacts are seen at moderate rates (2–20 Mg ha^{-1}), and negative impacts at relatively high rates (>50 Mg ha^{-1}). This response pattern has been observed in studies of plant growth and disease caused by *Rhizoctonia solani* in common beans (Jaiswal et al., 2015) and cucumber (Jaiswal et al., 2014), and in other plant–soil-borne pathogen (Graber et al., 2014) and plant–foliar pathogen (Elad et al., 2011) systems. However, the optimal rate for disease suppression does not always coincide with the optimum rate for growth response. Rates that are beneficial for plant growth in non-diseased systems can result in disease promotion in pathogen-infected systems (Jaiswal et al., 2015).

Few studies have examined *in planta* responses to biochar when faced with environmental pressures. Under sufficient and drought water conditions, *Chenopodium quinoa* and maize both grew significantly better in biochar treatments, which was attributed to improved plant traits (lower proline content and less negative osmotic potential) rather than to increased root zone water content (Ahmed et al., 2018; Kammann et al., 2011). Improved pepper plant productivity in biochar-treated plots in a multi-year trial conducted under extreme environmental pressures (high evaporation demand and vapor pressure deficit, high daytime temperatures (heat stress) at planting and low nighttime temperatures at fruiting, brackish water irrigation) was attributed to biochar-elicited acclimation responses in the plants (Kumar, Elad, et al., 2018). Tests with heat stress and biochar in Arabidopsis indicated early microstresses primed the plants to cope better with subsequent acute heat stress. Early microstresses elicited improved energy production and utilization mechanisms, while the acclimation mechanism against the acute heat was related to lower levels of reactive oxygen species. The ability of biochar to induce an early acclimated state to basal microstresses and to prime the plant for coping with subsequent acute stresses was postulated to explain biochar-mediated improvements in plant health, flowering, and growth due to factors other than nutrition, water, or soil structure (Elad et al., 2011).

In addition to *in planta* responses discussed above, biochars buffer pH and poise (equilibrate) Eh (Husson, 2013; Joseph et al., 2015) which can create and maintain conditions in the rhizosphere that support plant growth and resilience to a range of environmental pressures, such as drought, heat, pathogens and pollutants (Husson et al., 2018). Biochar can rapidly transfer charge (Sun, Levin, et al., 2017; Yu & Kuzyakov, 2021), which could also enhance plants' capacity to cope with oxidative stress (Husson et al., 2018).

In summary, biochar can create conditions in the rhizosphere that increase nutrient supply and uptake; immobilize or deactivate phytotoxic organic and mineral substances; release bioactive compounds that stimulate growth and development; promote beneficial organisms; and inhibit pathogens. Thus, biochar can support plant growth, health, and resilience to disease and environmental stressors.

2.3 | Stage 3: Long-term reactions

Several studies have examined the longer term interactions as biochar "ages" in soil, investigating effects on bulk soil properties and plant growth where biochar has been applied in previous crops, or examining biochar particles extracted from the soil. Disturbance through cultivation, exposure to wetting–drying and freeze–thaw cycles, and ingestion by soil fauna can lead to further fragmentation of biochar particles and oxidation of biochar surfaces exposed through detachment of microagglomerates (Wang et al., 2020).

Two studies identified the formation of porous organo-mineral heterogeneous microagglomerates with mineral phases consisting of Fe, Al, Si oxides, phosphates (Ca/Fe/Al), carbonates (Ca/Mg), and chlorides (K, Na), and dimensions from 1 to 50 nm, bound together by organic compounds and bonded to the biochar surface (Archanjo et al., 2017; Rafiq et al., 2020). Simultaneous occurrence of Fe(II) and Fe(III) present as magnetite and hematite could make N and P more available through redox cycling of Fe (Haider et al., 2020). This could contribute to long-term increase in P availability in response to biochar application, such as identified in the meta-analysis of Glaser and Lehr (2019), who reported enhancement lasting up to 5 years. Aged high-temperature wood biochar particles retain plant-available N as nitrates and ammonium, adsorbed onto the organo-mineral microagglomerates (Haider et al., 2020). The formation of microagglomerates increases the surface area, CEC and AEC, but the pore volume generally decreases compared to the fresh biochar after multiple crop cycles, for example, Dong et al. (2017). Rhizodeposits are protected in soil microaggregates and Fe (oxyhydr)oxides (Jeewani et al., 2020), and a decadal study indicates potential for this mechanism to provide long-term stabilization of newly added plant C (Weng et al., 2017). Biochar particles can also be protected within the soil microaggregates (Figure 3).

The biochar-enriched anthropogenic Terra Preta soils associated with pre-Columbian settlements in the Brazilian Amazon (Steiner et al., 2009) provide evidence of very

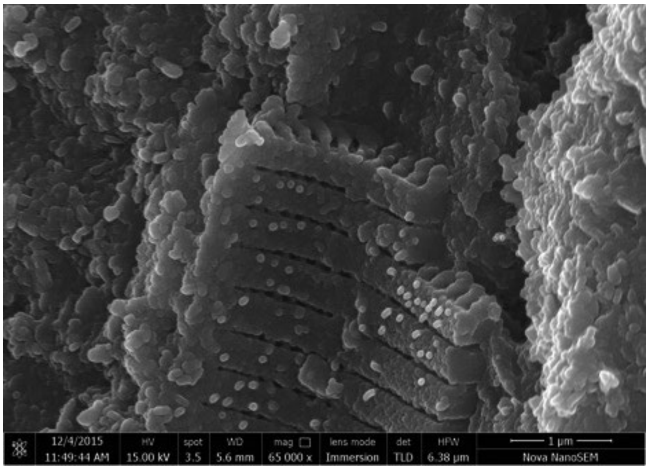

FIGURE 3 Fragment of biochar coated with nanoparticles that have a high concentration of Si, Fe, Al, Ti (see Figure S4) embedded in a soil microaggregate. Nanoparticles are the small spherical and ovoid particles on biochar lattice. Sample of biochar removed from a 9-year field trial of greenwaste biochar (Weng et al., 2017). Mineral nanoparticles on the biochar surface can play a key role in the formation of microaggregates that protect biochar from decomposition. The energy-dispersive X-ray spectroscopy (EDS) spectrum of this image is shown in Figure S4

long-term reactions of biochar in soil. Observations of Terra Preta soils identified that a substantial fraction of the biochar remained in particulate form, protected by Fe and Al oxides (Glaser et al., 2000).

Colloidal aged biochar particles consisting of microagglomerates and fragments of the C matrix may be more mobile in soil than fresh biochar (Wang, Zhang, et al., 2019). These particles can have higher negative charge on the surface compared with fresh biochar due to the higher concentration of C–O functional groups (Wang, Zhang, et al., 2019), further increasing CEC and capacity to adsorb organic molecules.

The bioavailability of heavy metals has been observed to increase or decrease as biochar ages in soil (Wang et al., 2020). For example, the reduction in uptake of Cd and Pb from a highly contaminated soil was sustained over 3 years after a single application of wheat straw biochar (Bian et al., 2014). Potentially, adding a small amount of biochar in a band every year could ensure heavy metals remain immobilized.

In their meta-analysis, Ye et al. (2020) reported an increase in crop yield over multiple years after a single biochar application, where fertilizer was applied. Rafiq et al. (2020) found that moderate rates (2–6 Mg ha^{-1}) of rice husk (high ash) biochar applied with fertilizer gave a residual benefit for pasture yield, lasting at least 3 years, associated with enhanced microbial activity and diversity. Kumar, Elad, et al. (2018) observed increased fruit yield and quality, and resistance to the pathogen causing powdery mildew and the arthropod pest broad mite, over three seasons in fertilized, irrigated peppers after application of greenwaste and woody biochars. Crop growth on Terra Preta soils is approximately double that on adjacent unamended soils, providing evidence that biochar can increase soil fertility over centuries (Lehmann et al., 2003).

There is a substantial body of literature examining biochar reactions over multiple years based on one-time application of biochar at high rates (e.g., 20–30 Mg ha^{-1} or 2–3% w/w), often in pots (e.g., Burrell et al., 2016), but there are few studies of biochar or BCF applied at low (commercially viable) rates, as single or repeated applications. Slow release of P from BCF and biochar can increase P-use efficiency in tropical soils over the medium- to long-term (Lustosa Filho et al., 2020), possibly through (i) input with high P biochars such as those made from manure or sewage sludge; and (ii) reduced P sorption due to DOM released from biochar (Schneider & Haderlein, 2016).

In summary, aging through interactions of biochar with soil minerals and microbes generally leads to functionalized surfaces consisting of organo-mineral microagglomerates, which can increase nutrient-holding capacity. Microagglomerates and portions of the C matrix can detach, and colloidal-sized particles can migrate through the soil profile. Aggregation can protect biochar and newly added organic matter, stabilizing new C for long periods in soil. Residual effects of single application of biochar on pH have been recorded, and some residual yield benefits have been observed.

3 | BIOCHAR'S ROLE IN SUPPORTING FOOD SECURITY

Over 1700 studies published between 2010 and 2020 (Web of Science) describe the effects of biochar on plant production. Meta-analyses have found yield responses of annual crops and trees of 10%–42% and identified site and biochar features giving greatest responses (Table 1).

Sandy soils and soils with CEC below 100 mmol$_c$ kg^{-1} or organic C content below 20 g kg^{-1} are most responsive (Dai et al., 2020; Ye et al., 2020). Soil pH is consistently identified as a key variable (Dai et al., 2020; Jeffery et al., 2011): Responses were greatest in acidic soils, because of the liming effect of biochar and a concomitant decline in available Al (Van Zwieten, Rose, et al., 2015). Importantly, Ye et al. (2020) identified that yield responses were greater in the third year after a single application, when fertilizer was applied with the biochar. This response most likely reflects the physicochemical and microbial changes that improve soil health as biochar ages (Section 2.3), rather than a simple soil pH response. A meta-analysis by Glaser and Lehr (2019) found availability of P increased on average by a factor of 4.6 in response to biochar application.

They noted that biochar increased P availability by a factor of 5.1 and 2.4 in acidic and neutral soils, respectively, but it had no effect in alkaline soils or at application rates below 10 Mg ha^{-1} or with biochars produced at HTT < 600 °C (Glaser & Lehr, 2019). The optimal biochar dose differed between studies (Table 1) and is dependent on the biochar characteristics, soil properties, and the constraint being addressed. Biochar may have no effect on yields when low-nutrient biochars are applied without fertilizer, or when biochar is applied to nutrient-rich soils (Ye et al., 2020). Negative effects can result from reduction in soil N and P availability (Nielsen et al., 2014; Prommer et al., 2014) especially at high rates of high temperature biochars (Kammann et al., 2015) through binding mechanisms described in Section 2.2.

A meta-analysis of the impacts of biochar on rice production (Awad et al., 2018) showed a net yield increase of 16%, with greatest response at 11–20 Mg ha^{-1} and with biochars produced at 400–450°C. The co-application of biochar with N fertilizer tended to provide the greatest yield increase, supporting previous evidence (Van Zwieten, Kimber, Morris, Chan, et al., 2010) that biochar can increase fertilizer N-use efficiency, and suggesting that biochar addition could maintain crop N uptake at lower doses of fertilizer N. Similarly, in two studies using BCF, N partial factor productivity increased by 37%–74% (Joseph, Graber, et al., 2013; Qian et al., 2014).

Biochars are generally found to increase soil water-holding capacity, which would enhance resilience of agricultural systems to drought, especially under climate change (Edeh et al., 2020) and may further explain the positive effects of biochars in sandy soils especially in arid and semiarid areas. Grass and straw biochars increase water-holding capacity to a greater extent than woody biochars (Burrell et al., 2016; Kroeger et al., 2020). Meta-analyses have shown increases in plant available water content of 33%–45% in coarse-textured soils and 9%–14% in clay soils (Edeh et al., 2020; Omondi et al., 2016; Razzaghi et al., 2020), with greatest response at 30–70 Mg ha^{-1}. Using X-ray μ-tomography, Quin et al. (2014) observed increases in total soil porosity, connectivity of pore space and number of fine pores across soils of different texture, explaining the results of Edeh et al. (2020) and Razzaghi et al. (2020).

The average 27% increase in photosynthetic rate in C_3 plants (but no effect on C_4 plants) observed in the meta-analysis of He et al. (2020) associated with increased stomatal conductance, transpiration rate, and chlorophyll content was attributed to the combined effects of biochar on water availability and N nutrition.

Heavy metal pollution in arable land significantly impacts plant growth and food safety (Luo et al., 2018) especially in developing countries (Hou et al., 2020). Application of biochar to contaminated soils could reduce heavy metal bioavailability via (1) direct interactions between biochar and heavy metals, and (2) indirect interactions that immobilize heavy metals through modification of soil properties (see Section 2.2.3), and could contribute to the yield benefits of biochar particularly in acid soils, as soil pH is a key property governing the speciation and mobility of heavy metals. Increase in soil CEC following biochar application can also reduce the bioavailability of cationic heavy metals (Mohamed et al., 2017). Biochar application can also alter soil Eh, impacting the speciation, mobility, and bioavailability of anionic heavy metalloids such as As (Yuan et al., 2017).

Heavy metals may be present in biochar produced from feedstocks such as sewage sludge and treated timber. Although the pyrolysis process concentrates most heavy metals, some metals such as Cd and Zn (Dong et al., 2015) and As (Zhang et al., 2020) can be partly volatilized during pyrolysis resulting in lower concentrations than the feedstock.

Application of biochar is a promising approach to mitigate heavy metal contamination; however, the remediation efficacy depends on the type of biochar, biogeochemical properties of soil, plant species, and the specific heavy metal (Albert et al., 2020; Palansooriya et al., 2020). Therefore, selecting the appropriate biochar type to address heavy metal contamination, suited to the soil properties, type of plant, and specific heavy metal, can result in effective remediation while safeguarding food quality.

Improved understanding of the key edaphic properties that constrain plant production and heavy metal uptake, and that can be addressed by biochar, enables design of "bespoke biochars" engineered for specific applications (Crombie et al., 2015) to contribute to food security.

4 | BIOCHAR'S ROLE IN CLIMATE CHANGE MITIGATION

Biochar has been recognized as a negative emissions technology (de Coninck et al., 2018; Cowie et al., 2020), in addition to reducing GHG emissions from soil, as reviewed below. Among carbon dioxide removal strategies, biochar is suggested as a preferred method due to comparatively low cost and large environmental benefits (Smith, 2016).

4.1 | Persistent carbon in biochar

Unlike other forms of biomass that are rapidly decomposed in soil, the majority of C in biochar has a mean residence time in the range of hundreds and thousands of years (Schmidt et al., 2011; Wang et al., 2016). Due to this high persistence, biochar can contribute significantly to long-term C sequestration (Lehmann, 2007). Sequential additions of biochar to soil will continue to build SOC stocks, whereas additions of unpyrolyzed organic matter (plant litter, compost, manure) will be rapidly mineralized, and will increase SOC stocks only until an equilibrium is reached where inputs equal decomposition rate (Figure 4).

The very slow decomposition of biochar in comparison to unpyrolyzed biomass is attributed to its aromatic structure, which results from chemical transformations of biomass during carbonization. Wood biochars pyrolyzed at temperatures above 450–500°C have a mean residence time of hundreds to a thousand years, compared with decades for manure biochars (Kuzyakov et al., 2014; Kuzyakov & Gavrichkova, 2009; Singh et al., 2012, 2015; Wang et al., 2016; Table 2). Kuzyakov et al. (2009) suggested that mean residence times calculated from incubations (Table 2), which maintain optimal conditions for decomposition, are around 10 times lower than under field conditions (Kuzyakov et al., 2009), although Rasse et al. (2017) found a similar rate of decomposition of *Miscanthus* biochar between laboratory and field conditions over a 90 day incubation period. The kinetics of formation of the fused aromatic C structure depend on the rate of heating, the ratio of lignin to cellulose and hemicellulose, time at the HTT, and mineral content (Budai et al., 2014; Leng & Huang, 2018; Rawal et al., 2016). The initial process of drying and depolymerization is endothermic and takes place between ambient temperatures and approximately 250°C. This is followed by an exothermic phase where most of the volatile gases are released, up to a temperature of approximately 350°C. The largely amorphous structure of biochars pyrolyzed at temperatures in excess of 400–450°C has been found to be persistent. Further heat converts the C matrix to a highly persistent three-dimensional nanographitic structure at around 600°C (McDonald-Wharry et al., 2016). Minerals present in biochar, especially Si and P, can increase persistence of biochar-C (Xu et al., 2017).

Estimating potential C sequestration through the use of biochar requires prediction of its persistence in soil. Temperature thresholds identified in the transformation processes can indicate persistence. Using hydrogen pyrolysis to assess relative chemical stability, McBeath et al. (2015) estimated, across a wide range of feedstocks, that <20% of the biochar is persistent at pyrolysis temperatures <450°C, with >80% persistent at 600–700°C. These findings are consistent with the structural changes observed by McDonald-Wharry et al. (2016).

While pyrolysis temperature is a convenient measure to obtain predictions for broad trends in persistence, and adequate for national GHG inventories (Ogle et al., 2019), material properties are a more rigorous approach to estimate biochar persistence for project-level GHG accounting and research applications. The elemental ratio of hydrogen to organic C expressed as H/C_{org} has been identified as a simple and reliable parameter for characterizing biochar persistence and recommendations for conservative thresholds have been provided (Budai et al., 2013). These thresholds are being refined as more data become available (Lehmann et al., 2015) and other methods, such as spectral and thermal methods and chemical oxidation, offer additional insights (Leng & Huang, 2018; Li & Chen, 2018).

Biochar properties are the key determinant of its persistence in comparison to mineralization of unpyrolyzed biomass, but edaphic and climatic factors are also influential. As discussed in Section 2.2, the formation of microaggregates through interaction of biochar with minerals and native SOM

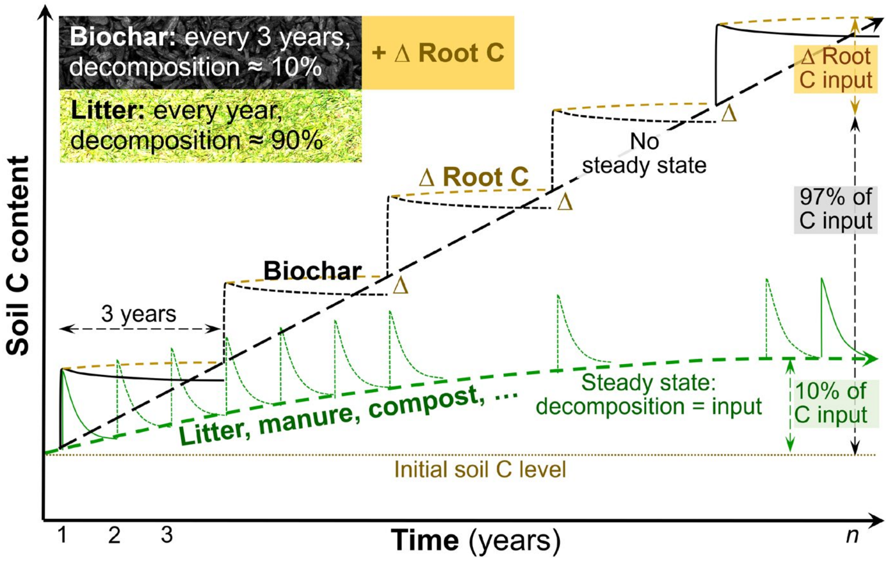

FIGURE 4 Accumulation of soil organic carbon (SOC) stocks with sequential biochar additions, due to (i) the highly persistent carbon in biochar, (ii) biochar-induced negative priming, and (iii) additional C input from plant roots through retention of rhizodeposits (Δ Root C), compared with limited SOC stock increase with addition of unpyrolyzed organic matter. Conceptual example for a scenario where biochar is added every 3 years and decomposes at 3% per year, compared with annual additions of unpyrolyzed biomass, of which 90% decomposes each year

TABLE 2 Mean residence time (MRT) of biochars, limited to studies >150 days duration

Study (experiment period)	Feedstock	Pyrolysis temperature (°C)	Soil	MRT (years)	Study (experiment period)	Feedstock	Pyrolysis temperature (°C)	Soil	MRT (years)
Maestrini et al. (2014)	Ryegrass	450	Cambisol without N	40	Zimmerman (2010)	Oak	650	Sand	5652
(158 days)	Ryegrass	450	Cambisol with N	40	(365 days)	Grass	650	Sand	370
Santos et al. (2012)	Pine	450	Granitic soil	605		Cedar	650	Sand	15621
(180 days)	Pine	450	Andesitic soil	389		Bubinga	650	Sand	3937
Nguyen et al. (2014)	Switchgrass	475	Typic Hapludalf	163		Sugar cane	650	Sand	7430
(189 days)	Switchgrass	475	Aquic Hapludult	138	Weng et al. (2015)	*Eucalyptus saligna*	450	Ferralsol (no plants)	484
	Switchgrass	475	Lithic Dystrudept	129	(388 days)	*E. saligna*	450	Ferralsol (planted)	449
	Switchgrass	475	Ultic Hapludalf	113	Wu et al. (2016)	Rice straw	500	Loamy soil	857
Naisse et al. (2015)[a] (222 days)	Maize silage	1200	Cambisol	105	(390 days)	Rice straw	500	Loamy soil	2829
	Maize silage (weathered)	1200	Cambisol	211		Rice straw	500	Clay loam	1896
Bai et al. (2013)[a] (200 days)	*Miscanthus* × *giganteus*	575	Inceptisol	28		Rice straw	500	Loamy soil	971
	Miscanthus × *giganteus*	575	Mollisol	33		Rice straw	500	Sand clay	617
	Miscanthus × *giganteus*	575	Inceptisol-Aquept	64	Herath et al. (2015)[a]	Corn stover	350	Alfisol	91
Budai et al. (2016)	Corncob	369	Inceptisol	252	(510 days)	Corn stover	350	Andisol	91
(364 days)	Corncob	416	Inceptisol	143		Corn stover	550	Andisol	91
	Corncob	562	Inceptisol	191		Corn stover	550	Alfisol	91
	Corncob	580	Inceptisol	138	Major et al. (2010)	Old mango tree	400–600	Typic Haplustox	600
	Corncob	796	Inceptisol	149	(730 days)				
	Miscanthus × *giganteus*	235	Inceptisol	4	Fang et al. (2014)[a]	*E. saligna*	450	Inceptisol	456
	Miscanthus × *giganteus*	369	Inceptisol	172	(730 days)	*E. saligna*	450	Entisol	342
	Miscanthus × *giganteus*	385	Inceptisol	165		*E. saligna*	450	Oxisol	342
	Miscanthus × *giganteus*	416	Inceptisol	118		*E. saligna*	450	Vertisol	342
	Miscanthus × *giganteus*	503	Inceptisol	125		*E. saligna*	550	Inceptisol	913
	Miscanthus × *giganteus*	600	Inceptisol	232		*E. saligna*	550	Entisol	913
	Miscanthus × *giganteus*	682	Inceptisol	123		*E. saligna*	550	Oxisol	685

TABLE 2 (Continued)

Study (experiment period)	Feedstock	Pyrolysis temperature (°C)	Soil	MRT (years)	Study (experiment period)	Feedstock	Pyrolysis temperature (°C)	Soil	MRT (years)
Maestrini, Abiven, et al. (2014)	Pine	450	Cambisol without N	191		*E. saligna*	550	Vertisol	685
(365 days)	Pine	450	Cambisol with N	430	Zimmerman and Gao (2013)[a]	Grass	650	Sand	104167
Zimmerman (2010)	Pine	400	Sand	1280	(1173 days)	Oak	650	Sand	588
(365 days)	Oak	400	Sand	1263	Singh et al. (2012)	*E. saligna*	400	Vertisol	294
	Grass	400	Sand	793	(1829 days)	*E. saligna* leaves	400	Vertisol	270
	Cedar	400	Sand	3967		Poultry litter	400	Vertisol	129
	Bubinga	400	Sand	2532		Cow manure	400	Vertisol	90
	Sugar cane	400	Sand	2740		*E. saligna*	550	Vertisol	1616
	Pine	525	Sand	2928		*E. saligna* leaves	550	Vertisol	572
	Oak	525	Sand	3223		Poultry litter	550	Vertisol	396
	Grass	525	Sand	1218		Cow manure	550	Vertisol	313
	Cedar	525	Sand	3465		Papermill sludge	550	Vertisol	102
	Sugar cane	525	Sand	1829	Kuzyakov et al. (2009) (1181 days)	Ryegrass	400	Luvisol	200
	Pine	650	Sand	2284	Kuzyakov et al. (2014) (3100 days)	Ryegrass	400	Luvisol	402

[a] Where not stated by the authors, we calculated MRT as the inverse of the degradation constant k_2, based on a two-pool exponential model.

can reduce the mineralization of biochar-C; thus, persistence is likely to be greater in soils dominated by minerals that form stable aggregates (kaolinite and sesquioxides), such as Oxisols and Ultisols (Fang et al., 2015; Fungo et al., 2017; Weng et al., 2017). There is some evidence that biochar persistence decreases as ambient temperature increases (Fang et al., 2017). The movement of biochar through the soil profile can increase persistence in some soil types (Singh et al., 2015).

4.2 | Priming effects

Change in the mineralization rate of SOM induced by organic or mineral amendments is known as "priming" (Kuzyakov et al., 2000). Historical addition of pyrogenic organic matter has been shown to slow SOM mineralization and enhance native soil organic C (SOC) stocks (Borchard et al., 2014; Downie et al., 2011; Hernandez-Soriano et al., 2016; Kerré et al., 2016; Liang et al., 2010). The direction of priming can be positive or negative, with an increase or decrease of SOM mineralization, respectively. Priming effects of biochar are reviewed in more detail in Text S3. Meta-analyses show that biochar application commonly induces positive priming initially (for 20 days: Maestrini et al., 2015; 2 years: Ding et al., 2018), followed by negative priming, of 3.8% on average (Wang et al., 2016). Wang et al. (2016) further identified that biochar decreased SOM mineralization by 20% with crop residue biochars, 19% with fast pyrolysis biochars, 19% with low temperature biochars (200–375°C), and 12% with low biochar application rates (0.1%–1% w/w) but increased SOM mineralization by 21% in sandy soils. Ding et al. (2014) found that the magnitude of negative priming increased with increasing pyrolysis temperature, time following biochar application, and soil clay content >50%, but decreased with an increasing C:N ratio of soil.

Mechanisms for biochar-induced positive priming include direct effects from: (1) greater microbial activity and enzyme production fueled by the addition of the easily mineralizable C from biochar (Luo et al., 2013; Singh & Cowie, 2014; Section 2.1), and (2) microbial nutrient mining (e.g., N and P); and indirect effects such as (1) amelioration of acidity by biochar that promotes microbial activities (Luo et al., 2011), (2) amelioration of nutrient constraints (Mukherjee & Zimmerman, 2013), (3) enhanced microbial habitat (Luo et al., 2013; Pokharel et al., 2020) and soil faunal activity, and (4) much better aeration because of increased size and stability of macroaggregates and lower soil bulk density, all leading to increased microbial activities.

Biochar can cause negative priming directly by (1) substrate switching where the easily mineralizable C from biochar may be preferentially consumed by microbes to temporarily replace the use of SOC (DeCiucies et al., 2018; Kuzyakov et al., 2000) and (2) a dilution effect of substrates where added biochar temporarily reduces the mineralization of the more readily mineralizable C in soil (Whitman et al., 2014) and indirectly from (3) the sorption of organic compounds by biochar (DeCiucies et al., 2018; Kasozi et al., 2010), (4) improved organo-mineral protection and stable aggregation slowing down the mineralization of SOC within the organo-mineral complexes (Fang et al., 2018; Weng et al., 2017, 2018), and (5) inhibition of microbial activity by polyaromatic toxic compounds (Zhang et al., 2018). Biochar amendments reduced the activities of soil enzymes associated with C cycling by 6% (Zhang et al., 2019), improved C-use efficiency (Liu, Zhu, et al., 2019, 2020), increased soil microbial biomass (Li et al., 2020), and lowered the metabolic quotient by 12%–21% (i.e., respiration rate CO_2-C per unit of microbial biomass C) compared with the unamended soils (Zhou, Zhang, et al., 2017), the latter attributed to improved microbial habitats and alleviation of environmental stresses including acid soil constraints. Negative priming is found to result mainly from substrate switching (Ventura et al., 2019) and dilution (DeCiucies et al., 2018) in the short term, with adsorption being more important after several weeks.

Biochar can affect new additions to soil of plant-derived C, and these rhizodeposits can also prime and act as a source of SOC. In a subtropical pasture on a Rhodic Ferralsol, a ^{13}C-depleted hardwood biochar (450°C) initiated positive priming up to 0.15 Mg C ha^{-1} over 62 days, switching to negative priming after 188 days in the presence of plants (Weng et al., 2015). Biochar builds SOC through soil aggregation processes that stabilize new C (i.e., rhizodeposits), by 6%–16% (Ventura et al., 2019; Weng et al., 2015, 2017), as well as by reducing priming caused by plant C input (Whitman et al., 2014). In a 6-year field experiment where woody biochar was applied to corn and bioenergy crops, SOC stocks increased by 14 Mg C ha^{-1}, twice the quantity of C added in the biochar, as a result of negative priming (Blanco-Canqui et al., 2020). Figure 4 illustrates how biochar application can lead to accumulation of SOC stocks through biochar-induced negative priming and enhanced retention of rhizodeposits.

4.3 | Effect on GHG emissions

The complex soil microbial communities that produce and consume N_2O and CH_4 in soil and the interrelated biotic and abiotic processes that take place, make predicting GHG emissions from soil extremely challenging. Microbiological N transformations are the main source of N_2O emissions from soil, with autotrophic nitrification and heterotrophic denitrification being the main N_2O formation pathways. Biochar can lower denitrification (the reduction of NO_3^- to N_2) by: (i) facilitating the last step of denitrification (the transformation of N_2O to N_2), and (ii) decreasing total denitrification activity (Cayuela et al., 2013; Weldon et al., 2019). Biochar can facilitate the reduction of N_2O to N_2 via: (i) increasing pH in acid soils (Obia et al., 2015) thus enhancing the *nosZ* gene (Harter, Guzman-Bustamante, et al., 2016); (ii) changing the relative abundance and composition of N_2O-reducing microbial communities (Harter, Weigold, et al., 2016); and (iii) facilitating extracellular electron exchange (Chen et al., 2014) or directly donating electrons to denitrifying bacteria (Pascual, Sánchez-Monedero, Cayuela, et al., 2020). The decrease in denitrification may result from decrease in availability of NO_3^- and bioavailable C substrate (Fiorentino et al., 2019; Hagemann, Kammann, et al., 2017; Heaney et al., 2020). Abiotic processes, in particular with biochars containing high Fe and Mn content (see Section 2.2.1), can directly catalyze the reduction of N_2O to N_2. It has also been shown that N_2O can be transformed to NH_3, pyridine, or pyrrole compounds on biochar surfaces, thus decreasing N_2O emissions (Quin et al., 2015).

Several meta-analyses have synthesized the results of studies on effects of biochar on soil GHG emissions, and sought to explain the differences between individual studies. Although there are gaps in process understanding, and identification of best management practices, there is solid evidence that biochar can mitigate soil N_2O and CH_4 emissions from soil, at least in the short and medium term (Borchard et al., 2019; Cayuela et al., 2014, 2015; Fan et al., 2017; Jeffery et al., 2016; Liu, Liu, et al., 2019; Liu, Zhang, et al., 2018; Verhoeven et al., 2017).

Early meta-analyses on N_2O emissions showed very high mitigation (around 50% reductions) of N_2O with biochar (Cayuela et al., 2014, 2015). These studies included laboratory experiments performed under controlled conditions, and with very high biochar application rates (>100 Mg ha^{-1}). A direct correlation between application rate and N_2O decrease was found (Cayuela et al., 2014), with lower N_2O mitigation (average 27%) under more realistic rates equivalent to 10–20 Mg ha^{-1}. Most experiments included in these meta-analyses were carried out under high moisture conditions favoring denitrification, where biochar is most effective in decreasing N_2O emissions (Cayuela et al., 2013; Weldon et al., 2019).

Later meta-analyses including a larger number of field studies and more realistic biochar application rates found lower average reductions, of 12% (Verhoeven et al., 2017) considering only field studies, and 38% (Borchard et al., 2019) including laboratory and field studies. This contrasts sharply with other (unpyrolyzed) organic amendments. For example, a meta-analysis on manure application to soil found an average increase of 33% in N_2O emissions compared to synthetic fertilizer (Zhou, Zhu, et al., 2017). Even high C:N amendments that tend to immobilize N in soil have been found to increase N_2O emissions. For instance, Xia et al. (2018) found an average increase of 22% in N_2O emissions when straw was applied. Therefore, although the averaged numbers differ between meta-analyses depending on the criteria for the inclusion of studies and the methodology used, there is strong evidence that biochar amendment reduces (on average) direct N_2O emissions from soil particularly when compared to other organic amendments.

Biochars produced by slow pyrolysis, with high degree of carbonization, high pH, and high surface area, are most effective in suppressing N_2O emissions (Borchard et al., 2019; Cayuela et al., 2015; Weldon et al., 2019). A dose of 10–20 Mg ha^{-1} has been found to significantly reduce N_2O emissions (Borchard et al., 2019; Cayuela et al., 2014). The effect of biochar might diminish with time, as biochar ages in soil (Borchard et al., 2019; Fungo et al., 2017; Liu, Zhang, et al., 2018). Nevertheless, the mitigation provided initially can be substantial, and repeated applications may maintain the mitigation benefit.

The impact of biochar on CH_4 fluxes has been widely evaluated in paddy and non-flooded soils. Whereas non-flooded soils mostly act as a sink of atmospheric CH_4, paddy soils can be a significant source of CH_4. Several meta-analyses found that, on average, biochar mitigates CH_4 emissions from flooded soils, particularly from acidic soils, but decreases the CH_4 sink of non-flooded soils (Jeffery et al., 2016). Ji et al. (2018) cautioned that the co-application of biochar with nitrogen fertilizers substantially decreased the effectiveness of biochar in reducing soil CH_4 emissions from paddies, however, their meta-analysis also showed that the biochar-induced decrease in CH_4 uptake by non-flooded soils was lessened when N fertilizer was also applied. Further, a recent study demonstrates the relevance of biochar properties to the effect on soil CH_4 uptake rates: biochars with high electrical conductivity and ash concentrations decreased CH_4 sink capacity whereas biochars from woody materials pyrolyzed at high temperatures and with high pore area increased soil CH_4 uptake rates (Pascual et al., 2020). Qian et al. (2014) found a decrease in N_2O and CH_4 emissions from paddy soil when a range of biochar-based BCFs was compared with NPK fertilizers.

4.3.1 | GHG intensity and yield-scaled emissions

To avoid overlooking potential trade-offs with crop yields, studies report GHG intensity (GHG per unit crop yield)

(Mosier et al., 2006) or yield-scaled emissions for N_2O (i.e., N_2O emissions in relation to N uptake of the aboveground crop) (Van Groenigen et al., 2010). Analyses of specific cropping systems show a decrease in GHG intensity with biochar application in vegetable fields (Fan et al., 2017) and in wheat–rice rotation systems (Wu et al., 2019). One of the first studies summarizing results on yield-scaled N_2O emissions was performed by Verhoeven et al. (2017) who found that biochar decreased yield-scaled N_2O emissions across the majority of the studied cropping systems, although a meta-analysis could not be carried out due to the low number of field studies and excessively high variance between studies. Later, Liu, Mao, et al. (2019) were able to incorporate a larger number of studies and showed an overall reduction of GHG intensity by 29% after biochar amendment, with higher reductions in non-flooded soils (−41%) compared to paddy fields (−17%). A meta-analysis focusing on vegetable fields in China also found that biochar application decreased yield-scaled N_2O emissions by an average of 35% (Gu et al., 2020).

4.3.2 | Potential trade-offs between C sequestration and non-CO_2 GHG emissions

In order to evaluate the full net GHG balance of biochar in soil, the fluxes of CH_4 and N_2O and the changes in SOC stocks need to be jointly assessed. Usually, CH_4 and N_2O emissions are expressed in CO_2-equivalents using 100-year global warming potential. In non-flooded soils, the relationship between SOC changes and N_2O emissions usually regulates the net GHG emission, since agricultural soils are often weak CH_4 sinks. One of the greatest difficulties for the comprehensive analysis of the balance between C sequestration and N_2O emission lies in the need for long-term studies to measure changes in SOC reserves (Smith et al., 2020) and the laborious nature of direct measurements of N_2O, which makes long-term N_2O studies (>10 years) very rare.

An increase in SOC is often associated with higher N_2O emissions, which could counteract the mitigation benefits derived from C sequestration (Davies et al., 2020). However, it is precisely in these trade-offs where biochar might have the greatest advantage compared to other soil amendments and other SOC sequestration strategies. Although a comprehensive meta-analysis on these trade-offs has not been published yet, results from separate meta-analyses on C sequestration (Bai et al., 2019) and N_2O emissions (Borchard et al., 2019; Liu, Liu, et al., 2019) point to a strong synergy between C sequestration and mitigation of N_2O emissions with biochar, which is much less evident for other SOC sequestration strategies (Guenet et al., 2021).

5 | BIOCHAR'S ROLE IN THE CIRCULAR ECONOMY

The circular economy concept aims to conserve resources, and minimize inputs and waste. Biochar can support the development of a circular economy at regional and farm scale by improving nutrient recovery and nutrient use efficiency. The economic case for biochar production is strongest for biochar made from residue materials, especially when the residues contain high concentrations of nutrients, such as animal manures and sewage sludge. Concerns that these feedstocks may contain contaminants restrict their beneficial reuse. Fortunately, most organic contaminants are destroyed with high efficiency during pyrolysis, by thermal degradation and volatilization followed by destruction during vapor combustion. This has been shown for PAHs (Zielińska & Oleszczuk, 2015), polychlorinated biphenyls (Bridle et al., 1990), per- and polyfluoroalkyl substances (PFAS; Kundu et al., 2021), microplastics (Ni et al., 2020), antimicrobials (Ross et al., 2016), antibiotics (Tian et al., 2019), antibiotic resistance genes (Kimbell et al., 2018), and hormones (estrogen; Hoffman et al., 2016).

While incineration destroys organic contaminants with similar efficiency to pyrolysis (Baukal et al., 1994), unlike incineration, pyrolysis retains a large portion of the feedstock C (typically around 50%), and most nutrients, in the biochar. In addition, pyrolysis gases can be captured for use as a renewable energy product (see Text S4). Of the main plant nutrients, P and K are fully retained in biochar at typical pyrolysis temperatures (300°–700°) (Bridle & Pritchard, 2004; Buss et al., 2016). Nonetheless, 50%–80% of N can be lost (Hossain et al., 2011; Ye et al., 2020; Yuan et al., 2018) depending on the N content of the feedstock (Torres-Rojas et al., 2020), with greater loss at high pyrolysis temperature. A meta-analysis found N, P, and K concentrations in biochars of 1.0%, 0.4%, and 1.9% (wood-derived biochars), 1.5%, 0.8%, and 4.1% (crop residue biochars) and 2.4%, 2.6%, and 2.5% (manure/sewage sludge biochars), respectively (Ippolito et al., 2020).

Notably, some sewage sludge biochars contain as much as 6%–20% total P (Faria et al., 2018; Roberts et al., 2017; Shepherd et al., 2016; Zhang et al., 2015). However, only a fraction of the total nutrients in biochar is available for plant uptake (in the short-medium term), in the order K>P>N. A meta-analysis found that, on average, the following percentages of the N, P and K present in biochar were bioavailable: 0.5%, 3%, and 9% (wood-derived biochar), 0.4%, 6%, and 22% (crop residue biochar) and 5%, 5%, and 17% (manure/sewage sludge biochar), respectively (Ippolito et al., 2020).

Biochar P availability can be increased by selecting low Ca feedstocks or doping feedstock with K, leading to preferential binding of P with K instead of Ca, Mg, Fe, or Al,

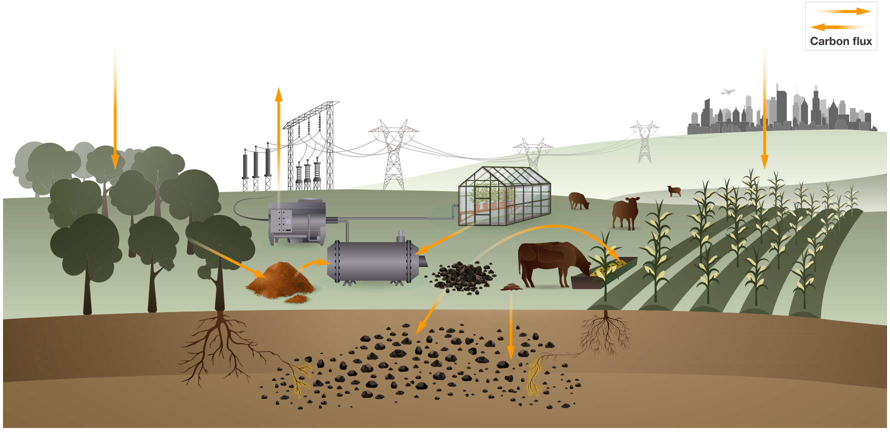

FIGURE 5 Biochar systems utilize organic residues, including forest, crop, and horticultural residues, to produce biochar that is used as a soil amendment directly, and indirectly via feeding to livestock. Pyrolysis gases and process heat, co-products of biochar production, can be used to supply renewable energy

forming highly soluble salts (Buss et al., 2020). Biochars can be optimized to sorb P or N from wastewater and hence be loaded with extra nutrients that are accessible to plants (Mood et al., 2020; Shang et al., 2018; Shepherd et al., 2016, 2017), reducing wastewater P and N concentrations, preventing eutrophication, and returning nutrients to agricultural land.

Controlled release biochar-fertilizer combinations can be produced from low-nutrient biomass mixed with mineral or organic nutrients before pyrolysis and/or organic nutrients after pyrolysis, or by composting to enrich with nutrients (Buss et al., 2019, 2020; Dong et al., 2019; Hagemann, Joseph, et al., 2017; Schmidt et al., 2015) and these can be effective at low application rates when applied in a band near the seed/plant (Qian et al., 2014; Schmidt et al., 2015; Yao et al., 2015; Zheng et al., 2017).

The use of biochar in composting of organic residues such as manures can reduce N losses through volatilization and leaching, reduce GHG emissions, increase C persistence, and reduce availability of heavy metals (Agyarko-Mintah et al., 2017; Akdeniz, 2019; Oldfield et al., 2018; Sanchez-Monedero et al., 2018).

Biochars, including BCFs and biochar used as a compost additive, thus improve nutrient recovery from organic residues, facilitate use of residues in soil amendment, and reduce environmental impacts of waste management. Biochar systems (Figure 5) thereby contribute to building a circular economy.

6 | CONCLUSION AND RECOMMENDATIONS

Soil and plant responses to addition of biochar can be negative, positive, or neutral, depending on many variables, including feedstock and pyrolysis temperature, application rate and method, and application context (crop, soil type, and environmental and biological stresses). Considering the heterogeneous nature of biochars and the complexity of the physical, biochemical, and microbiological processes underpinning the effects of biochars, reviewed above, it is not surprising that studies report a wide range of responses to biochar application. Results are also strongly influenced by experimental design aspects; studies that do not include plants, or are undertaken in soil-less media, or based on pot trials cannot readily be extrapolated to field situations.

Scientific understanding of the biochar–soil–plant processes and interactions has evolved over the last decade, providing the basis to interpret the divergent results in the literature and identify optimal uses of biochars. The following encapsulates current knowledge, as reviewed in this paper. Biochar catalyzes microbial and abiotic processes in the rhizosphere, decreasing the activation energy for biotic and abiotic reactions, which can increase nutrient mineralization and facilitate nutrient uptake by plants. Higher microbial activities lead to accelerated turnover of organic matter which enhances nutrient supply. Biochar reduces the availability of heavy metals, increases plant resistance to disease, and improves resilience to environmental stressors. The microscale processes on the biochar surface and in the rhizosphere mediate the macro responses of plants to biochar. The catalytic ability of biochar changes as it ages in soil through oxidation and interactions with minerals, microbes, soil fauna, and organic matter.

Significant yield increases occur where site-specific soil constraints, nutrient and water limitations are addressed by appropriate biochar formulations applied at an optimal application rate. Meta-analyses of crop responses to biochar show average yield increases of 10%–42%, with greatest responses in acidic and sandy soils where the biochar has been applied with organic and/or mineral fertilizers. On average, biochars increase P availability by a factor of 4.6, decrease plant tissue concentration of heavy metals by 17%–39%, build SOC through negative priming by 3.8% (range −21% to +20%), and reduce non-CO_2 GHG emissions from soil by 12%–50%.

To enable widespread adoption, biochar needs to be readily integrated with farming operations, and be economically viable. Formulations that combine biochar with mineral and/or organic fertilizers and minerals are likely to have high nutrient use efficiency and be the most cost-effective. Such formulations are the major focus of commercialization, but they have received limited attention in research studies, and very few field trials have been undertaken.

Knowledge gaps remain regarding biochar–soil–plant interactions in the field over the longer term, including longevity of yield response and reduction of N_2O emissions; the direction, magnitude, and duration of organic matter priming; and long-term effects of repeated applications. Research is needed on processes that influence the capture and release of heavy metals in the long term to determine optimum scheduling of re-application of biochar. Further research on the effects of biochar properties on root membrane potential and microbial nutrient cycling will inform the development of optimal formulations to increase nutrient uptake efficiency.

We recommend that guidelines on selecting and producing biochar formulations to meet specific soil and environmental constraints and increase farm profitability be developed, based on the findings of this review. Biochars can be tailored for specific applications through feedstock selection; by modifying process conditions; through pre- or post-production treatments to adjust pH, increase nutrient level and availability, carbon persistence and adsorptive properties; or co-application with organic or mineral fertilizers. Use of biochar in waste management, such as co-composting of animal manures and pyrolysis of sewage sludge, can capture nutrients and reduce GHG emissions.

This review presents strong evidence that biochar can contribute to climate change mitigation through carbon sequestration and reduction in soil GHG emissions, and that significant benefits to plant production are possible, particularly where site-specific soil constraints and nutrient and water limitations are addressed by appropriate biochar and fertilizer applications. Biochar has the greatest potential to increase crop yields in low-nutrient, high P-fixing acidic soils, common in the tropics and humid subtropics, and in sandy soils, particularly in dryland regions that are likely to be increasingly affected by drought under climate change. Biochar can also mitigate heavy metal pollution, that impacts food production and food safety in many developing countries, and enhance resource use efficiency. Thus, biochar can play a key role in addressing climate change and supporting global food security and the circular economy.

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CONFLICT OF INTEREST

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created in this study.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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Version 2.0
August 2024

Australian Biochar Industry

2030 ROADMAP

ANZ
BIOCHAR
INDUSTRY GROUP

Contents

Notification

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Version	Date	Summary of Changes
1.0	June 2023	Original as launched in Canberra
1.1	July 2023	Additional sponsors included
1.2	July 2024	Additional sponsors Included
2.0	August 2024	Inclusion of Commonwealth policy alignment page and additional sponsors.

Foreword

The Australian Biochar Industry Roadmap is a call to action. It demonstrates and explains the huge potential for growth of biochar production and use in Australia. Making this potential real will deliver major economic, environmental and social benefits.

Better utilisation of currently wasted and residual biomass resources for biochar production can provide valuable inputs into agriculture and industry. In agriculture, biochar can improve soil fertility and increase moisture retention. Fed to cattle or sheep, biochar can improve digestion so that more feed is converted into increased meat, milk and other animal products, and less methane is released. In industry, biochar can provide a renewable source of inputs that would otherwise be drawn from coal, oil or gas and contribute to carbon emissions. It can contribute this value while capturing and storing for long periods the carbon that has been absorbed from the atmosphere by plants. The long-term storage of carbon as biochar is recognised as a secure source of negative emissions.

The Australian Biochar Industry 2030 Roadmap comes at an important time, when we need to lower emissions quickly, and to develop new sources of economic growth.

The production of the Roadmap is a tribute to ANZBIG, the peak body of the growing biochar industry. The Roadmap embodies the results of extensive participant consultation. This not-for-profit group has attracted members and supporters from biochar producers, biochar users, capital providers, research scientists, engineers, and citizens with an interest in climate change action. ANZBIG's Roadmap will inform the community and illuminate the case for new policies from all Australian governments.

ANZBIG's Roadmap is especially timely. The 2020s are the critical decade, in which people with influence now will take decisive steps towards stopping the trend to higher global temperatures, or leave future generations with an impossible task.

Australia has the resources to strengthen its economy through developing net zero targets, while removing its own emissions and contributing substantially to net zero emissions in the rest of the world. Biochar can make significant additions to these important outcomes in the years to 2030, and much more after that.

The ANZBIG Roadmap demonstrates the contribution biochar can make to Australian economic and environmental goals. Community understanding of the Roadmap will drive removal of barriers to increased development of this new industry. High levels of investment will follow introduction of policies that recognise the value of innovation in a burgeoning industry that has potential for large expansion, and the value of removing carbon dioxide from the atmosphere.

I look forward to working with you in making progress in the directions defined by the Roadmap. And I look forward to the biochar industry making a major contribution to the emergence of Australia as a Superpower of the net zero world economy.

Ross Garnaut AC
Patron, ANZBIG, May 25, 2023

ANZBIG's Roadmap will inform the community and illuminate the case for new policies from all Australian governments.

Acknowledgments

This Roadmap represents the ideas and efforts of many people and organisations working in the biochar sector. It is a collective and collaborative process that has driven the concept and development of the Australian Biochar 2030 Industry Roadmap.

The extensive consultation and strategy work embodied within this roadmap was led by Russ Martin of MS2 and supported by Shaun Scallan of Sustainability Plus Projects. We recognise their significant work in preparing the draft Roadmap and strategy documents now embodied within this Roadmap.

Special mention is required for the significant contributions of Nigel Murphy, Craig Bagnall, Melissa Rebbeck, and Professors Stephen Joseph and Annette Cowie.

The ANZBIG Executive and Advisory Boards should also be acknowledged together with the staff of ANZBIG, capably led by CEO Don Coyne and Cluster Manager Samantha Zagami.

ANZBIG also acknowledges the biochar pioneers that have created our industry. Without their inspiration, persistence, and belief we would not be the exciting industry of today.

Design and layout: Rosie Moulton


We acknowledge the biochar pioneers that have created our industry. Without their inspiration, persistence and belief we would not be the exciting industry of today

Supporters and Sponsors

The development of the Australian Biochar Industry 2030 Roadmap has been supported by many organisations. We acknowledge and thank them for their support.

Diamond

- EARTH SYSTEMS – Environment | Water | Sustainability
- SYNDICATION GROUP
- CARBON STANDARDS international
- C-TWELVE
- WASTE CIRCOLOGY – Sustainable Carbon Technology

Silver

- energylink SERVICES
- CATALYST Environmental Management
- CARBON FARMERS OF AUSTRALIA
- ECHO2 – sky carbon to earth
- ksl sawmills – SPECIALISING IN PINE
- fasera
- HIWAY GROUP
- Vital Chemical
- Energy Farmers AUSTRALIA
- Southern Cross University
- RegenerativeAg ALLIANCE – Resilience through farming together
- EAL – Environmental Analysis Laboratory

Bronze

- Sustainable Timber Tasmania
- Agspand – healthy profitable agriculture – FEEDCHAR®
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- BarwonWater
- DECARB HUB – New South Wales Decarbonisation Innovation Hub
- BYGEN – CARBON BY DESIGN
- WATER CORPORATION
- OPTIMAL – optimised energy solutions
- METAMORF

Executive Summary

Biochar provides Australia with an important economic, social and environmental opportunity if scaled successfully. Over 50 million tonnes a year of commercially accessible sustainable biomass residues are currently being burned, landfilled, or under-utilised. This Roadmap, produced by the peak body for biochar in Australia, ANZBIG, outlines the approach required to successfully seize this opportunity by 2030.

The Australian biochar industry has world-leading biochar technologies, research and significant residual biomass resources. The industry is ready for scale-up, requiring a concerted effort from industry, research, government and capital investment to deliver on this opportunity.

Biochar has been identified as a key source of non-fossil carbon with the potential for many important applications in our society including as an enhancement to land and agriculture, and as an important additive for industrial applications.

Biochar production is one of the carbon dioxide (CO_2) removal methods, also known as negative-emissions technologies (NETs), recognised by the United Nations' Intergovernmental Panel on Climate Change (IPCC) as an effective method for climate change mitigation.

Successful implementation of this Biochar Roadmap by 2030 has the potential to reduce Australia's net carbon emissions by 10-15%, provide up to 20,000 permanent jobs (especially in regional and rural areas), improve soil health and agricultural productivity and return degraded lands to a higher value.

The production of biochar provides a sustainable and climate-friendly opportunity to convert millions of tonnes of wasted organic resources into valuable carbon products and renewable energy for a circular and regenerative new carbon economy.

The outlined Roadmap Actions will assist in scaling the current biochar industry to a multibillion dollar per year industry by 2030 (estimated to be at least $1-$5 Billion per annum) that sustainably drives economic efficiency and climate change mitigation in Australia.

The roll out of the Roadmap will require strong collaboration across Australia from industry, government, research and capital. The resourcing of the Roadmap should be a strong priority for the organisations that will benefit from a thriving biochar industry.

The implementation of the Roadmap Actions over the 2023 to 2030 period will provide a firm basis for a successful biochar industry in Australia and contribute substantially and economically to Australia's climate change mitigation obligations.

Nigel Murphy

Chairman, ANZBIG, June, 2023

The Roadmap Actions will assist in scaling the current biochar industry to a multibillion, dollar industry by 2030, sustainably driving economic efficiency and climate change mitigation in Australia.

An Introduction to the Roadmap

Why produce a Roadmap?

A biochar industry Roadmap is necessary to catalyse the sector. Whilst there has been significant development and growth in the sector over the last couple of years there are still many hurdles and obstacles to overcome to enable the industry in Australia.

ANZBIG as the peak body for the biochar industry has developed the Roadmap and is seeking an inclusive and consensus driven approach to growing the industry. Following industry consultation which noted key differences and needs, a separate roadmap for the biochar industry in New Zealand will also be developed.

Who is ANZBIG?

ANZBIG is a not-for-profit association that assists companies, governments and institutions in the effective production and use of biochar. The industry group facilitates and streamlines biochar education, research, collaboration and commercialisation activities to provide better outcomes for the biochar sector in Australia and New Zealand. ANZBIG has developed the Code of Practice for the Safe and Sustainable Production and Use of Biochar in Australia and New Zealand.

What is biochar?

Biochar is a charcoal-like product made by heating any form of organic matter (biomass) in a controlled process with limited oxygen, called pyrolysis. This product is called biochar when it is used as a soil amendment, or for other uses that store the carbon in a durable form.

The carbon content and properties of biochar vary depending on feedstock, but biochar can be more than 90% carbon. Biochar is characterised by distinct physical, biological and chemical properties and can have a positive effect on physical and biochemical processes. It is a non-fossil source of carbon. For more info, see video **here**

What are the uses of biochar?

There are many uses for biochar as a valuable solid carbon product which can be used in many soil and non-soil applications, many of which can provide carbon sequestration that is stable in the long term.

The many uses of biochar are well documented and supported in scientific literature including:

- Agricultural amendment for improving soils through physical and chemical interactions with soils, nutrients and water.
- Industrial agent for improving physical and chemical properties of materials including concrete, asphalt, industrial inks/paints and resins (e.g. bioplastics).
- Feed additive for livestock to improve health and condition.
- A non-fossil, concentrated carbon source that can substitute for carbon black, activated carbon and other carbon feedstocks used in various industries

See Figure 1. Appendix A for example uses and applications.

It is important to note that any use of biochar which involves combustion or oxidation does not provide CO_2 removal from the atmosphere, importantly however it can still reduce new emissions where fossil fuels are displaced/avoided by its use. Co-products of biochar production also have many uses as an energy source and pyroligneous acid / wood vinegar is a valuable biostimulant in the agricultural industry.

To ensure industry sustainability and benefit, systematic consideration of highest value use of feedstocks, biochar and co-product end uses should be a priority. This includes consideration of climate benefits among many other factors through processes such as triple bottom line assessment (environmental, economic and social).

Recent estimates indicate that biochar could mitigate up to 6.6 Billion tonnes of CO_2e globally per year by 2050[1]. This is indicatively equivalent to the USA's annual GHG emissions (1990-2019)[2].

(1) IPCC 6th Assessment Report, March 2022;
(2)UNEP Emissions Gap Report, 2020.

An Introduction to the Roadmap
continued

The UN Sustainable Development Goals (SDG's) are globally recognised by government, non-government and industry organisations to help guide such consideration. Sustainability for the Australian Biochar Industry is a core value of the ANZBIG Code of Practice and the development of further detailed guidance forms part of the initiatives and actions of this Roadmap.

How can biochar be beneficial to mitigating climate change?

Plants grow via photosynthesis using atmospheric CO_2. When plant biomass is turned into biochar, up to half the carbon contained within the feedstock is converted into a solid form of carbon (biochar) which is stable in the long term, effectively removing it from the natural carbon cycle as illustrated in Figure 2. CO_2 Removal (CDR), also referred to as 'drawdown', plays a critical role in combating climate change. When biochar is added to soil it can store carbon in a stable form, locking it away for hundreds or even thousands of years whilst also helping to regenerate degraded soils, with co-benefits. Soil applications typically represent a very high value use of biochar, and in cases such as enhancement of food production can represent the highest value use.

Non-soil applications of biochar also contribute to CO_2 drawdown where the biochar is embodied within long-lived materials and products (e.g. roads, concrete) that will not be combusted or decompose in the short term.

The Biochar Industry in Australia

The Australian biochar industry is in an early growth phase which is seeing the emergence of biochar production facilities in almost all States and Territories of Australia. These include a range of production facilities from small scale to multi-million-dollar investments. Australian biochar equipment companies are also exporting their technologies to Europe, Asia, and the Middle East.

The biochar industry includes the valuable co-products of biochar production including bio-oils, syngas, heat energy and wood vinegar. It also includes the suppliers of biomass and equipment, logistics, value-adding, carbon removal certificate generation, and the end use customers in the biochar industry supply chain.

Biochar scientific research in Australia is active with a number of universities and research institutions actively contributing to global knowledge. There are a number of start-ups and some mature companies actively innovating in the biochar sector.

Current industry estimates indicate that the size of the industry is $50 – 100 million, with successful scale up expected to increase the industry at least ten fold over the next eight years. This is consistent with overseas trends where industry growth rates of 50% to 60% are being experienced and forecast in the near future.

Current Australian biochar production is at a low level but is growing rapidly. As of 2020 it was estimated at 10-20,000 tonnes per annum, with many projects under way and emerging to significantly increase this in the short term.

The vision of ANZBIG is the safe, sustainable and climate positive production of biochar and associated products for the betterment of Australian and New Zealand Society.

Alignment with Multiple Government Policy Objectives

Carbon plays a central role in so many areas of our economy and in government policy objectives. The production and use of biochar can contribute positively toward multiple policy objectives concurrently, including (but not limited to) the following Commonwealth objectives below. State and Local government objectives are similarly assisted. Supporting the biochar industry to contribute to these important areas can leverage government investment toward achieving the targeted outcomes.

Climate Change / Climate Resilience / Net Zero

- Net Zero Plan (Net Zero by 2050). Biochar can provide significant contributions toward all six sectoral plans to achieve net zero:
  - Agriculture and Land; Built Environment ; Electricity and Energy
  - Transport & Infrastructure ; Industry ; Resources.
- 43% Emissions Reduction by 2030 (Climate Change Act, 2022, Paris Agreement)
- National Climate Resilience and Adaptation Strategy 2021 – 2025
- Net Zero in Government Operations Strategy
  - Australian Public Service Net Zero Emissions by 2030
  - *Partnership in the (international) Net Zero Government Initiative*
- National Strategy for Disaster Resilience
- Australian Disaster Preparedness Framework / Sendai Framework
- Australian Carbon Credit Unit (ACCU) Scheme – a cross industry working group including ANZBIG has lodged an EOI for a new method for Biochar Carbon Dioxide Removal.
- Bid to Co-Host COP31 (2026) - Enhancement of action supporting COP31 with the Pacific
- National Science and Research Priorities

Circular Economy / Sustainability / Waste

- National Wate Policy (NWP) (2018) and NWP Action Plan (2019)
  - 50% reduction in organic waste to landfill by 2030 (Target 6)
  - Recover 80% of all waste by 2030 (Target 3)
  - Significantly increase the use of recycled content by governments and industry (Target 5)
- National Circular Economy Framework
- Circular Economy Ministerial Advisory Group (CEMAG) – Priority action areas:
  - Built Environment and Net Zero
  - Innovation and Skills
  - Food, Resources and Regions
  - Circular Design & Consumption of Products
- 2030 Agenda for Sustainable Development and the Sustainable Development Goals
- Australian Sustainability Reporting Standards – (draft) Disclosure of Climate Related Financial Information (EDSR1).
- Remade in Australia – circular carbon that concurrently also provides climate action.
  - Environmentally Sustainable Procurement Policy & Reporting Framework
- National Science and Research Priorities

Agriculture (Production / Climate Resilience)

- Delivering AG2030: Australian Agricultures vision for a $100 Billion Industry by 2030
  - Production (output/yield); Biosecurity; Land Stewardship
  - Water and infrastructure; Innovation & Research
  - Human Capital – rural and regional skills and employment
  - $100B in agricultural production by 2030
  - Halve Food Waste by 2030
  - 20% increase in water use efficiency for irrigated agriculture by 2030
  - Produce more from existing land - maintain Australia's total farmed land at 2018 levels
- National Soil Strategy (2023-2028) and National Soil Action Plan
- Carbon Farming Outreach Program
- Australian government commitments to the UN Convention to Combat Desertification (UNCCD)
- Climate Resilient Agricultural Development and Food Security Program
- National Science and Research Priorities

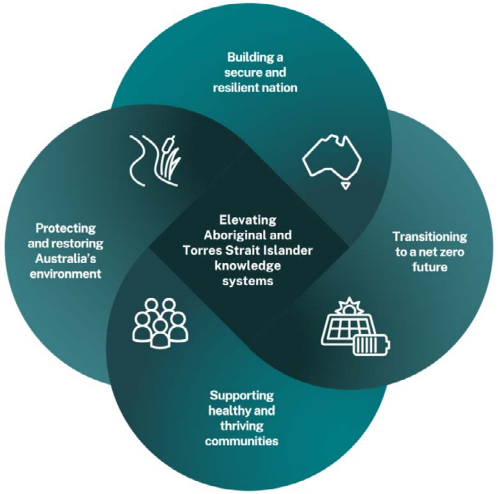
Alignment with Multiple Government Policy Objectives
Continued

Water Efficiency / Drought Resilience

- National Water Initiative;
- Resilient Rivers Water Infrastructure Program – 450GL target for water for the environment, including urban, industrial, mining, and on/off farm water efficiency.
- Murray Darling Basin Plan (efficiency measures), Sustainable Rural Water Use and infrastructure Program, & Restoring our Rivers Act (2023) – *"increase ways to deliver water for the environment to reduce reliance on buybacks"*
- First Nations Water Policy (access to water)
- National Science and Research Priorities

Energy / Storage / Fuels (Including Batteries / Hydrogen / Biofuels

- Powering Australia
  - commitments to support agriculture and carbon farming, transport and energy
  - 43% emissions reduction by 2030; Net Zero by 2050; 82% renewable electricity target
- Powering the Regions Fund – decarbonising existing industries, developing new clean industries, Carbon Capture, Utilisation and Storage (CCUS), and driving ACCUs.
- National Battery Strategy
- First Nations Clean Energy Strategy
- Australia's Future Gas Strategy
- National Hydrogen Strategy
  - Hydrogen Headstart Program - Biohydrogen
- Capacity Investment Scheme to encourage investment in renewables and storage
- Towards a Renewable Energy Superpower Report
- National Energy Transformation Partnership with the states
- Unlocking Australia's Low Carbon Liquid Fuels (LCLF) Opportunity (Future Made in Australia)
- National Science and Research Priorities



The overlapping nature of the National Science and Research Priorities.

Employment, Economic and Regional Resilience

- Future Made in Australia Agenda – enhancement of both major streams of the agenda: *Net Zero Transformation Stream*, and *Economic Resilience and Security Stream*.
- National Reconstruction Fund – priority areas for *Renewables & Low Emission Technologies, Agriculture, Forestry and Fisheries, Transport, Resources and Advanced Manufacturing.*
- Regional Investment Framework for strong and sustainable regions
- Boosting Supply Chain Resilience Initiative
- National Freight and Supply Chain Strategy
- Indo-Pacific Carbon Offsets Scheme - $100M support to climate action in the region
- Australian government programs and partnerships for International Climate Action
- Climate Resilient Agricultural Development and Food Security Program
- National Science and Research Priorities

Carbon plays a central role in so many areas of our economy and in government policy objectives.

Biochar soil applications and markets

Figure 1.
Biochar Soil Applications and Markets (Australia/NZ)

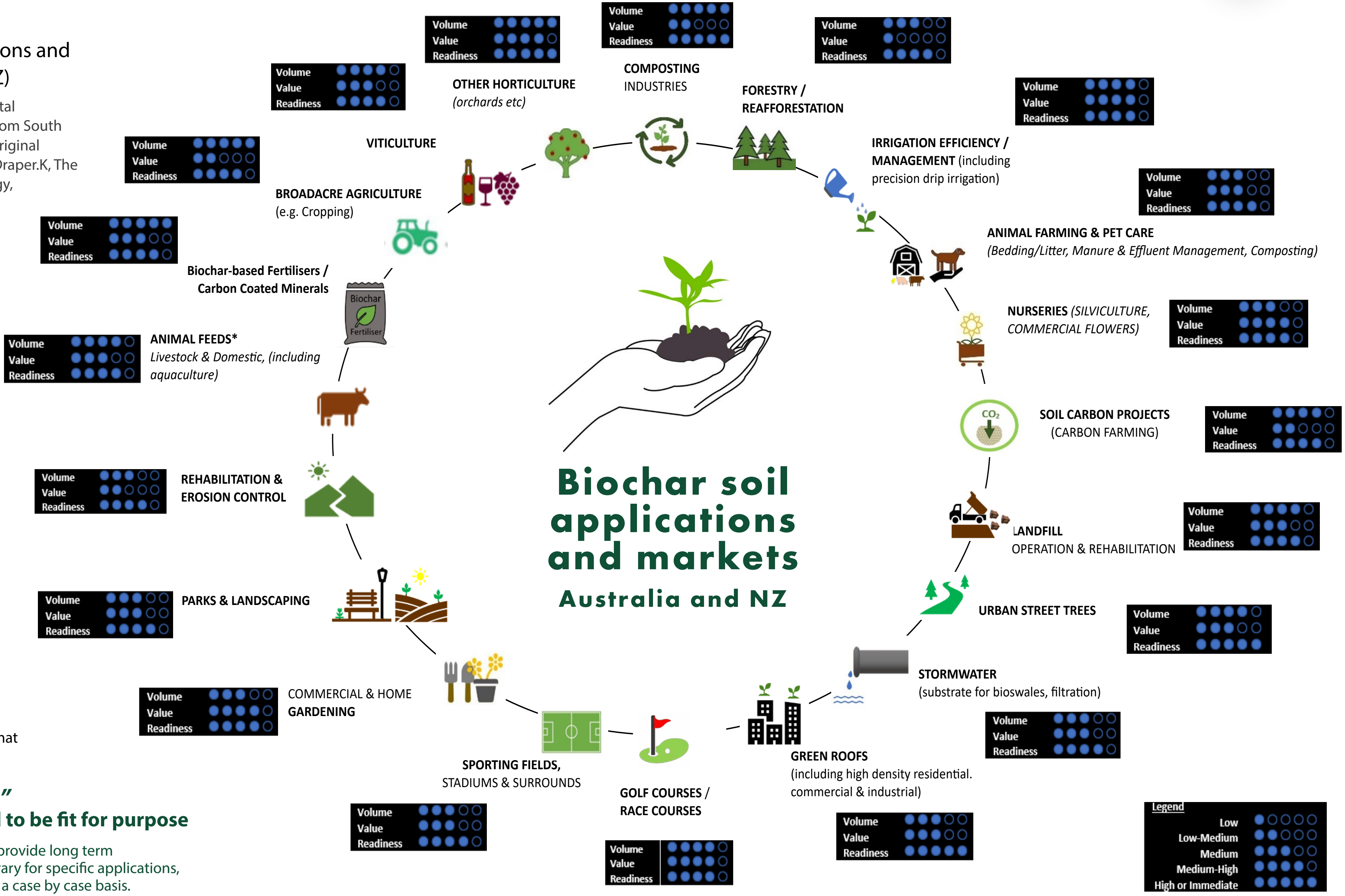
Source: Catalyst Environmental Management with support from South East Water Expanded on an original concept by Ithaka Institute (Draper.K, The Biochar Displacement Strategy, The Biochar Journal, **2016**)

ANZ BIOCHAR INDUSTRY GROUP

Please note: this document is intended for printing and viewing in A3 landscape format

"Chars Ain't Chars"
Biochars are tailored to be fit for purpose

Note: Many soil applications provide long term CO_2 Removal (CDR), but can vary for specific applications, which should be assessed on a case by case basis.



Biochar soil applications and markets
Australia and NZ

ANIMAL FEEDS* *Livestock & Domestic, (including aquaculture)*

Volume	●●●●○
Value	●●●○○
Readiness	●●●●○

Biochar-based Fertilisers / Carbon Coated Minerals

Volume	●●●●●
Value	●●●○○
Readiness	●●●●○

BROADACRE AGRICULTURE (e.g. Cropping)

Volume	●●●●●
Value	●●○○○
Readiness	●●●●○

VITICULTURE

Volume	●●●●○
Value	●●●○○
Readiness	●●●●○

OTHER HORTICULTURE *(orchards etc)*

Volume	●●●●●
Value	●●●●○
Readiness	●●●●●

COMPOSTING INDUSTRIES

Volume	●●●●●
Value	●●○○○
Readiness	●●●●●

FORESTRY / REAFFORESTATION

Volume	●●●○○
Value	●○○○○
Readiness	●●●●○

IRRIGATION EFFICIENCY / MANAGEMENT (including precision drip irrigation)

Volume	●●●●○
Value	●●●●○
Readiness	●●●●○

ANIMAL FARMING & PET CARE *(Bedding/Litter, Manure & Effluent Management, Composting)*

Volume	●●●○○
Value	●●●○○
Readiness	●●●●○

NURSERIES *(SILVICULTURE, COMMERCIAL FLOWERS)*

Volume	●●●○○
Value	●●●●○
Readiness	●●●●○

SOIL CARBON PROJECTS (CARBON FARMING)

Volume	●●●●○
Value	●●○○○
Readiness	●●●●○

LANDFILL OPERATION & REHABILITATION

Volume	●●●●○
Value	●●●○○
Readiness	●●●●○

URBAN STREET TREES

Volume	●●●●○
Value	●●●○○
Readiness	●●●●●

STORMWATER (substrate for bioswales, filtration)

Volume	●●●○○
Value	●●●○○
Readiness	●●●●○

GREEN ROOFS (including high density residential. commercial & industrial)

Volume	●●●○○
Value	●●●○○
Readiness	●●●●●

GOLF COURSES / RACE COURSES

Volume	●●●●○
Value	●●●●○
Readiness	●●●●○

SPORTING FIELDS, STADIUMS & SURROUNDS

Volume	●●●○○
Value	●●●○○
Readiness	●●●●○

COMMERCIAL & HOME **GARDENING**

Volume	●●●○○
Value	●●●●○
Readiness	●●●●○

PARKS & LANDSCAPING

Volume	●●●○○
Value	●●●○○
Readiness	●●●●○

REHABILITATION & EROSION CONTROL

Volume	●●●○○
Value	●●○○○
Readiness	●●●●○

Legend

Low	●○○○○
Low-Medium	●●○○○
Medium	●●●○○
Medium-High	●●●●○
High or Immediate	●●●●●

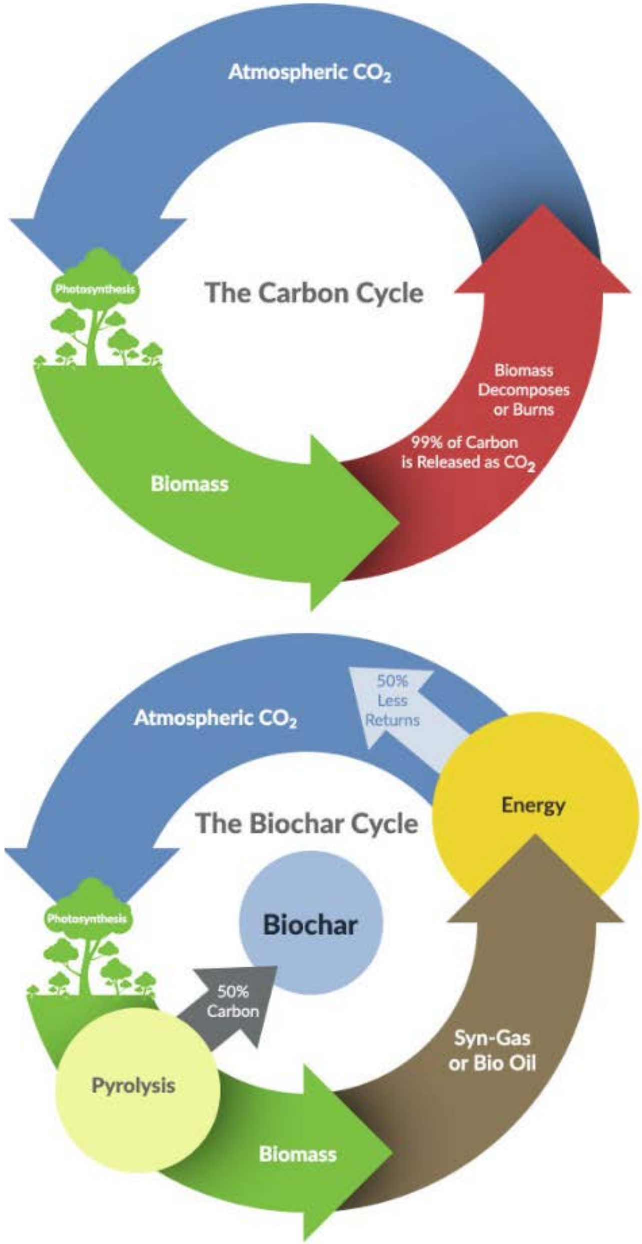


Figure 2.

Biochar CO_2 Removal (CDR).

Over 99% of CO_2 captured by biomass re-enters our atmosphere as part of the natural carbon cycle.

Pyrolysing wasted plant biomass into biochar **intercepts the cycle** and converts carbon into a form that is typically stable for **centuries to millennia**.

Figure 3.

Australian biochar can contribute to many of the world's climate and sustainability objectives, including many of the UN Sustainable Development Goals (SDGs).

Legend

- ✓ Direct contributions through biochar production and use
- ✓ Indirect contributions through biochar production and use

Roadmap Themes

Priority Themes

Collaborate and Enhance Partnerships

Encourage Recognition and Policy Support

Facilitate industry scale up

Funding and Resourcing Support

Encourage Investment

Establish Standards and Certification for industry production and usage.

Harmonise Regulatory Frameworks

Accelerate Markets (including Commercial Demonstrations)

Focus Innovation and Research

Communicate economic value and benefits

Initiative 1

Launch the Australian Biochar Industry 2030 Roadmap and fund industry scale up

Context: *The Biochar Industry 2030 Roadmap will be a catalyst for growth in the biochar sector. Launching and resourcing the Roadmap's path is critical to build momentum and bring together all key participants. Working groups will be convened Australia-wide to drive and open out the Roadmap.*

Action 1.1 Begin nation-wide Roadmap launch and establish forums and working groups across the country

Objective: Co-ordinate and streamline development of the Australian biochar industry

Key Performance Indicators

- Roadmap launched
- Strong pledges of nation-wide support for the Roadmap

Action 1.2 Resource Roadmap management, implementation and governance

Objective: Ensure sufficient resources and systems are in place to deliver the Roadmap

Key Performance Indicators

- Roadmap adequately funded. Proportion of Roadmap funding progress targets achieved (% of targets)
- Tracking system established and annual reporting achieved
- Aligned industries, government and non-government organisations contributing to Roadmap initiatives (financial and in-kind)

Action1.3 Identify complementary funding opportunities and resources to support scale up

Objective: Ensure sufficient financial resources are available to deliver the Roadmap. Align and compare the Roadmap with current public policy on climate change, agricultural productivity, circular economy, and waste strategy, and advocate for new policies as needed

Key Performance Indicators

- Amount of complementary funding
- Demonstrated incentives, initiatives and policy that support industry scale up

Action 1.4 Measure, monitor and evaluate the scale and growth of the biochar sector

Objective: Understand the success of initiatives to roll out the Roadmap initiatives and actions

Key Performance Indicators

- Deliver annual report on the state of the biochar industry sector in Australia
- Develop and document a monitoring system for measuring performance of Roadmap initiatives and actions

Initiative 2

Improve stakeholder awareness and education of biochar uses and benefits

Context: *Engaging with stakeholders and increasing awareness of biochar is an essential component for the long-term growth of the Australian Biochar Industry. Stakeholders can inform the development of initiatives to ensure the Australian Biochar Industry is taking a targeted and strategic approach to progressing the interests of the industry. As the industry is rapidly expanding, it is also important to continually update stakeholders on recent developments in biochar technology, regulations, products and benefits.*

Action 2.1 Refine biochar sector stakeholder mapping and communications strategy

Objective: Identify key stakeholder required for the expansion of the Australian biochar industry and facilitate connections between these stakeholder and the industry

Key Performance Indicators

- Integration and further stakeholder support
- Stakeholder engagement and communications materials developed/leveraged

Action 2.2 Develop fact/data sheets, videos and other visual communications for biochar and co-products, including applications

Objective: Enable greater access to suitable and relevant resources on the Australian biochar industry and the uses of biochar and co-products. Collaborate with national and international associated groups to accelerate reciprocal knowledge-sharing opportunities and platforms

Key Performance Indicators

- Development of fact/data sheets, videos, and resources for expanding the Australian biochar industry
- Identification of existing resources nationally/globally that can be leveraged or adapted to assist and engage with participants

Action 2.3 Engage with stakeholders regarding biochar and co-product value proposition, including development of technical working groups by industry sector to aid engagement and awareness

Objective: Grow the stakeholders network, and to provide and receive feedback from participants to expand the Australian biochar industry in alignment with participants' expectations and needs

Key Performance Indicators

- Breadth, number and regional extent of stakeholder forums, workshops and events
- Media interest and participants engagement via website, email and other forms of communication

Action 2.4 Grow awareness of *ANZBIG Code of Practice for the Sustainable and Safe Production and Use of Biochar* and other approved standards

Objective: Ensure awareness of relevant biochar standards for the safe and sustainable production and use of biochar

Key Performance Indicators

- Incorporation of the ANZBIG Code of Practice and other standards in communication with participants
- Training workshops on biochar standards and the Code of Practice
- Engagement with state government agencies across Australia to identify individual requirements additional to the Code of Practice to develop "bridging" guidance and to facilitate ease of industry participation and scale up

Initiative 2
continued

Improve stakeholder awareness and education of biochar uses and benefits

Action 2.5 Develop tools to demonstrate/ evaluate and promote the co-benefits of biochar (including triple-bottom line value)

Objective: Increase the use of biochar products and technology by supporting stakeholders to apply them efficiently and effectively

Key Performance Indicators

- Guidelines for the application and use of biochar for different uses including horticulture, cattle feed, broadscale agriculture and industrial applications
- Published cost benefit analyses of biochar applications

Action 2.6 Integrate Indigenous land knowledge and practices e.g. fire management, into educational and awareness materials

Objective: Acknowledge and support Indigenous knowledge and land practices that relate to biochar use and application

Key Performance Indicators

- Research and document Indigenous land practices related to biochar application and use
- Work with Indigenous groups to exchange knowledge and land practices around biochar use
- Support of Indigenous participation in the biochar industry

Action 2.7 Research industry and community attitudes to biochar

Objective: Understand the success or otherwise of initiatives to improve stakeholder awareness and education

Key Performance Indicators

- Yearly report on stakeholder knowledge of, and attitudes to, the Australian biochar sector

Initiative 3

Integrate and optimise industry and regulatory frameworks

Context: *Establishing the reliability of the production and use of biochar and co-products across all uses can accelerate the growth of the Australian Biochar Industry. The relatively novel nature of large-scale manufacturing and use of biochar and biochar co-products means existing regulations require review and revision as the industry grows and the range of potential biochar applications increases.*

Action 3.1 Identify existing barriers and potential regulatory approaches to harmonise and facilitate safe and sustainable operation across the Australian biochar industry

Objective: Optimise the regulatory and procedural framework for biochar to maximise benefits and reduce risks

Key Performance Indicators

- Conduct mapping exercise with stakeholders and partners which identifies regulatory and procedural barriers, and identifies remedies or alternative strategies

Action 3.2 Develop sustainability assessment guidance, including higher order use, for biochar feedstocks and end-use applications

Objective: Ensure feedstocks for biochar production are suitable for use

Key Performance Indicators

- Development of biochar feedstock sustainability assessment guidelines to integrate with the Biochar Code of Practice

Action 3.3 Consult with federal and state government departments and key stakeholders to address biochar barriers and market uncertainties

Objective: Engage with key stakeholders to ensure barriers are reduced and incentives increased to scale up sustainable biochar production and use

Key Performance Indicators

- Identification and consistent engagement with key government and non-government stakeholders

Initiative 4

Support biochar commercial demonstrations and trials

Context: *The results of commercial demonstrations and trials can increase confidence in the industry and open avenues for potential investment and scale up. Such activities can assist in the development of regulation, certification schemes, and application, or manufacture methodologies.*

Action 4.1 Demonstrate broad acre soil applications at a significant scale

Objective: Increase economic confidence in large-scale agricultural applications of biochar within Australia

Key Performance Indicators

- Outline criteria and seek expressions of interest for broad acre demonstration partners
- Establishment and documentation of broad acre trials and demonstrations

Action 4.2 Demonstrations to regenerate marginal /degraded land, including mine site rehabilitation

Objective: Increase economic confidence in the use of biochar as a remediation technology within Australia

Key Performance Indicators

- Outline criteria and seek expressions of interest from rehabilitation / remediation demonstration partners
- Establishment and documentation of rehabilitation / remediation demonstrations

Action 4.3 Support commercial-scale demonstration projects for non-broad acre soil applications of biochar

Objective: Increase economic confidence in many other soil applications of biochar, and to showcase the diversity of Australian soil-based industries with their potential to benefit from biochar and co-products

Key Performance Indicators

- Outline criteria and seek expressions of interest for potential demonstration partners
- Establishment and documentation of demonstration and trial projects

Action 4.4 Support commercial scale demonstration projects for non-soil industrial applications

Objective: Increase economic confidence in non-soil based applications of biochar and showcase the diversity of Australian industries with potential to benefit from biochar and co-products

Key Performance Indicators

- Outline criteria and seek expressions of interest for potential demonstration partners
- Establishment of demonstration projects

Action 4.5 Support co-pyrolysis demonstrations of plant biomass, biosolids, forestry residues, agricultural residues and food organics / garden organics (FOGO).

Objective: Increase economic confidence in utilising co-pyrolysis as a waste to value/resource management strategy to benefit from biochar and co-products

Key Performance Indicators

- Outline criteria and seek expressions of interest for potential demonstration partners
- Establishment of co-pyrolysis demonstration projects

Initiative 5

Leverage carbon emission reduction and CO_2 removal opportunities

Context: *The growth of the Australian biochar industry can be rapid if appropriately encouraged. Initiatives must be strategic, and opportunities taken to maximise benefits and optimise both emission reduction (ER) and CO_2 removal (CDR).*

Action 5.1 Promote inclusion of recognised accounting methods for biochar in national greenhouse gas emissions (GHG) inventories

Objective: Enable immediate contribution of biochar to national GHG emission inventories by using readily available IPCC accounting methodology for biochar[i] in the calculations

Key Performance Indicators

- Adoption of biochar in Australia's national GHG emissions inventory
- Adoption of biochar in national GHG emissions inventories of other countries

(i) intergovernmental Panel on Climate Change (IPCC), 2019, Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories; Volume 4: Agriculture, Forestry and Other Land Use; Appendix 4: Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments

Action 5.2 Develop biochar methodologies under Australia's Emissions Reduction Fund (ERF) for all soil uses and non-soil/industrial uses

Objective: Align biochar methodologies with the Australian ERF to support accreditation of emissions reduction and CO_2 removal using biochar

Key Performance Indicators

- Identification of the appropriate expert teams capable of developing biochar application methodologies for both soil, and non-soil/industrial uses, in accordance with the Australian ERF
- Development and implementation of work plans to prepare biochar application methodologies for soil and non-soil/industrial uses
- Acceptance of biochar production and use methodologies in soil and non-soil/industrial applications under the ERF

Action 5.3 Support development of a biochar method for feed chars to reduce methane from livestock under Australia's Emissions Reduction Fund (ERF)

Objective: Use biochar to accelerate climate action on critical livestock emissions in agriculture

Key Performance Indicators

- Support research initiatives showing the effect of feed chars on methane reduction
- Use positive research to develop methodology for this biochar application

Action 5.4 Collaborate with stakeholders with net zero or other carbon reduction targets to raise awareness of biochar's potential role in carbon drawdown

Objective: Build confidence in the Australian biochar production industry as a net zero technology

Key Performance Indicators

- Provision of biochar net zero awareness workshops
- Engagements with industry, promoting emission reduction and carbon drawdown initiatives

Action 5.5 Support biochar inclusion into Integrated Assessment Modelling

Objective: Facilitate the endorsement of biochar as a pillar technology in international strategies to combat climate change

Key Performance Indicators

- Support of existing efforts to include biochar in the Integrated Assessment Modelling domestically and abroad

Initiative 6

Encourage beneficial use of residual or waste biomass

Context: *Large quantities of residual or waste biomass are being sent to landfill or are being burned leading to increased global GHG emissions. Over 3% of global GHG emissions are derived from agricultural residues. Much of this waste biomass could be diverted to the biochar industry for change into biochar and co-products, reducing the potential for the release of harmful GHGs into the atmosphere.*

Action 6.1 Support the diversion from landfilling and uncontrolled burning of clean biomass

Objective: To utilise biomass residues more productively in Australia through conversion to biochar

Key Performance Indicators

- The amount of biomass diverted from landfill and not burned in an uncontrolled environment
- The continued development and commercial application of Australian technology for biomass residue conversion to biochar
- Policy developments that encourage use of biomass residues for biochar production and use

Action 6.2 Further encourage circular production of residual biomass to biochar

Objective: Incentivise through both emissions reduction methodologies, and penalties for uncontrolled burning, the transformation of waste and residual biomass to biochar

Key Performance Indicators

- Assessments and studies on the viability of further incentivising the circular production of residual biomass in Australia
- Establishment of emission reduction methodologies for biomass conversion to biochar

Action 6.3 Enhance and maintain biomass availability assessment tools to aid industry capacity to grow by reliably quantifying and sourcing sustainable biomass

Objective: Identify reliable biomass feedstocks that can facilitate biochar industry growth

Key Performance Indicators

- Quantification of residual biomass opportunities for biochar in every state and territory of Australia-
- Create industry specific biomass assessment tools

Action 6.4 Create a grading system for residual waste biomass to improve economic evaluation, and the safe use and production of biochar

Objective: To categorise potential biomass feedstocks to facilitate safe and sustainable use for biochar production

Key Performance Indicators

- Consultation with industry stakeholders including residual biomass producers, to establish a suitable grading system for residual biomass
- Establishment of a guideline on assessing suitability of residual biomass for biochar production

Initiative 7

Drive beneficiation and increased value of biochar products and co-products

Context: *Carbon is a very valuable component of our society and has many different uses. Much of this carbon including carbon black and activated carbon is derived from fossil carbon sources. Biochar can provide an alternative high value component for many uses.*

Action 7.1 Fund research into beneficial upgrading of biochar products

Objective: Increase biochar value by identifying specialty biochar products and uses

Key Performance Indicators

- Number of new biochar-related products entering the market
- Number of biochar-related patents being registered by Australian companies, organisations, and individuals

Action 7.2 Research and evaluate biochar substitution in traditional carbon markets

Objective: Facilitate the establishment of biochar as a replacement material for fossil derived carbon markets

Key Performance Indicators

- Uptake of biochar in traditional fossil carbon markets

Action 7.3 Drive technical and economic outcomes of co-products from biochar production (e.g. energy, hydrogen and wood vinegar)

Objective: Optimise the economic and environmental benefits of biochar production in Australia through development and commercialisation of co-technologies and products

Key Performance Indicators

- Number of new biochar related co-products entering the market
- Number of biochar co-product patents being registered by Australian companies, organisations, and individuals

Action 7.4 Establish sequestration and downstream emissions avoidance potential for different applications of biochar using different feedstocks

Objective: Maximise the carbon drawdown potential of biochar through establishing strong frameworks for understanding carbon sequestration potential of different applications

Key Performance Indicators

- Number of industry-accepted papers and guidance materials on carbon sequestration potential for different applications and feedstocks

Initiative 8

Safeguard responsible use and production of biochar

Context: *To build a strong biochar industry it is crucial that there are appropriate safeguards to ensure that the production and use of biochar is done safely and sustainably. The industry should help drive those standards and regulations to ensure the necessary safeguards are developed and certified, resulting in strong economic, social and environmental protections.*

Action 8.1 Fast-track the implementation of the ANZBIG Code of Practice and biochar certification for particular uses

Objective: Develop and implement the *Code of Practice for the Safe and Sustainable Production and Use of Biochar in Australia*

Key Performance Indicators

- Certified biochar production sites using the Code of Practice
- Certification of safe and sustainable biochar production linked to biochar-based emissions trading
- Development of branded certified biochar in Australia
- Recognition of the Code of Practice by regulatory authorities

Action 8.2 Provide support for integration with other standards for sustainable sourcing and use of biomass

Objective: Ensure sustainable biomass sourcing by linking with other existing programs and initiatives identifying sustainable biomass production and use

Key Performance Indicators

- Identification and verification of existing biomass certification schemes for applicability to biochar production and use
- Support for biochar producers in sustainable feedstock procurement through provision of suitable information

Action 8.3 Develop guidance for rate-based application of biochar in soil applications including supporting research and demonstration

Objective: Ensure consumers receive maximum benefit from biochar in soil applications

Key Performance Indicators

- Development of guidance material for biochar application rates for different soil and use applications

Action 8.4 Develop a long-term self-funding mechanism for safeguarding the ongoing development of the biochar sector such as through a certification levy

Objective: Safeguard the economic future of the Australian biochar industry to ensure sustained future industry collaboration and growth

Key Performance Indicators

- Undertake annual progress reviews of long-term funding needs and strategies to self-sustain the support and growth of the biochar industry

Initiative 9

Support government utility and industry procurement practices

Context: *Australian governments: federal, state, territory and local, have enormous influence on procurement through tendering and procurement practices. Governments are also custodians of many biomass resources and collection services. The benefits of biochar for circular economy and climate change mitigation should be encouraged in suitable opportunities and existing barriers removed.*

Action 9.1 Identify and promote replacement or for fossil derived carbon

Objective: Ensure that biochar is considered for suitable public and industrial applications and as a substitute or replacement for fossil fuel derived carbon

Key Performance Indicators

- Number of alternate uses and new applications for biochar
- Total biochar use in different industry and government applications
- Number of policy initiatives implemented by governments to support industry scale up such as incentives, grants and levies

Action 9.2 Establish biochar specifications for key procurement and use opportunities and identify carbon sequestration potential of these applications

Objective: Establish biochar specifications for key procurement and use opportunities and identify their carbon sequestration potential

Key Performance Indicators

- Development of biochar specifications and guidelines for use in different public and industrial use

Action 9.3 Develop biochar case studies and a biochar reference library for government and industry

Objective: Ensure that government agencies and industry are aware of how best to use biochar in a range of applications

Key Performance Indicators

- Biochar case studies generated per year
- Use of case studies and library visits measured by downloads and site visits

Initiative 10

Drive export of Australian biochar innovation internationally

Context: *The Australian biochar industry is making a strong contribution to the global biochar industry in production technologies, applications and biochar research. The further growth of the industry has the potential to increase Australia's contribution to UN Sustainable Development Goals including climate action.*

Action 10.1 Link with Australian federal and state trade export and overseas collaboration initiatives

Objective: Ensure the Australian biochar industry has a strong international network and is well placed for international trade opportunities

Key Performance Indicators

- Interaction with Australian and overseas trade initiatives and establishment of collaborative initiatives
- Successful export of Australian biochar technology and expertise

Action 10.2 Link with other global biochar initiatives such as IBI, EBIC, USBI and BNZ to exchange information and influence policy

Objective: Bring a co-ordinated and streamlined approach to the development of the global biochar industry reflecting the Australian perspective

Key Performance Indicators

- Attendance and presentations at global biochar forums and gatherings
- Strong participation as a member of IBI, an affiliate of EBIC and a supporter of BNZ

Action 10.3 Identify biochar production and use as part of Australia's global climate change contribution

Objective: Ensure that the actions and activities that are contributing to biochar carbon drawdown in Australia and through Australian activities elsewhere are articulated both domestically and internationally to key stakeholders

Key Performance Indicators

- Number of international climate change forums where the Australian biochar industry is prominent
- Number of publications, papers, presentations, and website hits related to biochar carbon drawdown activities

Concluding Remarks

The Australian Biochar Industry Roadmap identifies the actions required to scale up rapidly from an Australian industry valued in excess of $50 million today to a multibillion dollar industry in 2030 (estimated to be at least $1 - $5 billion per annum).

By doing this we will turn wasted resources into valuable carbon and energy products for agriculture and industry and in the process generate jobs, economic opportunities and sequester carbon.

The growth of the Australian Biochar Industry is in a pivotal alignment with rapidly increasing global action on climate change, both in reducing or avoiding new emissions and critically removing excess CO_2 already built up in the atmosphere.

Successful implementation of this Biochar Roadmap by 2030 has the potential to reduce Australia's current net carbon emissions by 10-15 % provide up to 20,000 permanent jobs (including in regional and rural areas), improve soil health and agricultural productivity and return degraded lands to a higher value.

This significant scale up is achievable and indeed necessary to generate the climate change and circular economy needs of our society.

A concerted effort in all parts of the economy whether it be industry and its affiliates, land management, capital, all levels of government and from research will collectively achieve, and benefit from, the implementation of this Roadmap.

Delivering this Roadmap will enable Australia to make a significant contribution to an emerging global industry and help us deliver our global climate change commitments.

Be a part of the growing biochar industry in Australia

Join The Australian Biochar Pledge at anzbig.org/biochar-industry-2030-roadmap

"We pledge to build a safe and sustainable biochar industry in Australia.

We know that valuable Australian biomass resources are being wasted each year which could be converted to energy and bioproducts that count towards Australia's Net Zero Economy.

We know that a scale up of the sustainable production and use of biochar will boost the Australian Net Zero Economy significantly.

We pledge to support ANZBIG in delivering the Australian 2030 Biochar Industry Roadmap for all Australians."

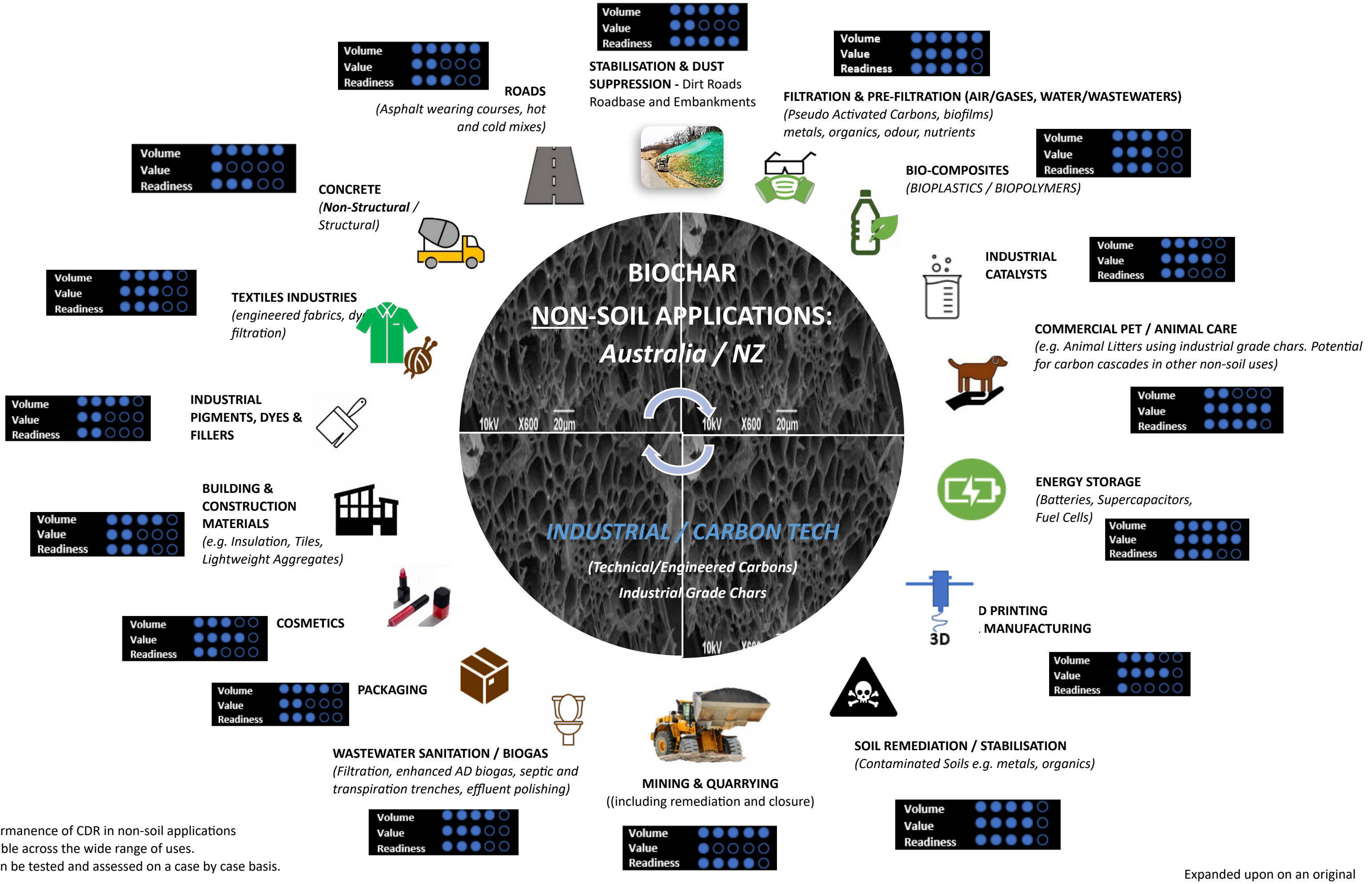
ANZBIG welcomes new members through our portal at www.anzbig.org/membership

APPENDIX A

Other Non-Soil Uses of Biochar and Biocarbons

Figure 1. Biochar Non-Soil Applications and Markets (Australia/NZ) – Industrial / Carbon Tech

Source: Catalyst Environmental Management with support from South East Water Expanded on an original concept by Ithaka Institute (Draper.K, The Biochar Displacement Strategy, The Biochar Journal, 2016)



ROADS
(Asphalt wearing courses, hot and cold mixes)
Volume ●●●●●
Value ●●○○○
Readiness ●●●○○

STABILISATION & DUST SUPPRESSION - Dirt Roads Roadbase and Embankments
Volume ●●●●●
Value ●●○○○
Readiness ●●●●●

FILTRATION & PRE-FILTRATION (AIR/GASES, WATER/WASTEWATERS)
(Pseudo Activated Carbons, biofilms)
metals, organics, odour, nutrients
Volume ●●●●●
Value ●●●●○
Readiness ●●●●○

BIO-COMPOSITES
(BIOPLASTICS / BIOPOLYMERS)
Volume ●●●●○
Value ●●●○○
Readiness ●●●○○

INDUSTRIAL CATALYSTS
Volume ●●●○○
Value ●●●●○
Readiness ●●○○○

COMMERCIAL PET / ANIMAL CARE
(e.g. Animal Litters using industrial grade chars. Potential for carbon cascades in other non-soil uses)
Volume ●●○○○
Value ●●●●●
Readiness ●●●●○

ENERGY STORAGE
(Batteries, Supercapacitors, Fuel Cells)
Volume ●●●●○
Value ●●●●●
Readiness ●●●○○

D PRINTING
. MANUFACTURING
Volume ●●●○○
Value ●●●●○
Readiness ●○○○○

SOIL REMEDIATION / STABILISATION
(Contaminated Soils e.g. metals, organics)
Volume ●●●●○
Value ●●●●○
Readiness ●●●●○

MINING & QUARRYING
((including remediation and closure)
Volume ●●●●●
Value ●○○○○
Readiness ●●●●○

WASTEWATER SANITATION / BIOGAS
(Filtration, enhanced AD biogas, septic and transpiration trenches, effluent polishing)
Volume ●●●●○
Value ●●●○○
Readiness ●●●○○

PACKAGING
Volume ●●●●○
Value ●●○○○
Readiness ●●●○○

COSMETICS
Volume ●●●○○
Value ●●●●○
Readiness ●●○○○

BUILDING & CONSTRUCTION MATERIALS
(e.g. Insulation, Tiles, Lightweight Aggregates)
Volume ●●●●○
Value ●●○○○
Readiness ●●●○○

INDUSTRIAL PIGMENTS, DYES & FILLERS
Volume ●●●●○
Value ●●○○○
Readiness ●●○○○

TEXTILES INDUSTRIES
(engineered fabrics, dy
filtration)
Volume ●●●●○
Value ●●●○○
Readiness ●●●○○

CONCRETE
*(**Non-Structural** / Structural)*
Volume ●●●●●
Value ●○○○○
Readiness ●●●○○

The permanence of CDR in non-soil applications is variable across the wide range of uses.
This can be tested and assessed on a case by case basis.

Expanded upon on an original
concept by Ithaka Institute 2016
(Draper,K: The Biochar Displacement Strategy,

Please note: this document is intended for printing and viewing in A3 landscape format

Legend	
Low	●○○○○
Low-Medium	●●○○○
Medium	●●●○○
Medium-High	●●●●○
High or Immediate	●●●●●

“Chars Ain’t Chars”….

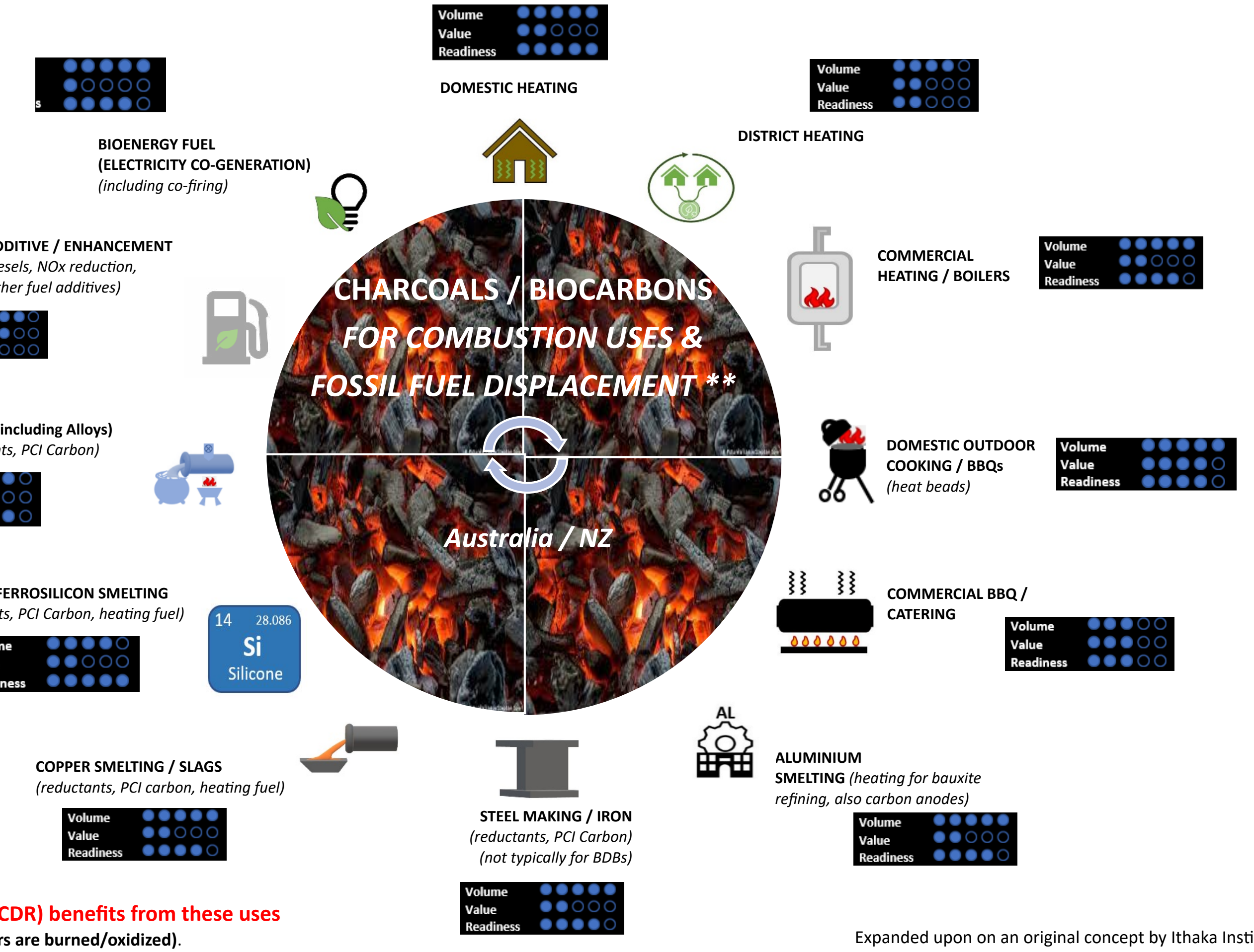
Biochars for Non-Soil Applications are engineered to be *Fit for Purpose*. They should be sustainably sourced and consider optimal use of available biomass resources and optimal use of land (including biomass cropping).

APPENDIX A

Other Non-Soil Uses of Biochar and Biocarbons

Figure 2. Charcoals/Biocarbons for Combustion Uses and Fossil Fuel Displacement

Source: Catalyst Environmental Management with support from South East Water Expanded on an original concept by Ithaka Institute (Draper.K, The Biochar Displacement Strategy, The Biochar Journal, 2016)



CHARCOALS / BIOCARBONS
FOR COMBUSTION USES &
*FOSSIL FUEL DISPLACEMENT ***

Australia / NZ

●●●●●
●○○○○
s ●●●●○

BIOENERGY FUEL
(ELECTRICITY CO-GENERATION)
(including co-firing)

Volume ●●●●●
Value ●●○○○
Readiness ●●●●●

DOMESTIC HEATING

Volume ●●●●○
Value ●●○○○
Readiness ●●○○○

DISTRICT HEATING

COMMERCIAL HEATING / BOILERS

Volume ●●●●●
Value ●●○○○
Readiness ●●●●○

DOMESTIC OUTDOOR COOKING / BBQs
(heat beads)

Volume ●●●●●
Value ●●●●○
Readiness ●●●●○

COMMERCIAL BBQ / CATERING

Volume ●●●○○
Value ●●●○○
Readiness ●●●○○

ALUMINIUM SMELTING *(heating for bauxite refining, also carbon anodes)*

Volume ●●●●●
Value ●●○○○
Readiness ●●●●○

STEEL MAKING / IRON
(reductants, PCI Carbon)
(not typically for BDBs)

Volume ●●●●●
Value ●●○○○
Readiness ●●●●○

COPPER SMELTING / SLAGS
(reductants, PCI carbon, heating fuel)

Volume ●●●●●
Value ●●○○○
Readiness ●●●●○

SILICON/FERROSILICON SMELTING
(reductants, PCI Carbon, heating fuel)

Volume ●●●●○
Value ●●○○○
Readiness ●●●●●

OTHER METALLURGY (including Alloys)
(heating fuel, reductants, PCI Carbon)

Volume ●●●●○
Value ●●○○○
Readiness ●●●●○

LIQUID FUEL ADDITIVE / ENHANCEMENT
(including biodiesels, NOx reduction, substitute for other fuel additives)

Volume ●●●●○
Value ●●●○○
Readiness ●○○○○

Expanded upon on an original concept by Ithaka Institute 2016
(Draper,K: The Biochar Displacement Strategy, the Biochar Journal Nov 2016)

**** No atmospheric CO_2 Removal (CDR) benefits from these uses**
(typically no CDR ('drawdown') when chars are burned/oxidized).
However, potentially significant reductions in additional/new emissions may be achieved via displacement of fossil carbon (i.e. avoided fossil emissions), pending LCA.

"Chars Ain't Chars"….

Biocarbons used to displace fossil fuels are typically tailored *Fit for Purpose.* They should be *sustainably sourced*, and should consider optimal use of available biomass resources and optimal use of land (including biomass cropping).

Please note: this document is intended for printing and viewing in A3 landscape format

Legend	
Low	●○○○○
Low-Medium	●●○○○
Medium	●●●○○
Medium-High	●●●●○
High or Immediate	●●●●●

APPENDIX B

Australian Biochar Industry 2030 Roadmap - Key Initiatives and Supporting Actions Summary Table

Scaling Biochar and Carbon Sequestration in Australia to a Multi Billion Dollar Industry by 2030

KEY INITIATIVES & SUPPORTING ACTIONS		OBJECTIVES	KEY PERFORMANCE INDICATORS	Aligned UN SDGs	Aligned Roadmap Priority Themes	TIMING			KEY BENEFITS					
						Short Term	Mid Term	Long Term	Regulator Confidence	User Confidence	ESD / Climate	Economic Value	Social Licence	Market Growth
1	**Launch the Australian Biochar Industry 2030 Roadmap and fund industry scale up**													
1.1	Begin nation-wide Roadmap launch and establish forums and working groups across the country.	Coordinate and streamline development of the Australian biochar industry.	1. Roadmap launched. 2. Strong pledges of nation-wide support for the Roadmap.	8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 13 CLIMATE ACTION 17 PARTNERSHIPS FOR THE GOALS	Communicate Economic Value & Benefits Facilitate Industry Scale Up Actively Seek Funding & Resourcing Encourage Investment	✓			✓	✓	✓	✓	✓	✓
1.2	Resource Roadmap management, implementation and governance.	Ensure sufficient resources and systems are in place to successfully deliver the Australian Biochar Industry Roadmap	1. Roadmap adequately funded. Proportion of Roadmap funding progress targets achieved (% of targets). 2. Tracking system establishment and annual reporting achieved. 3. Aligned industries, government and non-government organisations contributing to Roadmap initiatives (financial and in-kind).			✓	✓	✓	✓	✓	✓	✓	✓	✓
1.3	Identify complementary funding opportunities and sources to support scale up.	Ensure sufficient financial resources are available to deliver the Roadmap. Align and compare the Roadmap with current policy on climate change, agricultural productivity, circular economy, waste strategy and advocate for new policies as needed.	1. Amount of complementary funding. 2. Demonstrated incentives, initiatives and policy that support industry scale up			✓	✓							
1.4	Measure, monitor and evaluate the scale and growth of the biochar sector.	Understand the success of initiatives to roll out the Roadmap initiatives and actions.	1. Deliver Annual report on the state of the biochar industry sector in Australia. 2. Develop and document a monitoring system for measuring performance of Roadmap initiatives and actions			✓	✓	✓	✓	✓	✓	✓	✓	✓
2	**Improve stakeholder awareness and education of biochar uses and benefits**													
2.1	Refine biochar sector stakeholder mapping and communications strategy.	Identify key stakeholders required for the expansion of the Australian Biochar Industry and facilitate connections between these stakeholders and the industry.	1. Integration and further stakeholder support. 2. Stakeholder engagement and communications materials developed/leveraged.	8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 13 CLIMATE ACTION 17 PARTNERSHIPS FOR THE GOALS	Communicate Economic Value & Benefits Collaborate & Enhance Partnerships Encourage Recognition & Policy Support Facilitate Industry Scale Up Actively Seek Funding & Resourcing Encourage Investment Instil Confidence Focus Innovation & Research	✓	✓			✓			✓	✓
2.2	Develop data sheets and videos on biochar and co-product applications.	Enable greater access to suitable and relevant resources on the Australian Biochar Industry and the uses of biochar and co-products. Collaborate with national and international associated groups to accelerate reciprocal knowledge-sharing opportunities and platforms	1. Development of fact/data sheets, videos, and resources for expanding the Australian Biochar Industry. 2. Identification of existing resources nationally/globally that can be leveraged or adapted to assist and engage with stakeholders.			✓	✓			✓		✓	✓	✓
2.3	Engage with stakeholders regarding biochar and co-product value proposition, including development of technical working groups by industry sector to aid engagement and awareness.	Grow the stakeholder network, and to provide and receive feedback from stakeholders to expand the Australian biochar industry in alignment with stakeholder expectations and needs.	1. Breadth, number and regional extent of stakeholder forums, workshops and events. 2. Media interest and stakeholder engagement via website, email and other forms of communication.			✓	✓	✓		✓		✓	✓	✓
2.4	Grow awareness of ANZBIG Code of Practice for the Sustainable and Safe Production and Use of Biochar and approved standards.	Ensure awareness of relevant biochar standards for the safe and sustainable production and use of biochar.	1. Incorporation of the ANZBIG Code of Practice and other standards in communication with stakeholders. 2. Training workshops on Biochar standards and the Code of Practice. 3. Engagement with State government agencies across Australia to identify individual requirements additional to the Code of Practice to develop “bridging” guidance where required to facilitate ease of industry participation and scale up.			✓	✓		✓	✓	✓	✓	✓	✓
2.5	Develop tools to demonstrate/evaluate and promote the co-benefits of biochar (including triple-bottom line value).	Increase the use of biochar products and technology by facilitating stakeholders to efficiently and correctly apply biochar and co-products.	1. Guidelines for the application and use of biochar for different uses including horticulture, cattle feed, broadscale agriculture and industrial applications. 2. Published cost benefit analyses of biochar applications.			✓	✓							
2.6	Integrate indigenous land knowledge and practices (e.g. fire management) into biochar educational and awareness materials.	Acknowledge and support Indigenous knowledge and land practices that relate to biochar use and application.	1. Research and document indigenous land practices related to biochar application and use. 2. Work with indigenous groups to exchange knowledge and land practices around biochar use. 3. Support indigenous participation in the biochar industry.			✓	✓				✓		✓	
2.7	Research industry and community attitudes to biochar.	Understand the success or otherwise of biochar initiatives to improve stakeholder awareness and education.	1. Yearly report on stakeholder knowledge of, and attitudes to, the Australian biochar sector.			✓	✓	✓		✓			✓	✓
3	**Integrate and optimise industry and regulatory frameworks**													
3.1	Identify existing barriers and potential regulatory approaches to harmonise and facilitate safe and sustainable industry operation across Australia.	Optimise the regulatory and procedural framework around biochar to maximise benefits and reduce risks.	1. Conduct mapping exercises with stakeholders and partners which identifies regulatory and procedural barriers, and identifies remedies or alternative strategies.	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 13 CLIMATE ACTION 17 PARTNERSHIPS FOR THE GOALS	Communicate Economic Value & Benefits Collaborate & Enhance Partnerships Encourage Recognition & Policy Support	✓	✓		✓	✓	✓		✓	✓
3.2	Develop sustainability assessment guidance (including addressing higher order use) for biochar feedstocks and end-use applications.	Ensure feedstocks for biochar production are suitable for use.	1. Development of biochar feedstock sustainability assessment guidelines to integrate with the Biochar Code of Practice.			✓								
3.3	Consult with federal and state government departments and key stakeholders to address biochar barriers and market uncertainties.	Engage with key stakeholders to ensure barriers are reduced and incentives increased to scale up biochar production and use.	1. Identification and consistent engagement with key government and non-government stakeholders.			✓	✓		✓	✓	✓	✓	✓	✓

APPENDIX B

	KEY INITIATIVES & SUPPORTING ACTIONS	OBJECTIVES	KEY PERFORMANCE INDICATORS	Aligned UN SDGs	Aligned Roadmap Priority Themes	TIMING			KEY BENEFITS					
						Short Term	Mid Term	Long Term	Regulator Confidence	User Confidence	ESD / Climate	Economic Value	Social Licence	Market Growth
4	**Support biochar commercial demonstrations and trials**													
4.1	Support demonstration for broadacre soil applications at a significant scale.	Increase economic condfidence in large-scale agricultural applications of biochar within Australia.	1. Outline criteria and seek expression of interest for potential broadacre demonstration partners. 2. Establishment of broadacre demonstrations.	2 ZERO HUNGER 6 CLEAN WATER AND SANITATION 8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 13 CLIMATE ACTION 17 PARTNERSHIPS FOR THE GOALS	Communicate Economic Value & Benefits Collaborate & Enhance Partnerships Facilitate Industry Scale Up Encourage Investment Instil Confidence Focus Innovation & Research	✓	✓		✓	✓		✓		✓
4.2	Support demonstrations to regenerate marginal or degraded land, including mine site rehabilitation.	Increase economic condfidence in the use of biochar as a rehabilitation and remediation technology within Australia.	1. Outline criteria and seek expressions of interest for potential rehabilitation / remediation demonstration partners 2. Establishment of rehabilitation/remediation demonstrations.			✓	✓	✓	✓	✓	✓		✓	✓
4.3	Support commercial scale demonstration projects for non-broadacre soil applications of biochar.	Increase economic confidence in many other soil applications of biochar, and to showcase the diversity of Australian soil-based industries with potential to benefit from biochar and co-products.	1. Outline criteria and seek expressions of interest for potential demonstration partners. 2. Establishment of demonstration and trial projects.			✓	✓		✓	✓	✓	✓	✓	✓
4.4	Support commercial scale demonstration projects for non-soil industrial applications of biochar.	Increase economic confidence in non-soil based applications of biochar and showcase the diversity of Australian industries with potential to benefit from biochar and co-products.	1. Outline criteria and seek expressions of interest for potential demonstration partners. 2. Establishment of demonstration projects.			✓	✓		✓	✓	✓	✓	✓	✓
4.5	Support co-pyrolysis demonstrations of plant biomass, biosolids, forestry residues, agricultural residues and food organics / garden organics (FOGO).	Increase economic confidence in utilising co-pyrolysis as a waste to value/resource management strategy.	1. Outline criteria and seek expressions of interest for potential demonstration partners. 2. Establishment of co-pyrolysis demonstration projects.			✓			✓	✓	✓	✓	✓	✓
5	**Leverage Carbon Emission Reduction and CO_2 Removal opportunities.**													
5.1	Promote inclusion of recognised accounting methods for biochar in National GHG Emissions Inventories *(IPCC-2019*[1] *recommended method for estimating change in mineral Soil Organic Carbon Stocks from biochar amendments).*	Enable immediate contribution of biochar to national GHG emission inventories through inclusion of the readily available IPCC accounting method for biochar in the calculations.	1. Adoption of biochar in Australia's National GHG Emissions Inventory 2. Adoption of biochar in national GHG emissions inventories of other countries	13 CLIMATE ACTION 11 SUSTAINABLE CITIES AND COMMUNITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 8 DECENT WORK AND ECONOMIC GROWTH	Communicate Economic Value & Benefits Collaborate & Enhance Partnerships Facilitate Industry Scale Up Encourage Recognition & Policy Support Encourage Investment Instil Confidence Harmonise Regulatory Frameworks	✓			✓	✓	✓	✓		✓
5.2	Develop biochar methodologies under Australia's Emissions Reduction Fund (ERF) for all soil uses and non-soil/industrial uses.	Align biochar method(s) for soil and non-soil/industrial uses with the Australian ERF to support crediting of both emissions reduction and CO2 Removal provided through production and use of biochar.	1. Identification of the appropriate expert team capable of developing biochar methods for soil uses in accordance with the Australian ERF. 2. Identification of the appropriate expert team capable of developing biochar methods for non-soil/industrial uses in accordance with the Australian ERF. 3. Development and implementation of work plans to prepare biochar methods for soil and non-soil/industrial uses. 4. Acceptance of biochar soil use and non-soil/industrial use methodologies under the ERF.			✓			✓	✓	✓	✓		✓
5.3	Support development of a biochar method for feed chars to reduce methane from livestock under Australia's Emissions Reduction Fund (ERF).	Use biochar to accelerate climate action on critical livestock emissions in agriculture.	1. Support research initiatives to characterise the effect of feed chars on methane reduction. 2. Use research, if favourable, to develop a suitable methodology for this application of biochar.			✓								
5.4	Collaborate with stakeholders with Net Zero or other carbon reduction targets to help raise awareness of biochar's potential role in carbon drawdown.	Increase economic, public and industry confidence in the Australian biochar production industry as a Net Zero technology	1. Provision of biochar Net Zero awareness workshops. 2. Engagements with industry initiatives promoting emission reduction and carbon drawdown.			✓	✓	✓		✓	✓	✓	✓	✓
5.5	Support biochar inclusion into the Integrated Assessment Modelling.	Facilitate the adoption of biochar as a pillar technology in international strategies to combat climate change.	1. Support of existing efforts to include biochar in the Integrated Assessment Modelling domestically and abroad.			✓	✓			✓	✓	✓	✓	✓
6	**Encourage beneficial use of residual or waste biomass**													
6.1	Support the diversion from landfilling and uncontrolled burning of clean biomass.	To utilise biomass residues more productively in Australia through conversion to biochar.	1. The amount of biomass diverted from landfill and not burned in an uncontrolled environment. 2. The continued development and commercial application of Australian technology for biomass conversion to biochar. 3. Policy developments that encourage use of biomass residues for biochar production and use.	8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 13 CLIMATE ACTION 15 LIFE ON LAND	Communicate Economic Value & Benefits Facilitate Industry Scale Up Encourage Recognition & Policy Support Encourage Investment Instil Confidence	✓	✓	✓	✓	✓		✓		✓
6.2	Further incentivise circular production of residual biomass to biochar.	Incentivise through both emissions reduction methodologies and penalties for uncontrolled burning, the transformation of waste and residual biomass to biochar.	1. Assessments and studies on the viability of further incentivising the circular production of residual biomass in Australia. 2. Establishment of emission reduction methodologies for biomass conversion to biochar			✓	✓		✓	✓	✓	✓	✓	✓
6.3	Enhance and maintain biomass availability assessment tools to aid industry capacity to grow by reliably quantifying and sourcing sustainable biomass.	Identify reliable biomass feedstocks that can facilitate biochar industry growth.	1. Quantify residual biomass opportunities for biochar in every state and territory of Australia. 2. Create industry specific biomass assessment tools.			✓	✓							
6.4	Create a grading system for residual biomass to improve economic evaluation, and the safe use and production of biochar.	To categorise potential biomass feedstocks to facilitate safe and sustainable use for biochar production.	1. Consultation with industry stakeholders including residual biomass producers to establish a suitable grading system for residual biomass 2. Establishment of a guideline on assessing suitability of residual biomass for biochar production			✓			✓	✓	✓	✓	✓	✓

APPENDIX B

	KEY INITIATIVES & SUPPORTING ACTIONS	OBJECTIVES	KEY PERFORMANCE INDICATORS	Aligned UN SDGs	Aligned Roadmap Priority Themes	TIMING			KEY BENEFITS					
						Short Term	Mid Term	Long Term	Regulator Confidence	User Confidence	ESD / Climate	Economic Value	Social Licence	Market Growth
7	**Drive beneficiation and increased value of biochar products and co-products**													
7.1	Fund research into beneficial upgrading of biochar products.	Increase biochar value by identifying specialty biochar products and uses.	1. Number of new biochar related products entering the market. 2. Number of biochar related patents being registered by Australian companies, organisations and individuals.	8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 13 CLIMATE ACTION	Encourage Recognition & Policy Support Facilitate Industry Scale Up Actively Seek Funding & Resourcing Encourage Investment Instil Confidence Accelerate Markets	✓	✓	✓	✓	✓		✓		✓
7.2	Research and evaluate substitution of biochar in traditional carbon markets.	Facilitate the establishment of biochar as a replacement material for fossil fuel derived carbon.	1. Uptake of biochar in traditional fossil fuel carbon markets.			✓	✓	✓		✓	✓	✓	✓	✓
7.3	Drive technical and economic outcomes of co-products from biochar production (e.g. energy, hydrogen and wood vinegar).	Optimise the economic and environmental benefits of biochar production in Australia through development and commercialisation of co-technologies and products.	1. Number of new biochar related co-products entering the market. 2. Number of biochar co-product patents being registered by Australian companies, organisations and individuals.			✓	✓	✓		✓	✓	✓	✓	✓
7.4	Establish sequestration and downstream emissions avoidance potential for biochar used in different applications and with different feedstocks	Maximise the carbon drawdown potential of biochar through establishing strong frameworks for understanding carbon sequestration potential of different applications.	1. Number of industry accepted papers and guidance materials on carbon sequestration potential for different applications and feedstocks.			✓	✓	✓		✓	✓	✓	✓	✓
8	**Safeguard responsible use and production of biochar**													
8.1	Fast track the implementation of the ANZBIG Code of Practice and the certification of biochar for particular uses.	Develop and implement the Code of Practice for the Safe and Sustainable Production and Use of Biochar in Australia.	1. Certified biochar production sites using the Code of Practice. 2. Certification of safe and sustainable biochar production linked to carbon credit eligibility. 3. Development of branded certified biochar in Australia 4. Recognition of the Code of Practice by regulatory authorities	8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 13 CLIMATE ACTION	Communicate Economic Value & Benefits Facilitate Industry Scale Up Encourage Investment Instil Confidence Harmonise Regulatory Frameworks Accelerate Markets	✓	✓	✓	✓	✓	✓	✓	✓	✓
8.2	Provide support for integration with other standards for sustainable sourcing and use of biomass.	Ensure that biomass is sustainably sourced by linking in with other programs and initiatives that already identify sustainability of biomass production.	1. Identification and verification of existing biomass certification schemes for applicability to biochar production and use. 2. Support for biochar producers in sustainable feedstock procurement through provision of suitable information.			✓	✓	✓	✓		✓		✓	
8.3	Develop guidance for rate-based application of biochar in soil applications including supporting research and demonstration.	Ensure consumers receive maximum benefit from biochar in soil applications.	1. Development of guidance material for biochar application rates for different soil and use applications.			✓	✓	✓						
8.4	Develop a long term self funding mechanism for safeguarding the biochar sector such as through a certification levy.	Safeguard the economic future of the Australian Biochar Industry to ensure sustained future industry collaboration and growth.	1. Undertake annual progress reviews of long-term funding needs and strategies to self sustain the support and growth of the biochar industry.				✓	✓	✓	✓	✓	✓	✓	✓
9	**Support government, utility and industry procurement practices**													
9.1	Identify and promote replacement or alternative procurement opportunities for biochar.	Ensure that biochar is considered for suitable public and industrial applications and as a substitute or replacement for fossil fuel derived carbon.	1. Number of alternate uses and new applications for biochar. 2. Total biochar use in different industry and government applications. 3. Number of policy initiatives implemented by governments to support industry scale up such as incentives, grants and levies.	8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 13 CLIMATE ACTION 17 PARTNERSHIPS FOR THE GOALS	Communicate Economic Value & Benefits Facilitate Industry Scale Up Encourage Investment Instil Confidence Accelerate Markets	✓	✓	✓	✓	✓		✓		✓
9.2	Establish biochar specifications for key procurement and use opportunities and identify carbon sequestration potential of these applications.	Ensure that suitable biochar is used for specific applications in government and industry.	1. Development of biochar specifications and guidelines for use for different public and industrial uses.			✓	✓			✓	✓	✓	✓	✓
9.3	Develop procurement and carbon sequestration biochar case studies and a biochar reference library for government and industry.	Ensure that government agencies and industry are aware of how best to use biochar in a range of applications.	1. Biochar case studies generated per year. 2. Use of case studies and library visits measured by downloads and site visits.				✓			✓	✓	✓	✓	✓

APPENDIX B

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						Short Term	Mid Term	Long Term	Regulator Confidence	User Confidence	ESD / Climate	Economic Value	Social Licence	Market Growth
10	**Drive export of Australian biochar innovation internationally**													
10.1	Link with Australian federal and state trade export and overseas collaboration initiatives	Ensure the Australian Biochar Industry has a strong international network and is well placed for international trade opportunities.	1. Interaction with Australian and overseas trade initiatives and establishment of collaborative initiatives 2. Successful export of Australian biochar technology and know how.	8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 11 SUSTAINABLE CITIES AND COMMUNITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 13 CLIMATE ACTION 15 LIFE ON LAND 16 PEACE, JUSTICE AND STRONG INSTITUTIONS 17 PARTNERSHIPS FOR THE GOALS	Communicate Economic Value & Benefits Facilitate Industry Scale Up Encourage Investment Harmonise Regulatory Frameworks Accelerate Markets	✓			✓	✓		✓		✓
10.2	Link with other global biochar initiatives such as IBI, EBIC, USBI and BNZ to exchange and influence.	Bring a coordinated and streamlined approach to the development of the global biochar industry that reflects the Australian perspective.	1. Attendance and presentations at global biochar forums and gatherings. 2. Strong participation as a member of IBI, an affiliate of EBIC and a supporter of BNZ.			✓	✓	✓		✓	✓	✓	✓	✓
10.3	Identify biochar production and use as part of Australia's global climate change contribution.	Ensure that the actions and activities that are contributing to carbon drawdown in Australia and through Australian activities elsewhere are articulated both domestically and internationally to key stakeholders.	1. Number of international climate change forums where the Australian biochar industry is prominent 2. Number of publications, papers, presentations and website hits related to Australian biochar activities.			✓	✓	✓		✓	✓	✓	✓	✓

Notes:
Indicative Resourcing is expected to come from both private industry and government.
UN SDG's = United Nations Sustainable Development Goals

[1] Intergovernmental Panel on Climate Change **(IPCC), 2019, *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*** ; ***Volume 4:*** *Agriculture, Forestry and Other Land Use;* ***Appendix 4: Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments***

Please note: this document
is intended for printing and
viewing in A3 landscape format

ANZ BIOCHAR INDUSTRY GROUP

AIEN
Catalyst to achieving a circular economy

AUSTRALIAN BIOECONOMY CONFERENCE 2024

Circular and Regenerative Bioenergy:

Pathways for CO_2 Removal
and Renewable Energy for Net Zero
via the
Australian Biochar Industry 2030 Roadmap

September, 2024

Version 1.1
July 2023

Australian Biochar Industry

2030
ROADMAP

ANZ BIOCHAR INDUSTRY GROUP

Craig Bagnall
Executive Board, Technical Advisory Board - ANZ Biochar Industry Group
Director, Catalyst Environmental Management Director,
Environment & Regulatory, SEATA Group

Presentation Outline

- **ANZ Biochar Industry Group (ANZBIG)** – Who we are and what we do
- **Biochar and CO_2 Removal** (CDR, ‘*drawdown*’)
- **Fit For Purpose Biochars** – 3 biochar grades of the ANZBIG Code of Practice
- **Renewable Energy / Renewable Fuels *with* Drawdown**
- **Biochar uses and markets -** climate action and circular bioeconomy
- **ANZ Biochar Industry 2030 Roadmap**

> *“ If your house is on fire, you don’t tell the fireman to just let it simmer, you want to put the fire out ..we need carbon **removal** that actually **keeps the carbon out afterwards** ”*
>
> *Albert Bates*

Clarification & Limitation:

This presentation provides an indicative overview of potential applications and markets.
The information provided is not intended to and does not represent financial advice.

THE PEAK BODY FOR BIOCHAR IN AUSTRALIA & NEW ZEALAND

ANZ
BIOCHAR
INDUSTRY GROUP

Vision: *Australia and New Zealand as global leaders in the sustainable production and use of biochar.*

Mission:

- *The Australian and New Zealand Biochar Industry Group will facilitate and assist companies, governments and institutions in the effective use and production of Biochar.*
- *ANZBIG will focus and streamline Biochar education, research, collaboration and commercialisation activities to provide better outcomes for the societies of Australia and New Zealand.*

anzbig.org

ANZ
BIOCHAR
INDUSTRY GROUP

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Mail: C/o Unit 10, Level 2, 344 Hunter St, Newcastle West, NSW 2302

Emergence of the commercial biochar industry in ANZ:

- Inauguration in the 2000's, R&D at national and state levels
- World's longest running field trials located at Wollongbar NSW (NSW DPI)
- Biochar Researchers Network of ANZ (active until 2014)
- Formation of ANZ Biochar Initiative in 2017
- Evolution to an industry group in 2020 **(ANZ Biochar Industry Group)**:
  - Focused on: **education & awareness, standards & certifications, supply & market development, policy & regulations/ advocacy, resourcing**
  - ~200 members including corporates, entrepreneurs, academics, capital, and governments at all levels
  - Multiple Australian technologies (small mobile systems to large centralised plants)
  - ~20 members with multi-million dollar projects under way worldwide
- Established a national Code of Practice in 2021 (including biochar quality gradings)
- Established the **world first** biochar industry 2030 roadmap (June 2023)
- Member of the cross-industry working group for a proposed **ACCU method** for Biochar CO2 Removal (submitted Q2 2024)
- Recently released **Farmers Guide** for sustainable production and use of biochar

Australian Biochar Industry 2030 Roadmap

Download for free at www.anzbig.org

Version 1.1
July 2023

Australian Biochar Industry

2030
ROADMAP

ANZ BIOCHAR INDUSTRY GROUP

ANZBIG's
Roadmap will
inform the
community and
illuminate the case
for new policies
from all Australian
governments.

"The Australian Biochar Industry Roadmap is a call to action. It demonstrates and explains the huge potential for growth of biochar production and use in Australia.
Making this potential real will deliver major economic, environmental and social benefits….

…..I look forward to the biochar industry making a major contribution to the emergence of Australia as a Superpower of the net zero world economy. "

Ross Garnaut AC
ANZBIG Patron, May 2023

- **10 Priority Themes**
- **10 Key Initiatives**

- **Over 50 Million tonnes/yr** of commercially accessible sustainable biomass residues are **currently being burned, landfilled or under-utilized**.
- **Potential to reduce Australia's net carbon emissions by 10-15%, provide up to 20,000 permanent jobs** (particularly in regional and rural areas), improve soil health and agricultural productivity and return degraded lands to a higher value.

What is Biochar and why a Roadmap?

What Is Biochar video link

INTRODUCTION TO BIOCHAR

ANZBIG
Fact Sheet
#1

More than 50 million tonnes of residual biomass (including agriculture residues, green waste, and other organic waste) is burned or landfilled every year in Australia. This causes pollution, including greenhouse gas emissions, and wastes precious resources. These renewable resources can be converted into a solid form of carbon called biochar.

WHAT IS BIOCHAR?

Biochar is a charcoal-like product made by heating any form of organic matter (biomass) in a controlled process with limited oxygen, called pyrolysis. This product is called biochar when it is used as a soil amendment, or for other uses that store the carbon in a durable form.

Through the use of these technologies, we can capture, utilise and store carbon (CCUS) for the long term (centuries to millennia), reduce waste, produce clean and renewable bioenergy, and remove CO_2 from the atmosphere.

WHAT SECTORS WILL BENEFIT

There are many proven and emerging markets for biochar that increase profitability and reduce, or drawdown carbon including:

- Agriculture, horticulture, livestock and cropping
- Soil carbon sequestration
- Water management and filtration
- Mine and land rehabilitation
- Building and construction

BIOCHAR'S GLOBAL VALUE

The Intergovernmental Panel on Climate Change (IPCC) has recognised biochar as a Negative Emissions Technology (NET), urgently required at scale to remove excess carbon dioxide from our atmosphere, assessing its global potential at up to 6.6 Gt CO_2e per year, or the equivalent of 10-15% total annual global GHG emissions. Biochar is considered to be one of the lower-cost and scalable NETs, with the IPCC estimating that 1.3 -1.8 Gt CO_2e per year could be achieved for under USD \$100/tCO_2e.

Large international corporations committed to net-zero, including Microsoft, Shopify and Patch, already buy international voluntary market carbon removal certificates from Australian biochar producers.

With more uses for biochar emerging, the global market is growing and is estimated to be worth \$USD 3.82 billion by 2025. This is a substantial increase from its 2018 value of \$USD 1.48 billion. Potential and existing biochar industries in Asia, the US and Europe are rapidly expanding.

OUR BIOCHAR OPPORTUNITY

Australia is on the cusp of developing a world-leading biochar industry, thanks to our technologies, research, and high-potential resources.

Our industry is shovel-ready to scale up and create important economic, social, and environmental opportunities from a \$50-\$100 million dollar per annum industry to a minimum \$1-5 Billion dollar industry by 2030.

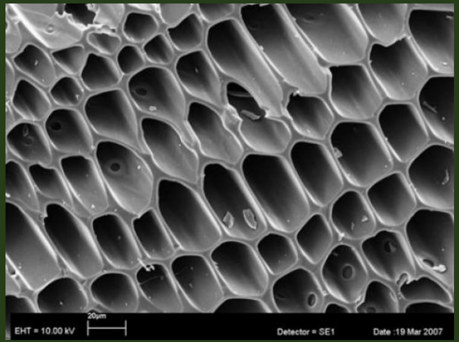
The next step is commitment and leadership from corporates, capital, government, entrepreneurs, and academics wanting to be Net-Zero. The Australian Biochar Industry 2030 Roadmap outlines a pathway forward for Biochar Industry scale up.

ANZ BIOCHAR INDUSTRY GROUP

Global leaders in the sustainable production and use of biochar

www.anzbig.org

"Biochar is a *charcoal-like* product made by **heating** any form of **organic matter (biomass)** in a controlled process **with limited oxygen**, called pyrolysis. This product is **called biochar when it is used** as a soil amendment, or for other uses that store the carbon **in a durable form**"



More Info:

Introduction to Biochar

- **Fact Sheet** available for download at https://anzbig.org/resources/

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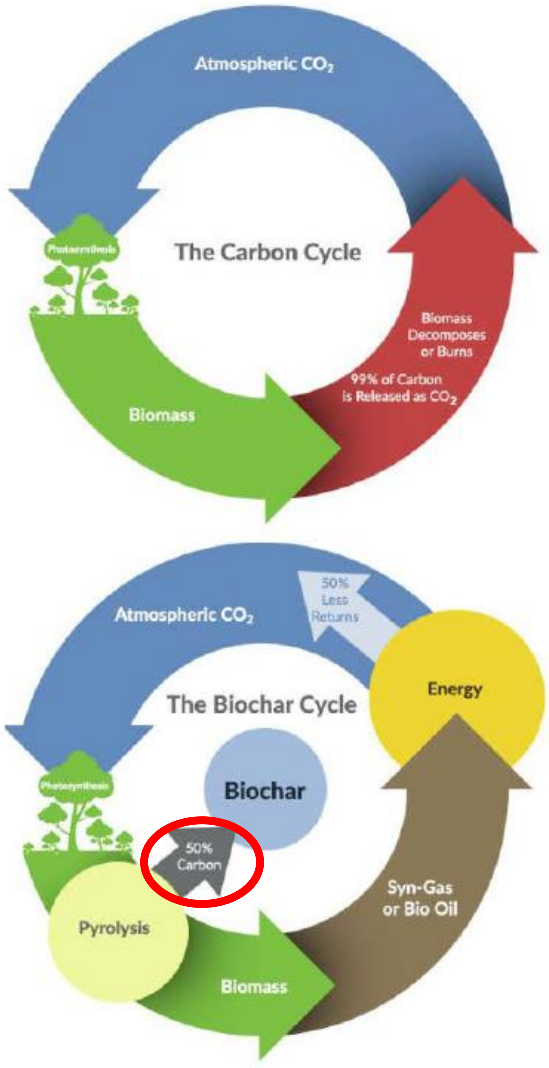
Biochar CO_2 Removal – priority climate action



Over 99% of CO_2 captured by biomass re-enters our atmosphere as part of the natural carbon cycle.

Pyrolysing wasted plant biomass into biochar **intercepts the cycle** and converts carbon into a form that is typically stable for **centuries to millennia**.

> *"The* ***deployment of CDR*** *to counterbalance hard to abate residual emissions is* ***unavoidable if net zero*** *(CO_2 and total GHG)* ***is to be achieved****."*
>
> IPCC 6th Assessment Report April 2022

Recent estimates indicate that biochar could mitigate up to 6.6 Billion tonnes of CO_2e globally per year by 2050[1]. This is indicatively equivalent to the USA's annual GHG emissions (1990-2019)[2].

(1) IPCC 6th Assessment Report, March 2022;
(2)UNEP Emissions Gap Report, 2020.

Circular BioEconomy:

Biochar for Circular Carbon & Climate Action

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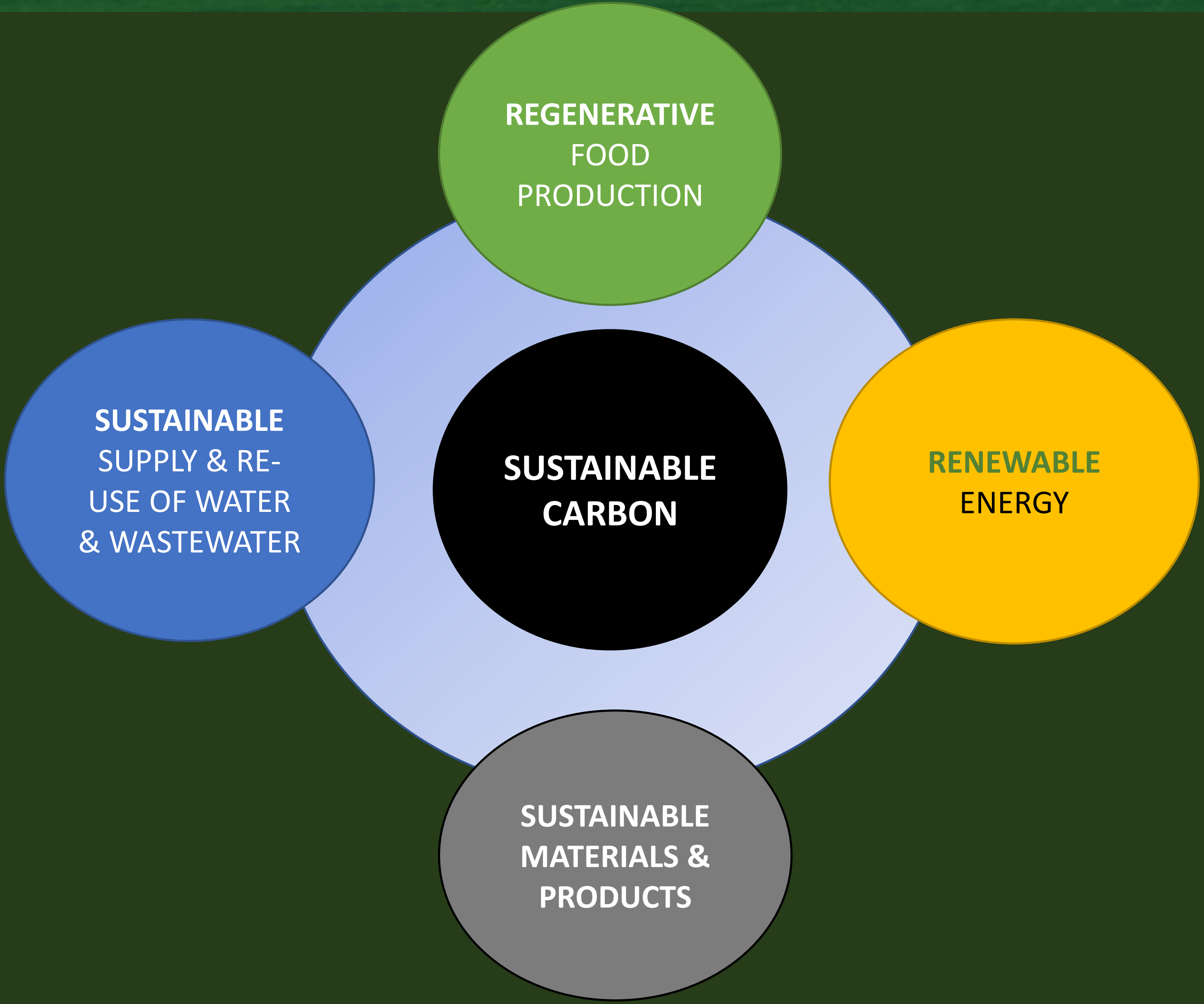
Carbon plays a key role in the food-energy-water nexus…



REGENERATIVE FOOD PRODUCTION

SUSTAINABLE SUPPLY & RE-USE OF WATER & WASTEWATER

SUSTAINABLE CARBON

RENEWABLE ENERGY

SUSTAINABLE MATERIALS & PRODUCTS

Carbon is the building block of all Life and for many of the things we make and use

…we need to remove the *excess* carbon from the sky and bring it back down into our soils and materials where it is needed most.

Harnessing atmospheric CO_2 via biochar bioenergy helps to displace fossil carbon with greener, circular, sustainable carbon that can help repair and restore degraded soils.

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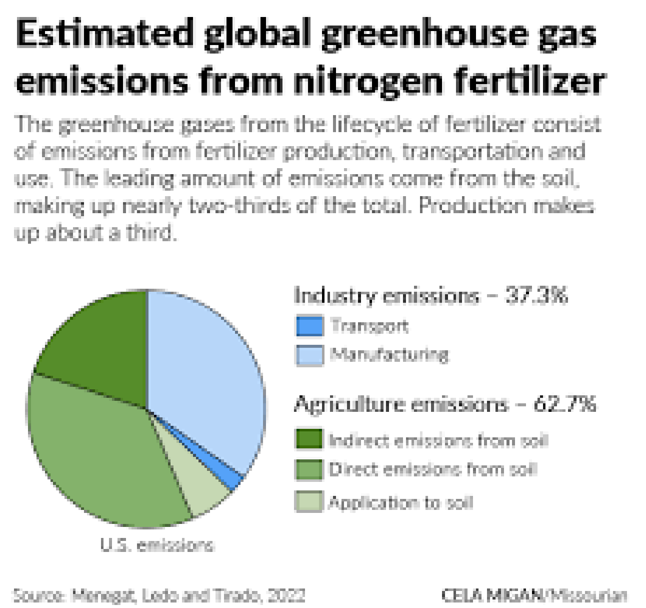
Displacing Fossil Carbon Throughout the Economy and its Supply Chains

Biochar - circular **‘green’ carbon** to **displace fossil carbon** in many applications

Assists decarbonisation of hard to abate industries (via both **ER+CDR,** with additional sustainability **co-benefits**)

Improved performance (e.g. strength, filtration enhancement, nutrient/water retention etc etc):

- *Displacement of Carbon Black (fossil carbon derived)*
- *Displacement of Activated Carbon (lignite/coal)*
- *Displacement of Coal (e.g. metallurgical reductants – “**biocarbons**”)*
- *Displacement of Peat (horticulture/nurseries/agriculture)*
- *Displacement / Reduction of Synthetic Fertilisers (derived from natural gas)*
- *Displacement of mined Graphite (fossil based) (used in battery anodes etc)*
- *Displacement of Recarburiser (fossil based) (used in foundries)*
- *Displacement of Plastics/Oil (e.g. fillers, biocomposites)*



Estimated global greenhouse gas emissions from nitrogen fertilizer

The greenhouse gases from the lifecycle of fertilizer consist of emissions from fertilizer production, transportation and use. The leading amount of emissions come from the soil, making up nearly two-thirds of the total. Production makes up about a third.

Source: Menegat, Ledo and Tirado, 2022

CELA MIGAN/Missourian

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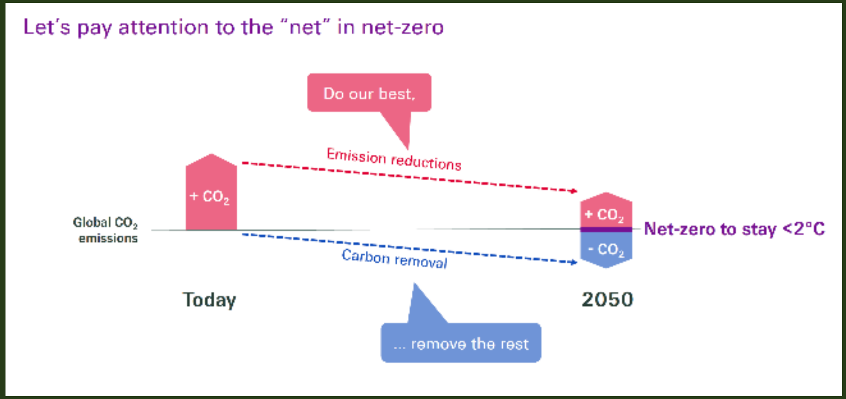
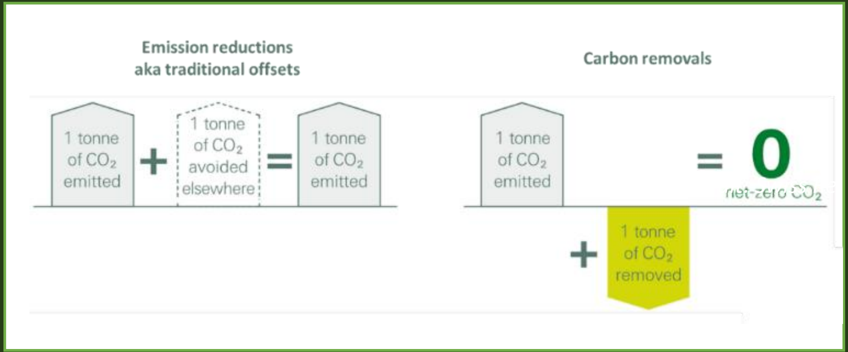
Multiple Converging Market Drivers

- Net Zero commitments (2030 / 2050) - IPCC calls for CDR urgently at scale
- Emissions Reduction (ER) Targets (2030/2050), Displacement of Fossil carbon
- FDR / Integrity: ASX Reporting, changes to curb *"Greenwashing"* to investors & markets
- Increased focus on genuine Sustainability (UN SDGs / ESG)
- Circular Economy / Waste to Value – national targets for CE/ waste diversion 2030
- Cost Vs *Value* (co benefits, Net User Benefit)
- Managing Emerging Contaminants (eg PFAS, microplastics) – thermal deconstruction
- More frequent, more severe impacts ($$$, significant insurance underwriting risk)



Source: Swiss Re

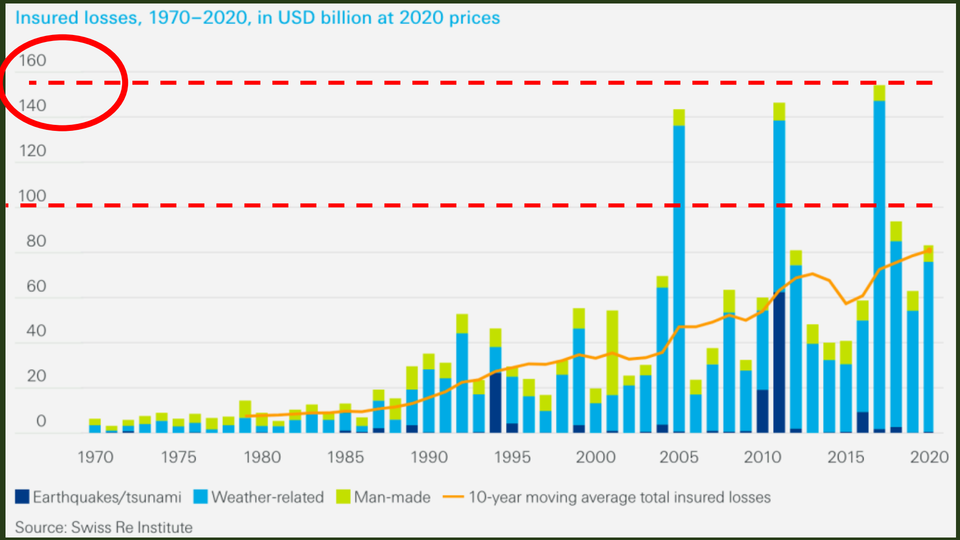


Green

Investors With $29 Trillion Demand Science-Based Climate Targets

Alastair Marsh
September 29, 2021, 9:01 AM GMT+10

A coalition of financial firms overseeing a combined $29.3 trillion of assets are calling on some of the world's biggest corporate emitters to "urgently" set science-based emissions reduction targets that are compatible with 1.5° Celsius of global warming.


Insured losses, 1970–2020, in USD billion at 2020 prices

Source: Swiss Re Institute

2021
US$320B
(total)

2022
US$240B
(total)

(insured
~$120B)

Source: Munich Re

"In 2050 the carbon net-negative economy needs to be as big as the oil industry is today." *Mariannne Tikkanen, Puro Earth (CDR Credit Market)*

Biomass Feedstocks: Sustainable, Renewable, Gt-Scale Drawdown

Global biochar CDR potential up to 6.6 Gt CO_2e/y (up to 1.8Gt/y at <u><USD$100</u>/t$CO_2$e) (IPCC, 2022)

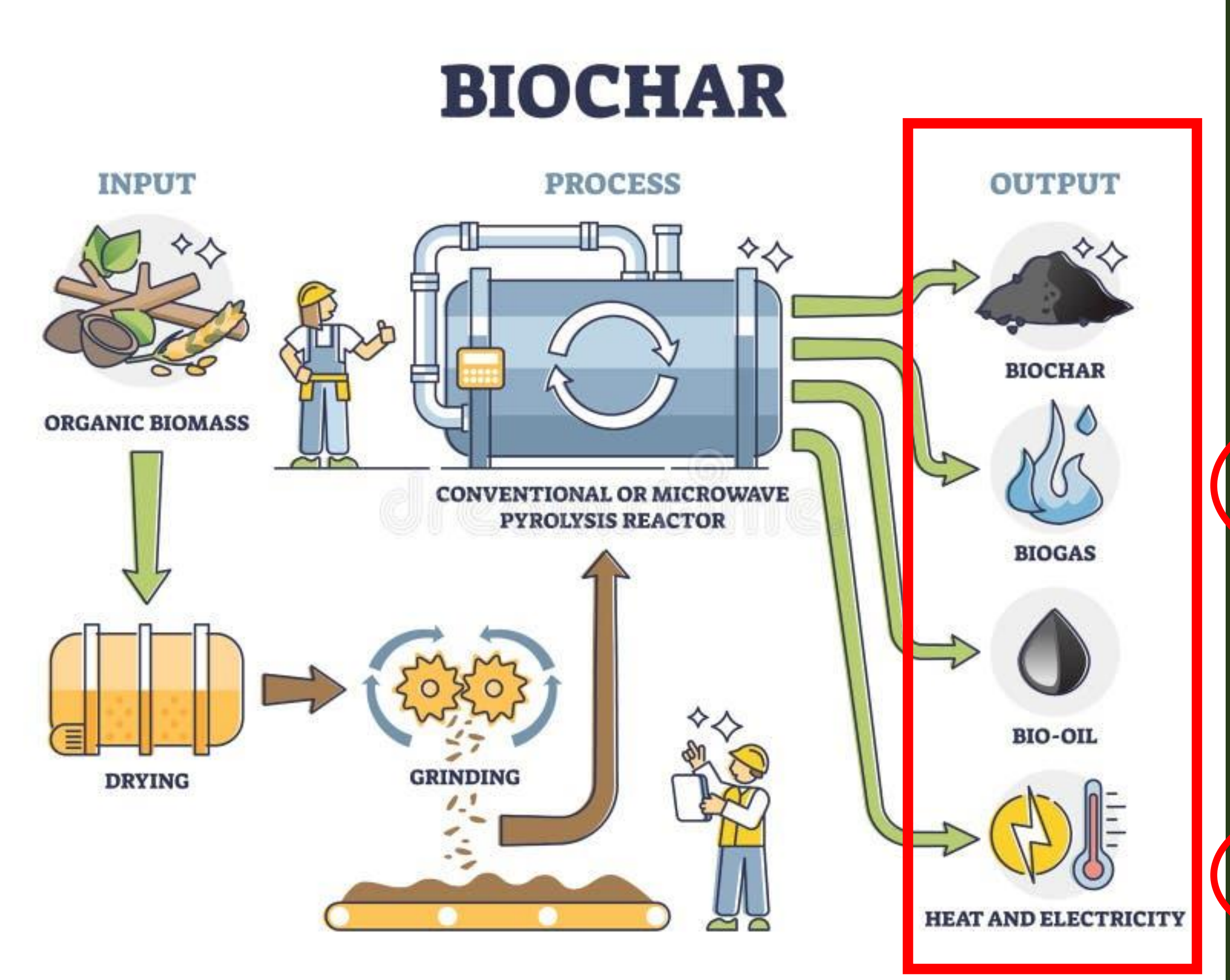
>> 50 Mtpa biomass is burned or landfilled in Australia alone (ANZBIG 2022)

(up to 80-110 Mtpa of biomass sustainably available, CSIRO 2016). Over 22M tpa biomass residues in NSW alone (NSWDPI 2021)

Biochar = <u>Enhanced</u> food production and security

Renewable Energy / Renewable Fuels *with* Drawdown (CDR)

"Having your cake & eating it too"



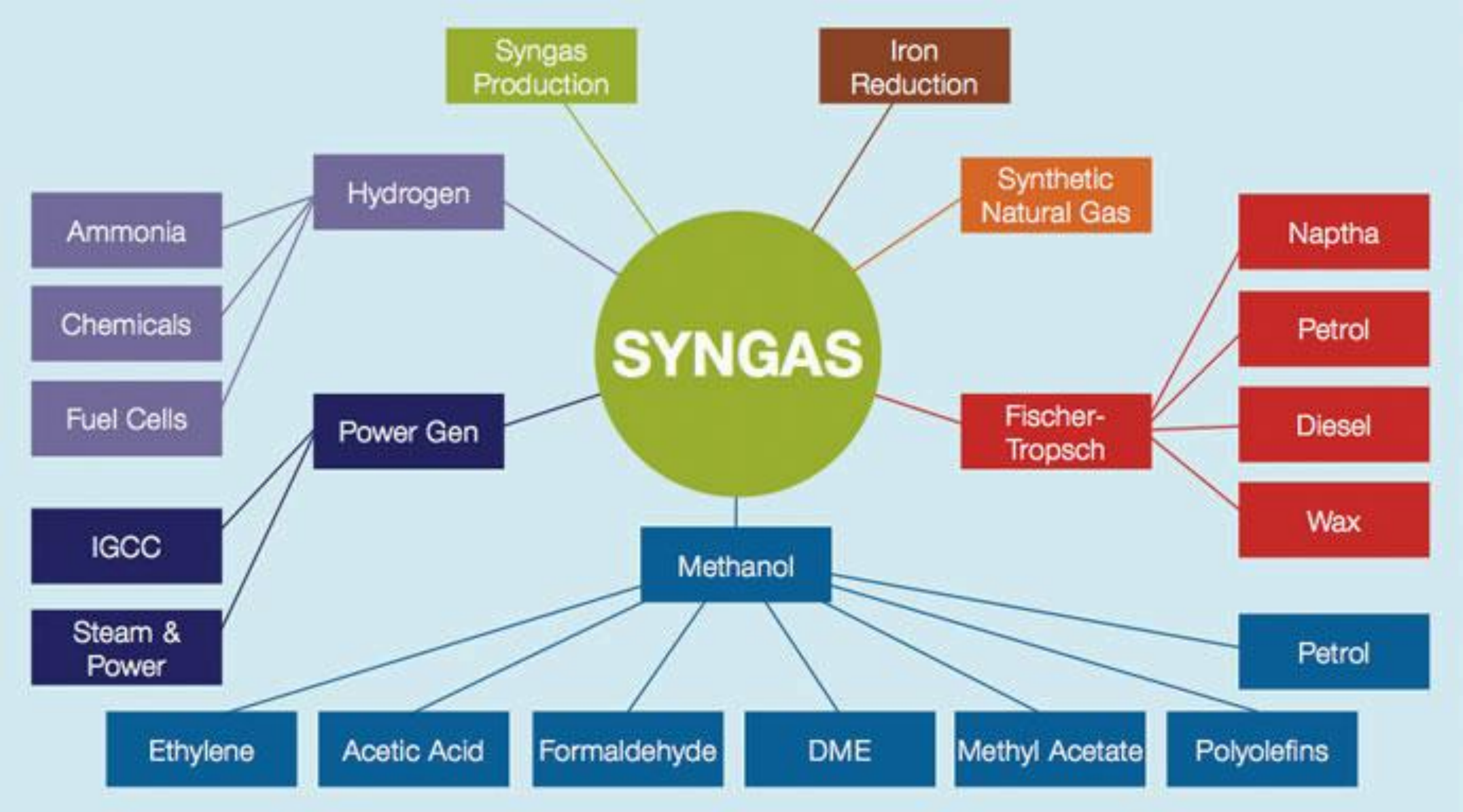
SOLID (biochar)

GAS (Syngas – majority H_2, CO)
- biohydrogen, renewable fuels, gas engines with 'clean' syngas

LIQUIDS (wood vinegars, bio-oils)

HEAT (**Heat to Power** - heat engines, conventional steam turbines, ORC etc); **Industrial Heat & Drying**)

Syngas Uses - Electricity *and much more*



- **Hydrogen and Carbon = chemical building blocks of MANY other derivatives** (biofuels, bioplastics / olefins etc)
- **H:C ratios important for scale up** (typically need 2:1. Leaving up to 50% of carbon in the solid char helps this)
- **Historically, syngas cleanup required**

➔ Clean/concentrated syngas helps facilitate scale

- **Hydrogen** separation via PSA (or WSR at scale)

Biogenic syngas for many **Renewable Fuels** (including hydrogen)

ANZ BIOCHAR INDUSTRY GROUP

Biochar technologies come in a very wide range of types, scales & outputs

Examples of Very Small Scale
(e.g. Flame-capped kilns)

Examples Mobile/Relocatable Commercial*
** Also provide larger commercial systems*

Example** Centralised & Decentralised Commercial & Industrial Plants
Australian technologies / ANZBIG members *(** more suppliers nationally/internationally)*

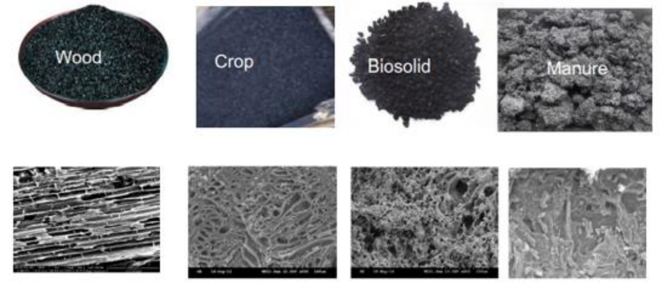
- More info available via ANZBIG members resources webpage *(including table summary)*

www.anzbig.org

ANZ BIOCHAR INDUSTRY GROUP

Which Biochar for the Job?...Starting with the End in Mind “Chars ain’t Chars”

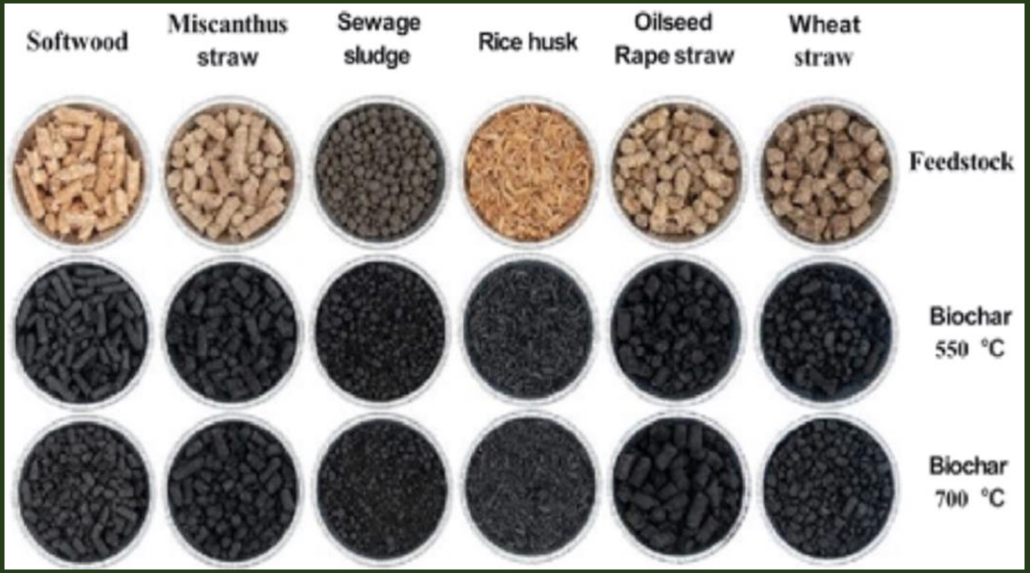
Modification of biochar properties
- Heating rate
- Temperature
- Feedstock
- Residence time
- Technology
- Blending / Co-pyrolysis
- Pre/Post Treatment

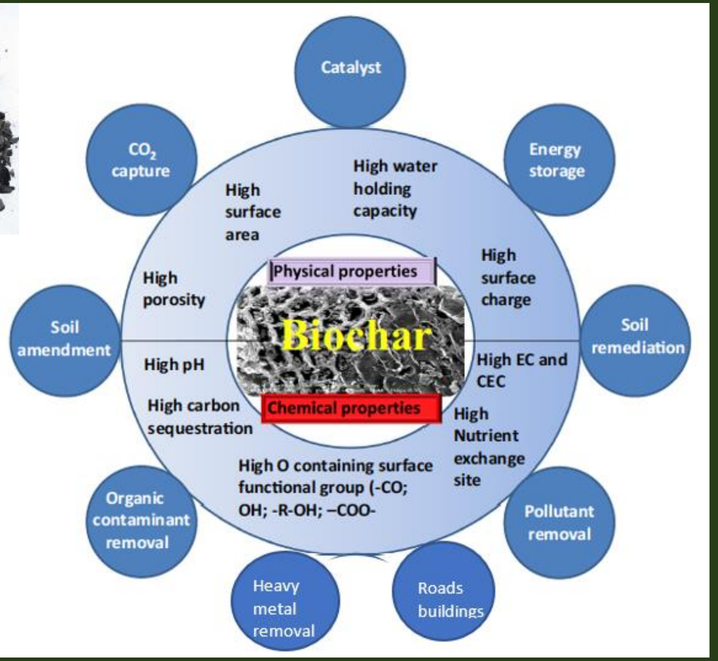


Credit: Dr G.Pan, 2020

- **Biochar properties dictate (and limit) its potential uses**
- Application needs are identified to engineer biochar properties to meet them.

➔ *ANZBIG Code of Practice (2021) classifies <u>3x Grades of biochars</u> for fit for purpose application:….Feed Grade (premium), Standard Grade (Soils), and Industrial Grades.*





↑ Temperature = ↓ Biochar Yield ↑ Syngas Yield

Fit For Purpose Products- *'Horses For Courses'*

'Clean' Feedstocks without significant impurities

ANZBIG Standard (or Feed) Grade Biochar

Higher Order Use of 'clean' resource

Agricultural / Soil
Applications

Example High Value Applications:

- High value Orchards / Horticulture
- Non-bulk/boutique distribution (e.g. bagged biofertilisers)
- Water filtration (cheaper substitute for activated carbon)

Example High Volume Applications:

- Broadacre Agriculture, Silviculture, Land / Mine Rehabilitation
- Amendment for Bulk Compost & Organic Fertilisers
- Feed Chars, Low Odour Animal Bedding / Litter

Code of Practice for the Sustainable Production and Use of Biochar in Australia and New Zealand

Version 1.0 – November 22, 2021

ANZ BIOCHAR INDUSTRY GROUP

ANZBIG COP Biochar Grades:

1. Feed Grade (FG)
2. Standard Grade (SG) (Soils)
3. Industrial Grade (IG)

Feedstocks with Impurities
(not suitable
for soil application)

Higher Order Use of 'unclean' resource

ANZBIG Industrial Grade Biochar

Industrial / Non-Soil
Applications

Example High Volume Applications:

- Roads & Construction / Concrete
- Carbon batteries (emerging)
- Fillers in plastics
- Inks (carbon black substitute)

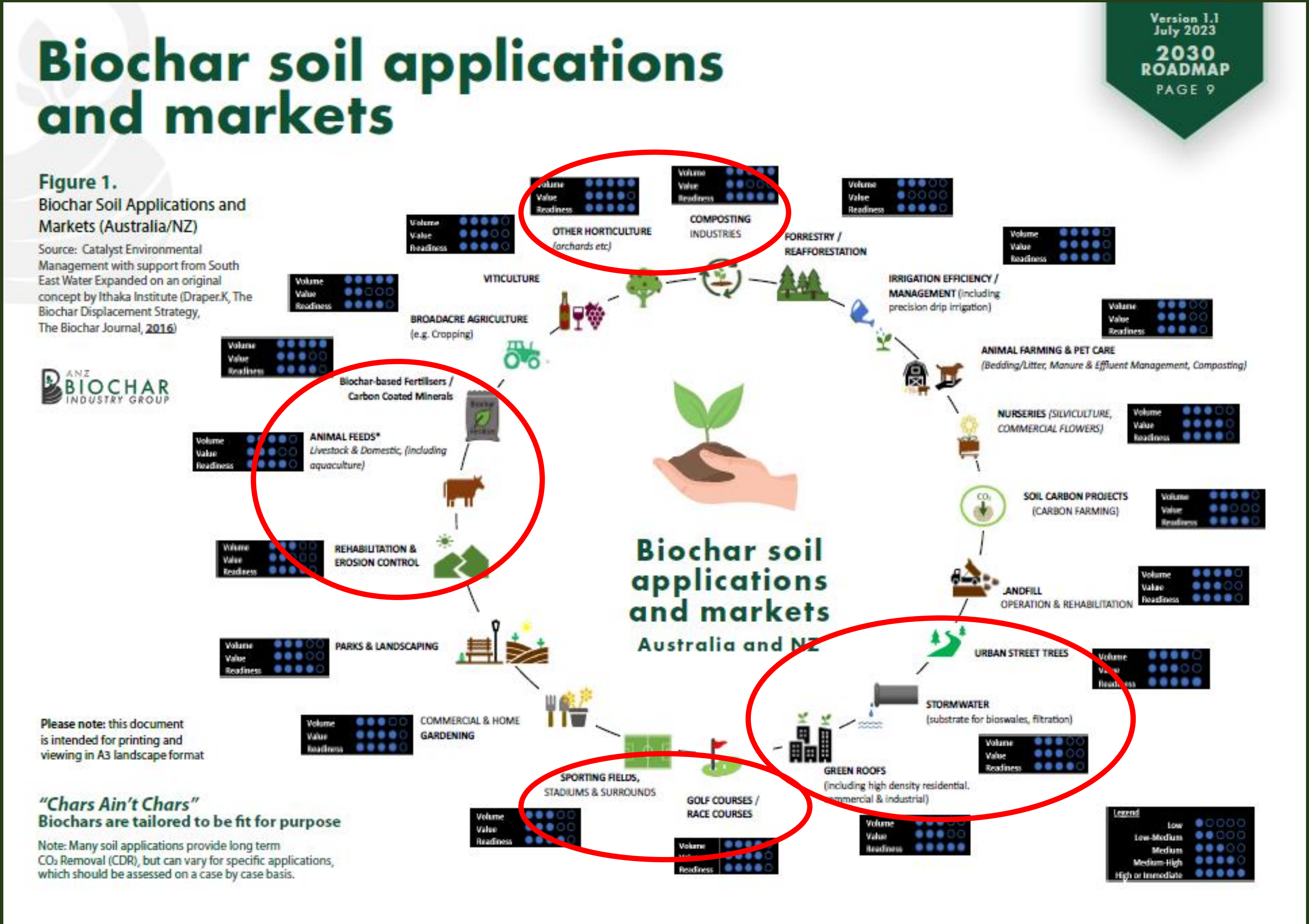
Example High Value Applications:

- Carbontech (broad range)
- Composites / Bio-plastics
- Contaminant Filtration (pseudo activated carbon)

Soil Applications for biochar – *Rural and Urban*

Standard Grade / Feed Grade Biochars

(ANZBIG Code of Practice)



Version 1.1
July 2023
2030 ROADMAP
PAGE 9

Biochar soil applications and markets

Figure 1.
Biochar Soil Applications and Markets (Australia/NZ)

Source: Catalyst Environmental Management with support from South East Water Expanded on an original concept by Ithaka Institute (Draper.K, The Biochar Displacement Strategy, The Biochar Journal, 2016)

ANZ BIOCHAR INDUSTRY GROUP

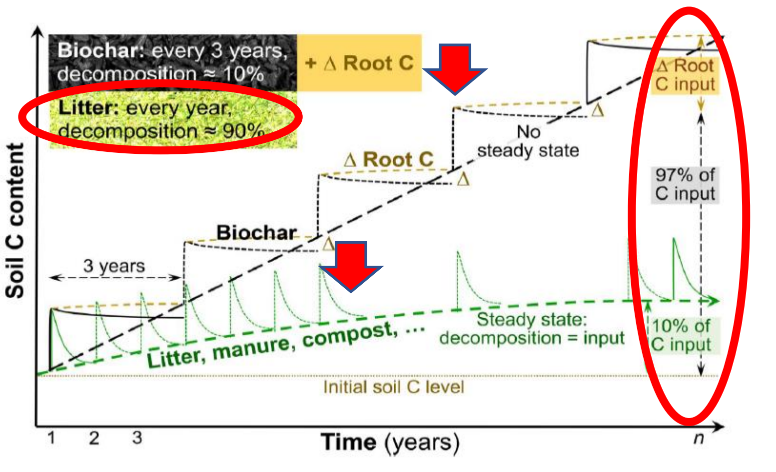
Please note: this document is intended for printing and viewing in A3 landscape format

"Chars Ain't Chars"
Biochars are tailored to be fit for purpose

Note: Many soil applications provide long term CO_2 Removal (CDR), but can vary for specific applications, which should be assessed on a case by case basis.

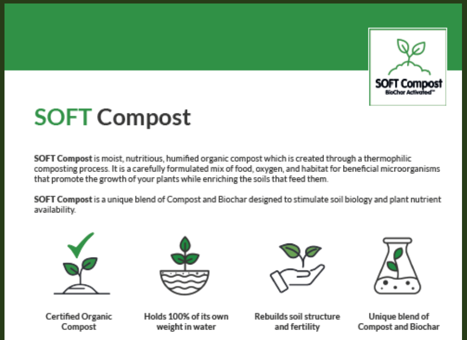
Compost Enhancement / Soil Ameliorants / Fertiliser Efficiency

- **Australian composters already using Biochar** (**Biogro**(Vic), **Jeffries** & **Peats Soils**(SA), **Soft Agriculture**, with others entering (e.g. **SoilCo**)
- **10-20% reduced composting time reported in windrows *(increased throughput/productivity/capacity)***
- **Lower GHG emissions in compost** (e.g. nitrous oxides)
- **Increased aeration, water holding capacity, inhibit / deactivate residual herbicides** (some US composters using ~30,000 CY/yr of biochar just to inhibit persistent herbicides in compost)
- **Improved Product Quality** (e.g. nutrient/water retention)
- **Premium / differentiated product** - US commercial composter selling a climate-friendly BC compost at ~2x price of normal compost.



Fertiliser Efficiency:

SA NTFA (2022): No Till Wheat DAP fertilizer requirements has potential to be cut by up to ~50% without yield loss when combined with biochar @35kg/ha according to SA trials over several years



SOFT Compost

SOFT Compost is moist, nutritious, humified organic compost which is created through a thermophilic composting process. It is a carefully formulated mix of food, oxygen, and habitat for beneficial microorganisms that promote the growth of your plants while enriching the soils that feed them.

SOFT Compost is a unique blend of Compost and Biochar designed to stimulate soil biology and plant nutrient availability.

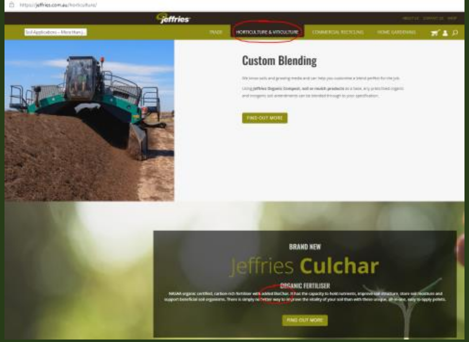


Figure 28: Example retail products from Australian commercial producers

Different Solid and Liquid Biochar Products Produced and Sold in China

- Many different liquid products, fine powders and granulated products sold on Alibaba (>50 companies advertising)
- Main use for tobacco, vegetables and then rice and other cereals.
- Bamboo BC for personal products
- President Xi has Supported the drawdown of Carbon into soils and could see a Carbon market in China by end of the year

ANZ BIOCHAR INDUSTRY GROUP

Green Cities & Infrastructure:

Climate mitigation *and* adaptation

Green roofs for Australian cities would help reduce flooding and save on bills, study shows

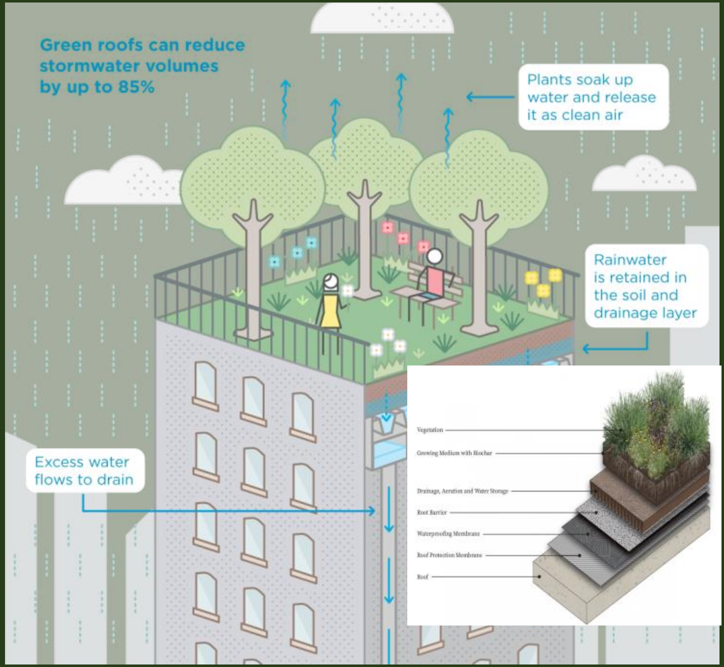
- Green roofs, facades, bioswales, infiltration basins
- Water/nutrient retention, runoff filtration, stabilisation
- **Copenhagen** – green roofs on all new buildings **2010+**.
- Uni of Melbourne study referenced by **City of Melbourne's** Growing Green/Green Roof Guidelines:

  *"…evaluated a wide range of water retention additives in substrates <for green roofs>….**biochar was the most effective**"*

- Council Street Tree Programs: Stockholm Project - largest BC use in Sweden; Dubbo Council pilot NSW- 2/3 less watering (drought resilience)


Dubbo

Stockholm




Japan


Beijing Airport


GROWING GREEN GUIDE

Melbourne

A GUIDE TO GREEN ROOFS, WALLS AND FACADES

IN MELBOURNE AND VICTORIA, AUSTRALIA

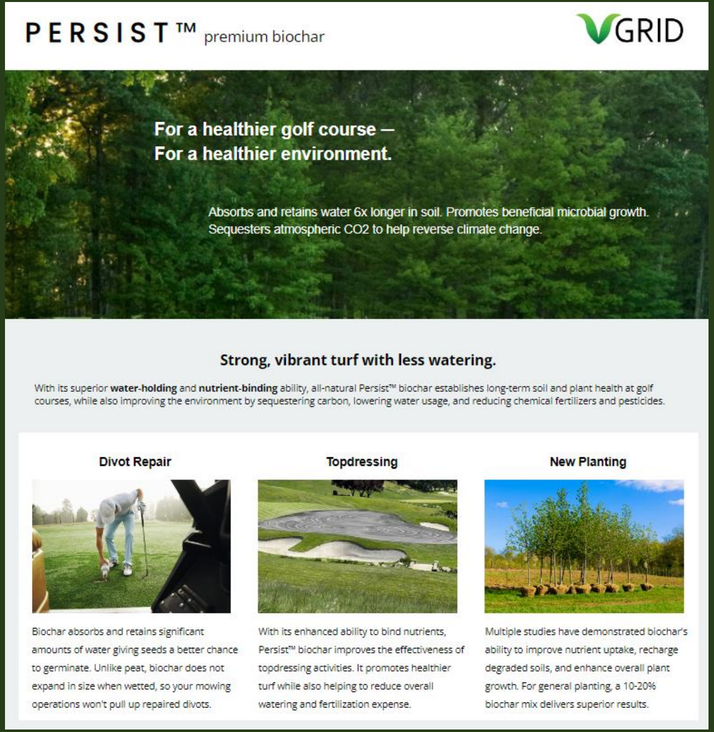

Japan

Golf Courses & Sporting Fields:

Water & Fertiliser Efficiency, Drought resilience

- Water savings a critical driver in some locations (cost, asset protection, drought resilience)
- **Significant cost savings in fertiliser use** ($$$), lower nitrate runoff
- Significant **reduction in fungicides**
- Colorado Case Study: user benefits **>$20,000 savings per tonne** of biochar used, with 30-65% water use reduction, improved turf and lower fertiliser use *(Biochar Users Report , Robb & Joseph 2019)*
- US golf courses trials over 2 years by Chargrow USA reported:
    - 5 Million gallon reduction in irrigation water
    - Fungicide reduction savings USD$30,000-40,000
    - 25% annual saving in fertilizer use
- USA & Europe to date, not well established yet in Australia
- *+….race courses, professional sporting fields etc..*

Duration of trial	6yrs of water savings
Area for trial	Golf course (~30 ha turf)
Area for analysis	Golf course
Biochar treatment	Single application
Biochar use	<91 t
Biochar cost/t	$2200/t
Finance option	None
Total cost of BC treatment	US$200,000
User net benefit	US$2,000,000
Benefit per tonne biochar	US$22,000
User ROI	10 x
Payback period	6 months



PERSIST ™ premium biochar

For a healthier golf course –
For a healthier environment.

Absorbs and retains water 6x longer in soil. Promotes beneficial microbial growth. Sequesters atmospheric CO2 to help reverse climate change.

Strong, vibrant turf with less watering.

With its superior **water-holding** and **nutrient-binding** ability, all-natural Persist™ biochar establishes long-term soil and plant health at golf courses, while also improving the environment by sequestering carbon, lowering water usage, and reducing chemical fertilizers and pesticides.

Divot Repair

Biochar absorbs and retains significant amounts of water giving seeds a better chance to germinate. Unlike peat, biochar does not expand in size when wetted, so your mowing operations won't pull up repaired divots.

Topdressing

With its enhanced ability to bind nutrients, Persist™ biochar improves the effectiveness of topdressing activities. It promotes healthier turf while also helping to reduce overall watering and fertilization expense.

New Planting

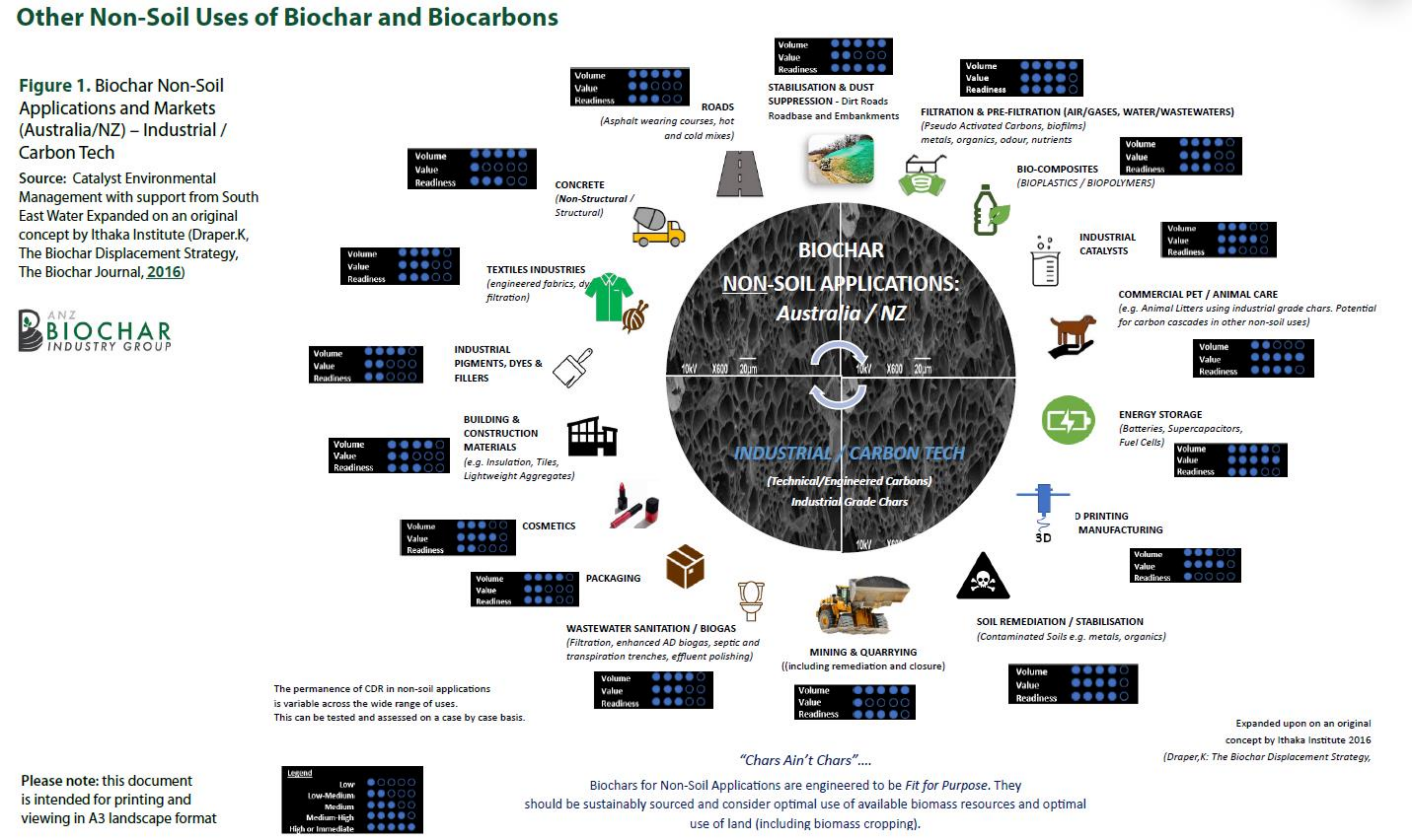
Multiple studies have demonstrated biochar's ability to improve nutrient uptake, recharge degraded soils, and enhance overall plant growth. For general planting, a 10-20% biochar mix delivers superior results.

Non- Soil / Industrial Applications for Biochar

Non-Soil Applications for biochar:

Industrial Grade Biochars
(or higher)

(ANZBIG Code of Practice)



Other Non-Soil Uses of Biochar and Biocarbons

Figure 1. Biochar Non-Soil Applications and Markets (Australia/NZ) – Industrial / Carbon Tech

Source: Catalyst Environmental Management with support from South East Water Expanded on an original concept by Ithaka Institute (Draper.K, The Biochar Displacement Strategy, The Biochar Journal, 2016)

BIOCHAR
NON-SOIL APPLICATIONS:
Australia / NZ

INDUSTRIAL / CARBON TECH
(Technical/Engineered Carbons)
Industrial Grade Chars

ROADS
(Asphalt wearing courses, hot and cold mixes)
Volume ●●●●●
Value ●●○○○
Readiness ●●●○○

STABILISATION & DUST SUPPRESSION - Dirt Roads
Roadbase and Embankments
Volume ●●●●●
Value ●●○○○
Readiness ●●●●●

FILTRATION & PRE-FILTRATION (AIR/GASES, WATER/WASTEWATERS)
(Pseudo Activated Carbons, biofilms)
metals, organics, odour, nutrients
Volume ●●●●●
Value ●●●●○
Readiness ●●●●○

BIO-COMPOSITES
(BIOPLASTICS / BIOPOLYMERS)
Volume ●●●●○
Value ●●●○○
Readiness ●●●○○

INDUSTRIAL CATALYSTS
Volume ●●●○○
Value ●●●●○
Readiness ●●○○○

COMMERCIAL PET / ANIMAL CARE
(e.g. Animal Litters using industrial grade chars. Potential for carbon cascades in other non-soil uses)
Volume ●●○○○
Value ●●●●●
Readiness ●●●●○

ENERGY STORAGE
(Batteries, Supercapacitors, Fuel Cells)
Volume ●●●●○
Value ●●●●●
Readiness ●●●○○

D PRINTING
MANUFACTURING
Volume ●●●○○
Value ●●●●○
Readiness ●○○○○

SOIL REMEDIATION / STABILISATION
(Contaminated Soils e.g. metals, organics)
Volume ●●●●○
Value ●●●●○
Readiness ●●●●○

MINING & QUARRYING
((including remediation and closure)
Volume ●●●●●
Value ●○○○○
Readiness ●●●●○

WASTEWATER SANITATION / BIOGAS
(Filtration, enhanced AD biogas, septic and transpiration trenches, effluent polishing)
Volume ●●●●○
Value ●●●○○
Readiness ●●●○○

PACKAGING
Volume ●●●●○
Value ●●○○○
Readiness ●●●○○

COSMETICS
Volume ●●●○○
Value ●●●●○
Readiness ●●○○○

BUILDING & CONSTRUCTION MATERIALS
(e.g. Insulation, Tiles, Lightweight Aggregates)
Volume ●●●●○
Value ●●○○○
Readiness ●●●○○

INDUSTRIAL PIGMENTS, DYES & FILLERS
Volume ●●●●○
Value ●●○○○
Readiness ●●○○○

TEXTILES INDUSTRIES
(engineered fabrics, dy
filtration)
Volume ●●●●○
Value ●●●○○
Readiness ●●●○○

CONCRETE
*(**Non-Structural** / Structural)*
Volume ●●●●●
Value ●○○○○
Readiness ●●●○○

The permanence of CDR in non-soil applications is variable across the wide range of uses.
This can be tested and assessed on a case by case basis.

Expanded upon on an original concept by Ithaka Institute 2016
(Draper,K: The Biochar Displacement Strategy,

Please note: this document is intended for printing and viewing in A3 landscape format

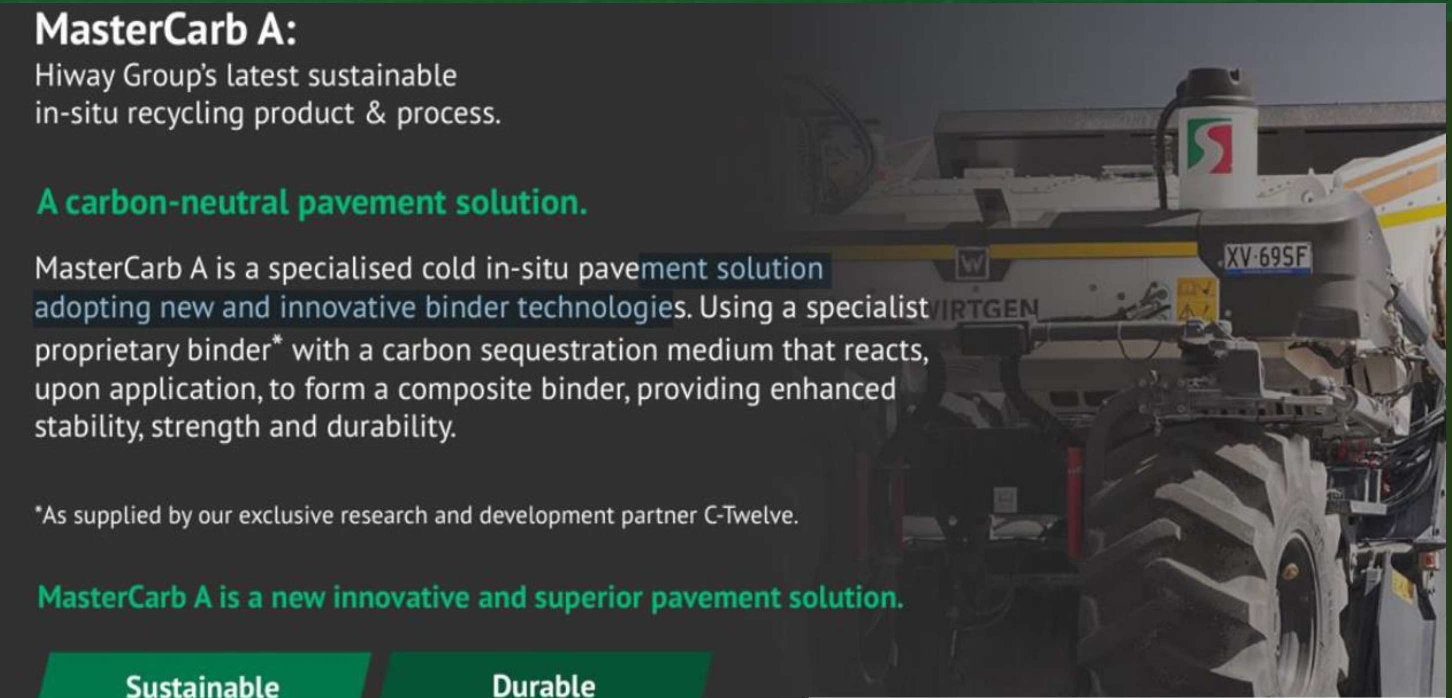
Legend
Low ●○○○○
Low-Medium ●●○○○
Medium ●●●○○
Medium-High ●●●●○
High or Immediate ●●●●●

"Chars Ain't Chars"….

Biochars for Non-Soil Applications are engineered to be *Fit for Purpose*. They should be sustainably sourced and consider optimal use of available biomass resources and optimal use of land (including biomass cropping).

Roads, Stabilisation, and Construction Materials

National Biochar Awards



MasterCarb A:

Hiway Group's latest sustainable
in-situ recycling product & process.

A carbon-neutral pavement solution.

MasterCarb A is a specialised cold in-situ pavement solution adopting new and innovative binder technologies. Using a specialist proprietary binder* with a carbon sequestration medium that reacts, upon application, to form a composite binder, providing enhanced stability, strength and durability.

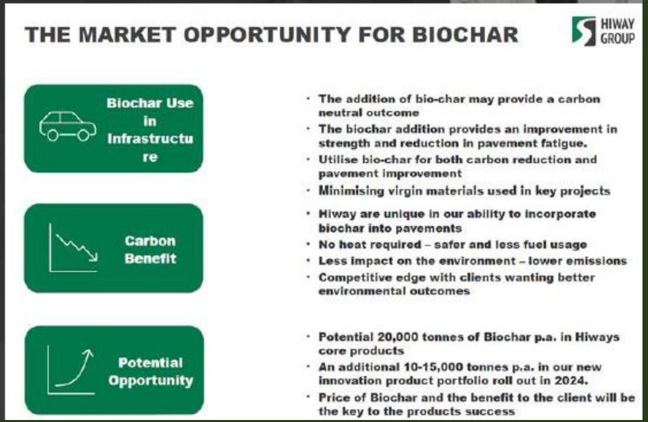
*As supplied by our exclusive research and development partner C-Twelve.

MasterCarb A is a new innovative and superior pavement solution.

- Sustainable
- Durable
- Resilient
- Rut Resistant

These attributes make MasterCarb A a superior option to conventional in-situ recycled cement/bitumen treatments and even dense-graded asphalt.

HIWAY GROUP



THE MARKET OPPORTUNITY FOR BIOCHAR

HIWAY GROUP

Biochar Use in Infrastructure

- The addition of bio-char may provide a carbon neutral outcome
- The biochar addition provides an improvement in strength and reduction in pavement fatigue.
- Utilise bio-char for both carbon reduction and pavement improvement
- Minimising virgin materials used in key projects

Carbon Benefit

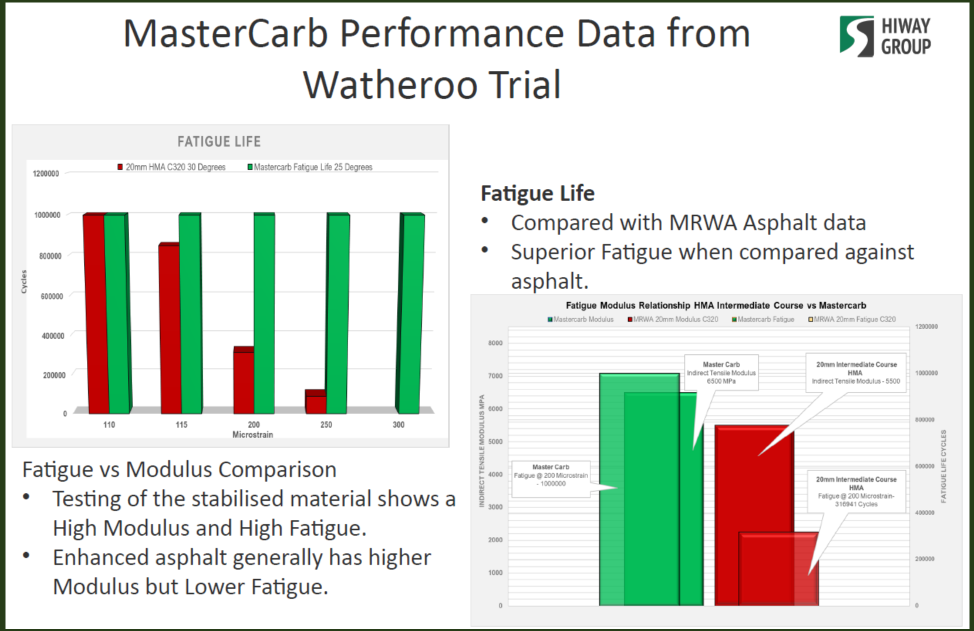
- Hiway are unique in our ability to incorporate biochar into pavements
- No heat required – safer and less fuel usage
- Less impact on the environment – lower emissions
- Competitive edge with clients wanting better environmental outcomes

Potential Opportunity

- Potential 20,000 tonnes of Biochar p.a. in Hiways core products
- An additional 10-15,000 tonnes p.a. in our new innovation product portfolio roll out in 2024.
- Price of Biochar and the benefit to the client will be the key to the products success

Outcomes

- More resilient pavement
- sustainably strengthened
- Minimised imported materials
- Maximum environmental benefits



MasterCarb Performance Data from Watheroo Trial

HIWAY GROUP

Fatigue Life

- Compared with MRWA Asphalt data
- Superior Fatigue when compared against asphalt.

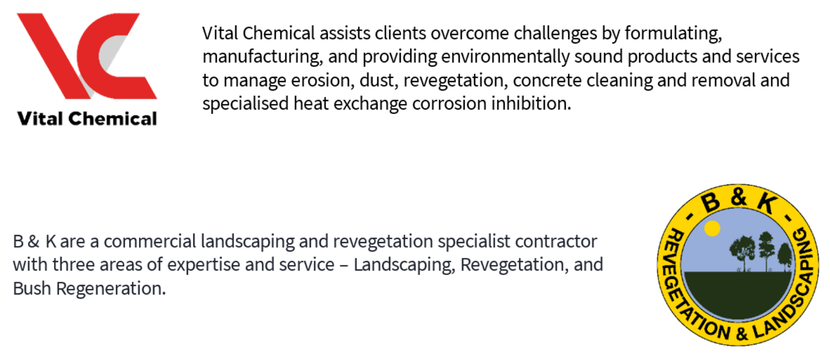
Fatigue vs Modulus Comparison

- Testing of the stabilised material shows a High Modulus and High Fatigue.
- Enhanced asphalt generally has higher Modulus but Lower Fatigue.

Large potential volumes of biochar for sub-base stabilization and surface pavements

Erosion Control, Revegetation & Rehabilitation

National Biochar Awards



Vital Chemical

Vital Chemical assists clients overcome challenges by formulating, manufacturing, and providing environmentally sound products and services to manage erosion, dust, revegetation, concrete cleaning and removal and specialised heat exchange corrosion inhibition.

B & K are a commercial landscaping and revegetation specialist contractor with three areas of expertise and service – Landscaping, Revegetation, and Bush Regeneration.

Vital Biochar Availability

Vital Biochar is available in three grades, 1-3mm, 4-7mm and 7-25mm within various pack sizes including 30L bags and bulk-a-bags.

Vital Chemical and B&K Revegetation & Landscaping are incorporating Vital Biochar at a dose rate of 10-20% within turnkey applications of VE Gro-Matt and VE Organic Matt.

- Highways & Roads, Landfills
- Mining & Quarrying
- Airports
- Urban Subdivisions

…All Large Soil Disturbance…..

Potential for Greener Concrete

3D CONCRETE PRINTING WITH BIOCHAR-CONCRETE @NUS

Concept:

Deployment of special biochar in 3D printing of concrete structures – for higher strength and durability

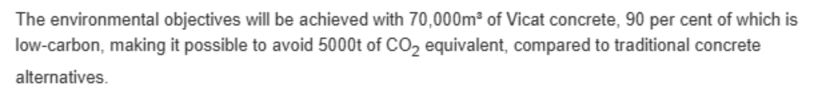
CARBON SEQUESTERING CONCRETE COMES TO OREGON

Watch the inspiring video about Solid Carbon's sustainable concrete pour at Remy Wines adaptive reuse production facility

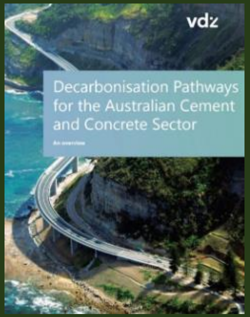
Vicat develops first carbon-zero binder

Vicat to construct housing and office project on site of Olympic village

By Peter Bell
13 August 2024

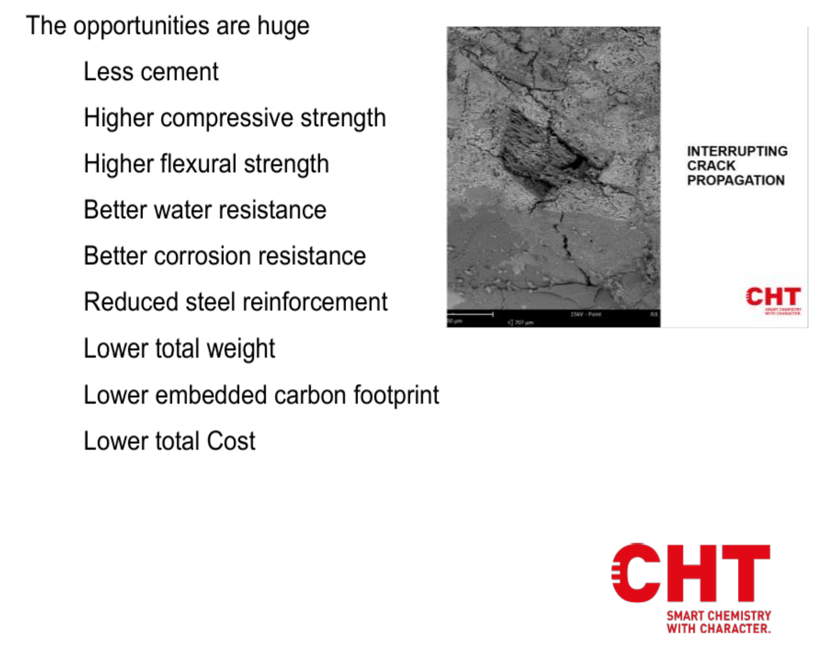


The environmental objectives will be achieved with 70,000m³ of Vicat concrete, 90 per cent of which is low-carbon, making it possible to avoid 5000t of CO_2 equivalent, compared to traditional concrete alternatives.



Decarbonisation Pathways for the Australian Cement and Concrete Sector

Environnement Du charbon vert pour sauver la planète ?



The opportunities are huge

- Less cement
- Higher compressive strength
- Higher flexural strength
- Better water resistance
- Better corrosion resistance
- Reduced steel reinforcement
- Lower total weight
- Lower embedded carbon footprint
- Lower total Cost

INTERRUPTING CRACK PROPAGATION

Other Non-Soil / Industrial Uses

Materials are the next frontier of decarbonization.

From 2050, materials will emit 28 gigatons of CO_2 annually, while Scope 3 emissions from materials are the hardest to abate.

“The next frontier of emissions reduction is materials. We make a carbon-negative filler that radically decarbonizes supply chains.”

Engineered Biochar as Supercapacitors

Below: Engineered biochar adsorbents for filtration *(Source: Stormwater Biochar USA)*

Audi AG unveils sustainable dealership model featuring carbon storing facade modules

Virus® Inks rethinks the black ink for textile screen printing creating a recycled product obtained from the disposal of organic waste.

23 FEBRUARY 2022 · COMPANY · SCREEN PRINTING · PRODUCTS ·

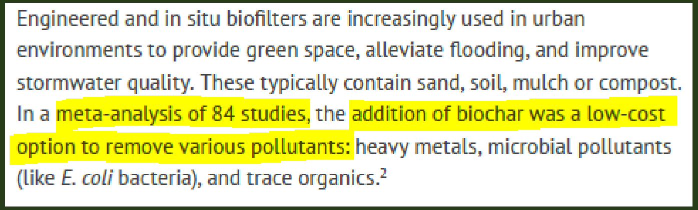
An organic sustainable alternative to fossil anodes in batteries

How we’re making batteries from trees: Lignode® by Stora Enso

Filtration/Pre-Filtration, Stormwater Management

- **Adsorbents** - **substitute for Activated Carbons** (e.g. GAC/PAC) conventionally made from coals, lignite or coconut shells.
- **Stormwater management** markets for biochar in USA are a focus. Bioswales, infiltration basins, engineered filtration systems, filter socks etc. Compliance driven (runoff / discharge water quality).
- Multiple synergies for wastewater treatment systems & networks
- **Customized chars** - Air (VOCs, H_2S), Odour, Water (incl. metals, PFAS, siloxanes, pesticides / herbicides, pharmaceuticals), Biological (E.Coli), biofilms nutrients.
- **Particle size**, SA, porosity, density, surface functionalities key
- **Targeted Activation, Pre/Post treatments – horses for courses**

- Global water filtration market USD$106B in 2021, forecast ~$175B by 2029 (TMR, 2022)
- Aust activated carbon market ~$60M/y (WPI,2020). Globally ~5.4M tpa market reportedly worth USD$4.7B/y


Engineered and in situ biofilters are increasingly used in urban environments to provide green space, alleviate flooding, and improve stormwater quality. These typically contain sand, soil, mulch or compost. In a meta-analysis of 84 studies, the addition of biochar was a low-cost option to remove various pollutants: heavy metals, microbial pollutants (like *E. coli* bacteria), and trace organics.[2]

Images: USBI 2022


Stormwater, Water and Remediation

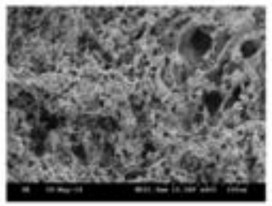
– includes stormwater cleanup, street and retention basin cleanup, disturbed soil stabilization, remediation and erosion control.

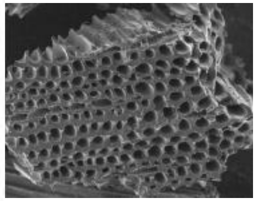
Feedstock sources: Woody biomass, crop residues, manures and litter

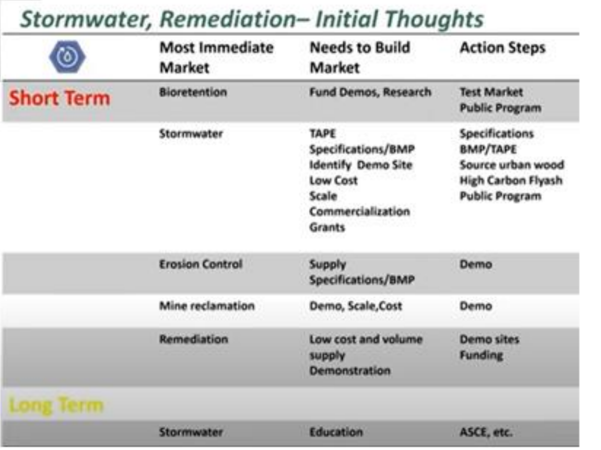
Biochar markets and uses: Bioretention facilities such as bioswales, green roofs, Public contracts roads, parks etc.), private industrial contracts (industrial parks, etc.), BMPs (Best Management Practices), site remediation, urban soils, filtration

Products: biochar, biochar mulch/hydromulch, biochar-compost socks, bulk (blower truck) application of biochar-bark/compost mix,

Packaging: 1 CF bags, 1-2 CY Bags, bulk in blower trucks.


BDB (Dr G.Pan 2018)


Hazelnut BC (USBI 2022)


Stormwater, Remediation– Initial Thoughts

	Most Immediate Market	Needs to Build Market	Action Steps
Short Term	Bioretention	Fund Demos, Research	Test Market Public Program
	Stormwater	TAPE Specifications/BMP Identify Demo Site Low Cost Scale Commercialization Grants	Specifications BMP/TAPE Source urban wood High Carbon Flyash Public Program
	Erosion Control	Supply Specifications/BMP	Demo
	Mine reclamation	Demo, Scale,Cost	Demo
	Remediation	Low cost and volume supply Demonstration	Demo sites Funding
Long Term			
	Stormwater	Education	ASCE, etc.

Below: Engineered biochar adsorbents for filtration *(Source: Stormwater Biochar USA)*


Stormwater vault. *Photo by Sarah Burch*


Photo by Sarah Burch


Stand alone filter system to filter metals from industrial sites. *Photo by Ryan Holmann, Stormwater Biochar; filters by BioLogical Carbon*

Oxidative / Combustion Uses for *'Biocarbons'**

* Termed *biocarbons* instead of *biochar* if no durable CDR

...displaces fossil fuels (ER), but no significant durable CDR benefit

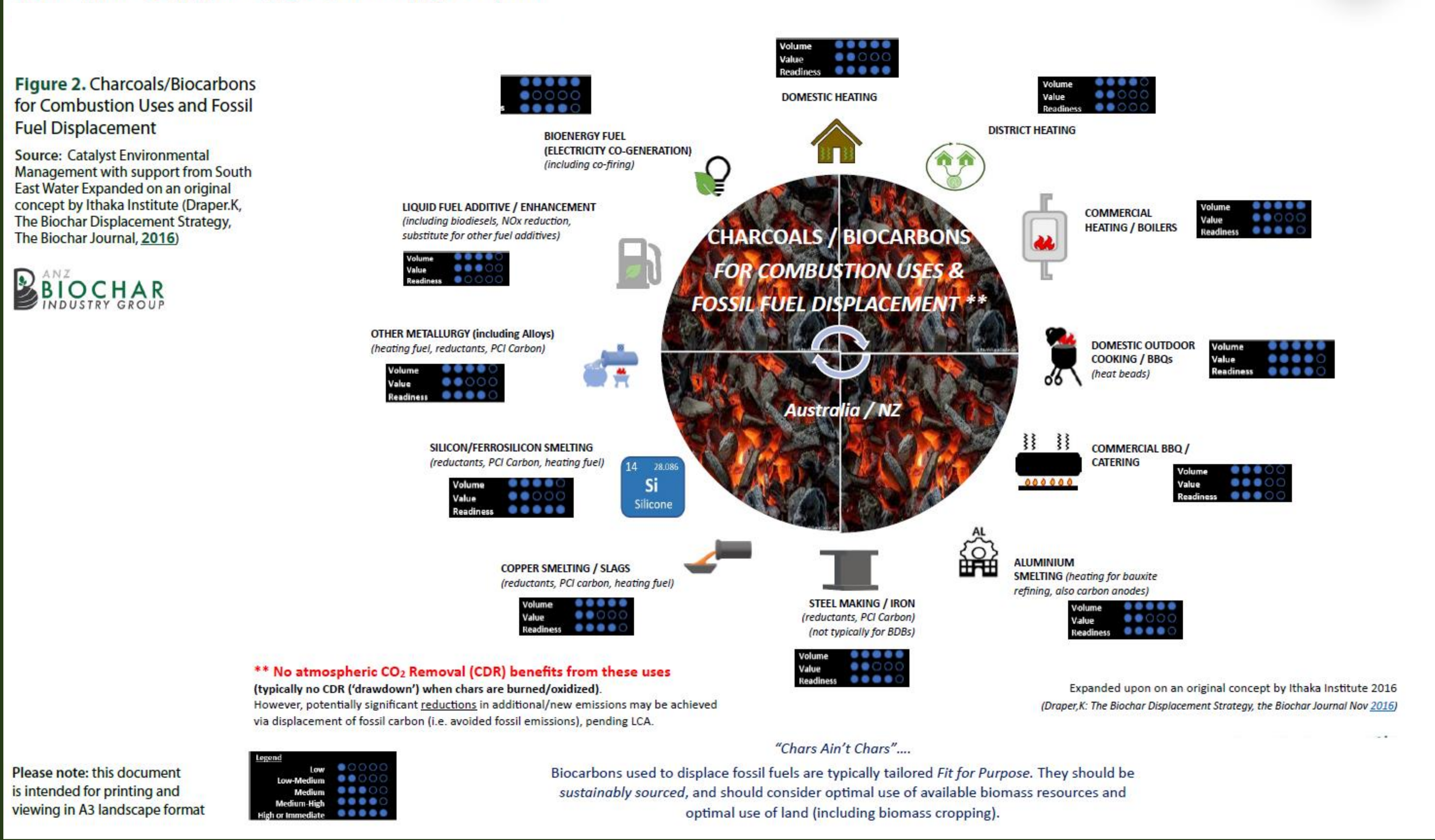


Figure 2. Charcoals/Biocarbons for Combustion Uses and Fossil Fuel Displacement

Source: Catalyst Environmental Management with support from South East Water Expanded on an original concept by Ithaka Institute (Draper.K, The Biochar Displacement Strategy, The Biochar Journal, 2016)

ANZ BIOCHAR INDUSTRY GROUP

CHARCOALS / BIOCARBONS *FOR COMBUSTION USES & FOSSIL FUEL DISPLACEMENT ***

Australia / NZ

DOMESTIC HEATING

Volume	●●●●●
Value	●●○○○
Readiness	●●●●●

DISTRICT HEATING

Volume	●●●●○
Value	●●○○○
Readiness	●●○○○

COMMERCIAL HEATING / BOILERS

Volume	●●●●●
Value	●●○○○
Readiness	●●●●○

DOMESTIC OUTDOOR COOKING / BBQs *(heat beads)*

Volume	●●●●●
Value	●●●●○
Readiness	●●●●○

COMMERCIAL BBQ / CATERING

Volume	●●●○○
Value	●●●○○
Readiness	●●●○○

ALUMINIUM SMELTING *(heating for bauxite refining, also carbon anodes)*

Volume	●●●●●
Value	●●○○○
Readiness	●●●●○

STEEL MAKING / IRON *(reductants, PCI Carbon) (not typically for BDBs)*

Volume	●●●●●
Value	●●○○○
Readiness	●●●●○

COPPER SMELTING / SLAGS *(reductants, PCI carbon, heating fuel)*

Volume	●●●●●
Value	●●○○○
Readiness	●●●●○

SILICON/FERROSILICON SMELTING *(reductants, PCI Carbon, heating fuel)*

Volume	●●●●○
Value	●●○○○
Readiness	●●●●●

OTHER METALLURGY (including Alloys) *(heating fuel, reductants, PCI Carbon)*

Volume	●●●●○
Value	●●○○○
Readiness	●●●●○

LIQUID FUEL ADDITIVE / ENHANCEMENT *(including biodiesels, NOx reduction, substitute for other fuel additives)*

Volume	●●●●○
Value	●●●○○
Readiness	●○○○○

BIOENERGY FUEL (ELECTRICITY CO-GENERATION) *(including co-firing)*

	●●●●●
	●○○○○
s	●●●●○

**** No atmospheric CO_2 Removal (CDR) benefits from these uses**
(typically no CDR ('drawdown') when chars are burned/oxidized).
However, potentially significant reductions in additional/new emissions may be achieved via displacement of fossil carbon (i.e. avoided fossil emissions), pending LCA.

Expanded upon on an original concept by Ithaka Institute 2016
(Draper,K: The Biochar Displacement Strategy, the Biochar Journal Nov 2016)

Please note: this document is intended for printing and viewing in A3 landscape format

Legend	
Low	●○○○○
Low-Medium	●●○○○
Medium	●●●○○
Medium-High	●●●●○
High or Immediate	●●●●●

"Chars Ain't Chars"....

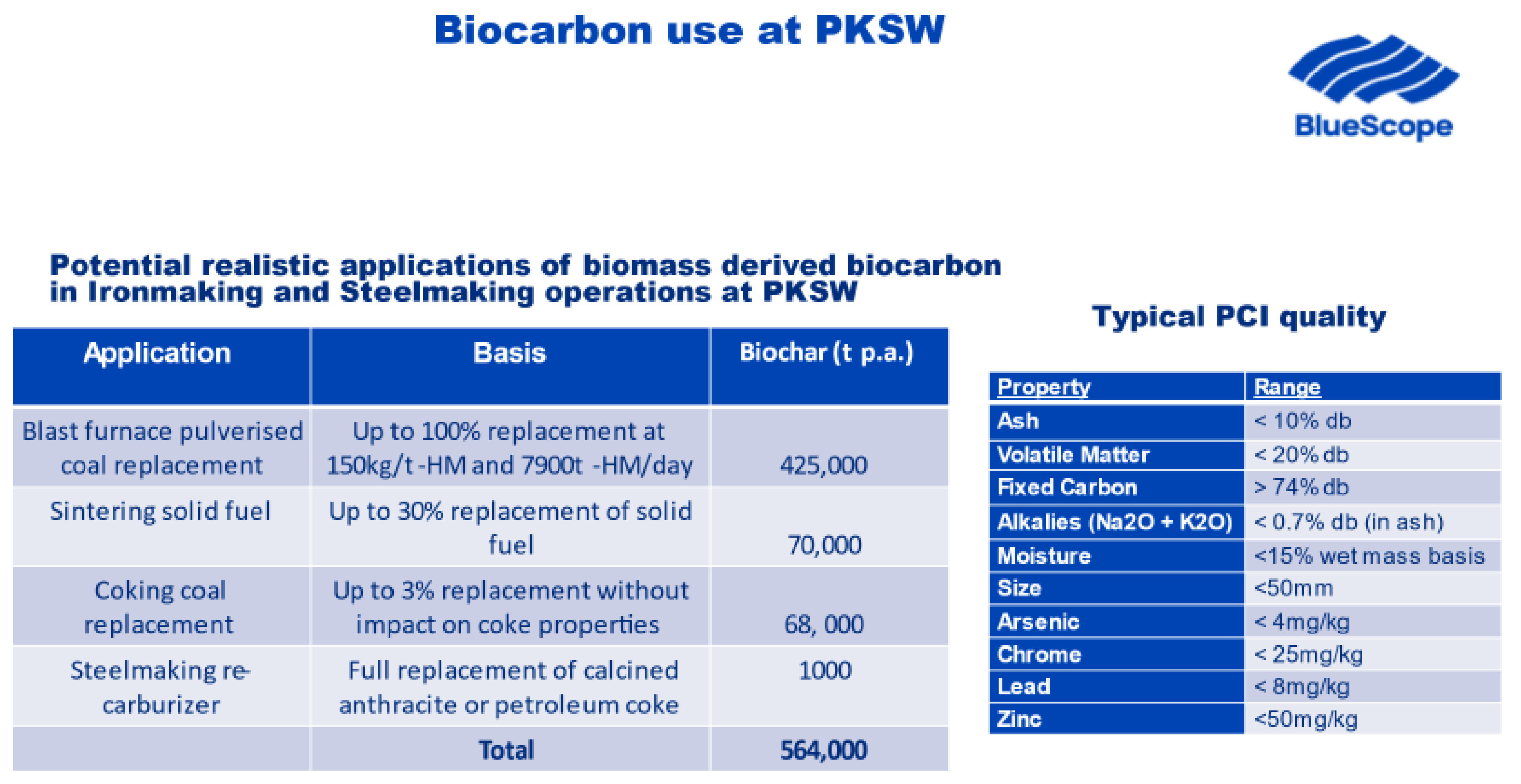
Biocarbons used to displace fossil fuels are typically tailored *Fit for Purpose*. They should be *sustainably sourced*, and should consider optimal use of available biomass resources and optimal use of land (including biomass cropping).

ANZ BIOCHAR INDUSTRY GROUP

Decarbonising Steel & Metallurgy- 'Biocarbons'

BlueScope is Looking to Biochar Tech to 'Future-Proof' Steel

- Biogenic chars as a green substitute for PCI carbon (Pulverised Coal Injection), coking coal, sintering carbon & recarburizer in steel and other metallurgical processing.
- Blast Furnace (BF), Basic Oxygen Furnace (BOF) and Electric Arc Furnaces (EAF)
- Also potential for *Biohydrogen* for new Direct Reduced Iron (DRI) systems
- Bluescope 1000t biocarbon trial (ARENA project) at PKSW was highly successful.
- Bluescope now seeking >>100,000 tpa of biocarbon (up to 400ktpa) , that's 5-10x current total national production in Australia
- Potential synergies with Industrial Grade biocarbons with appropriate properties (incl low target metals)



Biocarbon use at PKSW

BlueScope

Potential realistic applications of biomass derived biocarbon in Ironmaking and Steelmaking operations at PKSW

Application	Basis	Biochar (t p.a.)
Blast furnace pulverised coal replacement	Up to 100% replacement at 150kg/t -HM and 7900t -HM/day	425,000
Sintering solid fuel	Up to 30% replacement of solid fuel	70,000
Coking coal replacement	Up to 3% replacement without impact on coke properties	68, 000
Steelmaking re-carburizer	Full replacement of calcined anthracite or petroleum coke	1000
	Total	564,000

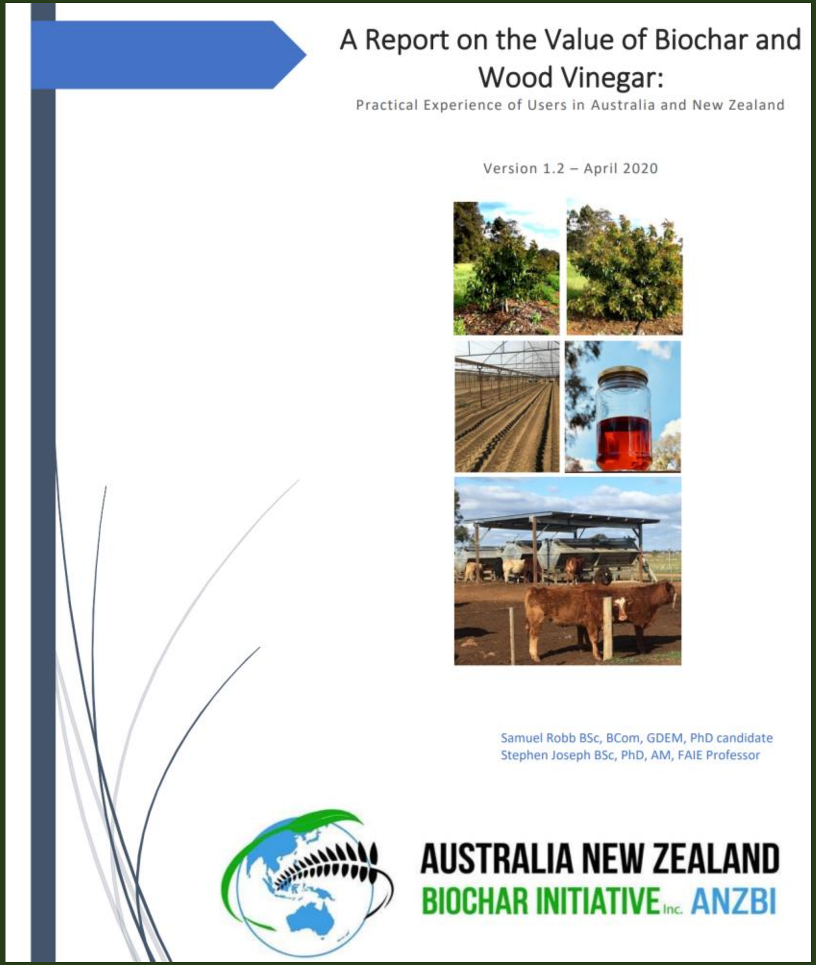
Typical PCI quality

Property	Range
Ash	< 10% db
Volatile Matter	< 20% db
Fixed Carbon	> 74% db
Alkalies (Na2O + K2O)	< 0.7% db (in ash)
Moisture	<15% wet mass basis
Size	<50mm
Arsenic	< 4mg/kg
Chrome	< 25mg/kg
Lead	< 8mg/kg
Zinc	<50mg/kg

BioCarbon Is Transforming Steelmaking: The Role Of Biochar In Decarbonising Steel

The Business Case for Biochar:

Biochar Users Report (Case Studies / Net User Benefit $$ per tonne BC)



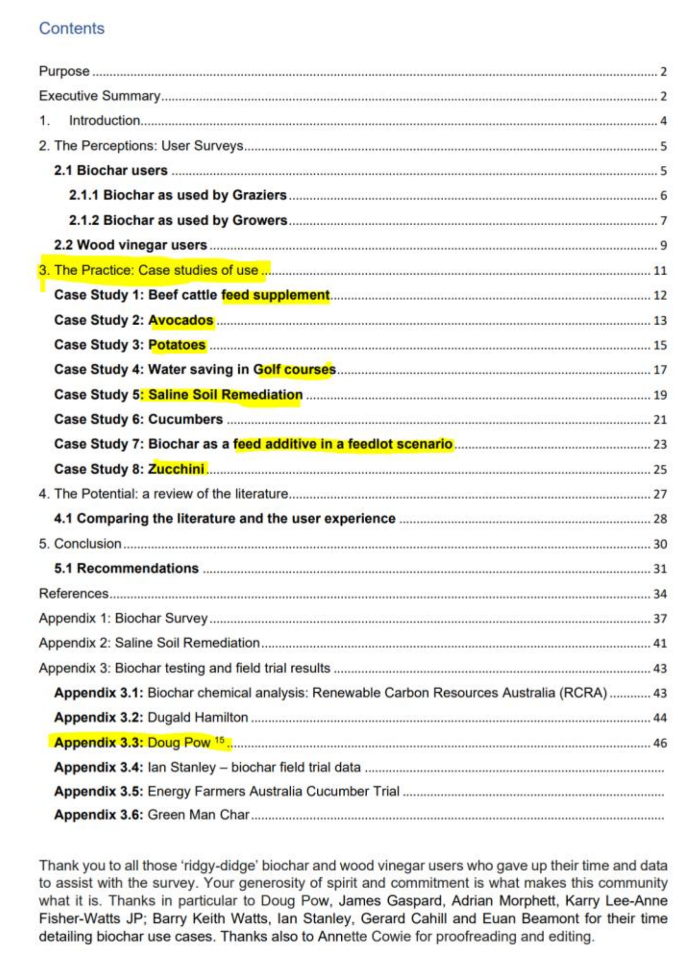
A Report on the Value of Biochar and Wood Vinegar:

Practical Experience of Users in Australia and New Zealand

Version 1.2 – April 2020

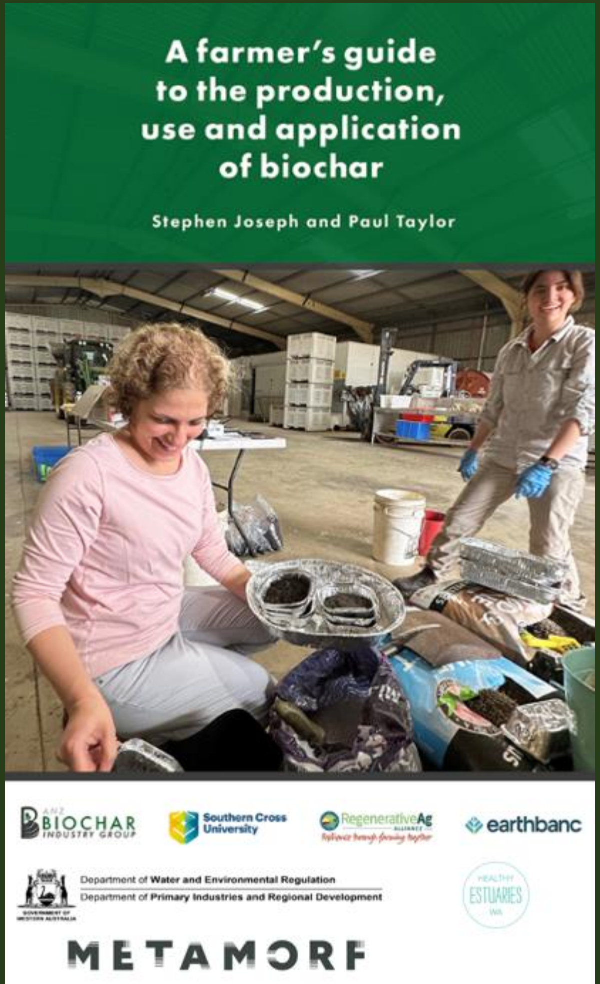
Samuel Robb BSc, BCom, GDEM, PhD candidate
Stephen Joseph BSc, PhD, AM, FAIE Professor

AUSTRALIA NEW ZEALAND
BIOCHAR INITIATIVE Inc. ANZBI



Contents

Thank you to all those 'ridgy-didge' biochar and wood vinegar users who gave up their time and data to assist with the survey. Your generosity of spirit and commitment is what makes this community what it is. Thanks in particular to Doug Pow, James Gaspard, Adrian Morphett, Karry Lee-Anne Fisher-Watts JP; Barry Keith Watts, Ian Stanley, Gerard Cahill and Euan Beamont for their time detailing biochar use cases. Thanks also to Annette Cowie for proofreading and editing.



A farmer's guide to the production, use and application of biochar

Stephen Joseph and Paul Taylor

BIOCHAR INDUSTRY GROUP
Southern Cross University
RegenerativeAg Alliance
earthbanc
Department of Water and Environmental Regulation
Department of Primary Industries and Regional Development
HEALTHY ESTUARIES WA
METAMORF

https://anzbig.org/resources/

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www.anzbig.org/farmers-guide-2024/

Australian Biochar Industry 2030 Roadmap


Download for free at www.anzbig.org

Version 1.1
July 2023

Australian Biochar Industry

2030
ROADMAP

ANZ BIOCHAR INDUSTRY GROUP

- **10 Priority Themes**
- **10 Key Initiatives**


ANZBIG's Roadmap will inform the community and illuminate the case for new policies from all Australian governments.

"The Australian Biochar Industry Roadmap is a call to action. It demonstrates and explains the huge potential for growth of biochar production and use in Australia.
Making this potential real will deliver major economic, environmental and social benefits….

…..I look forward to the biochar industry making a major contribution to the
emergence of Australia as a Superpower of the net zero world economy. "

Ross Garnaut AC
ANZBIG Patron, May 2023

- **Over 50 Million tonnes/yr** of commercially accessible sustainable biomass residues are **currently being burned, landfilled or under-utilized**.
- **Potential to reduce Australia's net carbon emissions by 10-15%, provide up to 20,000 permanent jobs** (particularly in regional and rural areas), improve soil health and agricultural productivity and return degraded lands to a higher value.

Alignment with Multiple Government Policy Objectives

Carbon plays a central role in so many areas of our economy and in government policy objectives. The production and use of biochar can contribute positively toward multiple policy objectives concurrently, including (but not limited to) the following Commonwealth objectives below. State and Local government objectives are similarly assisted. Supporting the biochar industry to contribute to these important areas can leverage government investment toward achieving the targeted outcomes.

Climate Change / Climate Resilience / Net Zero

- Net Zero Plan (Net Zero by 2050). Biochar can provide significant contributions toward all six sectoral plans to achieve net zero:
  - Agriculture and Land; Built Environment ; Electricity and Energy
  - Transport & Infrastructure ; Industry ; Resources.
- 43% Emissions Reduction by 2030 (Climate Change Act, 2022, Paris Agreement)
- National Climate Resilience and Adaptation Strategy 2021 – 2025
- Net Zero in Government Operations Strategy
  - Australian Public Service Net Zero Emissions by 2030
  - *Partnership in the (international) Net Zero Government Initiative*
- National Strategy for Disaster Resilience
- Australian Disaster Preparedness Framework / Sendai Framework
- Australian Carbon Credit Unit (ACCU) Scheme – a cross industry working group including ANZBIG has lodged an EOI for a new method for Biochar Carbon Dioxide Removal.
- Bid to Co-Host COP31 (2026) - Enhancement of action supporting COP31 with the Pacific
- National Science and Research Priorities

Circular Economy / Sustainability / Waste

- National Wate Policy (NWP) (2018) and NWP Action Plan (2019)
  - 50% reduction in organic waste to landfill by 2030 (Target 6)
  - Recover 80% of all waste by 2030 (Target 3)
  - Significantly increase the use of recycled content by governments and industry (Target 5)
- National Circular Economy Framework
- Circular Economy Ministerial Advisory Group (CEMAG) – Priority action areas:
  - Built Environment and Net Zero
  - Innovation and Skills
  - Food, Resources and Regions
  - Circular Design & Consumption of Products
- 2030 Agenda for Sustainable Development and the Sustainable Development Goals
- Australian Sustainability Reporting Standards – (draft) Disclosure of Climate Related Financial Information (EDSR1).
- Remade in Australia – circular carbon that concurrently also provides climate action.
  - Environmentally Sustainable Procurement Policy & Reporting Framework
- National Science and Research Priorities

Agriculture (Production / Climate Resilience)

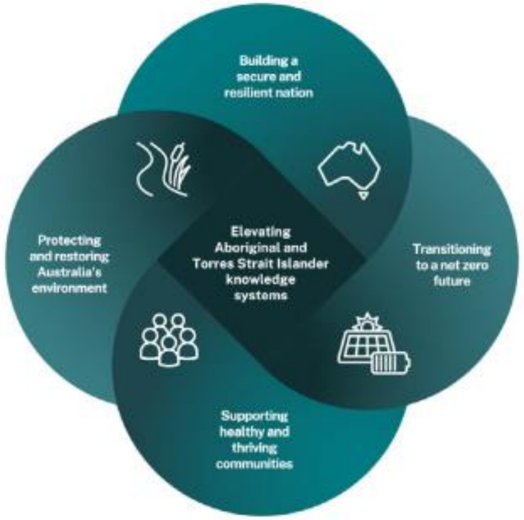
- Delivering AG2030: Australian Agricultures vision for a $100 Billion Industry by 2030
  - Production (output/yield); Biosecurity; Land Stewardship
  - Water and infrastructure; Innovation & Research
  - Human Capital – rural and regional skills and employment
  - $100B in agricultural production by 2030
  - Halve Food Waste by 2030
  - 20% increase in water use efficiency for irrigated agriculture by 2030
  - Produce more from existing land - maintain Australia's total farmed land at 2018 levels
- National Soil Strategy (2023-2028) and National Soil Action Plan
- Carbon Farming Outreach Program
- Australian government commitments to the UN Convention to Combat Desertification (UNCCD)
- Climate Resilient Agricultural Development and Food Security Program
- National Science and Research Priorities

Water Efficiency / Drought Resilience

- National Water Initiative;
- Resilient Rivers Water Infrastructure Program – 450GL target for water for the environment, including urban, industrial, mining, and on/off farm water efficiency.
- Murray Darling Basin Plan (efficiency measures), Sustainable Rural Water Use and infrastructure Program, & Restoring our Rivers Act (2023) – *"increase ways to deliver water for the environment to reduce reliance on buybacks"*
- First Nations Water Policy (access to water)
- National Science and Research Priorities

Energy / Storage / Fuels (Including Batteries / Hydrogen / Biofuels

- Powering Australia
  - commitments to support agriculture and carbon farming, transport and energy
  - 43% emissions reduction by 2030; Net Zero by 2050; 82% renewable electricity target



The overlapping nature of the National Science and Research Priorities.

- Powering the Regions Fund – decarbonising existing industries, developing new clean industries, Carbon Capture, Utilisation and Storage (CCUS), and driving ACCUs.
- National Battery Strategy
- First Nations Clean Energy Strategy
- Australia's Future Gas Strategy
- National Hydrogen Strategy
  - Hydrogen Headstart Program - Biohydrogen
- Capacity Investment Scheme to encourage investment in renewables and storage
- Towards a Renewable Energy Superpower Report
- National Energy Transformation Partnership with the states
- Unlocking Australia's Low Carbon Liquid Fuels (LCLF) Opportunity (Future Made in Australia)
- National Science and Research Priorities

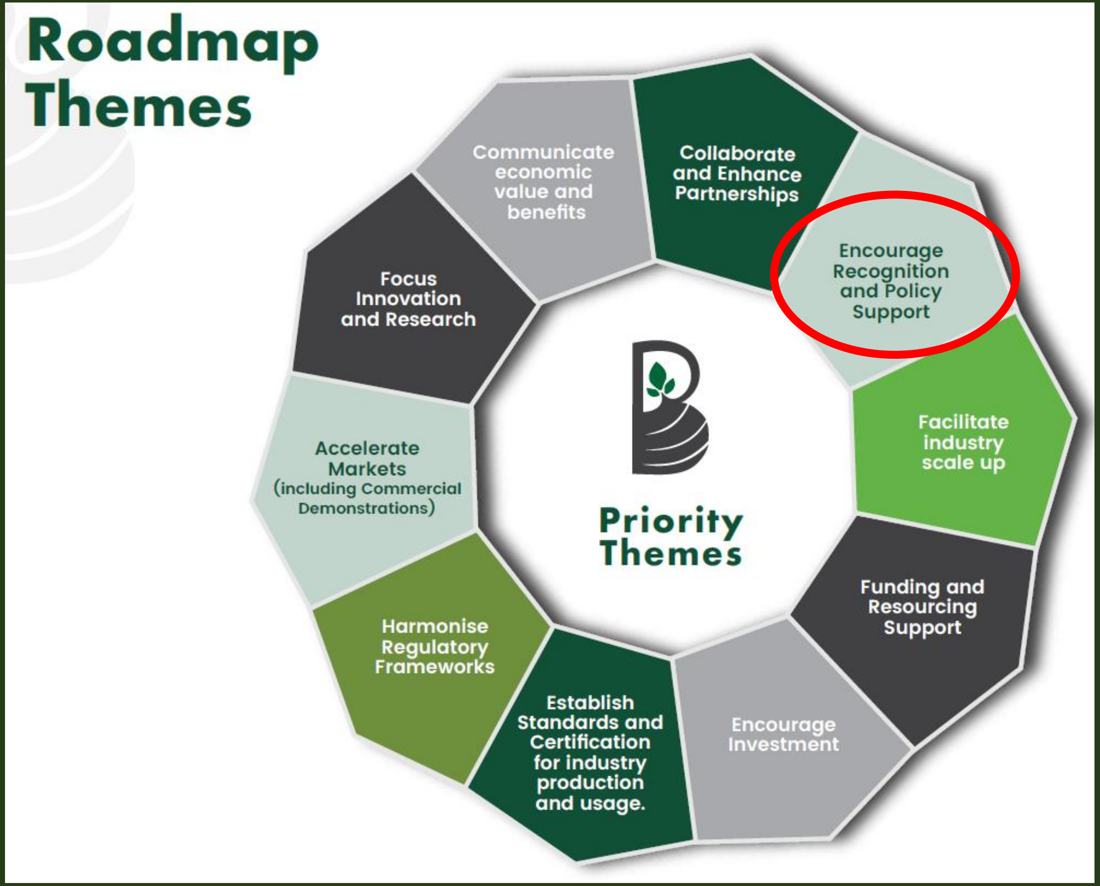
Employment, Economic and Regional Resilience

- Future Made in Australia Agenda – enhancement of both major streams of the agenda: *Net Zero Transformation Stream*, and *Economic Resilience and Security Stream*.
- National Reconstruction Fund – priority areas for *Renewables & Low Emission Technologies, Agriculture, Forestry and Fisheries, Transport, Resources and Advanced Manufacturing.*
- Regional Investment Framework for strong and sustainable regions
- Boosting Supply Chain Resilience Initiative
- National Freight and Supply Chain Strategy
- Indo-Pacific Carbon Offsets Scheme - $100M support to climate action in the region
- Australian government programs and partnerships for International Climate Action
- Climate Resilient Agricultural Development and Food Security Program
- National Science and Research Priorities

Carbon plays a central role in so many areas of our economy and in government policy objectives.

ANZ BIOCHAR INDUSTRY GROUP

Australian Biochar Industry 2030 Roadmap



Roadmap Themes

Priority Themes

Communicate economic value and benefits

Collaborate and Enhance Partnerships

Encourage Recognition and Policy Support

Facilitate industry scale up

Funding and Resourcing Support

Encourage Investment

Establish Standards and Certification for industry production and usage.

Harmonise Regulatory Frameworks

Accelerate Markets (including Commercial Demonstrations)

Focus Innovation and Research

- Over **50 Million** t/yr of commercially accessible sustainable biomass residues are currently being burned, landfilled or under-utilized.
- Potential to reduce Australia's net carbon emissions by 10-15%, provide up to 20,000 permanent jobs (especially in regional and rural areas), improve soil health and agricultural productivity and return degraded lands to a higher value.

- **10 Priority Themes**
- **10 Key Initiatives**

Figure 3. Australian biochar can contribute to many of the world's climate and sustainability objectives, including many of the UN Sustainable Development Goals (SDGs).

ROADMAP INITIATIVES

Ten (10) key Initiatives contributing directly to multiple priority themes:

1. Launch the Australian Biochar Industry Roadmap and fund Scale-Up Plan
2. **Improve Stakeholder Awareness and Education** of Biochar Uses and Benefits
3. **Integrate and Optimise Industry and Regulatory Frameworks**
4. **Support Biochar Commercial Demonstration Trials**
5. Leverage Carbon Emission Reduction and CO_2 Removal Opportunities
6. Encourage Beneficial Use of Waste Biomass
7. Drive Beneficiation and Increased Value of Biochar and Co-Products
8. **Safeguard Responsible Consumption and Production of Biochar**
9. Support Government, Utility, and Industry Procurement Practices
10. Drive Export of Australian Biochar Innovation Internationally

ANZ BIOCHAR INDUSTRY GROUP

Roadmap Working Groups

- Resourcing
- Education and communications
- Policy and Regulations
- Innovation
- Standards and Certification
- Supply and Market Development
- Governance and risk and auditing

With support to enable roadmap initiatives, the industry could easily grow to a multi-billion-dollar industry by 2030, generating green jobs whilst critically drawing down carbon to combat climate change

Initiative 4

Support biochar commercial demonstrations and trials

Context: *The results of commercial demonstrations and trials can increase confidence in the industry and open avenues for potential investment and scale up. Such activities can assist in the development of regulation, certification schemes, and application, or manufacture methodologies.*

Action 4.1 Demonstrate broad acre soil applications at a significant scale

Objective: Increase economic confidence in large-scale agricultural applications of biochar within Australia

Key Performance Indicators

- Outline criteria and seek expressions of interest for broad acre demonstration partners
- Establishment and documentation of broad acre trials and demonstrations

Action 4.2 Demonstrations to regenerate marginal /degraded land, including mine site rehabilitation

Objective: Increase economic confidence in the use of biochar as a remediation technology within Australia

Key Performance Indicators

- Outline criteria and seek expressions of interest from rehabilitation / remediation demonstration partners
- Establishment and documentation of rehabilitation / remediation demonstrations

Action 4.3 Support commercial-scale demonstration projects for non-broad acre soil applications of biochar

Objective: Increase economic confidence in many other soil applications of biochar, and to showcase the diversity of Australian soil-based industries with their potential to benefit from biochar and co-products

Key Performance Indicators

- Outline criteria and seek expressions of interest for potential demonstration partners
- Establishment and documentation of demonstration and trial projects

Action 4.4 Support commercial scale demonstration projects for non-soil industrial applications

Objective: Increase economic confidence in non-soil based applications of biochar and showcase the diversity of Australian industries with potential to benefit from biochar and co-products

Key Performance Indicators

- Outline criteria and seek expressions of interest for potential demonstration partners
- Establishment of demonstration projects

Action 4.5 Support co-pyrolysis demonstrations of plant biomass, biosolids, forestry residues, agricultural residues and food organics / garden organics (FOGO).

Objective: Increase economic confidence in utilising co-pyrolysis as a waste to value/resource management strategy to benefit from biochar and co-products

Key Performance Indicators

- Outline criteria and seek expressions of interest for potential demonstration partners
- Establishment of co-pyrolysis demonstration projects

Initiative 3

Integrate and optimise industry and regulatory frameworks

Context: *Establishing the reliability of the production and use of biochar and co-products across all uses can accelerate the growth of the Australian Biochar Industry. The relatively novel nature of large-scale manufacturing and use of biochar and biochar co-products means existing regulations require review and revision as the industry grows and the range of potential biochar applications increases.*

Action 3.1 Identify existing barriers and potential regulatory approaches to harmonise and facilitate safe and sustainable operation across the Australian biochar industry

Objective: Optimise the regulatory and procedural framework for biochar to maximise benefits and reduce risks

Key Performance Indicators

- Conduct mapping exercise with stakeholders and partners which identifies regulatory and procedural barriers, and identifies remedies or alternative strategies

Action 3.2 Develop sustainability assessment guidance, including higher order use, for biochar feedstocks and end-use applications

Objective: Ensure feedstocks for biochar production are suitable for use

Key Performance Indicators

- Development of biochar feedstock sustainability assessment guidelines to integrate with the Biochar Code of Practice

Action 3.3 Consult with federal and state government departments and key stakeholders to address biochar barriers and market uncertainties

Objective: Engage with key stakeholders to ensure barriers are reduced and incentives increased to scale up sustainable biochar production and use

Key Performance Indicators

- Identification and consistent engagement with key government and non-government stakeholders

Initiative 9

Support government utility and industry procurement practices

Context: *Australian governments: federal, state, territory and local, have enormous influence on procurement through tendering and procurement practices. Governments are also custodians of many biomass resources and collection services. The benefits of biochar for circular economy and climate change mitigation should be encouraged in suitable opportunities and existing barriers removed.*

Action 9.1 Identify and promote replacement or for fossil derived carbon

Objective: Ensure that biochar is considered for suitable public and industrial applications and as a substitute or replacement for fossil fuel derived carbon

Key Performance Indicators

- Number of alternate uses and new applications for biochar
- Total biochar use in different industry and government applications
- Number of policy initiatives implemented by governments to support industry scale up such as incentives, grants and levies

Action 9.2 Establish biochar specifications for key procurement and use opportunities and identify carbon sequestration potential of these applications

Objective: Establish biochar specifications for key procurement and use opportunities and identify their carbon sequestration potential

Key Performance Indicators

- Development of biochar specifications and guidelines for use in different public and industrial use

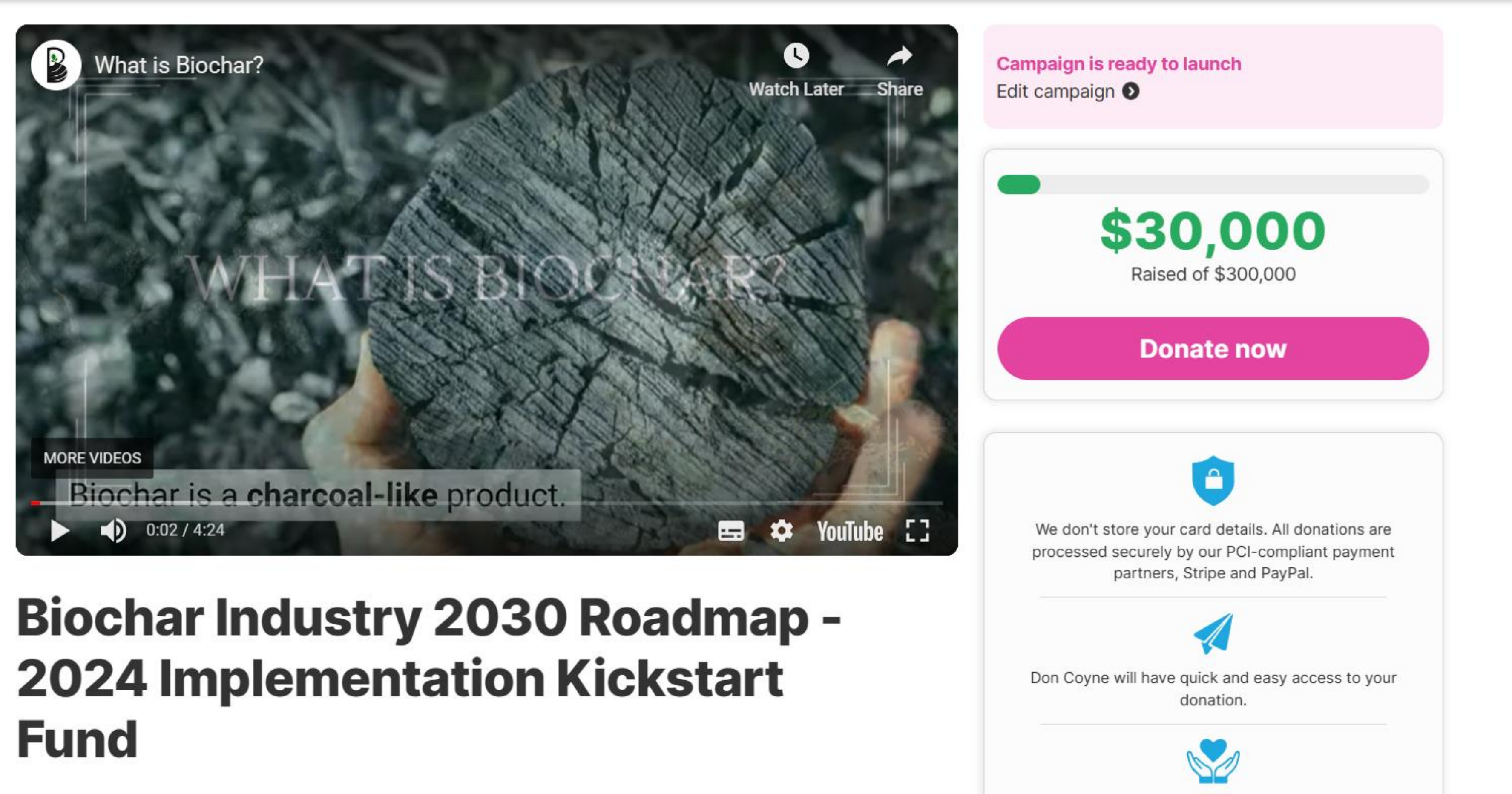
Action 9.3 Develop biochar case studies and a biochar reference library for government and industry

Objective: Ensure that government agencies and industry are aware of how best to use biochar in a range of applications

Key Performance Indicators

- Biochar case studies generated per year
- Use of case studies and library visits measured by downloads and site visits

Biochar Industry 2030 Roadmap - 2024 Implementation Kickstart Fund



Biochar is a charcoal-like product.

Biochar Industry 2030 Roadmap - 2024 Implementation Kickstart Fund

Campaign is ready to launch

$30,000

Raised of $300,000

We don't store your card details. All donations are processed securely by our PCI-compliant payment partners, Stripe and PayPal.

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The development of the Australian Biochar Industry 2030 Roadmap has been supported by many organisations. We acknowledge and thank them for their support.

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- SYNDICATION GROUP
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Thank you. Questions?

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www.anzbig.org

SEATA

Deconstructing the world's problems to create carbon negative solutions

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CATALYST Environmental Management

- Biochar Bioenergy Regulatory Assistance
- EIA / Approvals / Licencing
- Biochar Applications Market Opportunity Assessment
- Biochar Carbon Emissions Reduction / CDR Assessment
- GIS and Environmental Data Management
- EMS / Environmental Management Plans
- Environmental Reporting
- Waste & Water Management

> *" If your house is on fire, you don't tell the fireman to just let it simmer, you want to put the fire **out** ..we need carbon **removal** that actually **keeps the carbon out afterwards** "*
>
> *Albert Bates*