Current State of Biochar as a Carbon Dioxide Removal Solution

Status Report for Mission Innovation Countries and Beyond

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Key Messages for Decision Makers

Biochar is ready for deployment now

- Commercial technologies are already operating globally and delivering measurable carbon removal.

Biochar delivers multiple benefits beyond carbon removal

- Biochar combines carbon sequestration with waste management, soil improvement, and material applications.

The main barrier is not technology, but market demand

- Limited offtake and application pathways currently constrain large-scale deployment.

Sustainable biomass sourcing is critical

- Climate benefits depend on using waste and residual biomass and avoiding land-use conflicts.

Governments can accelerate deployment by

- Enabling waste-to-biochar pathways
- Supporting MRV and certification frameworks
- Creating demand through procurement incentives
- Clarifying regulation.

Executive Summary

Biochar is often described as an emerging climate and agricultural solution, yet its conceptual roots extend far into the past. The earliest and most well-known example—*terra preta de índio* in the Amazon Basin—demonstrates how intentional additions of charred organic material transformed highly weathered tropical soils into some of the most fertile and carbon-rich soils on Earth. These anthropogenic soils, created centuries ago, have retained elevated carbon content, nutrient availability, and biological activity long after their formation, offering early evidence of biochar's durability and multifunctional benefits.

For much of modern history, this knowledge remained localized and poorly understood. It was only in the late 20th and early 21st centuries that scientific inquiry began to reconnect these ancient practices with contemporary challenges in soil degradation, waste management, and climate change. Early research focused on explaining *why* terra preta soils persisted and *how* charred biomass influenced soil chemistry, structure, and microbial systems. This research laid the foundation for the modern concept of biochar: a deliberately produced, carbon-rich material designed for controlled application and measurable outcomes.

Over the past two decades, biochar has transitioned from a niche research topic into a globally recognized solution. Advances in thermochemical conversion technologies, combined with increasing pressure to address climate change, soil degradation, and industrial emissions, have expanded biochar's relevance well beyond its historical agricultural framing. What was once viewed primarily as a soil amendment is now increasingly understood as a material capable of supporting agriculture, enabling carbon removal, improving environmental performance, and substituting fossil-based carbon in industrial systems.

Biochar research, production, and deployment are being pursued across every major region of the world. Governments, academic institutions, farmers, industrial actors, and climate finance mechanisms are all contributing to a rapidly evolving understanding of what biochar can do, where it delivers the greatest value, and how it can be scaled responsibly. This growing interest reflects a broader shift in sustainability thinking: toward solutions that are multifunctional, locally adaptable, and capable of delivering both climate and economic benefits.

This report provides a global status overview of biochar's development, including feedstock availability, production methods, application trends, carbon dioxide removal (CDR) relevance, R&D trajectories, and country-level market and policy evolution.

Feedstocks for Biochar

Biomass is abundant globally, and many forms of organic waste—from forestry residues and agricultural by-products to sewage sludge, manure, and municipal solid waste—can serve as feedstocks for biochar, provided they contain sufficient organic carbon. For true carbon dioxide removal (CDR), the carbon must be biogenic, originating from photosynthesis, ensuring that pyrolysis converts short-cycle carbon into stable, long-cycle pyrogenic carbon.

Sustainable feedstock sourcing is essential for net climate benefits. Biochar delivers carbon removal only when the alternative fate of the biomass would lead to greater emissions, such as decomposition (potentially methane-forming) or open burning. Using waste or surplus biomass also addresses waste-management challenges while lowering production costs. However, sourcing must avoid competition with land for food production or ecosystems, as land-use change can negate climate benefits. Forestry residues and agricultural residues represent major sustainable feedstock pools globally, though quality and properties of resulting biochar vary significantly with lignocellulosic composition. Wood-based feedstocks typically produce high-carbon, low-ash biochars, while agricultural residues often yield - biochars richer in nutrients but with higher ash contents.

More complex waste streams can also be used, such as sewage sludge, digestates, and animal wastes. Pyrolysis can reduce contaminants—including organic pollutants and microplastics—while recovering carbon and nutrients, though metals remain in the biochar and must be carefully managed depending on the intended application. Municipal waste feedstocks require compliance with waste regulations and end-of-waste criteria, particularly concerning pollutants. Emerging feedstocks such as bioenergy crops, invasive species, and aquatic biomass (e.g., microalgae, seaweed) show potential but require careful evaluation of environmental trade-offs, salt content, and contamination risks.

Overall, we highlight that sustainable biochar systems must integrate responsible feedstock sourcing, appropriate pyrolysis technology, and well-matched end-use applications to maximize climate and environmental benefits.

Production and Properties of Biochar

Biochar is produced by thermochemical conversion of biomass, with feedstock composition and process severity—particularly temperature and residence time—being the dominant factors controlling product yield and properties. Among thermochemical routes, pyrolysis is the most relevant for targeted biochar production, generating a solid carbon-rich material alongside condensable liquids and permanent gases. Under slow heating conditions, pyrolysis promotes carbonization, yielding biochar with low volatile content, increased aromaticity, and enhanced chemical stability. Gasification can also be used as a biochar production option, but biochar is typically formed as a secondary product alongside synthesis gas, with generally lower solid yields and higher ash contents compared to pyrolysis-derived biochars.

Biochar yield and properties show a strong temperature dependence. Increasing production temperature leads to progressive devolatilization, removal of oxygen- and hydrogen-containing functional groups, and rearrangement of the carbon matrix into more condensed aromatic structures. As a result, biochar yield decreases, while carbon content, fixed carbon fraction, pH, surface area, and long-term stability increase. This creates a fundamental trade-off between maximizing biochar mass yield and maximizing carbon sequestration efficiency and material durability.

Feedstock composition plays a central role in determining biochar quality. Woody biomass typically yields biochars with high carbon content and low ash, whereas feedstocks rich in inorganic matter, such as manures or sewage sludge, produce chars with high ash content and lower relative carbon content. In such cases, high mass yields primarily reflect mineral retention rather than effective carbon storage, and careful interpretation of yields and carbon contents is required.

Key biochar properties relevant for large-scale application include mass yield, proximate and elemental composition, atomic H/C and O/C ratios as indicators of carbonization, surface area and pore structure governing sorption and water retention, and pH influencing interactions with soils and other materials. Higher-temperature biochars generally provide greater chemical stability and adsorption capacity, while lower-temperature biochars retain more functional groups that may be advantageous for nutrient retention and biological interactions. Interpreting these properties consistently requires careful consideration of analytical reference states (e.g. dry versus dry ash-free), especially when comparing biochars from different feedstocks or production conditions. Furthermore, what is considered a biochar of high quality is also strongly dependent on the intended application, as no single set of properties is optimal for all uses.

Overview of Biochar Applications

Biochar has multiple applications, ranging from agricultural soil quality improvement to sorbent for contaminants, filler in concrete and asphalt, replacement for coke in metallurgical processes and many more.

Application	Suitable feedstocks	Carbon removal effect	Other benefits	Trade-offs/challenges	Ref.
Carbon Conserving					
Agricultural soil amendment	Lignocellulosic, animal-based (expect marine biomass), sewage sludge (dependent on metal content)	Direct carbon storage in soil, potential for decreased negative priming (increased natural organic matter stabilization)	Increased water and nutrient retention potential for higher crop yields (increased plant growth), improved soil aggregation, potential for reduction of N2O-emissions, high yield chars produced moderate temperature can be used	Clean biochars needed, low solubility of phosphorus accumulated in biochar, priming effect negligible or positive in poor fertility, alkaline, temperate soil	[1–3]
Sorbent stabilization of contaminated soils	Lignocellulosic, sewage	Direct carbon storage in soil, potential for decreased or negative priming (increased natural organic matter), offset if fossil activated carbon is replaced	Strong binding of contaminants that reduces leaching and bioavailability	High temperature and hence low yield biochars typically needed, issues related to leaching from metal enriched biochars not fully explored	[136–138]
Sorbent stabilization of contaminated sediments	Lignocellulosic	Direct carbon storage in sediment, offset if fossil activated carbon is replaced	Strong binding of contaminants that reduces leaching and bioavailability	High temperature and hence low yield biochars typically needed, potential negative effects on bentic fauna, potential release of arsenic and antimony in multi-contaminated sediments	[138–141]
Additive in concrete	Potentially all	Direct carbon storage in concrete by biochar addition, and potential for improvement of carbonation process which can sequester CO_2 released from concrete	Potential for reducing environmental footprint of concrete through lower emissions from transport extraction of natural materials if lightweight biochar partially replaces conventional fillers and aggregates	Can lead to reduced strength of concrete	[41,64,137,138]
Additive in asphalt	Potentially all	Direct carbon storage in asphalt by biochar addition	Can improve temperature susceptibility, rutting resistance, and ageing effects of asphalt. Can also contribute to waste management by making use of low quality waste biochars.	Unknown (low TRL)	[40,64,140]
Additive in cement stabilization of peat and quick clay	Potentially all	Direct carbon storage in cement stabilized clay or peat. Can reduce amount of cement used in the process	Biochar improves solidification strength in peat soil stabilization	Some biochars can reduce solidification strength in clays - more research needed to understand effects	[140,141]

Application	Suitable feedstocks	Carbon storage effect	Other benefits	Trade-offs/challenges	Ref.
Potentially carbon conserving					
Additive to composting	Lignocellulosic	Depends on final disposal of compost - could be direct storage if applied to soil	Accelerates composting process by catalyzing microbial processes and improves compost effect as a fertilizer/soil amendment	None	[133,135]
Feed additive	Lignocellulosic	Potential reduction of methane from animals, further effects depend on final disposal of manure - could be direct storage if applied to soil	Improved animal growth performance, blood profiles, egg yield, ability to resist pathogens, and removal of toxins. Soil amendment benefits expected if biochar-containing manure is applied to soils	Clean biochars needed; reduced availability of minerals and vitamins due to strong binding	[135,142]
Additive to anaerobic digestion	Potentially all	Depends on final disposal of digestate - could result in direct carbon storage if used as a soil amendment	Increases methane generation and microbial resilience through catalysing anaerobic digestion and hence the process potential for replacing fossil gas with biogas	Mechanisms not fully understood, input cost vs. generated benefits unclear at present	[143,144]
Sorbents for water treatment	Lignocellulosic, sewage sludge, microalgae	Depends on final disposal - could be none if incinerated or direct storage if landfilled, offset if fossil activated carbon is replaced	Allows for value chain generation combining products from wastewater treatment with generation of sorbent for the same treatment process	Issues related to release of metals and nutrients present in biochar sorbents not thoroughly explored	[4–7]
Electrode material	Lignocellulosic	Replaces fossil based electrode materials. Further biogenic CDR effect depends on final disposal of spent electrode material.	Lower overall environmental footprint. Reduced costs.	Somewhat lower effect than traditional materials	[142,143]
Electrochemical treatment of contaminated groundwater	Animal-based, sewage sludge, modified lignocellulosic	Potentially direct carbon storage in aquifers (expected, but not explored)	Treatment of contaminated groundwater where biochar act as a catalyst for electrochemical reactions that decompose organic contaminants	Relatively small amounts needed, hence low BCS effect expected	[144–146]
Carbon converting					
Metallurgy	Lignocellulosic (wood)	Replacement for fossil carbon, which leads to net reduction in emissions	Could contribute to lower NO_x and SO_x emissions from electric arc furnaces in steelmaking	Sensitive to impurities requires high calorific (mainly clean wood biochars). Large demand which can usurp other more environmentally beneficial	[8,9]
Fuel	Potentially all	Replacement for fossil carbon, which leads to net reduction in emissions	Can improve local air quality through reduced emissions when replacing coal in cooking fires.	Best effect from biochars with high calorific value (wood biochars). Binders needed to produce briquettes which result in higher emissions. Can usurp other more environmentally beneficially applications	[147,148]

Biochar and Carbon Dioxide Removal (CDR)

Biochar has emerged as one of the most deployment-ready and scalable carbon dioxide removal (CDR) methods, owing to its production via mature pyrolysis technologies, its capacity for long-term carbon storage, and its ability to integrate into existing agricultural and industrial systems. Since the IPCC formally recognized biochar/pyrolysis as a Negative Emission Technology in 2018, biochar has become the dominant source of durable carbon removal credits in voluntary carbon markets, with rapidly growing global production and adoption.

Biochar delivers carbon removal by converting biogenic carbon—originally fixed by plants—into stable aromatic carbon structures that resist decomposition for centuries to millennia. The durability of stored carbon is quantified as the permanent carbon fraction (F_{perm}), reflecting the proportion expected to remain over 100, 200, or 1000 years. Biochar systems also produce additional mitigation benefits: (1) co-production of heat and power that can substitute fossil energy, (2) significant reductions in N_2O emissions when applied to soils, and (3) avoidance of CH_4 emissions when waste biomass is pyrolyzed instead of left to decompose.

Biochar’s exceptional permanence stems from two pyrolysis-driven chemical transformation phases. Aromatization (≈350–500 °C) forms stable aromatic rings, sharply reducing hydrogen and oxygen content. Condensation (≥500 °C) fuses these rings into polyaromatic sheets, producing highly recalcitrant carbon. Environmental factors—such as mineral interactions, physical protection within soils, and encapsulation in long-lived materials (e.g., concrete, asphalt)—further enhance longevity. Together, these mechanisms explain the persistence of charred carbon in soils for thousands of years.

Direct long-term measurements are impossible, so stability assessments rely on isotope-labelled incubation experiments combined with modelling. To enable practical and affordable carbon accounting, chemical proxies calibrated to these incubation datasets are widely used. The most common is the H/C_{org} ratio, which reliably indicates degree of carbonization and predicts long-term persistence. Newer analytical approaches, such as Random Reflectance (Ro), suggest that the most condensed high-temperature biochars may persist far longer than current conservative estimates indicate—potentially millennial scale. Priority research should validate these longer residence times in soil.

Multiple registries now incorporate permanence into crediting frameworks. Most use conservative, proxy-based methods grounded in H/C_{org} and production temperature, often assigning 100- or 200-year durability for crediting. Some (e.g., Isometric) provide 1000 year permanence labels for biochars meeting reflectance-based inertinite criteria. Standards increasingly differentiate between soil application and “inert” uses such as building materials, where decomposition is negligible over relevant timeframes.

Beyond storing biochar carbon itself, soil application can increase overall soil carbon stocks through improved soil structure, moisture retention, microbial processes, and enhanced plant productivity. These indirect mechanisms can meaningfully contribute to long-term carbon removal but remain difficult to quantify consistently and are not yet fully integrated into certification frameworks.

Biochar offers a rare combination of technological readiness, verifiable long--term carbon storage, and co-benefits for soil, waste management, and industry. Conservative accounting indicates residence times of centuries, while emerging evidence suggests even higher stability for well-carbonized biochars. With growing regulatory recognition (e.g., EU CRCF) and rapid market uptake, biochar is positioned to play a central role in near-term, scalable CDR deployment—provided that robust MRV, sustainable feedstock sourcing, and continued research on permanence are maintained.

Agricultural Applications

Biochar plays multiple roles in agriculture, primarily as a soil amendment, fertilizer enhancer or biostimulant, sorbent and filter material, and feed additive. Early biochar initiatives focused on converting agricultural residues into stable carbon-rich material that improves soil and supports carbon dioxide removal. Its effects on soils and crops stem from increased cation exchange capacity, higher pH and base saturation, greater plant-available water, improved nutrient retention, and interactions with soil biology, including enhanced mycorrhizal functioning. Yield responses vary widely, with changes ranging from decreases to substantial increases, and with tropical, weathered soils showing the strongest positive responses.

Biochar’s benefits are most pronounced in degraded or acidic soils under warm climates. Effective applications typically require high doses—often 20–60 tonnes per hectare—although targeted placement strategies like root-zone application with minimum tillage can reduce the required quantities to around 4 tonnes per hectare. In temperate regions, agronomic benefits tend to be modest, creating limited economic incentives where biochar prices remain high.

When used in fertilizers or biostimulant formulations, biochar supports crops at lower application rates, often around 1 tonne per hectare per year. Combining biochar with mineral or organic fertilizers frequently yields better crop performance than fertilizers alone, though mechanisms remain unclear. Promising developments include biochar-clay composites, biochar-urea blends, and biochar-compost products, with emerging evidence that such combinations enhance nutrient cycling and reduce nitrous oxide emissions.

Biochar also performs well as a sorbent and filter medium due to its capacity to adsorb gases and dissolved pollutants. Although its effectiveness for reducing nutrient leaching from soils is limited, it functions well in waste-management settings. In composting and biogas systems, biochar helps reduce emissions, retain nitrogen, moderate inhibitory compounds, and improve methane yields. Engineered biochar filters can capture ammonia emissions from livestock operations, generating nitrogen-enriched materials that can later be applied as fertilizers.

As a feed additive, biochar improves animal health and productivity, enhances gut function, reduces disease vulnerability, and lowers methane emissions in ruminants. Typical feed inclusion rates are low (around 0.3%), making this one of the most economically viable agricultural uses today.

Overall, the agricultural potential of biochar is significant, but most applications requiring large quantities remain economically challenging. Soil-focused uses are most promising on nutrient-poor, acidic and/or arid tropical soils. Integrating carbon credits, improving product performance, and reducing costs will be key to realizing biochar's full role in agricultural sustainability and climate mitigation.

Industrial Applications

Biochar can be used in several large-scale industrial applications beyond soils, particularly in construction materials and metallurgical processes, where it can either store biogenic carbon in long-lived products or replace fossil carbon inputs.

In concrete, small additions of biochar can partially replace cement, directly reducing the carbon footprint while embedding stable carbon in durable infrastructure. At low dosages, biochar can improve compressive strength, durability, and resistance to cracking by acting as a microfiller and internal curing agent. Its porous structure promotes hydration, reduces permeability, and mitigates shrinkage, with benefits arising mainly from physical rather than chemical interactions with the cement matrix. Concrete is relatively tolerant to variability in biochar quality, making it a promising large-volume application for carbon storage in the built environment.

In asphalt, biochar can be incorporated into the bitumen binder or mineral fraction, introducing biogenic carbon into pavements that remain in service for decades. Moderate biochar additions generally increase stiffness, improve high-temperature performance, and slow oxidative and UV aging of the binder. However, higher loadings may reduce low-temperature flexibility or lead to phase separation, requiring careful optimization. Given the very large production volumes of asphalt, even limited substitution offers significant potential for long-term carbon storage and fossil carbon displacement.

Biochar can also replace fossil carbon carriers in metallurgical applications, where carbon is required for reduction reactions, energy supply, carburization, and slag control. In this case, the carbon is typically oxidized and released as CO_2, so the substitution alone does not constitute carbon dioxide removal. However, when combined with carbon capture and storage at large point sources, the use of biogenic carbon can contribute to net-negative emissions. Metallurgical use places strict requirements on biochar quality, generally limiting suitable feedstocks to woody biomass and often requiring further processing to ensure consistent physical and chemical properties.

Research & Development

Research and development activities on biochar have expanded rapidly in recent years, reflecting its growing relevance as a multifunctional climate solution. Current efforts focus on improving process efficiency, tailoring biochar properties for specific applications, and understanding long-term environmental performance. Key research needs include the validation of carbon permanence, optimization of biochar use in soils and industrial materials, and the development of safe and scalable production systems. In parallel, there is a growing need for standardized methods, robust monitoring, and high-quality data to support certification schemes and regulatory frameworks. Continued R&D will be essential to enable large-scale, sustainable deployment of biochar across agricultural and industrial sectors.

Status of biochar in Mission Innovation Countries

The approaches to biochar's adoption into national practices, policies and economies vary greatly across the globe, driven and shaped by a number of factors. These factors include, but are not limited to, biochar's intended use, feedstock price and availability, technology readiness, valorisation of heat, energy and syngas, and the national policy landscape.

In developed regions, extensive research and development and deployment of pyrolysis and gasification technologies are creating opportunity for scaled production of biochar. In regions such as continental Europe (EU, Norway, UK, Switzerland) biochar supply for the carbon removals market has been a major driver of production and innovation, while dependent on the valorisation of renewable poly-generative products to make biochar production competitive and economical. In regions such as North America (Canada & USA), Australia and New Zealand, biomass availability and demand for new biomass valorisation, particularly for residual and waste biomass markets, are driving opportunity for large scale production for both domestic and foreign markets. Countries including China, Japan, India and Saudi Arabia demonstrate pathways for improving local carbon and agricultural residue management through biochar, all taking tailored approaches to local issues in maximizing value and effectiveness. In the global south, biochar is offering an opportunity to improve conditions of agricultural soils and cooking fuels, while coordinated efforts to realize carbon removals through biochar are providing income streams for farmers and families. In unison, biomass availability is creating fast implementation of various projects in the global south, producing large biochar volumes dedicated to carbon removal applications.

Globally, offtake and application of biochar remains the largest hurdle to scale production to its potential. Beyond policy commitments to recognize and integrate biochar as a carbon removal technology, application markets must develop to realize the climate service biochar provides. The development of biochar marketplaces, both regionally and internationally, is still to be seen.

A very positive takeaway from the research is biochar's recognition as a CDR method, as biochar CDR projects can be found across the globe, demonstrating the effectiveness of the voluntary carbon market (VCM). Many countries were found to be progressing in adopting biochar in their regulatory carbon markets, demonstrating foundational commitments to biochar production in the future, with numerous states having sector-based regulations already adopted for both biochar production and application.

Terms and Abbreviations

The terminology surrounding biochar is not standardized and a variety of terms are used across different sectors and applications. Recognizing this fragmentation, several initiatives are currently ongoing working to harmonize terminology and develop clearer, more consistent definitions for biochar. So as to not pre-empt the respective outcomes and for simplicity, the term **biochar** is used universally in this report regardless of specific application or classification.

Abbreviations

AAFC	Agriculture and Agri-Food Canada
ACCU	Australia’s Carbon Credit Unit Scheme
ANZBIG	Australia and New Zealand Biochar Industry Group
BCE	Biochar Europe
BCR	Biochar Carbon Removal
BCS	Biogenic carbon sequestration
BECCS	Bioenergy with carbon capture and storage
BPCA	Benzene polycarboxylic acid
C	Carbon
CA	Conservation agriculture
CCC	Climate Change Committee
CCS	Carbon Capture and Storage
CCTS	Carbon Credit Trading Scheme
CDR	Carbon dioxide removal
CE	Conformité Européenne
CEC	Cation exchange capacity
CER	Clean Energy Regulatory
CRCF	Carbon Removal Certification Framework
CRIA	Carbon Removal India Alliance
CSA	Climate-smart agriculture
DAC	Direct air capture
DESNZ	Department of Energy Security and Net Zero
DfT	Department for Transport
EBC	European Biochar Certificate
EEA	European Economic Area
EOW	End-of-waste
ETS	Emissions Trading System
EU	European Union
GDP	Gross domestic product
GGR	Greenhouse gas removal
GGR-D	Greenhouse Gas Removal Demonstrators
GHG	Greenhouse gas emissions

HCl	Hydrochloric acid
IEA	International Energy Agency
IMC	Intermunicipal cooperation
IPCC	Intergovernmental Panel on Climate Change
JBA	Japan Biochar Association
JBC	Japan Biochar Consortium
JBRC	Japan Biochar Research Center
LCA	Life cycle assessment
MRV	Monitoring, reporting, and verification
MSW	Municipal solid waste
NEDO	New Energy and Industrial Technology Development Organization
NET	Negative emission technology
NMR	Nuclear magnetic resonance
NMVOC	Non-methane volatile organic carbon
NSW	New South Wales
ORC	Organic Rankine Cycle
PAH	Polycyclic aromatic hydrocarbon
PFAS	Per- and polyfluorinated alkylsubstances
R&D	Research and Development
R0	Random Incident Light Reflectance
REACH	Registration, evaluation, authorization and restriction of chemicals
RU	Ritsumeikan University
SBRG	Saudi Biochar Research Group
SDI	Steel Dynamics Inc.
SEER	Strategic Environmental & Energy Resources
SGI	Saudi Green Initiative
SPF	Strategic Priorities Fund
SRUC	Scotland’s Rural College
SV2030	Saudi Vision 2030
TLUD	Top-lit Up-draft
TSP	Total suspended particulate matter
UKRI	UK Research and Innovation
UN	United Nations
US	United States
USBC	United States Biochar Coalition
USBI	United States Biochar Initiative
USDA	United States Department of Agriculture
VCM	Voluntary carbon market
WWF	World Wildlife Fund
WWTP	Wastewater treatment plant

1. Introduction

Biochar is often described as an emerging climate and agricultural solution, yet its conceptual roots extend far into the past. The earliest and most well-known example—*terra preta de índio* in the Amazon Basin—demonstrates how intentional additions of charred organic material transformed highly weathered tropical soils into some of the most fertile and carbon-rich soils on Earth. These anthropogenic soils, created centuries ago, have retained elevated carbon content, nutrient availability, and biological activity long after their formation, offering early evidence of biochar's durability and multifunctional benefits.

For much of modern history, this knowledge remained localized and poorly understood. It was only in the late 20th and early 21st centuries that scientific inquiry began to reconnect these ancient practices with contemporary challenges in soil degradation, waste management, and climate change. Early research focused on explaining *why* terra preta soils persisted and *how* charred biomass influenced soil chemistry, structure, and microbial systems. This research laid the foundation for the modern concept of biochar: a deliberately produced, carbon-rich material designed for controlled application and measurable outcomes.

Over the past two decades, biochar has transitioned from a niche research topic into a globally recognized solution space. Advances in thermochemical conversion technologies, combined with increasing pressure to address climate change, soil degradation, and industrial emissions, have expanded biochar's relevance well beyond its historical agricultural framing. What was once viewed primarily as a soil amendment is now increasingly understood as a platform material, capable of supporting agriculture, enabling carbon dioxide removal, improving environmental performance, and substituting fossil-based carbon in industrial systems.

Today, biochar research, production, and deployment are being pursued across every major region of the world. Governments, academic institutions, farmers, industrial actors, and climate finance mechanisms are all contributing to a rapidly evolving understanding of what biochar can do, where it delivers the greatest value, and how it can be scaled responsibly. This growing interest reflects a broader shift in sustainability thinking: toward solutions that are multifunctional, locally adaptable, and capable of delivering both climate and economic benefits.

This report aims to give a broad overview of the current status of biochar, its feedstocks and production principles, properties and how they are influenced, applications with a specific focus on carbon dioxide removal solutions as well as the status of biochar utilization in the Mission Innovation Countries.

1.1 The relevance of biochar in the global CDR market

The carbon dioxide removal (CDR) market has emerged as a critical component of global climate strategies, driven by the recognition that emissions reductions alone are insufficient to meet international climate targets. While decarbonization efforts remain essential, scientific assessments consistently show that removing existing CO_2 from the atmosphere is necessary to limit long-term warming. The CDR market encompasses a broad spectrum of natural and technological approaches that differ significantly in cost, scalability, durability, and measurability. At present, the market operates primarily through voluntary carbon markets, where companies and, increasingly, governments purchase carbon removal credits to fulfil net-zero commitments or to prepare for future regulatory requirements. The market's functioning relies on the generation of verifiable CO_2 removals by suppliers, the demand from buyers seeking high-quality climate action, and robust monitoring, reporting, and verification (MRV) systems that ensure removals are real, additional, and stored for the claimed duration.

Within this evolving landscape, biochar has become one of the most relevant and rapidly scaling CDR methods. The combination of high storage durability and relatively straightforward measurement of carbon content makes biochar an especially credible and attractive option for buyers seeking reliable carbon removal. Unlike many engineered CDR technologies that are still in early development, biochar can be deployed at scale today and can offer additional environmental and agricultural benefits, such as improved soil fertility, enhanced water retention, and the sustainable utilization of agricultural or forestry residues. Biochar as a CDR method is attractive because the time between contracting and delivery is short (a few months compared to several years for other methods), the prices comparably low, and the purchase volumes flexible and scalable.

Since the emergence of the carbon dioxide removal market, biochar has been the leading method for delivering durable carbon dioxide removals (cf. Figure 1).

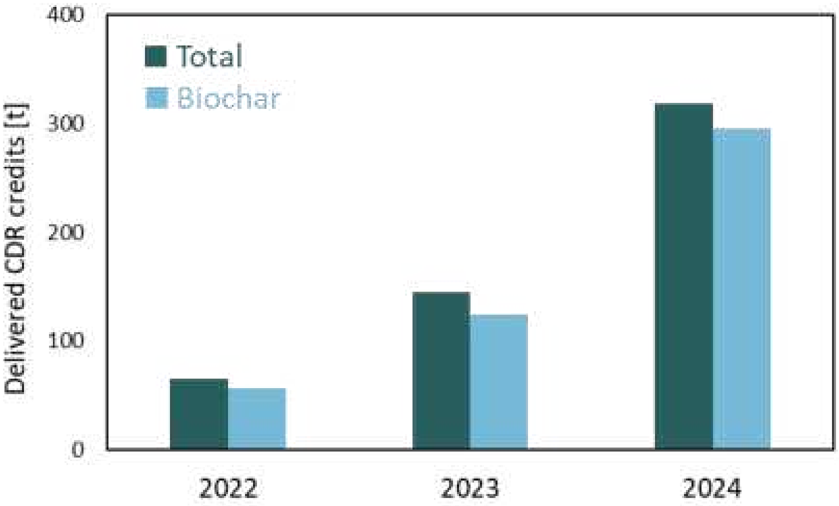

Figure 1 Delivered CDR credits in total, and share of biochar-based CDR [10]

2. Feedstocks for biochar

Biomass is a major resource, with global production estimated at 104.9 billion tonnes per year, of which 53.8% and 46.2% are of terrestrial and oceanic origins, respectively [11]. Biomass can be both fresh biomass as well as residual materials, and not all of this amount can necessarily be used as biochar feedstock. A wide range of biomass and waste has been tested as feedstocks for biochar production with examples spanning virgin wood/prunings, wood waste, nutshells, straw, leaves, corn cobs and other agricultural residues, sewage sludge, manure, biogas digestates, bone meal and municipal solid waste [12–23].

2.1 Feedstock sourcing

The main requirement for a biochar feedstock is that it contains organic carbon which can be converted to elemental carbon/pyrogenic "fixed" carbon in the pyrolysis or gasification process [24]. Even plastic, electrical circuit boards and scrap tires have been tested as char feedstocks. In a carbon removal perspective, however, biochar can only be made from carbon of a biogenic origin, as the premise for biogenic carbon sequestration (BCS) leading to CDR is organisms producing organic carbon from CO_2 through photosynthesis, which is then converted to stable, storable pyrogenic carbon. To summarize – biochar must be produced using biomass. In practice, biochar is primarily derived from lignocellulosic biomass. The feedstock consists of agricultural, forestry, and industrial residues (e.g., crop stover, wood chips, biowastes). Feedstock must be dried [25] – the pyrolysis energy can be used for this. Conversion of these materials addresses the challenge of waste management, as they are often low-value waste streams. Moreover, CO_2 is fixed in the form of stable carbon. Utilizing readily available residues lowers the economic input costs for biochar production. Bioheat is co-produced and can be used for district heating, industrial purposes, or drying biomass.

Requirements for biomass sourcing and associated biochar certification procedures have been established by researchers to ensure a sustainable production process [26]. Sustainable production means that net environmental benefits are met. The carbon removal of biochar may lead to both avoided emissions and emission offsets through production, but this is strongly dependent upon biomass sourcing [14,26]. It is therefore important to view biomass sourcing and biochar production in a life cycle perspective.

The main principle of BCS is that there will only be a net carbon removal effect if the alternative (i.e., not biochar) fate of the biomass leads to higher carbon emissions than making biochar as a means to store carbon in stable molecules - then more carbon is stored than emitted [27,28]. This requirement is typically met when waste or surplus biomass is used, such as agricultural residues that are otherwise incinerated or left to decompose [29], with part of the decomposition leading to methane emissions [26]. Additional benefits can be gained if energy generated in the pyrolysis process is used to offset fossil emissions [30,31], or if the waste feedstock causes other problems, such as pollution, that are mitigated by using it for biochar production [14,19].

An integral part of the sustainable production principle is that biomass sourcing should not compete with other land use alternatives such as food production or leaving the land in its natural state, as such land-use changes can negate the positive life cycle impacts of biochar [32] Land clearance for biochar production will often have negative effects on ecosystem conservation and release soil carbon, with the result typically being excessive carbon-payback times before net negative effects of atmospheric CO_2 are realized [26] (see Section 2.2.1 for more details about tree planting for the sole purpose of biochar making).

Global availability of sustainable waste biomass feedstocks as estimated by Woolf et al. [26] and summarized by Sri Shalini S. et al. [29] are presented in Table 1. It should be noted that such estimates are rough and subjected to revisions based on continuous research.

Table 1 Available carbon in sustainable feedstock for biochar production [26].

Feedstock category	Available carbon [billion tonnes C per year]
Forestry residues	0.14
Agroforestry residues	0.62
Green/wood waste	0.14
Rice residues	0.28
Cereal residues	0.18
Sugar cane residues	0.13
Crop residues	0.60
Animal waste	0.19
Sewage sludge	0.06*
Total	2.33

**Rough estimate based on Norwegian amounts of sludge.*

As the biogenic CDR principle is based upon biogenic carbon, fossil carbon, e.g., in plastic waste, is excluded as a biochar feedstock. It should be noted, however, that waste streams that include fossil carbon residuals, such as microplastics in digestates or sewage sludges, should not be excluded from the biogenic CDR concept as long as the overwhelming majority (quantity for cut-off yet to be determined; could e.g. be >95%) of the feedstock carbon is biogenic and the life cycle impact gives net carbon removal. Particularly if pyrolysis treatment improves the net environmental impact of waste handling [33]. Meanwhile, even though all emissions from all technologies processing all feedstocks have to be investigated properly, contaminated feedstocks warrant extra scrutiny in order to control the fate and potential emissions of said contaminants [34,35].

When sustainable feedstock sourcing is ensured, the next step is connecting biochar production to application. Synergies between feedstock sourcing, biochar production, and application will both reduce the environmental impact of the processes and reduce net costs

[31,36]. Biochar properties vary greatly depending on feedstock, pyrolysis/gasification technology and pyrolysis conditions [37,38]. Hence, application needs can to a certain extent be met through process optimization, but intrinsic feedstock properties impose limits. In the following sections, we describe how feedstock types influence biochar properties, in addition to other important considerations.

2.2 Lignocellulosic feedstocks

Structural plant molecules, making most of the biomass of feedstocks used for pyrolysis, belong to three main families – lignin (10-40%), cellulose (20-25%), and hemicellulose (15-40%), hence the name lignocellulosic is often used to describe plant-based feedstocks. These feedstocks only contain a minor fraction of inorganic elements [17], which leads to the generation of highly carbonaceous biochars with low ash and metal contents, making them ideal for agricultural soil application. However, some wood residues can have high ash contents, like bark. A high ash content can in some cases be more beneficial for agricultural soil application as the resulting biochar can help balancing acidic soils through its alkalinity.

Furthermore, lignin-rich feedstocks generally result in high biochar yields, porosity, and stability [14]. Biochar properties vary significantly when produced from wood-based feedstocks or other agricultural residues [17], and it is hence useful to make a distinction between feedstocks generated from forestry residues and agricultural residues.

2.2.1 Wood residues

Wood residues have two main sources, forest with residues left after harvesting and residues at sawmills. Sourcing is particularly important to limit potential negative impacts. Wood based feedstocks are typically highly sought after, e.g., from the metallurgical industry [8,9] as they generate high quality biochars which are typically characterized by high concentrations of stable carbon, low ash contents and low concentrations of contaminants [39].

Sourcing woody feedstocks can be contentious, as wood has multiple high-value usages and could be related to land clearance if strong forest management practices are not in place, with potentially significant carbon payback times [26]. In practice, this means using wood in waste products or wood from value chains that offer multiple benefits and do not compete with other high value usages [40]. It also means that wood should not be grown solely for biochar production. Using byproducts or leftovers from forestry and wood processing, such as wood shavings from lumber mills, is a good alternative. Such forestry residues have been estimated to offer 0.14 billion tonnes C per year [26], so there is great potential for carbon removal from this feedstock. Extracting these residues can, however, be prohibitive in terms of costs, and hence the use of portable pyrolysis units has been suggested as a way of avoiding both costs and emissions related to collection and transport [41]. It is, however, important to ensure that forest soil carbon is not compromised by intensive biomass harvesting [42]. Studies have suggested leaving 30-60% residues in the field depending on soil conditions is a good rule of thumb here [43].

Although crops or trees grown specifically for the purpose of biochar generation might lead to diminished environmental benefits [40], the practice occurs. Such cases will benefit from applying sustainable forestry practices rather than intensive harvesting to ensure soil carbon is not compromised and to avoid the high carbon payback times from land clearance [26,42]. However, optimally co-benefits should be achieved when growing trees for biochar making - for example the use of mangrove trees as bioshields providing protection and land restoration for coastal communities while also providing feedstock for biochar production.

Sourcing wood-based feedstocks from contaminated wood waste has also been explored [35,44,45]. The majority of metals in the feedstocks accumulate in the biochar, however, limiting direct soil application, but not necessarily application in concrete or asphalt [46,47] or application as a sorbent for contaminants [34].

Figure 2 Example of woody feedstock from logging residues and resulting biochar. Photos: Daniel Albert

2.2.2 Agricultural residues

Surplus material and residues from agriculture have been investigated thoroughly as biochar feedstocks with popular examples being rice husks, rice straw, corn stover, coconut shells, wheat straw, coffee hulls, and palm fibers [48,49]. Agricultural residues are used as fodder and fertilizer, as well as for erosion control and water harvesting. However, part of them have no other beneficial uses, so they are often left to decompose or incinerated possibly creating air quality issues. Biochar quality is typically lower for many of these feedstocks compared to pure wood feedstocks, due to higher ash contents, lower porosity and lower stable carbon content [39,48,49]. While these properties might not always suit all biochar applications, biochars made from agricultural residues are well suited for reuse as soil amendments. These biochars can retain relatively large amounts of the nutrients present in the original biomass, especially

P, which makes agricultural soil amendment a direct route for returning nutrients extracted from the soil back to the soil [50].

2.2.3 Bioenergy crops and invasive species

Second-generation bioenergy crops—such as Miscanthus, switchgrass, and eucalyptus—are characterized by rapid growth and a strong capacity for carbon sequestration. They are widely used in future climate-mitigation scenarios (e.g., BECCS). Increasing attention has been given to cultivating these bioenergy crops on marginal lands (e.g., abandoned cropland) as a feedstock for biochar production, which can avoid competition for primary agricultural residues [51]. As with the case of wood-feedstocks, this can result in carbon removal through biochar application, but at the same time net benefits are more uncertain as they can be reduced by deforestation and fertilizer demand [40]. As has been stated previously, the highest biogenic CDR effect is typically achieved by using waste biomass as feedstock and establishing value chains around biochar production and application [36]. Invasive plants such as some acacia species in Sub-Saharan Africa and Eupatorium ("forest killer") in Nepal and western Africa [52] are examples of excellent lignocellulosic feedstocks, as their removal brings benefits to local ecosystems rather than a burden from harvesting [19]. Other examples of more sustainable harvest of purposely produced biomass include using plants from phytoaccumulation remediation of metal contaminated soils [34].

2.3 Municipal Solid Waste (MSW)

When sourcing waste-based feedstocks it is important to consider national waste regulations as such legislation potentially places limits on how waste can be handled and treated. Legislation will vary between nations but can impose criteria that inhibit or limit pyrolytic treatments and/or subsequent usage of biochar. If a waste fraction is subject to restrictions on use, it is important that the biochar product generated from the waste feedstock fulfils end-of-waste criteria. End-of-waste criteria are defined as criteria that must be met for a waste to no longer be considered a waste [53]. Such criteria vary but are typically related to removing or reducing the presence of pollutants or pathogens.

There are several nutrient rich wastes, such as sewage sludge, manure and aquaculture residues that contain high concentrations of N and P, while also containing pollutants. Using these wastes as feedstocks for pyrolysis could help solve the pollutant emissions through degradation of the contaminants and reduce eutrophication issues, while recovering nutrients [54]. Pyrolysis over 600 °C has been shown to even reduce the most stable organic contaminants (PFAS) contents by > 97%, and that of other contaminants such as phthalates, dioxins, PCBs and pesticides by > 99% [55,56].

2.3.1 Emission monitoring

Waste pyrolysis is also likely to be subject to emission monitoring and compliance with threshold values. At present, data are lacking on emissions from full-scale pyrolysis units, and the need for and potential effect of various flue gas cleaning options are not well understood. Data from a few limited studies indicate that emissions from pyrolysis are generally lower than emissions from waste incinerators [18,35]. In the case of sewage sludge, pyrolysis however, there is a risk of elevated SO_2, HCl emissions, in addition to potential decomposition products from per- and polyfluorinated alkylsubstances (PFAS), which could warrant flue gas treatment [18,55]. Emission limits specific for biochar are in place in several states of the Germany, for CO, NO_x, non-methane volatile organic carbon (NMVOC), benzene, smoke, arsenic, mercury, dioxins, polycyclic aromatic hydrocarbons (PAHs) and hydrochloric acid (HCl). Pyrolysis emission benchmarks for CO, NO_x, non-methane volatile organic carbon and PM10 have been adopted in Switzerland where cantonal authorities have drawn up a document that deals with various types of facilities for the production of biochar and provides information on which emission limit values should be applied, for example, for total dust, CO, NO_x, and VOC [57]. In countries where no specific biochar emission benchmarks have been adopted, waste regulations need to be followed.

2.3.2 Sewage sludge and digestate feedstocks

Sewage sludge (biosolids) is a biomass fraction produced at wastewater treatment plants, which contains about 60% carbon (d.w.) in addition to high concentrations of nutrients, such as N and P, making it a valuable fertilizer product heavily used in agriculture worldwide [58,59]. Digestate is a biomass waste product from biogas production. In this process, organic waste such as sewage sludges and food waste is subjected to anaerobic digestion to produce methane and other combustible gases. The digestate fraction contains less carbon than the starting material, as some of the carbon is converted to gases but the nutrients are mainly retained, which has encouraged extensive use as soil amendment.

Increasing awareness on legacy contaminants, potentially toxic metals, and emerging contaminants, such as pPFAS, microplastics, bisphenols, and pharmaceuticals, has resulted in calls to reduce agricultural usage of both sludge and digestates [60–62]. In Germany, for example, this has led to a strong increase of sewage sludge incineration [63]. Due to the sheer size of this waste fraction, which in Europe was estimated at 8.7 million tonnes (d.w.) per year in 2020 [64], there is a strong need for treatment processes which remove the contaminant while conserving carbon and nutrients [58,59].

Pyrolysis is now a thoroughly explored option for sewage sludge and digestate management and environmental benefits have been documented [33,58,65]. Organic contaminants and microplastics are largely removed or destroyed in the process, provided sufficient process conditions (high temperatures around 800 °C, residence time and clean gas combustion) are used [56,66–68].

Pyrolysis does not solve the problem of potentially toxic metals as easily. High temperature pyrolysis accumulates metals in the biochar but appears to render them mostly immobile [69,70]. Meanwhile, what happens to metals accumulated in sludge biochars when applied to soils over time is still an underexplored topic. Upstream solutions which reduce metal loads in sludge are encouraged while industrial sludge with elevated metal concentrations should overall be avoided as a biochar feedstock when the goal is soil application [69,71]. As for biochar made from metal contaminated wood, sludge biochars with high metal concentrations could possibly be used in low-risk applications such as concrete or asphalt [72,73]. While this will lead to carbon removal, this is a less-than-ideal option as it does not allow for N and P reuse. For contaminated feedstocks such as sewage sludge, it is crucial to ensure adequate process control to guarantee safe handling of toxic components. This might require a certain facility size, flue gas treatment and product characterization.

2.3.3 Animal waste feedstocks

Various animal-related waste streams, such as manure, bone meal, meat and sludge from aquaculture have been explored as feedstocks for pyrolysis [74–76]. Manure and other animal wastes have been used as fertilizer products in direct soil application throughout human history, but increasing awareness of pollutants such as pharmaceuticals, antibiotic resistance genes, and pathogens have led to restrictions on use [74]. As for sewage sludge, pyrolysis thermal treatment is expected to resolve the pollutant issue [66] while conserving valuable nutrients in the process. Nitrogen is mostly lost, unless removed in pretreatment, but biochars made from manure and other animal wastes are expected to have relatively high nutrient loads, including Ca, K, Mg, and P [74]. Biochars from manure and animal wastes are hence well suited for soil amendments and composting applications and contribute to reducing fertilizer usage [75].

Waste streams from aquaculture have been dubbed as potential P-rich feedstocks for biochar production. At present, these waste streams have not yet been thoroughly explored as biochar feedstocks, but it is suspected that limitations on applications will exist for marine biomass feedstocks due to elevated salt and metal contents [77].

2.3.4 Other waste feedstocks

The scientific literature contains multiple examples of other waste feedstocks that have been tested as biochar feedstocks. A few examples include cotton textiles [78], used car tires [79], and residues from paper production [80]. Because many such feedstocks are subject to waste legislation and biochar production would have to fulfill end-of-waste criteria, they fall out of the main theme of this report. Adhering to waste regulations could be challenging as the resulting biochar qualities vary greatly. In the case of scrap tire pyrolysis, biochar quality is poor, and significant emissions are expected from the process. The quality of biochar products from textile feedstocks also varies greatly due to the presence of plastics and chemical additives. The carbon content and type in these feedstocks typically varies a lot, and they can contain significant amounts of fossil carbon from plastics. Hence, there are uncertainties related to the potential carbon removal effect from the pyrolysis of such wastes. However, while there are a number of uncertainties, the general benefit from waste pyrolysis is a potential for waste management improvement and generation of new value chains.

2.4 Aquatic feedstocks

Aquatic biomass has not been explored as a potential biochar feedstock to the same degree as terrestrial biomass. There is now a growing focus on the potential of microalgae and seaweed as biochar feedstocks due to the high photosynthetic effect of marine organisms which make them highly productive systems for generating biomass [77,81]. Marine biomass can however contain elevated salt and metal concentrations which reduce biochar quality and the applicability for biochar in soil [77]. In addition, the high chloride content can lead to corrosion issues during production [82] as well as formation of dioxins and furans. As marine biomass biochar quality issues could limit soil application, pretreatment processes [77] or alternative applications such as sorbents for wastewater treatment have been suggested [7]. For alternative applications, the carbon removal effect will rely on how the biochar sorbents are disposed of. There are promising synergies for using microalgae grown in wastewater treatment as a feedstock for biochar, as this provides benefits for the wastewater treatment process (reduction of nutrients in wastewater) while capturing carbon in algae biomass which can be converted to biochar [83].

Figure 3 Examples of biochars from different feedstocks: sawdust (a), bark (b), garden waste (c), tomato residues (d), sugar kelp (e), and fish sludge (f). Photos: Daniel Albert

3. Production and properties of biochar

This chapter provides an overview of the underlying thermochemical principles of biochar production as well as how the choice of feedstock and production process influence the biochar's properties.

3.1 Thermochemical principles of biomass conversion

Biomass can be converted into heat or secondary energy carriers through thermochemical conversion processes, in which heat drives the decomposition of organic matter. The main governing parameters are temperature, heating rate, residence time, and the availability of oxygen. Chemically, biomass consists primarily of carbon, hydrogen, oxygen, nitrogen, water, and inorganic components. The energy content is stored in carbon and hydrogen, which release heat when oxidized to CO_2 and H_2O. Depending on oxygen availability and process conditions, biomass follows different thermochemical conversion pathways [84].

Combustion aims at complete oxidation of biomass, converting organically bound carbon and hydrogen to CO_2 and H_2O while releasing heat. The solid residue is ash, consisting of oxidized inorganic components.

Gasification operates with limited oxygen supply, resulting in incomplete oxidation and the formation of a combustible synthesis gas containing CO, H_2, CH_4, CO_2, and higher hydrocarbons. Part of the carbon remains as a solid residue (gasification char). Although individual reactions may be exothermic or endothermic, the overall process is endothermic. Product gas composition can be influenced by the choice of gasification medium, such as air, steam, or CO_2.

Pyrolysis is the thermal degradation of biomass in the absence of externally supplied oxygen. While some oxidation reactions occur due to oxygen inherent in the biomass, no oxidant is added. Product distribution depends strongly on process conditions, with fast pyrolysis favoring liquid bio-oil and slow pyrolysis producing a carbon-rich solid, biochar.

Biomass can also be converted hydrothermally at elevated temperatures (typically 180–250 °C) and pressures in the presence of water. Depending on process conditions, this yields hydrochar (hydrothermal carbonization), bio-oil (hydrothermal liquefaction), or hydrogen-rich gas (hydrothermal gasification). These processes are well suited for wet feedstocks, as drying is unnecessary. Although hydrochars are sometimes referred to as biochars, their chemical stability is significantly lower and they are therefore not relevant for long-term carbon dioxide removal or fossil carbon substitution [85]. Hydrochars are not considered further in this report.

3.2 Biomass pyrolysis

Pyrolysis is the thermal decomposition of biomass in the absence of oxygen (λ=0). The process converts organic matter into a mixture of solid biochar, condensable liquids (tar or pyrolysis oil), and non-condensable gases (CO, CO_2, H_2, CH_4, and light hydrocarbons). The product distribution depends strongly on the temperature, heating rate, residence time, as well as on the feedstock composition [86,87].

The process proceeds in several overlapping stages: drying (below 150 °C), devolatilization (200-500 °C), and secondary reactions of vapours and residual char. The main structural components of biomass decompose at different temperature ranges – hemicellulose (230-300 °C), cellulose (300-400 °C), and lignin (up to 600 °C) – which leads to varying yields and compositions of the resulting products [86].

Pyrolysis processes are often classified according to their heating rate, Table 2.

Table 2 Classification of pyrolysis processes [87,88]

Type	Temperature [°C]	Heating rate	Vapour residence time	Main product	Characteristic features
Torrefaction	230-290	Low	Minutes-hours	Solid (torrefied biomass)	Mild thermal treatment, increases energy density and grindability
Slow pyrolysis	400-800	Low	Minutes	Solid (biochar)	Maximized char yield, classic process for biochar production
Intermediate/fast pyrolysis	450-650	High	Seconds	Bio-oil and gases	Fast heating and quenching required
Flash pyrolysis	800-1000	Very high	milliseconds	Bio-oil	Very rapid conversion, vapours are removed and cooled before the can react further

Torrefaction is a mild form of pyrolysis, carried out at temperature below 300 °C. The process is well known as roasting from food processing, such as coffee roasting. The goal of torrefying biomass is to improve mechanical characteristics while retaining most of the mass. Torrefaction has for example been used to improve heating value and increase brittleness of wood pellets for co-combustion in coal-fired power plants. The temperature range of torrefaction is typically too low to achieve the properties desired for biochar (e.g., high carbon content, high surface area, chemical stability).

During slow pyrolysis, the biomass is heated under low heating rates (a few Kelvins per minute) to the desired temperature, at least 400 °C. The retention time of the solid phase is typically in the range of several minutes to hours. If the reactor design allows for contact between the evolving gases and the solid phase, secondary reactions between the phases can occur. The slow reaction conditions promote carbonization, producing a solid biochar with a high degree of aromaticity and low volatile content.

Slow pyrolysis is often the process of choice for producing biochar. Nevertheless, a significant portion of the feedstock is not converted into solid. Depending on feedstock and production conditions (cf. Section 3.5.1), about 25-40% (by mass) remain as biochar, while 30-40% are transferred into a condensable liquid, and 20-30% into permanent gas.

There is a clear temperature-dependence of biochar yield and properties. As the process temperatures is increased, the biomass structure is degraded and rearranged. Functional groups are detached, gases are released, leading to a decrease in oxygen and hydrogen content, and a resulting increase in relative carbon content. This devolatilization process can lead to a porous structure, increasing the surface area of the solid significantly. The remaining carbon is rearranged, forming aromatic structures that are chemically highly stable.

The liquid, often referred to as bio-oil or simply condensate, is a complex mixture of hydrocarbons of various chain lengths (phenols, furans, acids, ketones, and tars) as well as a large share of water. Depending on this water content, the oil can present in one phase, or in two phases – a phase high in water content and one with a high number of organic components. The gaseous by-product of slow pyrolysis consists mainly of CO_2, CO_2, H_2, CH_4 and small hydrocarbons.

At process temperature, the bio-oil is in the gas phase. Due to its complexity and high oxygen content, upgrading the oil to enable material use can be challenging and expensive. Furthermore, condensates from pyrolysis can be cancerogenic and highly corrosive. Typically, this condensate is therefore combusted together with the permanent gas to provide heat. When using a dry feedstock with low ash such as wood this combustion yields sufficient heat to maintain the pyrolysis process as well as provide heat for external applications. This energy balance may look very different for feedstocks with higher amounts of water and ash, and a heat surplus is therefore not always given [89].

The target of pyrolysis under slow heating conditions is the production of char. Other pyrolysis schemes can target the production of biooil, i.e. flash and fast pyrolysis. The vapour residence time in the reactor is so short that secondary cracking and polymerisation reactions are supressed. As a result, a much larger fraction of volatile product leaves the reactor and are collected as condensable vapours. To achieve process temperature throughout the feedstock, while maintaining a short residence time, the biomass needs to be heated quickly. In the fast of flash pyrolysis, where heating rates are in the range of 1000 K/s, this is only possible by pulverizing the biomass before the process. Intermediate, fast and flash pyrolysis also produce biochar. The process is however not optimized for high biochar yields or tailored properties and fast pyrolysis processes therefore not of relevance for targeted biochar production [87].

3.3 Gasification

Gasification, the incomplete oxidation of a feedstock, has gained some relevance as a production method for biochar. As the name suggests, the primary goal of gasification has traditionally been the production of a combustible gas (syngas), while biochar is generated as a solid by-product.

Gasification is typically carried out at temperatures in the range of 700 – 1000 °C and under sub-stoichiometric conditions, using air, oxygen, steam, CO_2, or combinations therefor as gasifying agents. Under these conditions the feedstocks undergoes drying and devolatilization, followed by partial oxidation and a series of heterogeneous gas-solid reactions, including char oxidation, steam gasification and the Boudouard reaction [84]. Due to the high operating temperatures and the presence of oxidizing agents, gasification is generally associated with lower solid yields compared to pyrolysis. Nevertheless, biochar can be produced by operating the profess in a char-oriented mode, for example by limiting the extent of oxidation, reducing residence time of the solid phase, or extracting char from intermediate zones of the reactor. The resulting gasification-derived biochar typically exhibits a high degree of carbonization, low volatile matter content, and an increased ash fraction due to both thermal severity and mineral enrichment [90].

3.4 Production Technologies

While the preceding sections described the thermochemical principles and reaction regimes of biomass conversion, the following section presents the main technical concepts for producing biochar and charcoal in practice. These range from traditional batch systems still used for fuel charcoal production to modern industrial installations designed for continuous operation, energy integration, and process control. In general, it is important to match feedstock, production technology and process conditions to each other to achieve the desired biochar properties.

3.4.1 Traditional charcoal production

Although biochar and charcoal are chemically similar – both being solid carbon-rich materials produced by pyrolysis of biomass – their purpose, quality requirements, and production practices differ significantly. The biochar market has developed rapidly in the last decade with countless new technology providers and biochar producers emerging, while the charcoal market is well established and remains somewhat disconnected from biochar.

Traditional charcoal production is one of the oldest thermochemical processes practiced by humans. It typically involved slow pyrolysis of wood in earth-covered pits, brick kilns, or simple mound kilns, operated with limited air supply to restrict combustion. The heat for the process is generated by partial oxidation of the feedstock, while the rest of the materials is carbonized under low-oxygen conditions. Temperatures in such systems typically range from 300 – 500 °C, depending on the air flow, feedstock, and operator control [91].

These systems are simple and inexpensive to build but can be inefficient. Large quantities of volatile compounds such as CH_4, CO, and tars escape unburned, leading to substantial energy losses and local air pollution. Charcoal remains a major source of household and industrial energy in many parts of the world, particularly Africa, South America, and Southeast Asia, where most global charcoal production takes place.

To improve efficiency and reduce emissions, several improved kiln designs have been developed. Metal drum kilns and retort kilns enable better air control and partial recovery of exhaust gases for heating, increasing yield and product uniformity. Shaft kilns represent a modernized form of charcoal production, operated in semi-continuous batches with improved air control, sometimes gas cleaning and energy recovery. They can achieve higher carbon yields and lower emissions compared to traditional systems but still produce charcoal primarily as energy carrier. Despite these technological improvements, the focus of the charcoal industry remains on fuel quality rather than carbon stability or other properties.

Figure 4 Traditional charcoal production in earth mound kilns in rural Uganda.
Photos: Kathrin Weber

3.4.2 Industrialized biochar production

Industrial biochar production applies engineered pyrolysis technologies that enable precise control of process parameters, consistent product quality, and effective energy integration. These systems are designed to optimize carbonization efficiency while meeting environmental and safety standards. In contract to traditional kilns, industrial plants operate in continuous and semi-continuous mode, allowing for stable operation, reproducibility, and gas and condensate management. Depending on reactor design and heat supply, industrial systems can be broadly categorized as:

- **Fixed bed reactors**, where biomass remains stationary while heat is applied externally or by recirculated gases. These systems are simple and robust, suitable for coarse feedstocks and smaller-scale installations.
- **Rotary kilns**, consisting of a slowly rotating, inclined cylinder that transports feedstock through temperature zones. They are widely used for wood- and residue-based biochar production and can handle varying particle sizes and moisture levels.
- **Auger (screw) reactors**, where biomass is conveyed mechanically through a heated tube. Residence time and temperature can be controlled precisely, making this type common among medium-sized commercial producers.
- **Fluidized-bed reactors**, in which fine biomass particles are suspended in a stream of hot gas, ensuring good heat transfer and uniform product quality. These are typically found in large-scale or research installations due to their higher complexity.

Process heat can be supplied autothermally, by partial combustion of pyrolysis gases, or allothermally, through external heat exchangers or burners. In both cases, the energy contained in the gaseous and liquid by-product is commonly recovered for process heating, drying, or district heating – although condensation and external utilization is possible.

Modern facilities are equipped with monitoring and control systems that held maintain the desired process conditions. Many production technologies are designed to process woody feedstocks or other dry lignocellulosic materials, but there exist also manufactures specializing on waste materials such as sludges. The requirements for process control and emission reduction may vary a lot depending on the feedstock, but also on the location of a facility and the locally relevant laws and guidelines.

The size of industrial biochar production facilities ranges from containerized modular units producing a few hundred tonnes per year to centralized plants exceeding 10 000 tonnes annually. Production facilities are often integrated into a network of nearby heat consumers or district heating networks that can utilize surplus heat [92].

Figure 5 Examples of industrial biochar production. Upper left and right: Pyreg technology (Photos: Pyreg) Bottem left: Biogreen technology, bottom right: CHE technology (Photos: VOW)

Figure 6 Example of farm-based biochar production. Left: aerial view, right: Biomacon technology. Photos: Mære Landbruksskole, Tove Hatling Jystad

Figure 7 Examples from an industrialized biochar production facility. Feedstock storage (upper left), biochar filling into big bags (upper right), and reactor hall with conversion unit (below), Photos: Syncraft

3.4.3 Low-tech artisanal methods

Traditional kiln technologies for charcoal production are slow and without treatment of the pyrolysis gases, resulting in emissions of gases (mainly methane and carbon monoxide) and aerosols that are both toxic and contribute to greenhouse gas emissions. In retort kilns pyrolysis gases are led back to a combustion chamber. This can reduce emissions substantially but is costly and consumes a considerable amount of valuable ignition material such as wood during start-up. To overcome these problems, a novel type of technology, the Kon-Tiki flame curtain pyrolysis, has been developed. This artisanal technology combines the simplicity of the traditional kiln with the combustion of pyrolysis gases in the flame curtain (similar to retort kilns), also avoiding use of external fuel for start-up (see Figure 8).

The most important low-technology production methods for biochar include:

- *Traditional earth mound or earth covered pit kilns* usually deliver good quality biochar though only high-value wood logs can be used as feedstock. The main environmental drawback is that toxic pyrolysis gazes are emitted unburned into the atmosphere generating significant gas emissions [93]. In addition, yields are relatively low (10-20%) and the pyrolysis process is very slow, taking several days [93]. These types of kilns are a gigantic problem in Africa and Asia, wasting over 80% of heating value and causing widespread pollution that poses a significant health hazard.
- The development of the Adam retort kiln and similar devices such as basic steel retort systems introduced the partial afterburning of pyrolysis gases, making them cleaner and more efficient. In these retort systems the feedstock wood can be mixed with dry biowaste materials like prunings, rice husks or maize cobs but a lot of valuable start-up wood is still needed [93–95]. Such medium-scale improved retort technologies, where the pyrolytic gases are recirculated into the combustion chamber and combusted internally [94], produce around 75% lower deleterious gas emissions (mainly CO, CH_4, aerosols) and higher conversion efficiencies of 30-45% than traditional systems. Energy contained in the recirculated carbon- and hydrogen rich syngas is thus used to sustain the pyrolysis process so that less heat from the endothermic pyrolysis reactions is needed to sustain the process [93].
- Household-scale cooking stoves, so-called TLUDs (Top-Lit Up-Draft stoves) [96] can generate biochar while using the energy produced for cooking. Advantages include that they burn cleanly avoiding negative health effects due to indoor air emissions [97], can use various waste biomasses as feedstock and are fuel-efficient. Pyrolytic gases are mostly combusted in the flame front, reducing emissions of CO, CH_4 and aerosols by around 75% [98] compared to traditional cooking. Small-scale TLUDs may be applicable for horticulture or small kitchen gardens [99] but they generate too little biochar (0.5-1 kg per run for household devices and up to 10 kg for bigger community stoves) to supply enough biochar for farming or selling as charcoal. In addition, the stove needs to be actively quenched after each cycle, which is impractical in daily use.

Thus, the implementation of biochar into agricultural practice and the efficiency of the charcoal industry have been hindered by the absence of a low or zero-cost but clean charcoal-producing technology that would allow the on-farm production of high-quality charcoal in sufficient amounts. A recent development has been the introduction of the *Kon-Tiki* flame curtain kiln, designed in 2014 in Switzerland and rapidly spreading since by open-source technology transfer to farmers in more than 100 countries [100–102].
One run of a 2 m^3 flame curtain kiln with an upper diameter of 2.4 m produces 500 kg of biochar (dry matter basis) and close to 2 MWh of heat from shrubs, husks, straw, prunings and other organic farm waste in about three hours needing one worker to maintain and control the process. In contrast to medium-sized retort kilns, no startup wood is needed for flame curtain kilns. The cheapest way is a mere conically shaped soil pit which would essentially be for free, and as clean as the more improved models.

With benefits such as high-quality biochar, low emission, no need for start-up fuel, fast pyrolysis time and, importantly, easy and cheap construction and operation the flame curtain technology represents a promising possibility for sustainable rural biochar production.

Figure 8 Conical Kon Tiki soil pit for cheap, clean, fast and easy artisanal biochar making.
Photos: Gerard Cornelissen (left), Kathrin Weber (right)

During recent experiments in Lima, Peru, the effect of feedstock moisture content on emissions from flame curtain kilns was tested, for both the simple soil pit kiln and an improved, insulated and ventilated kiln with the same principle (El Horno – see Figure 9) [103].

Figure 9 El Horno and flame curtain kilns, with the same principle. Emission measurements in Lima, Peru, published in [103]. Photos: Gerard Cornelissen

3.4.4 Gas emission factors

The most important result of the Peru study was that there were no to low methane emissions for both kilns operated on dry or half-dry feedstock (0.0 g kg^{-1} biochar for the Kon-Tiki; 3.6 g kg^{-1} biochar for El Horno).

In contrast, when run on moist feedstock with >40% moisture, excessive methane emissions of > 600 g kg^{-1} biochar were observed for both kilns. This clearly underscores the utmost importance of dry feedstock to keep the flame curtain intact. Methane emissions of 600 g kg^{-1} biochar correspond to 15 kg CO_2-eq kg^{-1} biochar (using the 100-year global warming potential of methane of 25 [104], by far exceeding the approximately 2 kg CO_2-eq that are sequestered by biochar amendment to soil [105].

Emission factors for CO were between 40 and 100 g kg^{-1} biochar, and a little lower for the El Horno kiln than for the Kon Tiki, probably because of the ventilation system providing oxygen to the flame curtain, making sure most of the CO was converted to CO_2.

Aerosols (smoke; TSP; PM_{10}) were in the order of 10 g kg^{-1} biochar and showed no clear trend with feedstock moisture.

In a subsequent recent study gas and aerosol emissions were documented for common non-woody feedstocks and to compare emissions from finely grained, high-lignin feedstock (coffee husk) with those from coarser, low-lignin feedstocks (maize cobs, grass, sesame stems) [106].

Methane emissions were nearly zero (< 5.5 g/kg biochar) for the pyrolysis of three dry (~10% moisture) maize cobs, grass, and a 1:1 mixture of grass and woody twigs. Especially grass and shrubby invasive species are promising feedstocks in tropical agriculture. In contrast, the pyrolysis of finely grained coffee husks generated significant methane (200 g per kg biochar) and aerosol emissions, indicating that technologies other than flame curtain kilns are more suitable for finely grained feedstocks. The emission results from this study suggest that certification of biochar made from dry maize, sesame, and grass biomass using low-tech pyrolysis should be encouraged. Meanwhile, more advanced systems with syngas combustion are needed to sufficiently reduce CO, CH_4, and aerosol emissions for the pyrolysis of finely grained biomasses such as rice, coffee, and nut husks.

3.5 Biochar properties

Biochar properties vary widely and determine its suitability for different applications. They can be influenced in three ways: feedstock selection, process parameters, and reactor design. The choice of feedstock is the most dominant influencing factor, as the feedstock composition and structure directly affect the biochar quality, e.g. a feedstock rich in inorganics will always lead to a biochar with a high ash content and consequently a low carbon content. Process parameters are the second major factor influencing biochar properties. Pyrolysis temperature, heating rate, and residence time determine the extent of carbonization and the balance between organic and inorganic fractions. Higher temperatures and longer residence times are associated with a higher degree of biomass degradation and structural rearrangement, yielding biochars with increased aromaticity, greater carbon stability, higher pH, and reduced yields. Lower temperatures preserve more volatile compounds and reactive surface groups, with higher yields and lower matrix stability. The choice of reactor influences the product properties by directly enabling the desired carbonization conditions. In addition, the reactor design may also lead to contamination, i.e., by enabling recondensation of gaseous products on the biochar, which may lead to increased amounts of toxic components, such as polycyclic aromatic hydrocarbons (PAHs). The formation of those can be avoided by a rapid separation of biochar and pyrolysis gases so condensation of PAH is hindered [107].

High-temperature biochar has a higher carbon (C) content and a higher proportion of condensed, "hard", fixed, recalcitrant C (that cannot be degraded microbially) and is therefore more stable and contributes more to CDR (Figure 10). However, biochar yield decreases with temperature, so there is an optimum between carbon retention and CDR in the form of stable carbon. Also, often porosity increases with increasing pyrolysis temperature – up to internal surface areas of up to 1000 m^2/g. Higher porosity and higher degree of aromaticity increase the binding of organic pollutants including PFAS, increasing both capacity and affinity, respectively. Higher porosity in the µm size range also increases water retention, which can provide climate change adaptation especially in tropical soils. For positive effects on soil fertility, however, lower-temperature biochar is often more beneficial, since functional groups contribute positively to nutrient retention.

Biochar can also catalyze chemical redox reactions (see chapter 8, Research and Development) [108]and aid in degradation of certain pollutants [109], as well as enhance beneficial soil microbial processes [110] and even the digestion in husbandry animals [111]. Also, nitrification is enhanced, for example leading to lower N_2O emissions [108]. In the case of biochar produced at high-temperatures, more aromatic structures are formed, resulting into better electron conductivity [112].

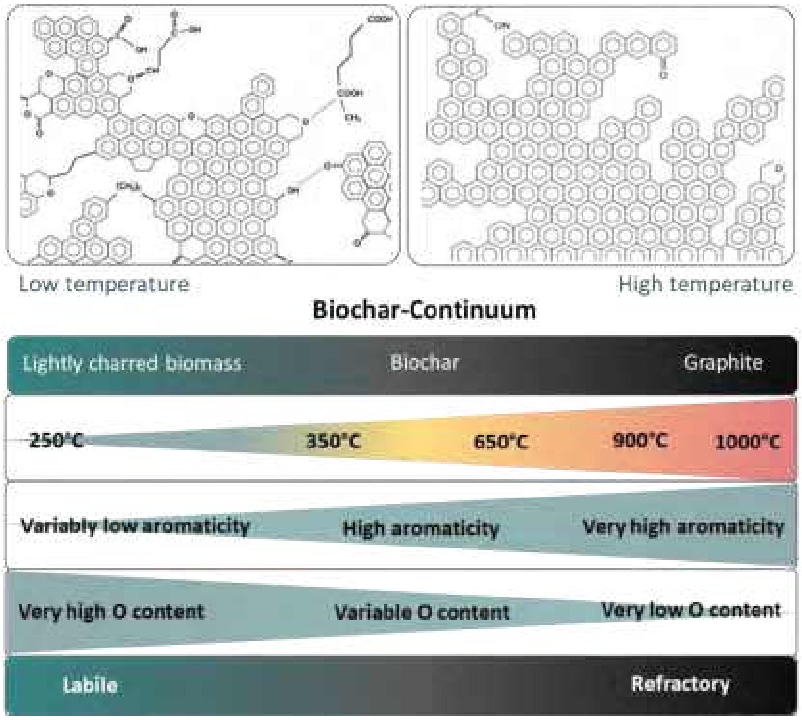

Figure 10 Properties of biochar produced at various temperatures. Adapted from [113]

This section provides an overview of the main properties of biochar and the factors that influence them. Given the wide range of possible feedstocks and the diversity of measurable properties, only a selection can be presented here. Ideally, the focus would be on the most important properties; however, what is considered most important depends strongly on the intended application. Therefore, the properties discussed in this chapter are those often regarded as the most relevant for large-scale biochar use, especially in the context of carbon dioxide removal. The chapter is based on an extensive literature evaluation where experimental data from many scientific publications were collected, combined and compared to show the impact of feedstock and production conditions on the various properties. The property changes during pyrolysis are mainly shown in relation to the production temperature. This approach has been chosen as the production temperature is the production setting that has the most influence on the properties of biochar. Furthermore, pyrolysis temperature is the parameter that is uniformly reported in biochar literature, providing a foundation for comparison. A production temperature of zero in the graphical evaluation corresponds to the feedstock.

3.5.1 Product yield

The product yield, i.e. how much biochar is produced from a given amount of feedstock, is an essential parameter for biochar production. It shows not only how much material can be produced, but also gives an indication about the biochar qualities, such as carbonization degree and ash content. The mass yield is best determined gravimetrically by weighing feedstock and biochar and relating them to one another. Figure 11 shows the mass yield of biochars from woody feedstocks produced at different temperatures.

The mass yield of woody biochars decreased systematically with increasing pyrolysis temperature. At around 350 °C, typical yields range between 40% and 55%. As the temperature rises to 600 °C and beyond, the yield commonly drops to around 35-30%. This trend reflects the progressive devolatilization of the feedstock, where hemicellulose, cellulose, and finally lignin decomposes and releases volatiles. Above approximately 500 °C, the loss rate slows, and the yield approached a lower asymptote corresponding to the remaining fixed carbon and inorganic ash fraction.

The strong temperature dependence of mass yield is one of the key parameters defining the trade-off between quantity and quality in biochar production. Higher temperatures improve carbonization, aromaticity, and long-term stability of the char, but come at the cost of reduced yield. Therefore, the selected pyrolysis temperature determines whether the process is optimized toward maximizing carbon removal efficiency (high-temperature chars with low yield and high stability) or toward material recovery (lower-temperature chars with higher yield and greater volatile content).

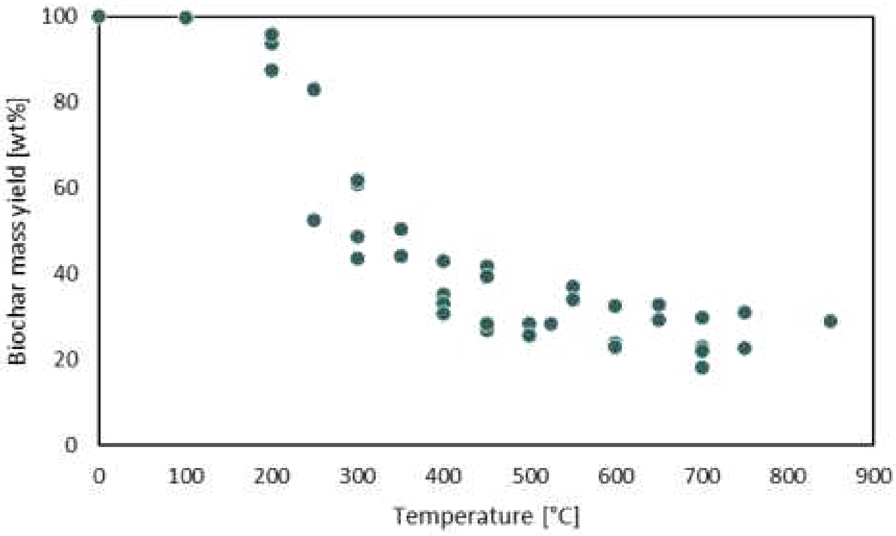

Figure 11 ***Mass yield*** *of biochars produced from* ***wood*** *at different pyrolysis temperatures [114–122].*

The inverse relation between pyrolysis temperature and product yield is well established for wood-based materials and generally less pronounced for feedstocks with higher ash content. This is because much of the biomass ash (inorganics) remain in the solid phase at typical pyrolysis conditions.

Figure 12 shows the mass yield of biochars produced from sewage sludge and manure. In contrast to woody feedstocks, the yield for sludge-derived biochars remains much higher across the entire temperature range, often exceeding 60% even at temperatures above 600 °C. This high yield is largely due to the high mineral content of sewage sludge. During pyrolysis, the organic fraction of the sludge volatilizes, while the inorganic matter – silicates, phosphates, carbonates, and metal oxides – remain largely as solid residue. As a result, the reported biochar mass yield reflects not only the carbonized organic fraction, but largely the non-combustible ash, which does not contribute to the carbon sequestration potential of the product. Therefore, while a high mass yield may seem desirable at first glance, in ash-rich materials it is not necessarily a sign of a good biochar or an efficient pyrolysis process. The elevated yield represents mineral retention rather than increased carbon recovery.

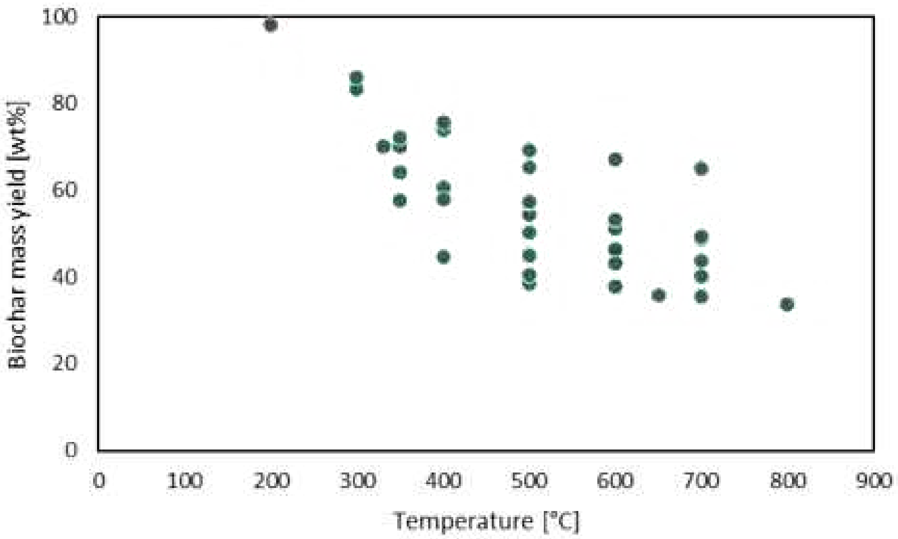

Figure 12 ***Mass yield*** *of biochars produced from* ***sewage sludge*** *and* ***manure*** *at different temperatures [123–133].*

3.5.2 Structural and chemical characteristics

During the carbonization process, the biomass structure is degraded and rearranged. As a result, the chemical composition and characteristics of the material undergo significant changes as carbonization conditions become more severe (i.e., increased temperature or residence time).

One common way to characterize solid fuels is by their **proximate composition**: volatile matter, ash, and fixed carbon. Volatile matter is the amount of mass that is easily volatilized into gaseous products during heating. Ash is the inorganic fraction that remains after combustion. Fixed carbon is calculated by difference between non-volatile matter and ash, while moisture is determined separately during proximate analysis. As biochar is hygroscopic, moisture content is strongly influenced by humidity and storage conditions and does not represent an intrinsic material property; fixed carbon is therefore reported on a dry basis. While fixed carbon from proximate analysis is a widely used and standardized metric for comparing biochars and assessing trends with increasing carbonization severity, it is an indirect measure, and uncertainty can be reduced through controlled pre-drying, replicate analyses, and complementary elemental analysis when evaluating carbon sequestration potential.

The proximate composition of biochar changes systematically with increasing carbonization severity. As shown in Figure 13, the share of volatile matter decreased steadily with rising pyrolysis temperature, while the fraction of fixed carbon increases correspondingly[1]. This shift reflects the gradual loss of oxygenated compounds, leaving more of the condensed aromatic structures that form at relatively low temperatures. For most lignocellulosic feedstocks, fixed carbon is the main component of the biochar produced at high temperatures.

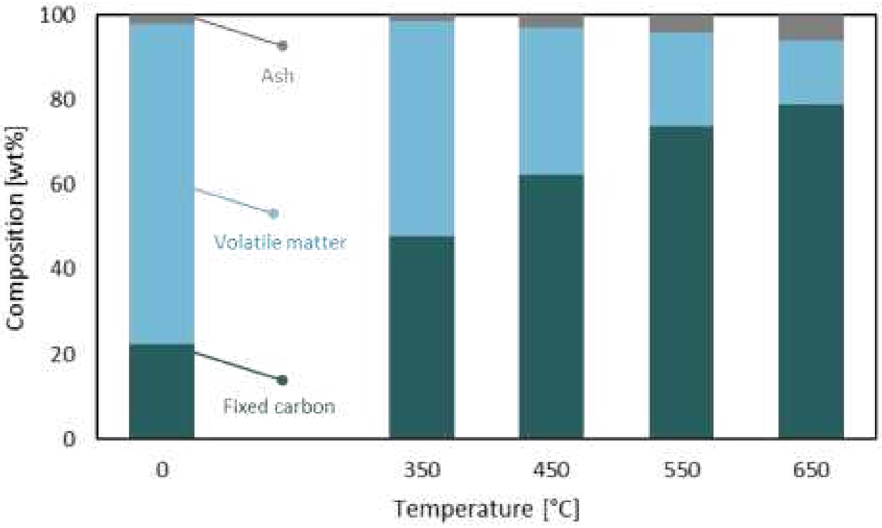

*Figure 13 **Proximate** composition (dry basis) of **wood** and wood-derived biochars produced at different temperatures [134]*

This correlation between volatile matter content and fixed carbon content is shown in Figure 14. Woody biomass contains around 80% (by weight) of volatile components. With increasing degree of carbonization, these are reduced to a share of less than 20% for pyrolysis

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[1] It should be noted that volatile matter and ash are determined analytically, whereas fixed carbon is calculated as the remaining difference to one hundred percent.

temperatures above 600 °C. Consequently, the relative fixed carbon content is increased from below 20% in wood feedstocks to around 90% for high pyrolysis temperature.

With sufficiently severe carbonization conditions (a combination of temperature and residence time), it is possible to remove most of the volatiles from the biomass – regardless of feedstock. This yields a very high fixed carbon content (both on a dry ash free and dry basis) for woody biochars, because the feedstock is typically low in ash content. For other materials with a higher share of inorganics, similarly high fixed carbon contents are not achievable due to the ash accumulation.

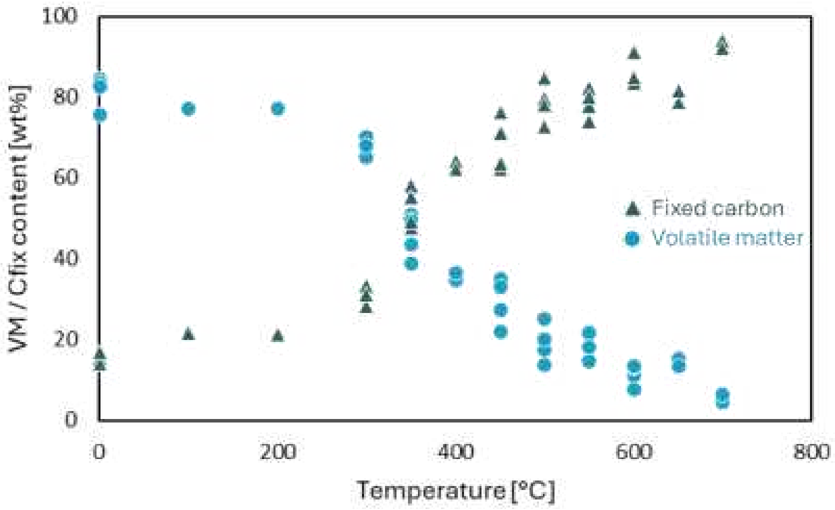

Figure 14 ***Volatile matter*** *and* ***fixed carbon*** *(dry basis) of biochars produced from* ***wood*** *at different pyrolysis temperatures [118,134,135]*

The **ash content** typically increased with pyrolysis temperature, as illustrated in Figure 15. This is not because minerals are formed during pyrolysis, but because the organic matter is progressively removed while the inorganic portion largely remains in the solid phase. Consequently, the apparent ash fraction grows then expressed on a mass basis. The extent of this increase depends strongly on the feedstock. Aquatic and herbaceous materials, but especially sludges, often contain substantially higher initial as content than woody biomass, leading to a higher residual ash after carbonization.

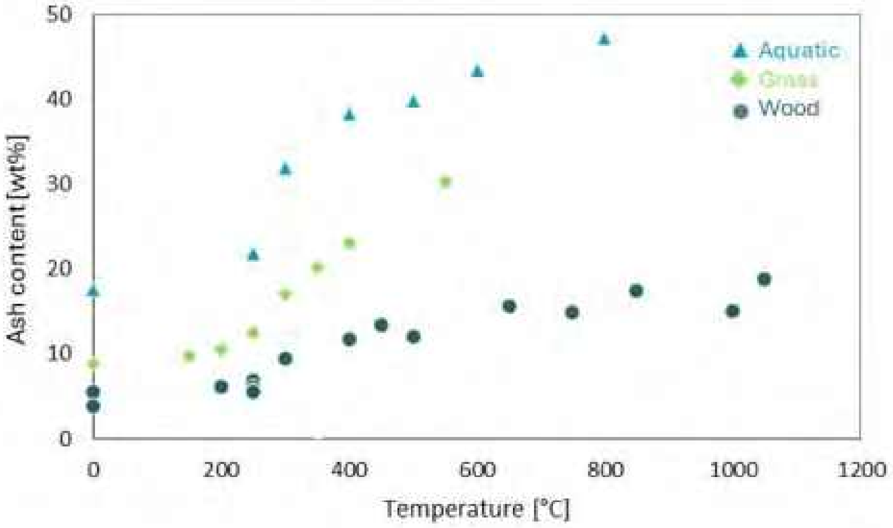

Figure 15 ***Ash content*** *(dry basis) of biochars from different feedstocks produced at different pyrolysis temperatures [117,136]*

From a functional point of view, the proximate composition provides a rapid first indication of biochar properties. A high fixed carbon content and low volatile matter content are typically associated with a greater thermal stability, lower reactivity, and improved long-term carbon sequestration potential.

Closely related to its proximate composition is the elemental composition, i.e., the relative content of carbon C, hydrogen H, nitrogen N, and oxygen O. The difference between the carbon content and the fixed carbon content is that the latter represents the solid carbon fraction remaining after release of volatiles during pyrolysis, whereas the total carbon content also includes carbon contained in volatile or oxygenated compounds. The fixed carbon thus reflets the degree of carbonization and energy density, while the elemental composition provides a more direct picture of the chemical structure and reactivity of the material.

The carbon content is a property that is almost always reported for biochar and serves as a quality indicator to guide possible applications. In addition to reporting biochar properties, it is important to consider the reference state of the biochar product, which defines the basis in which analytical results are expressed – for example, *as received*, *dry*, or *dry ash-free*. They specify whether moisture and ash are included in the calculation of percentages. Biochar is completely dry directly after pyrolysis due to the high production temperature. Biochar produced at scale is often quenched with water, both to rapidly decrease the temperature of the material after the process, but also for safety reasons to minimize risk of dust and fire. A carbon content reported on a dry basis therefore represents the intrinsic composition of the solid, but the actual product as delivered may contain much less carbon per unit weight. Without specifying the reference state, such differences can easily lead to misinterpretations when comparing results and estimating carbon yields.

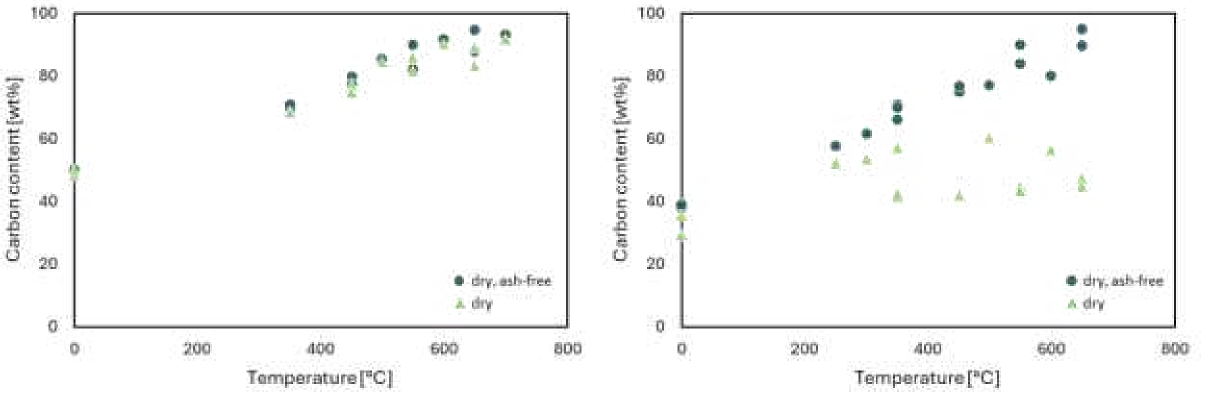

*Figure 16 Comparison of **carbon content** reported on **dry** and **dry ash-free** basis for woody biochars (left) and biochars from residues and waste (right) [137,138].*

Figure 16 illustrates this effect for the ash content. On the left, the carbon content for woody biochars is shown. The circles depict the dry ash-free basis, whereas the triangles show the corresponding carbon values on a dry basis. Biochars from stemwood tend to have a very low ash content, which is why the carbon values for the dry and dry ash-free reference states are close together and would likely make only a small difference when interpreting results. This is different however for feedstocks with a high amount or inorganic components. Figure 16 right shows the carbon content for the same two reference states for biochars from residues and waste. For a production temperature of 600 °C, the carbon content in this example is around 90% on a dry and ash-free bases. However, when including the ash content, the carbon content is only just over 40%. In practice, the biochar cannot be used in a dry ash-free state, and it is therefore important to consider the correct reference state for the purpose.

Figure 17 shows the evolution of carbon and corresponding oxygen contents (on a dry, ash-free basis) with increasing pyrolysis temperature for woody feedstocks. The figure illustrates nicely how the two elements undergo a mirrored evolution during pyrolysis. As the temperature rises, carbon becomes progressively enriched due to the condensation of the organic matrix, while oxygen is gradually removed through dehydration, decarboxylation, and decarbonylation reactions. This inverse relationship reflects the increasing degree of aromaticity and thermal maturity of the material. At higher temperatures, the resulting biochar approaches a composition dominated by elemental carbon with only minor oxygen functionalities, indicating chemical stability and reduced polarity compared to low-temperature chars.

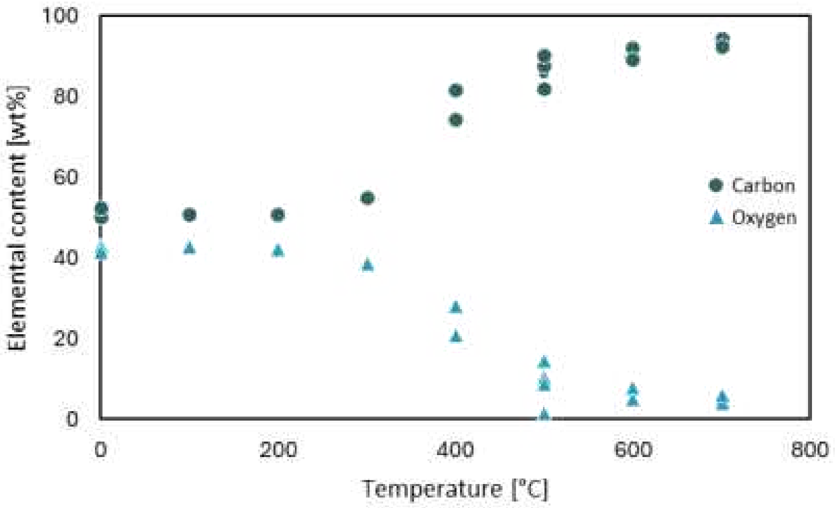

Figure 17 ***Carbon*** *and* ***oxygen*** *(dry ash-free) content of biochars made from* ***wood*** *at different pyrolysis temperatures [139,140].*

Figure 18 presents the Van Krevelen diagram, showing the relationship between atomic hydrogen-to-carbon (H/C) ratio and oxygen-to-carbon (O/C) ratios for woody biochars produced at different pyrolysis temperatures. The clear downward and leftward trend reflects the progressive removal of oxygen and hydrogen relative to carbon with increasing temperatures. Biomass has a high amount of aliphatic and oxygenated structures. A rise in temperature leads to dehydration, decarboxylation and condensation reactions, which drive the composition toward the lower left, representing highly aromatic and thermally stable carbon matrices. At the highest temperatures, the composition approaches the compositional range of graphite, demonstrating the transformation of the original biomass into a condensed, carbon-rich solid with strongly reduced polarity and reactivity. A particularly steep change occurs in the temperature range of torrefaction (200-350 °C), where both atomic ratios decrease sharply within a relatively narrow temperature interval. During these conditions, exothermic reactions may occur, which can accelerate structural and chemical changes, and make this temperature window much more difficult to control in terms of the consistent and predictable product quality. Beyond this stage, further increase in temperature causes slower, more gradual decreases in atomic ratios, reflecting the continued aromatization and condensation of the carbon matrix.

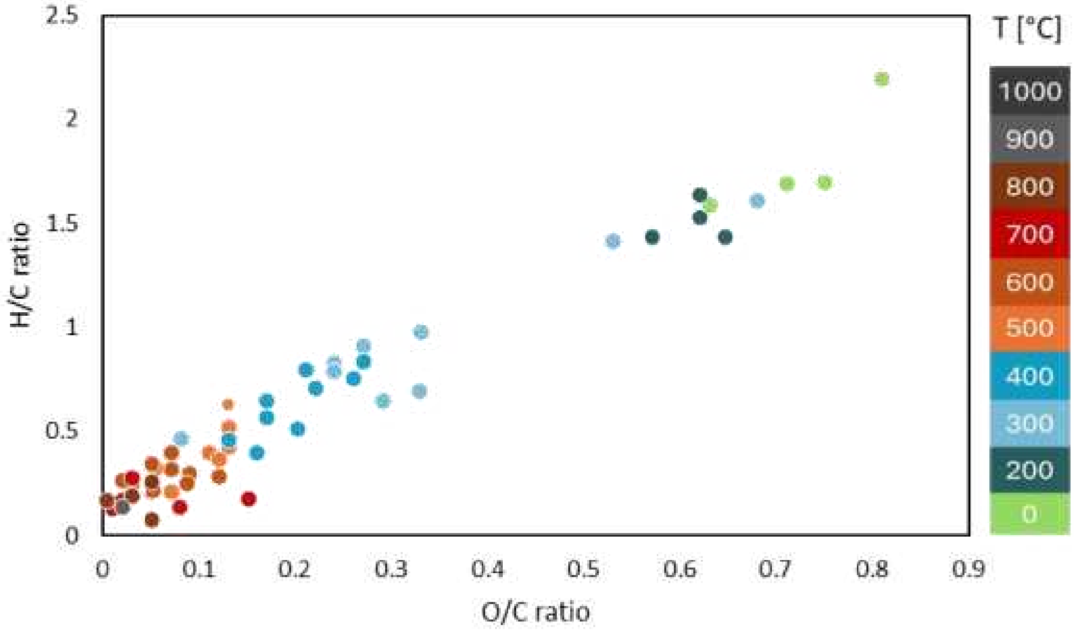

Figure 18 Evolution of ***molar ratios*** *O/C and H/C during increasing pyrolysis temperature,* ***woody*** *feedstocks [120,137,140–145]*

The **surface area** (and the closely related porosity) of biochar is one of its most important functional properties, determining its capacity to adsorb gases, retain moisture, and bind organic or inorganic molecules. The development of surface area and porosity is closely linked to the extent of carbonization. It is also a property that varies significantly for different feedstocks. Figure 19 shows a compilation of literature-reported surface areas for wood-derived biochars produced at different temperatures. Overall, the values show very large variations for the same production temperature. However, the clear trend is the increase of surface area with increasing pyrolysis temperatures. Woody biomass does not have a noteworthy surface area, often of only a few square meters per gram. The progressive volatilization and the formation of a porous carbon network as the structure becomes more ordered and aromatic leads to a rapid increase in surface area with increasing temperature. For pyrolysis temperatures above 600 °C, surface areas of several hundred square meters per gram are common.

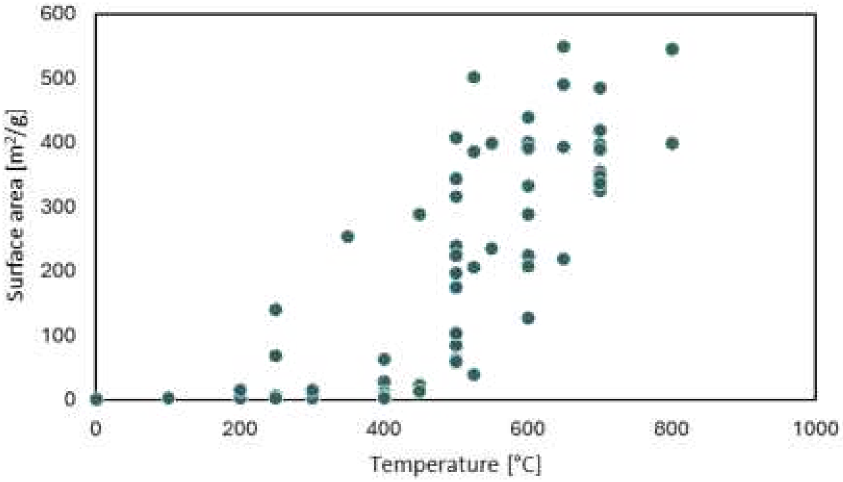

Figure 19 ***Surface area*** *(measured with BET and* N_2*) of biochars produced from* ***wood*** *at different pyrolysis temperatures [114,115,118,121,144,146–152]*

The surface area may look very different for other feedstocks. Figure 20 shows the surface area of biochars produced from manure. Also here, an increasing trend for surface area with increasing production temperature can be seen. However, the total surface area seems to stay below 100 m^2/g, and with that, far below the surface area of wood biochars.

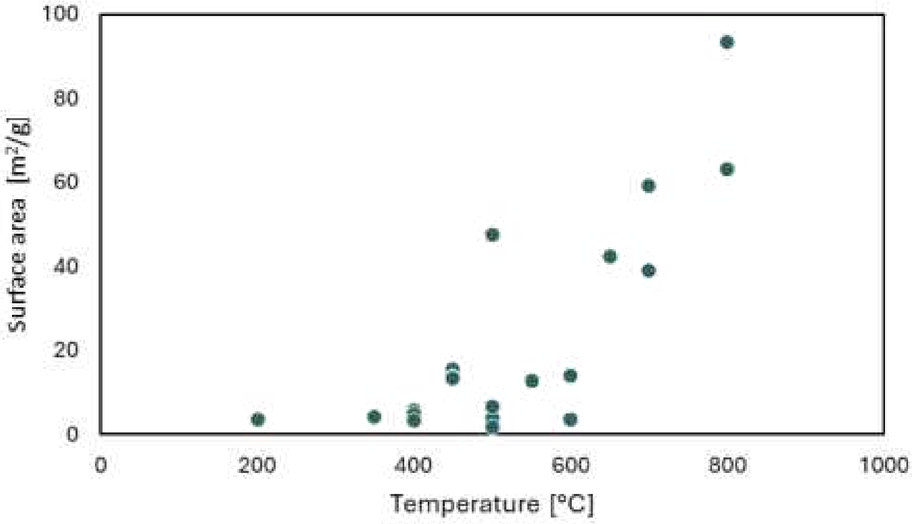

Figure 20 ***Surface area*** *(measured with BET and* N_2*) of biochars produced from* ***manure*** *at different pyrolysis temperatures [129,130,153–156]*

Different measurement techniques provide complementary insight into pore size distribution. CO_2 adsorption at 0 °C is used to quantify fine pores (<1.5 nm), which are particularly relevant for the sorption of small gas molecules such as CO_2, N_2O, and H_2O. N_2 adsorption at –198 °C captures pores in the range of roughly 1.5–30 nm, important for the binding of larger organic molecules and pollutants. Mercury porosimetry extends the measurable range up to about

400 µm, mainly characterizing meso- and macropores that influence water retention, while gas permeation measurements (100–500 µm) reflect the connectivity of larger pores relevant for moisture transport and air flow.

The overall pore structure of biochar is thus spanning several orders of magnitude in size. Micropores contribute most to surface area and adsorption of gases, while meso- and macropores dominate water retention and flow properties. Figure 21 shows examples of the porous structure of woody biochars.

The evolution of surface area with temperature therefore mirrors the transition from a heterogeneous, polymeric biomass to a more graphitized carbon matrix. This property underlies many of the functional advantages of biochar, from its reactivity and sorption capacity to its persistence as a stable carbon form in environmental and technical applications.

Surface area reported in the literature is mostly measured with N_2, and the result of the measurement therefore a characterization of the surface area of the respective pores. When measuring with CO_2, the result may look very different. Assessing biochar's surface area should therefore always be done with the desired application in mind.

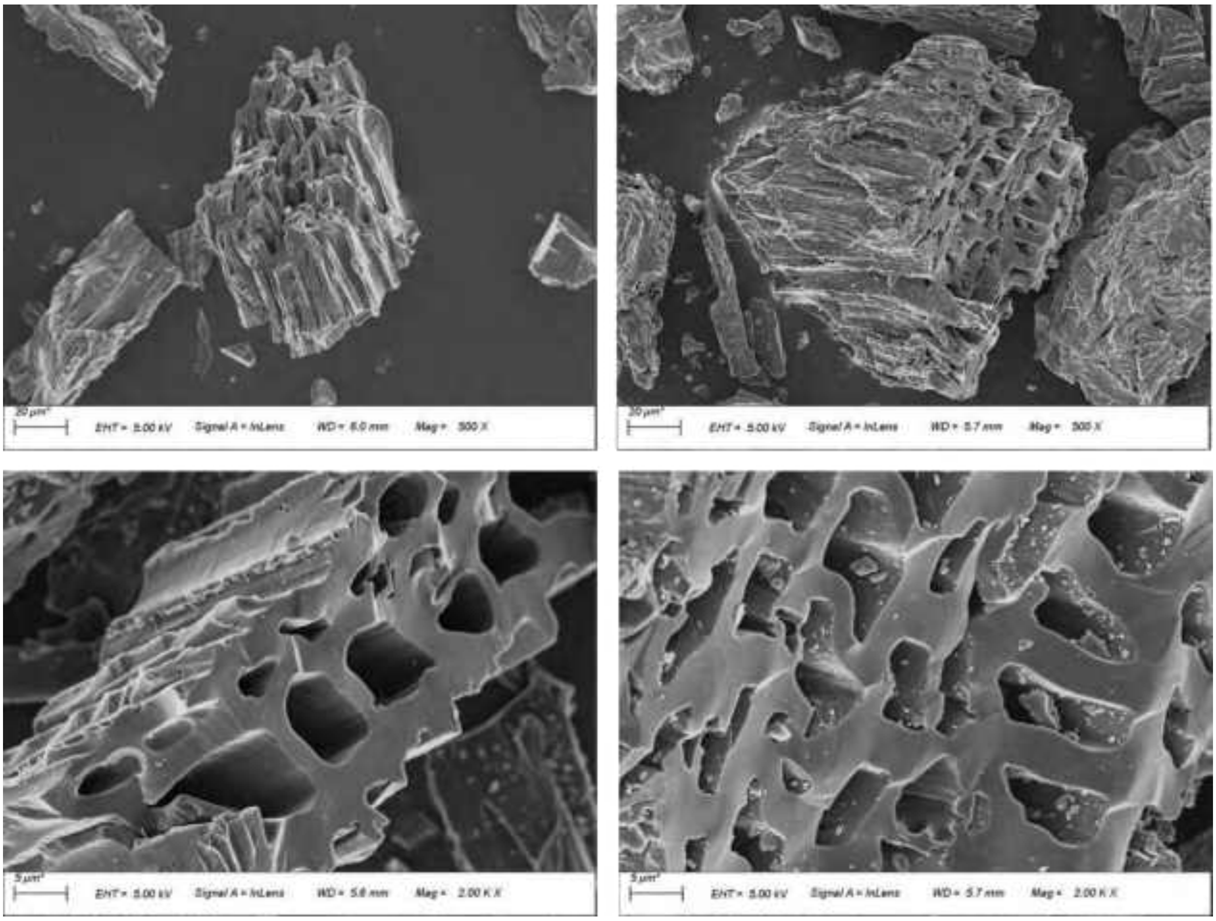

Figure 21. Biochar made from forestry residues - wood chip pellets at 500 C. The images, 20 µm scale (500x magnification) above, 5 µm (2000x mag) below, illustrate the porous nature of biochar particles. Seen as the openings and channels at a few µm size. Photos: Erlend Sørmo

The **pH** of biochar is another key property influencing its interaction with soils, water, and other materials. Ash shown in Figure 22, the pH of wood-derived biochars increases with pyrolysis temperature. At low temperatures around 300 – 400 °C, typical pH values range from about 6 to 8, while biochar produced above 700 °C can reach values exceeding 10.

The progressive alkalinization with temperature results from several concurrent processes. During pyrolysis, acidic functional groups – such as carboxyls and phenols – are decomposed and volatilized, reducing the number of proton-donating sites on the biochar surface. At the same time, basic mineral components (carbonates, oxides, and hydroxides of alkali and alkaline earth metals) become increasingly concentrated in the solid phase as organic matter is removed. Together, these effects shift the surface chemistry towards more basic conditions.

Due to the effect of inorganics on the pH of biochars, biochars produced from wood generally show more moderate pH values, while those derived from ash-rich materials such as crop residues, manures and sewage sludge can exhibit higher alkalinity even at moderate process temperatures.

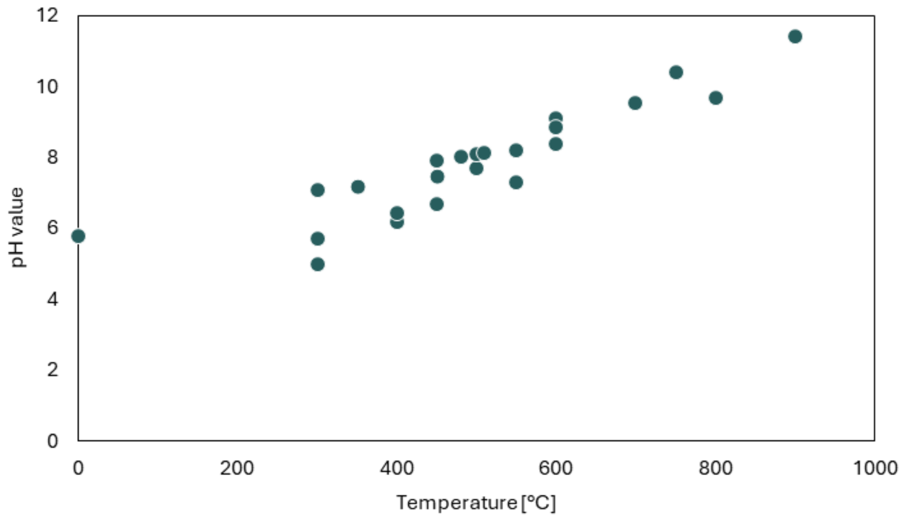

Figure 22 ***pH*** *of* ***woody biochars*** *produced at different temperatures [114,115,150,157–163]*

The pH of biochar is an important indicator of its potential applications. More alkaline chars can act as liming agents and help neutralize acidic soils, while low-temperature, near-neutral chars may be better suited for use in systems sensitive to pH changes, such as potting substrates or microbial growth media. In engineered materials, high pH biochars are sometimes preferred for catalysis or adsorption processes, where basic surface sites can enhance reactivity toward certain compounds.

3.5.3 Summary of biochar properties

Biochar properties are highly variable and primarily controlled by feedstock composition and production conditions. Key characteristics include carbon content, ash content, pH, surface area, pore structure, and atomic H/C and O/C ratios, which indicate the degree of carbonization and long-term stability.

Increasing pyrolysis temperature generally reduces yield but increases carbon content, aromaticity, surface area, and stability, while lower temperatures preserve more functional groups relevant for nutrient retention and biological interactions.

Feedstock plays a central role: woody biomass typically yields high-carbon, low-ash biochars, whereas agricultural residues and waste-derived feedstocks produce more ash- and nutrient-rich biochars with lower relative carbon content.

Overall, no single biochar is universally optimal. Instead, properties must be tailored to the intended application, balancing carbon stability, surface functionality, and mineral composition. Moreover, what is considered a “good” biochar, is highly dependent on the application.

4. Overview of biochar applications

Biochar has multiple applications, ranging from agricultural soil quality improvement to sorbent for contaminants, filler in concrete and asphalt, replacement for coke in metallurgical processes and many more [3,164]. The motivation of using biochar can be to make use of its carbon and/or energy content, benefit from its high surface area or store carbon. Some applications can have multiple motivations. One way to distinguish biochar applications is to classify them according to whether or not the carbon is conserved. Feedstock selection and production conditions affect application directly, which means that the whole process of feedstock selection, production and application should be an integrated design to achieve maximum benefits [36]. The degree to which each application has been researched varies substantially. Table 3 summarizes areas of application which have been relatively thoroughly documented in scientific literature. The suitable feedstocks, the carbon removal mechanism involved, and other benefits are also presented. Note that this summary is not exhaustive – there are novel and niche applications being introduced continuously. See e.g. [164] for an overview of novel alternative applications.

Table 3 Overview of biochar applications

Application	Suitable feedstocks	Carbon removal effect	Other benefits	Trade-offs/challenges	Ref.
Carbon Conserving					
Agricultural soil amendment	Lignocellulosic, animal-based (except marine biomass), sewage sludge (dependent on metal content)	Direct carbon storage in soil, potential for decreased negative priming (increased natural organic matter stabilization)	Increased water and nutrient retention potential for higher crop yields (increased plant growth), improved soil aggregation, potential for reduction of N2O-emissions, high yield chars produced moderate temperature can be used	Clean biochars needed, low solubility of phosphorus accumulated in biochar, priming effect negligible or positive in poor fertility, alkaline, temperate soil	[1–3]
Sorbent stabilization of contaminated soils	Lignocellulosic, sewage	Direct carbon storage in soil, potential for decreased or negative priming (increased natural organic matter), offset if fossil activated carbon is replaced	Strong binding of contaminants that reduces leaching and bioavailability	High temperature and hence low yield biochars typically needed, issues related to leaching from metal enriched biochars not fully explored	[136–138]
Sorbent stabilization of contaminated sediments	Lignocellulosic	Direct carbon storage in sediment, offset if fossil activated carbon is replaced	Strong binding of contaminants that reduces leaching and bioavailability	High temperature and hence low yield biochars typically needed, potential negative effects on bentic fauna, potential release of arsenic and antimony in multi-contaminated sediments	[138–141]
Additive in concrete	Potentially all	Direct carbon storage in concrete by biochar addition, and potential for improvement of carbonation process which can sequester CO_2 released from concrete	Potential for reducing environmental footprint of concrete through lower emissions from transport extraction of natural materials if lightweight biochar partially replaces conventional fillers and aggregates	Can lead to reduced strength of concrete	[41,64,137,138]
Additive in asphalt	Potentially all	Direct carbon storage in asphalt by biochar addition	Can improve temperature susceptibility, rutting resistance, and ageing effects of asphalt. Can also contribute to waste management by making use of low quality waste biochars.	Unknown (low TRL)	[40,64,140]
Additive in cement stabilization of peat and quick clay	Potentially all	Direct carbon storage in cement stabilized clay or peat. Can reduce amount of cement used in the process	Biochar improves solidification strength in peat soil stabilization	Some biochars can reduce solidification strength in clays - more research needed to understand effects	[140,141]

Application	Suitable feedstocks	Carbon storage effect	Other benefits	Trade-offs/challenges	Ref.
Potentially carbon conserving					
Additive to composting	Lignocellulosic	Depends on final disposal of compost - could be direct storage if applied to soil	Accelerates composting process by catalyzing microbial processes and improves compost effect as a fertilizer/soil amendment	None	[133,135]
Feed additive	Lignocellulosic	Potential reduction of methane from animals, further effects depend on final disposal of manure - could be direct storage if applied to soil	Improved animal growth performance, blood profiles, egg yield, ability to resist pathogens, and removal of toxins. Soil amendment benefits expected if biochar-containing manure is applied to soils	Clean biochars needed; reduced availability of minerals and vitamins due to strong binding	[135,142]
Additive to anaerobic digestion	Potentially all	Depends on final disposal of digestate - could result in direct carbon storage if used as a soil amendment	Increases methane generation and microbial resilience through catalysing anaerobic digestion and hence the process potential for replacing fossil gas with biogas	Mechanisms not fully understood, input cost vs. generated benefits unclear at present	[143,144]
Sorbents for water treatment	Lignocellulosic, sewage sludge, microalgae	Depends on final disposal - could be none if incinerated or direct storage if landfilled, offset if fossil activated carbon is replaced	Allows for value chain generation combining products from wastewater treatment with generation of sorbent for the same treatment process	Issues related to release of metals and nutrients present in biochar sorbents not thoroughly explored	[4–7]
Electrode material	Lignocellulosic	Replaces fossil based electrode materials. Further biogenic CDR effect depends on final disposal of spent electrode material.	Lower overall environmental footprint. Reduced costs.	Somewhat lower effect than traditional materials	[142,143]
Electrochemical treatment of contaminated groundwater	Animal-based, sewage sludge, modified lignocellulosic	Potentially direct carbon storage in aquifers (expected, but not explored)	Treatment of contaminated groundwater where biochar acts as a catalyst for electrochemical reactions that decompose organic contaminants	Relatively small amounts needed, hence low BCS effect expected	[144–146]
Carbon converting					
Metallurgy	Lignocellulosic (wood)	Replacement for fossil carbon, which leads to net reduction in emissions	Could contribute to lower NO_x and SO_x emissions from electric arc furnaces in steelmaking	Sensitive to impurities requires high calorific (mainly clean wood biochars). Large demand which can usurp other more environmentally beneficial	[8,9]
Fuel	Potentially all	Replacement for fossil carbon, which leads to net reduction in emissions	Can improve local air quality through reduced emissions when replacing coal in cooking fires.	Best effect from biochars with high calorific value (wood biochars). Binders needed to produce briquettes which result in higher emissions. Can usurp other more environmentally beneficial applications	[147,148]

5. Biochar and carbon dioxide removal (CDR)

Biochar offers one of the few ways to permanently remove CO_2 from the atmosphere while providing a material enriched in permanent carbon with a porous structure that may be used for several applications (see Chapter 4). While it was scarcely heard of two decades ago, biochar has emerged as one of the most ready-to-deploy CDR options, notably because pyrolysis is a proven and scalable technology increasingly recognized by farmers and the industry. By 2018, the UN's IPCC (Intergovernmental Panel on Climate Change) formally acknowledged biochar/pyrolysis as a promising NET (Negative Emission Technology) [165], and one year later, biochar entered carbon markets with its first issued CDR [166]. In more recent years, biochar has constituted the bulk of durable carbon removal credits issued in voluntary carbon markets. Globally, biochar has established itself as one of the most mature CDR methods, with significant scaling-up underway and support from scientists, the market and policymakers alike.

While there are ongoing discussions about the precise definition and interpretation of CDR and whether biochar produced from agricultural and forestry residues classifies rather as reduced emissions [167] than as CDR, the whole biochar chain fulfills the purpose of CDR with potential to be net negative. Since CO_2 removal from the atmosphere is an essential part of CDR, the time lag between storage and removal for long rotation feedstocks could be a consideration in future discussions. The Carbon Removal Certification Framework (CRCF), formally established by Regulation (EU) 2024/3012 and expanded by the February 3, 2026 delegated act, is a voluntary EU-wide standard designed to certify high-quality carbon removals [168]. Its primary purpose is to scale up carbon removal technologies to meet the EU's 2050 climate-neutrality goals while preventing "greenwashing" through a unified, rigorous verification system, and it has formally categorized BCR as a permanent carbon removal activity. Biochar systems have substantial potential to contribute to climate change mitigation, with recent global estimates placing sustainable CDR potential at around 2.7 Gt CO_{2eq} per year [169]. The CDR potential of biochar, through C storage in soils, is not the only climate mitigation effect generated by biomass pyrolysis. Three additional effects occur. First, there can be a co-production of combined heat and power (CHP), which can be as large as the CDR effect of biochar, thereby doubling its climate change mitigation effect [30]. Second, applying biochar to soils has been proven to substantially reduce N_2O emissions [170]. Third, pyrolyzing certain types of bio-resources, such as sugarcane bagasse and rice husk, avoids large CH_4 emissions caused by untreated, decaying waste biomass. Here, pyrolysis converts waste biomass into a bioresource. Taking all these positive effects into consideration, the total global mitigation effect of pyrolysis for biochar production reaches up to 10.3 Gt CO_{2eq} per year [169]. In other words, the total mitigation effect can be substantially higher than the amount of carbon sequestered in biochar itself. Estimated potentials vary: lower, yet still significant, values come from sustainable scenarios using existing biomass wastes, while higher values assume dedicated biomass production and crediting of energy by-products. These figures are projections for the future, and their realization depends mainly on how quickly industries scale up and how effectively policies create supportive frameworks.

Most carbon sequestration estimates assume biochar is applied to soils, since this is the primary intended use that also improves soil fertility and remediates environmental pollutants. However, biochar carbon is stable in many environments, including building materials, cement, and asphalt as discussed in Sections 7.1 and 7.2. The following sections in this chapter present how biochar permanence is defined (Section 5.1), the science behind biochar stability in soil (Section 5.2), and the different methods currently applied for quantifying permanence (Sections 5.3). Positive effects of biochar on increasing the amount and stability of non-biochar C in soils, i.e., indirect CDR through so-called priming, is presented last in Section 5.4.

5.1 Biochar permanence - what it is and why does it matter

Permanence describes the fraction of biochar carbon that remains out of the atmosphere over a defined period – typically 100, 200 or 1000 years. It is expressed as a *durable fraction* (F_{perm}), which represents how much of the biochar's carbon is expected to stay stored over time [171]:

$$t_{CO_2eq\ stored} = \text{biochar mass} \times C_{org} \times F_{perm} \times 44/12$$

where C_{org} is the biochar's organic carbon content, and 44/12 is the molecular mass ratio between CO_2 and C. Note that $t_{CO2eq\ stored}$ represents the total carbon sequestration and not the net climate effect, which needs to be calculated through a life cycle analysis.

Permanence is essential because it underpins the climate credibility and reliability of biochar projects. Durable storage is what separates carbon removals from short-lived mitigation measures. Regulators and carbon market actors therefore require transparent, evidence-based methods for determining F_{perm}. A consistent approach builds trust, ensures environmental integrity, and lowers investment risk by providing clear, comparable metrics across projects and programs.

In simple terms, the durable fraction answers the question *"Of all the carbon in a given biochar, what percentage will still be stored after the chosen time period?"*

For example, if F_{perm} = 0.70 on a 200-year horizon, about 70% of the biochar's carbon is expected to remain after 200 years. Programs convert that remaining carbon into tonnes of CO_2 equivalent using the 44/12 ratio.

As anthropogenic CO_2 emissions remain in the climate system for centuries, the CDR measures deployed for mitigation, such as biochar, must be valid for an equivalent time frame. Biochar Carbon Removal (BCR) is such a measure, providing permanent carbon removals. Because not all biochar products are equally stable, their degree of permanence needs to be assessed as accurately as possible. Such a permanence assessment serves three functions: 1) it guarantees precise climate accounting, 2) it ensures integrity of reporting by preventing over-crediting and strengthens confidence in reported outcomes, and 3) it provides a common basis for comparing projects that differ in feedstock, production, or end use, expressing storage durability as a standard fraction over 100, 200 or 1,000 years.

5.2 The science in brief: why biochar lasts for centuries to millennia

Biochar is a carbon-rich material formed when biomass is heated under low-oxygen conditions. The stability of biochar structures results from two successive and complementary chemical transformation processes that occur during pyrolysis: first aromatization, then condensation.

The first phase, aromatization, occurs primarily at pyrolysis temperatures between 350 °C and 500 °C, and involves the formation of aromatic rings, which are molecular structures highly resistant to breakdown. During aromatization, most oxygen, hydrogen, and other volatile elements are released as gases, which increases the carbon concentration in the biochar. As discussed earlier, this process is characterized by a substantial loss of mass (see Fig. 8 and 9) and a sharp, easily measurable decrease in the H/C_{org} ratio (see Fig. 15). Advanced molecular methods, such as ^{13}C nuclear magnetic resonance (^{13}C NMR), can also be used to study the aromatization process. These methods help scientists and engineers understand and adjust the pyrolysis process for specific feedstocks and applications. However, a simple measurement of the H/C_{org} ratio is sufficient for determining the degree of aromatization of a biochar at an operational level [172].

The second phase, condensation, involves the merging of individual aromatic rings (or small groups of rings) into larger polyaromatic sheets, a process that occurs with increasing intensity at pyrolysis temperatures above approximately 500 °C. This phase leads to further loss of oxygen and hydrogen atoms, although at a slower and more gradual rate than during aromatization. Consequently, the H/C_{org} ratio continues to decrease progressively. Advanced chemistry methods, such as determining benzene polycarboxylic acid (BPCA) biomarkers, can provide a deeper understanding of the condensation process. Nevertheless, for practical purposes, a simple measurement of the H/C_{org} ratio is a reliable indicator of how well the biochar has been carbonized, i.e., its position within the aromatization-condensation transformation continuum.

During this process, much of the biomass transforms into aromatic carbon structures, which are chemically stable and highly resistant to microbial decomposition. As the temperature of pyrolysis increases, these ring-shaped structures become more condensed and ordered, giving the resulting biochar its exceptional durability (see also structural drawing in Fig. 7 in section 3.5).

The aromatization and condensation processes convert easily degradable molecular structures present in plant biomass into highly recalcitrant and long-lived aromatic molecular structures. While fresh plant residues and compost typically decompose within months to years, biochar remains in soil for centuries or longer. This long-term stability explains why naturally occurring charred materials are still found in soils and sediments thousands of years after their formation [173,174].

In addition to biochar having exceptional intrinsic resistance to decomposition, there are environmental factors contributing to additional stabilization leading to increased long-term storage:

- Mineral interactions: Biochar can bind to soil minerals, protecting soil carbon from microbial access and oxidation (see also section 5.4).
- Low nutrient conditions: In poor soils, limited microbial activity further reduces decomposition.
- Matrix protection: When biochar is incorporated into long-lived materials such as concrete or asphalt, it becomes physically shielded, adding another layer of permanence.

Overall, biochar's chemical structure and environmental behaviour make it one of the most stable forms of organic carbon. This stability underpins its strong potential as a durable carbon dioxide removal (CDR) option, whether used in soils or embedded in building materials.

5.3 Quantifying permanence

Biochar C markets depend on having a reliable assessment of the long-term stability of biochar in soils, (the abovementioned F_{perm}). The scientific community has dedicated a lot of effort over the last 15 years to exactly this question, which is as challenging as it is important. Based on different lines of evidence, there is broad consensus that the residence time of biochar in soils ranges from centuries to millennia. This broad consensus, however, is not sufficient for operational purposes, and we need stability evaluations that can be applied affordably to all biochar types. Here, we will consider these different aspects.

5.3.1 Evidence base: What we can observe directly

The strongest empirical evidence for long-lived persistence comes from (i) long-term field observations and (ii) laboratory incubation studies designed to isolate biochar-derived CO_2 fluxes.

Long-term field evidence is now emerging for modern, deployed biochar. In one of the longest cultivated-field observations reported to date, biochar applied to a vineyard in 2009 (22 t/ha) was unearthed and characterised after ~15 years under conventional agricultural management. The study reports that key indicators of the durable fraction (including inertinite/semi-inertinite assessed by random reflectance, see below) were nearly unchanged between the original and recovered biochar (after accounting for inclusion of exogenous soil material), supporting the interpretation that a substantial fraction of the carbon remained highly persistent under real farm conditions [175].

Long-term field evidence is still limited in number and site diversity, but it is particularly valuable because it captures real-world drivers (management, weathering, soil mixing, mineral interactions) that cannot be fully reproduced in controlled incubations.

Anecdotal "evidence" is also coming from ancient sites where biochar was applied in the Amazon region (so-called Terra Preta soils) and in Japan. Biochar found in these regions has been dated to be over 2000-3000 years old, providing proof of its longevity. Also, these biochars still provide increased soil fertility, indicating long-term positive effects on soils as well.

5.3.2 Soil incubations and decay modelling: Strengths and Limitations

As direct measurement of biochar stability over centuries is not possible, the key method has been to measure biochar decomposition in soil extremely precisely over a few months to years, and extrapolate the data through modelling. The very high precision is reached through the use of C isotopes, either ^{14}C or ^{13}C.

The logic for this approach is robust: 1) biochar is actually incubated in soils, as in its intended use, 2) the approach is likely conservative, as it is based on the "initial" decomposition rate. To conduct accurate assessment of the stability of biochar in soils, the incubation of isotopically-labelled biochar in soils has been, until recently, the only gold standard used by the scientific community. Isotopic labelling renders possible to measure extremely low rates of biochar mineralization rates, i.e., the transformation of very small amounts of biochar C structure into CO_2. Such incubation studies have generally found biochar to be stable for at least centuries.

Rapid and cost-effective assessment of the long-term stability of any new biochar product cannot be achieved through isotopic incubations, as these are lengthy, expensive, and highly demanding analyses. Consequently, the scientific community has been developing chemical tests that can directly relate measurable properties of biochar to its stability in soils. These tests function by comparing a chemical property of a new biochar product to the same property measured on standard biochar series with published long-term stability data based on isotopic soil incubations (as described above). Of relevant chemical properties, the H/C_{org} atomic ratio is the most widely used [172,176] and the random reflectance (R0) is a more recent upcoming method.

5.3.3 Composition- and structure-based proxies

Because isotopic incubation is too slow and resource-intensive for routine certification of all biochar batches, permanence quantification has increasingly relied on simpler measurements of biochar characteristics, so-called proxies, that relate measurable biochar properties to expected stability.

5.3.3.1 H/C_{org} ratio (Hydrogen to Organic Carbon ratio)

Of all proxies, H/C_{org} remains the most widely used bulk proxy to determine the degree of carbonisation and aromaticity [172,176], and it is embedded in several permanence approaches. Recent work confirms H/C_{org} as a robust indicator of carbonisation. It only gives one number per biochar sample, though. Thus, one pitfall occurs when the biochar contains multiple carbon pools [177].

5.3.3.2 Random Incident Light Reflectance and Inertinite Benchmarking

Random Incident Light Reflectance (R_0) quantifies the presence of highly aromatised (persistent) carbon fractions and shows heterogeneity in composition. A rapidly expanding body of work applies R_0 to characterise biochar carbon structure and infer permanence-relevant fractions. Building on the concept that inertinite macerals represent extremely stable organic carbon, an “inertinite benchmark” approach has been proposed. An elegant feature of random reflectance measurements is that the biochar sample can be scanned and R_0 measured at hundreds of spots on the sample. Thus, a fraction of stable, permanent carbon is obtained for the individual sample. Measurements of R_0 also indicate that actual stability of biochar could extend from thousands to tens of thousands of years rather than hundreds of years [178]. An uncertainty with the random reflectance method is that it is based on reservoir geology under anoxic conditions. Currently there is a need for measurements of the mean residence time of inertinite in (oxic) soils to provide the ultimate evidence of the R_0 method for the quantification of biochar permanence [179].

5.3.3.3 Raman spectroscopy and molecular fingerprints

Several recent contributions advocate multi-method evidence, highlighting the value of combining spectroscopic and molecular fingerprinting approaches with bulk chemistry and reflectance:

- Micro-Raman comparisons show that biochars produced across a wide carbonisation temperature range exhibit structural evolution similar to naturally formed highly stable semifusinite/fusinites and propose multiple Raman benchmarks that could complement reflectance-based benchmarks for identifying highly carbonised (“inertinite-like”) material [180].

- Integration studies comparing R_0, H/C_{org}, Raman parameters, and pyrolysis gas chromatography-mass spectroscopy (Py-GC/MS) fingerprints show that, for many single-pool biochars, mean R_0 and H/C_{org} provide similar stability measurements. However, for multiple-pool biochars rich in highly stable aromatic carbon, the random reflectance method is needed for the demonstration of the highly carbonised fraction [181].

5.3.3.4 Implications for operational permanence quantification

Biochars produced at different temperatures can have distinct environmental functions, e.g., increasing soil fertility versus serving as a strong contaminant sorbent in remediation. Therefore, understanding how each measurement reflects stability directly affects how we can match the environmental benefits of biochar with the generation of carbon credits.

In summary, the scientific community currently has a robust method to evaluate biochar stability in soils: chemical proxies (H/C_{org}) calibrated on incubations of isotopically-labelled biochar in soils. However, this method may underestimate the real stability of the biochar. The newer inertinite method suggests that stability could be significantly higher for higher temperature biochars.

5.3.4 Commercial Standards

The methodologies outlined are implemented across a range of commercial standards and certification schemes, ensuring consistency and transparency in how biochar permanence is accounted for. Most current biochar carbon crediting standards take a conservative, science-based approach to permanence, using decay-curve models or fixed stability thresholds anchored by biochar properties to estimate long-term carbon retention. In practice, they rely on key durability indicators (especially the H/C_{org} stability ratio, often combined with factors like production temperature and end-use) and generally credit only the fraction of carbon expected to remain sequestered over a ~100-year horizon, with some programs introducing extended-duration credits (e.g. 200-year or 1000-year permanence labels) for exceptionally stable biochar. Table 4 provides an overview of current commercial standards used for certifying CDR from biochar.

Table 4 Overview of current commercial standards for BCR

Standard / Registry	Current Version / Date	Approach	Key Determinants	Crediting Horizon / Label
Global Biochar C-Sink (Carbon Standards International, CSI)	Formulas & Emission Factors (2025)	Curve-based permanence function (no single fixed period). Uses H/C_{org} stability classes and a conservative soil decay curve; non-soil applications can be treated as effectively inert within the illustrative window.	H/C_{org} class; end-use category (soil vs. material use).	Curve-based representation; outcomes often illustrated at 100 years. Longer (incl. millennial-scale) persistence may be addressed in supporting documentation.
EBC (material standard)	EBC Guidelines 10.4E (2024)	Material quality and stability thresholds (e.g. H/C_{org} gates) for biochar. Carbon accounting and permanence curves for biochar CDR are referenced to Global Biochar C-Sink rather than defined in EBC itself.	H/C_{org}; process / technology class.	No fixed accounting period under EBC. Permanence and crediting are handled via Global Biochar C-Sink (curve-based permanence).
Puro.earth (Biochar Methodology)	Edition 2025	Incubation-derived decay model from a harmonized dataset to estimate the durable carbon fraction; spectral reflectance is optional supplementary evidence for reporting.	H/C_{org}; production temperature; site-specific parameters embedded in the model.	CORC200+ label (≥200-year durability for the credited carbon fraction).
Isometric	Biochar Storage in Agricultural Soils Module v1.2	Two permanence pathways: (a) 200-year permanence via an H/C_{org} -based decay curve; (b) 1,000-year permanence via an inertinite benchmark (random reflectance) calibrated to the measured inertinite-like fraction.	H/C_{org} and temperature class (200-year path); random reflectance and inertinite-like fraction (1,000-year path).	200-year and 1,000-year permanence options.
Verra VCS – VM0044	v1.2 (2025)	Decay-curve–based quantification (H/C_{org} and temperature) embedded in the full VCS framework for baseline, project emissions, leakage and non-permanence risk.	H/C_{org}; application temperature class; end-use (soil vs. materials).	Typically 100-year permanence accounting consistent with VCS rules.

Standard / Registry	Current Version / Date	Approach	Key Determinants	Crediting Horizon / Label
Climate Action Reserve (CAR) – U.S. & Canada Biochar	v1.0 (2024)	Decay-curve framework with end-use and mean annual soil-temperature bins to derive the retained biochar carbon fraction over 100 years; provides explicit equations.	End-use class; mean annual temperature bin; H/C_{org} / carbon content.	100-year permanence accounting.
C-Capsule / I-TRACK – Distributed Biochar Methodology	v1.0 (2024)	Proxy-based approach using thresholds and fixed 100-year retention fractions (H/C_{org} and kiln temperature classes), combined with explicit permanence buffers; supports dMRV for distributed kiln fleets.	H/C_{org} bin; kiln temperature class; non-permanence / leakage buffer.	100-year permanence accounting (BC+100 / mean residence time formulation).
BioCarbon Registry – BCR0011	Consultation draft v01/08/2025; results published 2025-09	Stability gate ($H/C_{org} \leq 0.7$, C_org ≥ 50%) defining a Stable Soil Carbon (SSC) fraction over 100 years, combined with an explicit reversal-risk buffer.	H/C_{org}; C_{org} ; end-use; buffer and risk-management rules.	100-year permanence accounting for the SSC fraction.
CapChar – Biochar Carbon Code (UK)	Public consultation (2025)	Fixed permanence assumption (≈80% remaining at 100 years) combined with H/C_{org} and process requirements for eligible biochar.	H/C_{org}; process temperature band (approx. 480–600 °C).	100-year permanence accounting with ~80% remaining carbon fraction at 100 years.

5.4 Indirect CDR through biochar application to soil

In addition to storing carbon directly, biochar can influence carbon cycling in soils and thereby contribute to indirect carbon dioxide removal. When added to soil, biochar can affect the balance between carbon inputs from plant residues and carbon losses through microbial decomposition. These changes can lead to a net increase in soil organic carbon beyond the carbon contained in the biochar itself.

Several mechanisms have been proposed to explain these effects. Biochar can improve soil structure and moisture retention, create habitats that protect organic matter from decomposition, and influence microbial activity and nutrient availability. In some cases, these interactions slow down the breakdown of existing soil organic matter, while in others, improved plant growth increases carbon inputs to the soil.

The overall effect depends on soil type, climate, and management practices. While not as easily quantified as the direct carbon stored in biochar, these indirect CDR effects can make an additional, long-term contribution to climate change mitigation. Ongoing field and modeling studies continue to refine our understanding of these processes and how they can be effectively integrated into carbon accounting frameworks [182,183].

6. Agricultural applications

Early biochar projects were centered around the pyrolysis of agricultural residues into biochar for agronomic purposes. Numerous value chains have since been developed and biochar has still a high potential for CDR. Biochar has multiple applications in agriculture, which revolve mainly around four main categories: 1) soil amendments, 2) fertilizer enhancement and biostimulant, 3) sorbents and filter materials, and 4) feed additives.

Ensuring high-quality biochar products for soil use is essential, yet regulations governing biochar application differ greatly worldwide. Many countries and regulatory bodies lack specific legislation, which can either severely restrict or permit biochar use without limitations [184]. Where regulations exist, they often focus on aspects such as the degree of carbonization (e.g., $H/C_{org} < 0.7$), pyrolysis temperature, salinity, pH, ash content, contaminant limits (including PAHs, PCBs, dioxins, and heavy metals), and the feedstock's origin (like clean wood) [184]. Overall, legislation around biochar application to soils continues to evolve, and ongoing adaptations are expected to support and streamline the use of quality-certified biochar products in the near future.

6.1 Effects on soil parameters and crop yield

As biochar becomes a mainstream soil amendment, it is important to guarantee that the types of biochar being promoted do not negatively influence soil biology and, by extension, soil health. Such concerns emerged early on. Although no clearly and consistently negative effects have been reported, further research was considered necessary in the early 2010s [185]. Overall, soil microorganisms seem to benefit from biochar addition, but changes in microbial and fungal community structures in soils are difficult to interpret [85]. Biochar has been shown to have particularly positive effects on soil microbiology when it alleviates contaminant-induced stress [186]. When it comes to earthworms, considered critical soil engineers central to healthy soils, evaluations remain unclear. Earthworms appear to avoid soil where high doses of biochar have been applied, although negative effects on the earthworms themselves appear limited [187]. Such high doses of biochar are unlikely to be used, as 5 to 20% biochar in soil would represent approximately 150 to 600 tonnes per hectare, which are not realistic application amounts. At realistic application rates (1 to 30 tonnes per hectare), negative effects are not observed [188]. Positive effects of biochar on earthworms have also been reported. Additionally, biochar application to soil has been found to be favourable for microarthropods and enchytraeids [188]. In conclusion, biochar application does affect soil microorganisms, but not in a particularly negative way. It also affects the mesofauna, both positively and negatively, but negative effects seem to appear only at unrealistically high doses. However, it is important to consider that biochar is not a single, defined product, and quality tests will always be needed to guarantee the agronomic quality of the products being applied.

Earlier research has attributed the effect of biochar on crop yield to increased cation exchange capacity (CEC; the main measure for the ability for a soil to retain nutrients) [189,190] increased pH and base saturation [191], increased available P [191] and increased plant-available water [192].

Soil biological parameters have also been demonstrated to be affected by the addition of biochar, however often as a side effect of chemical changes in the soil. For example, the release or sorption of organic molecules from biochar may in some cases be responsible for increases or decreases in abundance and activity of soil (micro)biota [185]. Biochar could especially influence mycorrhizal abundance and/or functioning, allowing improved uptake of nutrients by plants, further enhancing CDR through the CO_2 taken up by plant growth [193].

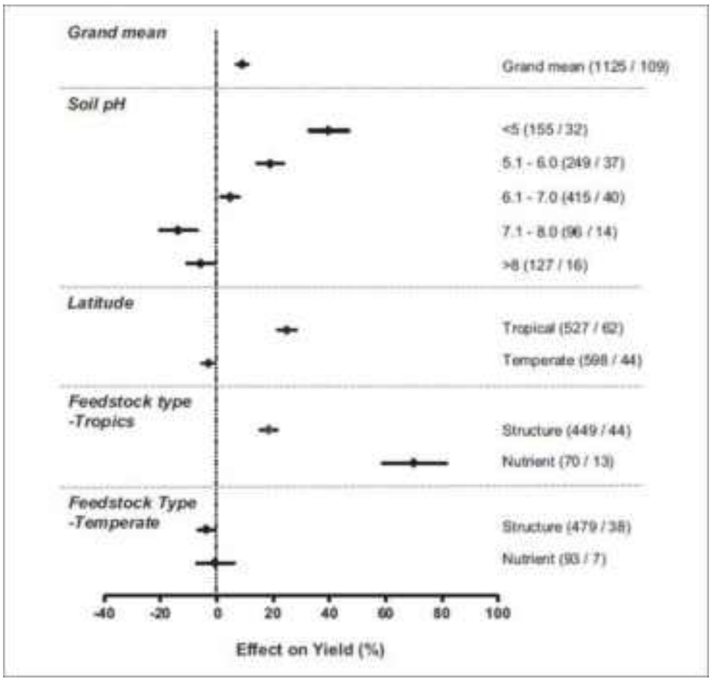

Figure 23 Overall meta analysis of yield effect of biochar amendment in tropical and temperate regions: Influence of initial soil pH, latitude, and feedstock type on crop yields following biochar application. Points show mean, bars show 95% confidence interval. Numbers in parentheses show the number of pairwise comparison on which statistic is based (left) and the number of publications from which data were drawn (right) [194]

Meta-analyses showed plant-available water and pH increase along with nutrient retention increases as the most important factors explaining the effect of biochar addition on plant growth [194,195]. These meta-analyses showed that the effect of biochar on crop yield is variable, ranging from −28% to +39%, with a grand mean of +10%. Better fertility effects were shown for weathered tropical soils than for temperate ones (Figure 23) [194].

6.2 Biochar as soil amendment

As a soil amendment, biochar is expected to improve soil quality and therefore plant yields, but the yield effect appears to be dependent on the rate and properties of the biochar, the soil and crop type and the management system that biochar is applied in [196,197]. Biochar have been shown to increase soil quality by increasing e.g. SOC and soil pH [196], but this effect is most notable on low quality soils in regions with mean temperatures above +10 °C, typically in weathered old soils in Africa, South America and Australia [1].

Most biochar products increase soil pH, on average by 6%, but the effect is larger on acidic soils with low cation exchange capacity [198]. Biochar does not only increase soil pH, but it also increases the acid buffering capacity of the soil, which renders the soil more resilient to further acidification [199]. Biochar effects on soil pH appear low at application rates < 10 t ha^{-1}, moderate between 10-20 t ha^{-1} and substantial (i.e., + 8% on average) over 20 t ha^{-1} [198]. Biochar reduces bulk density (BD) when large quantities are used, e.g. a significant reduction of soil BD by 0.1 g cm^{-3} was observed when miscanthus biochar was applied at 35 tonnes per hectare but not at 11 tonnes per ha [200]. Biochar application increases the capacity of soil to retain water available to plants by over 20% across studies [201,202]. The increase in available soil water is largest for coarse texture soil and with biochar applied in particle sizes smaller than 1 mm [199,201]. To reach effects in such soils, applications rates between 30 and 70 tonnes per ha appear most effective [202].

Here we see that, in order to function as a soil amendment, biochar requires applications rates that are quite high, generally in the range of 20 to 60 tonnes ha^{-1}. Such rates agree well with the goal of permanent C sequestration in soils, as a biochar containing 75% C (while commercial biochars in Norway contain up to 90% C) would correspond to 15 to 45 t C per ha. Assuming that biochar is incorporated throughout the plough layer, such application rates would increase the soil organic C content of soil by 0.5 to 1.5% in absolute values (i.e. in proportion of total soil mass). Such an absolute increase in SOC, represents from 12.5 to 37.5 years of C accumulation under the ideal scenario of the 4 permill initiative for soil C storage [203]. Although this scenario seems quite ideal, most soils of temperate and higher latitude regions are above C and pH thresholds where biochar can have a substantial effect on cereal yield as an amendment [198]. The marginal agronomic benefits obtained in these regions generate little economic incentive to support application of expensive biochar products tailored as soil amendments [204]. In contrast, in some tropical soils, such as notably found in sub-Saharan Africa, the soil amendment effect of biochar appears sufficient to making it a profitable solution, but it may take many years of cereal yield improvement to cover the investment of a one-time application [204]. High application rates of 20-60 tonnes ha^{-1} are often unsurmountable for small-scale subsistence farmers, though. Root-zone application in combination with minimum-tillage regimes (where only 10% of the soil is ploughed) are a solution for this and strong positive effects of biochar application have been observed at application rates of 4 tonnes per ha in combination with min-till in so-called “climate-smart agriculture” (CSA) or “conservation agriculture” (CA) [192,205,206].

Figure 24 Examples of agricultural application of biochar, in Norway (top left, photo: Adam O’Toole), southern Germany (top right, photo: Kathrin Weber), Uganda (bottom left, photo: Gerard Cornelissen) and South Africa (bottom right, photo: Gerard Cornelissen).

6.3 Biochar-based fertilizers and biostimulants

Developing efficient biochar-based fertilizers is a key goal to make biochar more attractive and economically viable for farmers. As a fertilizer carrier and biostimulant product, biochar is expected to contribute to increasing yields at fairly low application rates, typically at a target of about 1 tonne biochar per ha for fertilizers [207]. However, the repeated nature of fertilizer applications implies that cumulative application amounts over the years will be substantial, e.g. 10 tonnes per ha every 10 years. So far, there is some evidence that combining biochar and mineral or organic fertilizers into compound products creates synergistic effects on yield, but the magnitude of the effect remains very uncertain due to the lack of proper control in many reported experiments [1,197,207].

The rationale for using biochar as a fertilizer carrier is based on the observation that while biochar alone does not substantially improve yield in many soil types, combining biochar with fertilizer often outperforms fertilizer-only treatments, with an average yield increase of 15% [208]. This suggests positive interactions between biochar application and the nitrogen cycle in agro-ecosystems, though the underlying mechanisms remain poorly understood. The idea that biochar could act as a slow-release carrier for mineral nitrogen (especially NH_4^+) has largely been dismissed, as biochar's capacity to retain ammonium and nitrate is both lower than that of many clay materials and too transient—what little is absorbed is released rapidly, failing to provide the magnitude or release dynamics needed for a meaningful slow-release fertilizer effect [209]. It has also been hypothesized that the positive yield effects observed with some biochar-based fertilizers stems from biostimulant compounds produced during pyrolysis [209]. Such an effect needs to be better researched but would likely be higher for lower-temperature biochars, which are richer in active molecules. An attractive hypothesis for the good effectiveness of biochar-compost formulations is the formation of an organic coating on the biochar surface where nutrient-providing redox reactions take place [210,211]. However, such coatings cannot explain the immediate effect of rapidly mixed industrially produced biochar-fertilizer formulations.

Biochar-based fertilizers are available for the horticulture and hobby gardening sectors, but economically viable products appear to be lacking for major crops, where acreage (and thus biochar volume) is significantly higher. Although biochar-based fertilizer products are not currently used in mainstream cropping systems, R&D activities are actively underway to develop attractive and economically feasible solutions. Approaches such as impregnating biochar with molten urea or creating biochar–clay composites show particular promise [209] as do biochar-bokashi (fermentation) products. As research progresses, important breakthroughs in these areas are likely in the coming years.

Reduction of N_2O emissions from soils through biochar addition has been clearly demonstrated over the years, with larger effects observed in the first couple of years following addition to soil [212–214]. As compared to C farming methods, this makes biochar one of the few soil C sequestration technologies free from trade-off with N_2O emissions, i.e. a win-win solution for mitigating both CO_2 and N_2O emissions [170]. Although this is certainly a key positive property of biochar, it is not easily leveraged for economic viability or large-scale implementation at present. One reason is that carbon credit methodologies do not currently account for reductions in soil N_2O emissions, and national greenhouse gas inventory reports to the UNFCCC are only beginning to recognize biochar carbon storage using Tier 1 or 2 approaches (e.g.,[215]), whereas a full Tier 3 methodology would be needed to properly report and account for biochar's positive effects on N_2O emissions.

Here we see that biochar-based fertilizers remain a key solution where large amounts could be applied through the years on vast cropping surfaces, thereby reaching substantial climate mitigation effect. However, highly efficient and economically viable products still appear to be lacking, and research should be prioritized in this area.

6.4 Biochar as sorbent and in filter applications

Sorbent and filter materials are another key application of biochar in agriculture. This effect relies on the capacity of biochar to adsorb a large array of inorganic and organic chemical species both from water solutions and in gaseous form from the air. However, the sorption capacity is largely dependent on the type of molecules. Early on, a promising application of biochar was considered to be the reduction of nutrient leaching from cultivated soils, especially N and P forms. This effect has now been shown to be limited. There are two main reasons for this, the first one being that most biochars are negatively charged, and therefore not efficient at sorbing the key anionic forms of N and P in soils, especially NO_3^- [209]. The second is that nearly all biochar have a fairly low affinity for NH_4^+, which is difficult and costly to boost [209]. As a sorbent in agriculture, biochar has met greater success in dedicated applications, for which we provide a few examples below.

Several studies have tested biochar addition to waste feedstock in order to improve the composting process. Co-composted biochar has been shown to adsorb organic molecules, forming a coating on the external and internal surfaces of biochar, which helps retain substantial amounts of NO_3^- in the composted biochar [211,216]. Biochar has also been shown to reduce N_2O emissions from composting facilities [217] but not in all instances [216]. Adding biochar as a bulking agent in composting facilities has shown promising results in reducing NH_3 losses [218].

Biochar has also been shown to improve CH_4-yield in biogas reactors. This effect has been attributed to biochar sorption of NH_3 and volatile fatty acids, which are otherwise inhibiting methanogenic bacteria [219].

Biochar-based filters show great promises in capturing polluting ammonia gas (NH_3) emitted by agricultural facilities. Emissions from animal manure and composting are a major environmental challenge in agriculture, contributing to air pollution, soil acidification, ecosystem disruption, and loss of valuable nitrogen for fertilization. Engineered biochar filters, especially those treated with strong oxidants (e.g., phosphoric acid), have demonstrated high efficiency in adsorbing NH_3 gas, with some studies reporting up to 4–9% nitrogen content in the resulting biochar [220–222]. Developing biochar filters for large-scale animal husbandry and composting facilities presents several challenges. More research is needed to design systems that combine high sorption capacity with sustained flow rates throughout the filter's operational lifespan. One particularly promising aspect of capturing polluting NH_3 gas with biochar filters is the potential to reuse the nitrogen-enriched filter material as a fertilizer on agricultural soils.

Biochar used in sorbent and filter technologies for agricultural applications shows great potential for generating positive cascading effects throughout the value chain. As mentioned, biochar sorbents used in compost and biogas digestate will eventually be applied to soil in a nitrogen-enriched form, just like biochar filter materials used for NH_3 removal. These added benefits, combined with the possibility of earning carbon credits, could make such applications economically viable in addition to their environmental advantages. However, the quantity of biochar used in these applications is likely to remain moderate compared to the broader ambitions of sequestering large amounts of carbon through biochar technologies.

6.5 Biochar as a feed additive

Adding biochar to animal feed has been shown to enhance animal growth, improve blood parameters, increase yields of meat, milk, and eggs, and strengthen resistance to diseases, while also reducing methane emissions from ruminants [223]. Additionally, biochar's high sorption capacity helps remove toxins and contaminants from animals and their environment, supporting better overall health and productivity [223]. For example, in Norway, it has been reported at the annual meeting the of Norwegian Farmer's association that pig farmers who start supplementing their animals with biochar mixed in feed generally chose to do so because of excellent and apparently profitable results. The typical inclusion rate for biochar in animal feed is 0.3% (range: 0.25–5%) [224]. Adding biochar to animal feed appears as the application with the highest probability to be economically viable at this point [225], however results are specific to each animal production type [223].

6.6 Summary of agricultural applications

In summary, most current agricultural applications of biochar are not economically viable due to high production costs. The few exceptions, such as its use as an animal feed additive or as a filter material, require relatively small amounts of biochar. In contrast, applications that demand large quantities, like soil amendment or, to a lesser extent, fertilizer enhancement, are generally not profitable at present, except for some application on tropical weathered soils. This underscores the importance of integrating carbon credits for soil carbon storage with agronomic benefits to create viable implementation strategies. The success of such approaches will depend on both the practical ease of use and the evolution of the value of carbon credits and their implementation systems, as well as breakthroughs in enhancing biochar's agronomic functions, which is an area where significant research is ongoing.

7. Industrial applications

This chapter gives an overview of the use of biochar in selected large-scale non-soil applications, mainly the addition to construction materials or the replacement of fossil carbon carriers in metallurgical applications.

7.1 Biochar addition to concrete

Concrete is among the most carbon-intensive construction material due to its dependence on cement, which is responsible for a significant share of global anthropogenic CO_2 emissions [226]. The incorporation of biochar into concrete can partially replace cement, which directly lowers the carbon footprint. The immobilization of stable carbon in the structure creates a carbon sink.

When added in small amounts, typically below 5% (by weight), biochar can improve the mechanical and durability performance of concrete. The fine pores and high surface area of woody biochar allow them to fill voids in the matrix and provide additional nucleation sites for hydration products. As a result, biochar-amended concrete tends to develop a denser microstructure with improved strength and lower permeability. Modest addition of wood-derived biochar to structural-grade concretes can increase compressive strength, while reducing water sorption and permeability [227]. Similar effects have been observed for ultra-high-performance concrete. Biochar addition enhanced hydration kinetics and achieved compressive strength similar to those of a reference mix, despite a reduction on cement content [228]. Comparable trends have been reported for biochars from agricultural residues, such as rice husk and bagasse, which also led to notable gains in tensile and flexural strength [229,230].

Besides mechanical strength, biochar can improve the resilience of concrete under harsh conditions. When concrete containing small amounts of biochar is exposed to elevated pressure, is can exhibit higher residual strength and less internal damage to moderate internal pore pressure and prevent microcrack formation during heating [227]. The inclusion of biochar in concrete can also maintain higher internal relative humidity in cement pastes and reduced autogenous shrinkage, illustrating its capacity of self-curing [231].

The benefits are not limited to strength and shrinkage. In lightweight and foamed concretes, biochar has been found to increase fracture energy and flexural strength, producing more tortuous and energy-absorbing crack paths without compromising stiffness [232]. When used in thermally insulating concretes, biochar can lower the thermal conductivity of the composite while improving sound absorption, demonstrating potential for multifunctional building applications [233,234].

The improvements induced by biochar seem to stem primarily from its physical rather than chemical properties. Microscopic studies indicate that cement hydrates deposit within and around the pores of biochar particles, forming a dense and well-bonded interfacial transition zone [228]. The biochar particles themselves serve as both fillers and moisture buffers, storing water during mixing and releasing it during hydration. This process promotes more complete hydration of the surrounding cement, particularly in low water-content systems. Importantly, there is little evidence of any adverse chemical interaction between biochar and cement matrix. The effects are mechanical and physical, stabilizing the microstructure and reducing porosity [227,231].

Most studies on biochar in concrete have focused on biochar produced from woody biomass. This feedstock tends to yield more predictable material quality, often with well-developed pore structure and relatively low ash content – properties that make compatible with cementitious systems. Across the literature, there is evidence that the addition of small amounts of biochar, typically in the range of 0.5 – 5 wt% of cement, can enhance the performance of concrete. Improvements are most often reported in terms of increased compressive strength, reduced permeability, and better resistance to cracking and thermal damage. These effects arise primarily from the physical role of biochar as a microfiller and internal curing agent rather than from any chemical interaction with the cement matrix. As the properties of biochar from other feedstocks can vary significantly, the effects that biochar can have on cementitious materials is highly type-dependent and may be completely different than described in this section if another feedstock is chosen.

Despite the performance benefits, the principal motivation for using biochar in concrete is not necessarily product enhancement, but rather carbon dioxide removal (CDR). By embedding stable biogenic carbon in long-lived construction materials, biochar-concrete composites offer a way to store carbon for decades or even centuries with simultaneously reducing the need for high-emission cement.

Concrete may be one of the most tolerant applications for utilizing biochar. The concrete matrix can accommodate minor impurities or variability in biochar composition without significant performance losses. This robustness could enable the use of lower-grade or mixed-source biochars derived from waste streams, expanding the opportunities for biochar deployment at scale and reinforcing its role as a practical tool for carbon-negative construction.

There are several large-scale demonstrations of biochar application in concrete. These include a full-scale test slab beneath a new theatre venue in London, where Holcim and CWG used biochar from forestry residues and spent coffee ground to achieve net-zero concrete [235]; the construction of a barn in southern Norway, on a ground floor containing biochar-amended concrete (“biocrete”) and using precast sandwich elements for walls that were filled with biocrete [236]; or CarStorCon, who has tested 5000 m^3 of biochar-amended concrete in various buildings [237]. The amount of biochar needed to compensate for the climate impact of concrete is highly dependent on the type of concrete and type of biochar (including emissions throughout their respective production chains), but these projects demonstrate that it is possible to achieve net-zero concrete by adding biochar.

Figure 25 shows examples of large-scale application of biochar in concrete.

Figure 25 Examples of large-scale application of biochar in concrete. Photos: CarStorCon

7.2 Biochar addition to asphalt

Asphalt is among the most widely used construction materials, covering the vast majority of roads and paved surfaces worldwide. In Europe and North America alone, roughly 650 million tonnes are produced each year, with over 90% of road networks surfaced using asphalt concrete. This composite material consists primarily of mineral aggregates bound by bitumen—a viscous, carbon-rich residue derived from petroleum refining. While reclaimed asphalt is commonly recycled, the enormous production scale means that asphalt manufacturing still represents a significant fossil carbon flow.

Because pavements are produced in large quantities and remain in service for decades, even small material substitutions can have substantial long-term effects on carbon storage and resource use. Incorporating biochar into asphalt introduces biogenic carbon into a durable and inert environment, thereby creating a potential carbon sink within the built infrastructure.

Biochar can be utilized in asphalt through several routes: *Binder modification*, where powdered biochar is mixed directly with bitumen, influencing viscosity, stiffness, and resistance to oxidative or UV aging. *Aggregate modification*, where biochar is blended with mineral components, potentially enhancing adsorption capacity and immobilization of pollutants. In addition to that, the bio-oil (the liquid by-product of biochar production) can partially replace fossil-based bitumen.

To qualify as a viable carbon sink, biochar-modified asphalt must maintain acceptable mechanical performance. The most relevant criteria include rutting and fatigue resistance, flexibility at low temperatures, long-term aging stability, and ease of processing. Research to date indicates that biochar additions up to about 10 wt.% of the binder can increase stiffness and high-temperature stability while lowering susceptibility to oxidation and UV degradation. However, reduced ductility at low temperatures and potential phase separation at higher loadings remain important technical challenges.

Overall, the integration of biochar into asphalt presents a promising strategy to embed carbon dioxide removal into a long-lived, high-volume material stream. In addition to its mitigation potential, biochar may improve the durability and environmental performance of pavements, aligning material innovation with climate goals.

Most research on biochar-modified asphalt has focused on blending fine biochar powder directly into the bitumen binder. The addition of biochar generally increases binder stiffness and elevates the softening point, effects attributed to the solid carbon particles reinforcing the matrix. At moderate inclusion levels—typically up to about 10 wt.% for woody biochars—processing remains feasible, and viscosity stays within acceptable limits for pumping and mixing at standard production temperatures (around 135 °C) [220,221].

Improved rutting resistance is one of the most consistent findings, with the stiffness increase enhancing high-temperature stability. However, higher stiffness can also reduce ductility and flexibility, making the material more prone to cracking under low-temperature conditions. The extent of this trade-off depends on biochar type and dosage: some studies report only moderate reductions in flexibility at 10–12 wt%, while others observe substantial losses in elongation capacity. Optimizing the biochar concentration is therefore essential for maintaining balanced mechanical performance [220–222].

Biochar can also improve binder aging resistance. The presence of oxygenated surface groups and a porous structure appears to stabilize lighter, oxidation-prone components of the bitumen, reducing hardening and delaying degradation during thermal or UV exposure. The carbon-rich structure of biochar contributes to UV absorption, further limiting photo-oxidative aging [220,223].

At higher concentrations, phase separation between bitumen and biochar may occur, especially during prolonged storage at elevated temperatures. This limits the practical loading range to relatively low percentages unless improved dispersion or stabilization methods are developed [220,221].

Overall, moderate additions of biochar can enhance binder stiffness, thermal stability, and resistance to aging—offering both performance and carbon storage benefits—provided that ductility and homogeneity are preserved through careful formulation.

There are several large-scale demonstration projects, in which biochar addition to asphalt has been tested at scale. In 2025, Novocarbo together with Hansa Asphalt launched a pilot project, where a total of 7 tonnes of biochar were mixed into asphalt for the top layer of a road surface, replacing about 3% of the total material, also issuing carbon credits for the project (Figure 26) [242]. In 2024, Verde Resources (together with Oregon Biochar Solutions and NCAT) installed 110 tonnes of asphalt, containing 5 tonnes of biochar on a test track, also certifying carbon credits [243]. These projects are examples that show that biochar asphalt has progressed beyond laboratory studies, to full-scale validation.

Figure 26 Demonstration of biochar addition to asphalt. Photos: Novocarbo

7.3 Replacement of fossil carbon carriers in metallurgical applications

The metallurgical industry is one of the largest consumers of carbon materials, using them primarily as reducing agents, carburizers, and energy carriers [244]. Traditionally, these roles are fulfilled by fossil carbons such as coke, coal, or graphite. Substituting a portion of these with biochar can significantly reduce fossil CO_2 emissions. The replacement of fossil carbon with biogenic carbon in metallurgical processes is not a CDR, as the biochar's carbon content is largely oxidized and released again to the atmosphere. However, metallurgical plants are typically large-scale point sources of CO_2 and thereby also suitable for carbon capture and storage (CCS). CDR can then be achieved by coupling the oxidating use of biochar with CCS.

Carbon fulfils several functions in metallurgical systems [245]:

- Chemical reduction: Metal oxides are reduced to metals by reaction with carbon or carbon monoxide.
- Energy supply: The oxidation of carbon provides high-temperature heat for smelting reactions.
- Carburization: In steelmaking, carbon is added to adjust the carbon content of the molten metal.
- Slag foaming and structure: Carbon influences slag properties and melting behaviour.

For biochar to be a viable substitute, it must match the physical and chemical performance of coke or coal in these functions, while being a renewable carbon source (in contrast to fossil coal, coke or graphite).

Metallurgical applications can be quite sensitive to impurities in the biochar as they may influence the process and products negatively. They have specific requirements on various physical and chemical properties, and these can vary between different metallurgical processes. In general, biochar used in the metal industry can only be produced from woody feedstocks to meet desired characteristics like a high fixed carbon content and a low ash and sulphur content. The biochar might also have to be agglomerated (pressed to pellets or briquettes) to provide homogeneity, density, mechanical stability and strength as well as ease the handling process. Given that biochar can meet the specifications and/or and metallurgical process can be adapted to accommodate available biochars, the metallurgical sector will be able to replace significant shares of fossil carbon, thereby likely becoming one of the largest consumers of wood-based biochars [246,247].

7.4 Summary of industrial applications

Biochar is increasingly being explored in large-scale non-soil applications, particularly in construction materials and metallurgical processes, where it can either be embedded as a stable carbon phase or substitute fossil carbon carriers. In concrete, small additions of biochar (typically below 5 wt.%) can enhance mechanical performance, reduce permeability, and improve durability, while simultaneously lowering cement demand and enabling long-term carbon storage. Several pilot and early commercial projects demonstrate the feasibility of biochar-concrete in real structures. Creating a carbon-negative product with biochar addition is possible.

In asphalt, biochar can be incorporated as a binder modifier or filler, improving stiffness, aging resistance, and high-temperature performance. Full-scale pilot projects in Europe and the United States confirm that biochar-modified asphalt can be produced and applied using conventional infrastructure, while also offering the potential for carbon storage and carbon credit generation.

In metallurgical applications, biochar can partially replace fossil carbon sources such as coal or coke, contributing to reduced fossil CO_2 emissions. Although the carbon is largely re-released during processing, coupling biochar use with carbon capture and storage (CCS) can enable net carbon removal.

Across all applications, the scalability of biochar use is supported by the large material volumes involved, though performance depends strongly on biochar properties and process integration.

8. Research and development

This chapter gives some examples of current research and development needs from various areas. This list does not claim to be exhaustive, and the topics are listed in no particular order.

8.1 Feedstocks and sustainability

8.1.1 Biochar feedstock availability in tropical agriculture

In tropical agriculture, residues are often used for other purposes, mainly fodder and residue retention (mulching). In those cases where residues are burnt, such as rice straw and sugar cane waste, pyrolysis is a highly attractive option avoiding emissions and air pollution. In many cases however obtaining sufficient feedstock is a challenge. Fine-grained feedstocks such as coffee husk, nut husk or rice husk may be available but require higher-technology and more costly pyrolysis methods than provided by artisanal flame curtain kilns because of high methane emissions from the latter [106]. Feedstocks such as maize stalks, sesame stems or sunflower stalks may be available but compete with use for mulching [248]. Maize cobs constitute only 2% of maize biomass and provide too little feedstock [106]. Prunings may be available but compete with use as fodder, especially for leguminous trees such as Gliricidia [249].

Solutions may be to grow a fast-growing crop with a lot of biomass on part of the holding (bamboo, pigeon peas), the use of invasive species such as Eupatorium [250] or certain Acacia species [251], or using grass that has shown not to lead to methane emissions using artisanal methods [106].

8.2 Process and product optimization

8.2.1 Emission monitoring and flue gas cleaning

A limited number of studies have documented emissions from pyrolysis of various feedstocks at full scale [18,35,55,56,101,103]. Concentrations of pollutants in emissions from both low-tech (artisanal) and high-tech pyrolysis processes are relatively low when using dry and clean feedstocks [103]. Even without flue gas cleaning emission concentrations are generally low compared to waste incinerators with advanced flue gas treatment [103]. Emissions from pyrolysis of clean feedstocks are therefore not expected to result in air pollution issues unless operated at large scale. More data from full-scale operations is nevertheless needed to confirm this.

Pyrolyzing contaminated feedstocks generates further challenges, however. Most organic contaminants are expected to be fully thermally decomposed in the pyrolysis reactor or combusted in a flue gas combustion chamber in the pyrolysis process, resulting in only minor emissions of combustion by products and highly persistent residuals [55]. Highly persistent PFAS compounds, on the other hand, are not expected to fully decompose and could result in emissions of a range of volatile decomposition products which are hard to measure [55]. More data is therefore needed on emissions of such volatile fluorinated decomposition products from pyrolysis of PFAS containing wastes, such as sewage sludges. Laboratory studies have suggested adding catalysts such as calcium hydroxide to the process can greatly improve PFAS mineralization at relatively modest temperatures down to 500 °C [252]. This should be tested at scale.

Pyrolysis of sewage sludge can also lead to elevated emissions of HCl, SO_2 and volatilized metals such as Cd [18]. As emissions from contaminated feedstock pyrolysis cannot be expected to be completely curbed through process optimization, the effect of different flue gas cleaning alternatives, e.g. scrubbers, on pyrolysis emissions needs to be investigated.

National threshold limits for emissions from pyrolysis are furthermore needed. For some gases such limits are in place in Switzerland and Germany. Thresholds should be based on emission data from full scale operations and expected effects of flue gas treatment.

8.2.2 Tailored biochar production for metallurgical applications

The metallurgical sector is likely to become a large-scale consumer of biochar, replacing fossil carbon in their production processes. Depending on the process, the requirements on both chemical and physical properties can be strict, often excluding all but clean wood as potential feedstocks and possibly requiring additional treatment and processing such as agglomeration.

Providing sufficient feedstock in a sustainable way to meet the enormous carbon demand of the metal industry might require expanding the feedstock base. Research should therefore focus on upgrading a wider range of feedstocks into biochars that meet the specifications required for different metallurgical processes.

8.2.3 By-product valorization and process integration

During biochar production, only about 25–30% of the feedstock (for woody biomass) is retained as solid biochar, while the majority is converted into gas and condensable vapors. In many practical applications, these by-products are combusted on-site to sustain the process and generate usable heat. While this ensures energy self-sufficiency, it may not fully exploit the potential value of these streams.

A key research need is the improved valorization of by-products, particularly the condensate fraction. Bio-oil and aqueous condensates contain a range of organic compounds that could potentially be upgraded into valuable chemicals, fuels, or functional materials. However, their complex and variable composition, especially when derived from mixed or waste-based feedstocks, poses challenges for direct utilization. Further research is needed to characterize these streams, develop upgrading and refining pathways, and assess their economic and environmental viability.

In parallel, enhanced process integration offers opportunities to improve overall system efficiency. This includes optimized use of process heat for feedstock drying, which is particularly important when using wet or heterogeneous waste-based feedstocks. Smart heat integration strategies—such as cascading heat use, coupling with district heating systems, or integration into existing industrial processes—can significantly improve energy efficiency and reduce operational costs.

8.3 Application and performance

8.3.1 Biochar permanence in soil

As explained in Section 5 of this report - the current standard for evaluating biochar stability in soils, i.e. the H/C_{org} ratio, is likely to be exceedingly conservative. The newer inertinite method suggests that residence times, particularly for higher temperature biochars, are significantly longer than currently estimated through the H/C_{org} method. The strength of the H/C_{org} method is that it is calibrated on incubations of isotopically labelled biochar in soils, such as those conducted by the authors of this report [85]. Its weakness lies in the limited number of such incubations, cost-saving choices in the expansive isotopic labelling methods, and the methods used to extrapolate the time-limited incubation data over very long periods. Combined, these limitations make it difficult to see beyond the “centuries horizon”. However, it is well within our reach, with a well-funded research program, to improve such analytical methods and confirm the reflectance-based estimates that the stability of higher temperature biochar extends beyond the millennium time frame. We highly recommend prioritising such a research program.

8.3.2 Holistic remediation approaches on pyrolysis waste treatment and biochar sorbents

Biochar offers the highest potential for carbon storage and other positive environmental impacts when applied in synergistic systems. Novel examples include the use of pyrolysis to destroy pollutants in sewage sludge and then use the sewage sludge biochars as sorbents to remove further pollutants from water [253]. Or the application of pyrolysis to treat plants used for phytoextraction of heavy metals from soil with subsequent application of the biochar in applications where elevated metal contents do not pose a problem [34]. A complete reuse cycle, dubbed “the Virtuous Cycle” has been suggested to treat soils diffusely contaminated with PFAS, by planting hyperaccumulator plants to remove mobile PFAS from the soil, then use pyrolysis to destroy PFAS in the plant biomass, with subsequent use of the biochar as fodder to reduce uptake of PFAS in grazing animals and in soil stabilization to bind the PFAS that are not so easily taken up in plants [254]. Already the authors are using the Virtuous Cycle in a pioneering project in Europe, where a PFAS factory has contaminated soils, sediments and local reeds. Biochar from the local reeds turned out to very effectively reduce PFAS leaching from the soils at the site: 1% of biochar amendment reduced PFAS leaching and bioavailability by up to 99%.

The combination of biochar soil application with phytomanagement strategies generally appears to be a promising direction. Biochar can potentially improve plant growth and hence serve both phytomanagement and feedstock generation, while providing other synergistic effects in the soil such as increased degradation of petroleum hydrocarbons or PAHs [255,256].

8.3.3 Biochar as a catalyst in electrochemical degradation of contaminants

The aromatic structures and surface functional groups allow biochars to act as both electron donors and acceptors in redox reactions, which in practice means that they can serve as catalysts in electrochemical reactions and direct interspecies electron transfer [257]. These properties are being exploited in groundwater remediation of persistent organic contaminants, such as chlorinated solvents and pesticides [258]. In this novel approach an electron donor source, such as green rust waste, is added together with a biochar catalyst, typically made from sewage sludge or bone meal. It is assumed that chlorinated chemicals adsorb to the biochar surface and subsequently chlorine atoms are stripped off through reductive dechlorination [259] leaving harmless carbohydrates.

8.3.4 Biochar effect on soil biology

Currently, a lot is known of the effect of biochar on soil chemistry and physics (acidity, nutrients and moisture) [52]. However, many positive effects on soil fertility and crop yield stem from more subtle effects of biochar, especially on the many redox reactions responsible for nutrition of plants and soil ecosystems. These effects are due to an “electron shuttling” effect of biochar [257], where biochar catalyzes the reactions of importance for nutrient uptake and digestion of soil biota, microbiota and fungi. There are indications that biochar can positively affect mycorrhizae (fungi that aid plants in the uptake of nutrients, especially phosphorous) and soil bacteria [193,260]. However, the exact mechanisms of these effects need further study in various soil types and climatic zones.

8.3.5 Long-term performance of biochar in asphalt

Biochar has been investigated as an additive in asphalt, with studies demonstrating potential benefits such as improved stiffness, enhanced durability, and partial replacement of fossil-based components. A few large-scale demonstrations exist. A key research gap is the lack of knowledge on long-term performance under real operating conditions. In particular, there is insufficient understanding of how biochar-modified asphalt behaves over time when exposed to varying climatic conditions, including temperature fluctuations, freeze-thaw cycles, moisture exposure and UV-radiation. Future research should focus on long-term trials and monitoring across different climatic zones.

8.4 Safety and logistics

8.4.1 Biochar safety

Despite the close contact with which humans work with biochar, it’s direct impact on human health via inhalation, ingestion, or skin contact has received little attention. The few studies published in peer-reviewed literature highlight potential risks from biochar fine particles and chemical contaminants. Biochar particles easily become airborne during soil application, and respiratory damage through inhalation is potentially a cause for concern, especially with biochars containing contaminants or those produced from certain feedstocks that yield dust with more hazardous components [261]. While ingestion of biochar produced from a clean feedstock is not likely of concern, biochar containing contaminants presented toxic effects in a study on mice [262]. Similarly, occasional skin contact with clean biochar is unlikely to cause serious harm, but ongoing or extensive dermal exposure to biochar containing toxic substances could pose risks and should be investigated.

8.4.2 Transportation and storage safety

Many biochars exhibit self-heating and, in some cases, self-ignition behaviour, particularly when stored or transported in bulk. This creates challenges for safe handling, storage, and shipping, and may limit large-scale deployment if not properly addressed.

Research into the mechanisms driving self-heating and ignition—such as residual volatiles, surface reactivity, moisture content, and particle size distribution—remains essential.

This topic is gaining increasing importance as international regulations become more stringent. In particular, recent guidelines from the International Maritime Organization (IMO) have introduced stricter requirements for the transport of biochar and similar materials [263]. Further research is therefore needed to support compliance, improve material stability, and enable safe and cost-effective logistics across the biochar value chain.

8.5 Policy and MRV

8.5.1 Full impact of biochar systems on net GHG balance

Estimates of the global climate change mitigation potential of biochar vary, mostly because of differences in scope and assumed feedstock availability. Furthermore, assessments carried out thus far considered only a subset of the mitigation contributions that can be delivered through biochar systems [169]. The full impact of biochar systems on net GHG emissions should include CH_4 and N_2O emissions and also changes in soil organic C stocks due to priming. Biochar addition may change native SOC due to either positive or negative priming effects. However, obtaining this information requires long-term studies for different soil types and environmental parameters.

8.5.2 Data provision and validation for legislation

The biochar market is developing rapidly, while existing legislation and regulatory frameworks are often not designed for, or adapted to, biochar applications. In many cases, outdated or incomplete regulations create barriers to implementation and slow down market uptake.

The development and revision of legislation require a robust, transparent, and non-biased data basis. Research should therefore support the systematic generation and validation of reliable data needed for regulatory decision-making. This includes standardized testing methods, long-term field data, and comprehensive assessments of environmental and health impacts. Providing such evidence is essential to enable informed policymaking, reduce uncertainty, and facilitate the safe and scalable implementation of biochar technologies.

9. Country reports

The development and deployment of biochar vary widely internationally, reflecting differences in policy priority, feedstock availability, technological maturity, and market incentives. Some nations have established dedicated biochar industries supported by regulatory frameworks and carbon removal mechanisms, while others might still be in earlier stages of development.

The following overview summarizes the status of biochar activities in Mission Innovation countries as well as some other noteworthy examples. The country-specific sections all follow the same structure. However, the level of detail in each section is limited by data availability. Much effort was given to provide the best narrative for each country, however, it must be noted that the companies, institutes and projects mentioned should be considered key examples and not a comprehensive list of actors and activities. The information about production, markets, and research and development is shown for the main players and activities per country.

Most country sections have been revised by dedicated country representatives. The countries are presented in alphabetical order.

9.1 Australia

9.1.1 Overview

Australia is a large country of 7.69 million km² in the south Pacific with a variety of landscapes, from deserts in the central lands to tropical rainforests to the north-east and mountains in the south-east. 18% of the mainland is desert and over 40% of the country's interior is permanent rangeland and pasture. Its forests make up 17% of its land base while 4% of the country is considered arable land. Climatically, the country supports an array of ecosystems from inland deserts to coastal rainforests in the northeast and mountains in the southeast. With a low population density of 3 persons per km², the majority of its 25-million-person population is largely concentrated along its eastern coastline [224].

Australia is a net exporter of coal and natural gas, while using these resources heavily in its electricity production [224]. In 2024, the Australian government reported 64% of Australia's electricity production came from fossil coal and gas sources. Renewable power from wind (12%) and solar (18%) is however growing [225]. IEA also reported bioenergy's use to be small in comparison to its domestic potential. In November 2021, the Australian Renewable Energy Agency [226] published Australia's Bioenergy Roadmap which showed the potential for bioenergy to contribute 20% of Australia's total energy production by 2050 [226].

Australia's biochar industry is represented by the Australian & New Zealand Biochar Industry Group (ANZBIG), who assists companies, government and institutions in their biochar efforts [227]. ANZBIG is backed by roughly 25 active members The industry is within early growth phase in Australia however, is produced in each of the country's provinces.

9.1.2 Production

Technology Providers

Australia is home to a number of technology providers, ranging in scale, feedstock utilization and targeted output. Examples include Rainbow Bee Eater and their ECHO2 system, BioCarbon, Energy Farmers Australia, Pyrochar and Pyrocal and IQ Energy Australia to name a few [228–233].

Biochar Production

According to Don Coyne, former CEO of ANZBIG, production sites in Australia range from small to large-scale, with an approximated 20,000 to 25,000 tonnes produced annually today. A number of large-scale projects are under construction and will soon increase production capacity [227]. Australia's biochar production can be considered quite diverse. There are so-called "traditional" market actors who produce various biochar-based products for soil-based applications which includes companies Byron Biochar, Green Man Char and Jefferies [234–236]. However, Australia exhibits a range of driving factors which is seeing an increase in biochar projects developing in the country.

Australia also boasts sewage sludge biochar production adoption into its wastewater treatment plants (WWTP). The city of Loganholme in eastern Australia has implemented a biosolid gasification unit at its WWTP, which handles 90% of the city's water and 34,000 tonnes of biosolids annually. Using Pyrocal's Continuous Carbonisation Technology, it turns 90% of human waste into heat energy and biochar, while also eliminating PFAS molecules, 63% of micro and nanoplastics, and 94% of persistent organic pollutants within [237,238]. Before the project's implementation, the facility shipped 6 truckloads of biosolids 300 km to be used as a soil amendment, costing the city AUD$ 1.8M annually, or 30% of the WWTP. In addition, the operation reduces GHG emissions by 6,000 tonnes a year [239].

Another notable sewage sludge biochar project is IOTA's PYROCO's pilot with various municipal wastewater treatment facilities. The pilots concluded successfully and PYROCO's heat recovery fluidized bed pyrolysis technology will be market-ready late-2026 [238,240].

Extreme forest and climatical conditions are also driving biochar's production. For example, project developer Biomass Projects has launched a project in Pilbara, Western Australia to remove an overrun mesquite infestation which is threatening the local ecosystem on 225,000 hectares of land. The project will be one of the largest biochar projects worldwide, with plans to pyrolyze 10.5 million tonnes of biomass over a 20-year span and produce 500,000 carbon removal credits annually [241]. The project has developed in partnership with Puro Earth and Carbonfuture to provide the project's MRV and plans to meet full operation in 2028 [242].

Another large-scale project is the Kangaroo Island Project which will be in full capacity in 2026. The project will process burned wood from a forest fire which damaged 210,000 hectares of forest land. This project will reduce the risk of further fires on the land by processing 100,000 tonnes of wood annually [243].

In addition to the wide range of feedstocks already listed, it is noted that bioenergy production varies largely. Examples of noted feedstocks used in bioenergy, not necessarily biochar production, include forestry residues, sugarcane, organic and piggery waste, fisheries & horticulture waste, dairy waste and cereal straw [244].

9.1.3 Applications

Biochar's application in Australia appears to be largely focused on agriculture, including the use of sewage sludge biochar, which is coherent given biochar's effectiveness in hot, arid environments such as Australia. Moreover, ANZBIG's 2030 Roadmap has a heavy focus of biochar application in Australian soils, demonstrating the industry's focus in Australia [227]. These applications are also in line with utilizing biochar as CDR.

Other applications, such as for the metallurgical sector, are also under development, including the BioCarbon project in Bulahdelah, NSW. BioCarbon will produce 8,000 tonnes of biochar which will feed a local electric arc furnace for steel production, replacing fossil coke [245].

9.1.4 Research and development

Prominent research groups in Australia include the Commonwealth Scientific and Industrial Research Organisation [246], who led projects in various aspects of biochar, including agricultural applications, biochar production and application to replace fossil carbon in steelmaking. In 2023, licensing rights for their pyrolysis technology targeting the steel production industry was acquired by Pyrochar [246].

Deakin University can also be included, especially the Water-Energy Nexus Research Group, which has been working on the effectiveness of waste feedstocks, such as sewage sludge, as absorbent and resilient materials when applied to soils [247]. Their Recycling and Clean Energy Commercialisation Hub, which fosters collaboration between industry, research and partner institutions, has partnered with municipal wastewater authority Barwon Water to explore biochar's effectiveness in soil applications, battery production [248].

Other notable universities include, but not limited to, University of Newcastle and the University of New South Wales who have a [249,250].

9.1.5 Policy, frameworks, and national strategies

Carbon Removals

Australia's Carbon Credit Unit Scheme (ACCU) is the country's main regulatory cap-and-trade tool driving the reduction and removal of GHG. A milestone in biochar as a carbon removal technology was achieved in 2025, as the country's Clean Energy Regulatory (CER) recognized the biosolids-to-biochar pathway as a carbon removal method in ACCU [251]. However, CER has not yet published a methodology for biochar but it is presumed to be under development [252].

End-of-Waste

Fitting the country's governing structure, states have implemented waste-to-product policies which allow for end-of-waste (EOW) for biochar to be reestablished as a resource. One successful example is in the state of Queensland, who adopted an EOW Code for biochar, which is key specifically for feedstocks labelled as waste such as sewage sludge [253]. Frameworks exist in other states, yet their regulation of biochar is not clear.

National Strategies

ANZBIG's *Australian Biochar Industry 2030 Roadmap* represents the blueprint to growing the country's biochar industry. The roadmap lays out ten initiatives to scale the industry, covering strategic funding, stakeholder engagement and policy integration. It is unclear to what extent the roadmap has been adopted by the Australian government [251].

In 2021, ARENA published *Australia's Bioenergy Roadmap*, showcasing demand and resource potential. The roadmap does not address biochar or pyrolysis directly however; it does address the need for Australia to improve its bioenergy sector. It includes relevant themes such as enabling market opportunities for hard-to-abate sectors such as renewable heat supply for industry; renewable electricity production, biomass utilization and improving the bioenergy ecosystem by improving knowledge sharing, business models and communications [226]. ARENA has a history of funding pyrolysis and gasification projects, predominantly in the management of municipal waste [254–256].

Although not mentioning biochar, Australia published its *National Soil Strategy* for 2021 to 2041. The strategy makes the prioritization of soil health, empowerment of soil innovation and stewards and strengthening soil knowledge and capacity, national priorities. The strategy, which is planned to be updated every five years, is also backed by a National Action Plan and is the basis for funding in soil health projects in the country [257].

9.1.6 Gaps, challenges, and opportunities

Gaps and Challenges

- A lack of adoption of biochar into ACCU presents an immediate hurdle in growing the biochar sector, especially with strong focus in soil improvement and agricultural applications and projects. Having biochar integrated as a CDR method within regulatory emissions pathways would be a catalyst for biochar production and use.
- Large-scale production means large-scale application. Off-take markets must quickly be developed to support the boom in production from projects recently announced. Local use cases will be most economically viable considering Australia’s geographic position as transportation costs are an added hurdle for price and logistical competitiveness on the international market.

Opportunities

- Mastering and replication of municipal sewage sludge biochar systems would be financially advantageous for Australia’s waste management. According to Don Coyne of ANZBIG, new regulations have come through in Australia to allow sewage sludge biochar to be applied in agriculture.
- Sharing how end-of-waste hurdle was overcome in Australia would be helpful for other states to learn how to integrate sewage sludge biochar into their policies.
- Agricultural applications of biochar may be key tool for Australia, especially in dry, arid regions, as climate changes makes growing conditions more challenging.
- Large-scale projects and production may position Australia to be an exporter of biochar to foreign industrial markets, such as steel and metallurgy.

9.2 Canada

9.2.1 Overview

Canada is the world's second largest country in terms of landmass, spanning 9.97 million km², with a very low population density of roughly 4.6 people per km² [258,259]. 39% of Canada's landmass consists of forested area, mainly boreal with deciduous areas to the south, which supported an annual harvest of 131 million m² in 2022 [260]. Agricultural lands make up 6% of the country, supporting Canada as one of the largest net exporters in the world with a total of $100 billion in agriculture and food exports in 2024 [261].

Bioenergy does not play a significant role in Canada, contributing only 6% to total primary energy in 2021, however has grown over the past two decades and is expected to contribute to Canada achieving net zero [262].

Canada's initial climate action has focused heavily on emissions reduction through pricing and complementary actions aiming for a 40-45% reduction in GHG emissions by 2030, with a goal to reach net zero emissions by 2050. Because of high transportation emissions, Canada has also invested heavily in the biofuel industry [258]. The country's carbon removal sector can be considered largely focused on DAC and BECCS technologies. Only 14 Canadian companies have purchased BCR credits on the voluntary market and there is no framework to purchase any biochar-based offsetting credits through the regulatory purchasing framework to-date [263].

9.2.2 Production

Canada's vast and established bioeconomy creates favourable conditions for large-scale biochar production across the country. In recent years Canada has enabled large-scale projects, with numerous projects rooted in strategic partnerships between key actors in the biochar supply chain, often involving a forestry processing plant, a biochar project developer and an end industrial user.

Examples include the Biolesna and the CARBONITY projects. in Quebec. Biolesna's Carrot River project offered a solution for limited sawmill residual markets, where bioenergy markets were not an option. Today, the site produces a biochar utilizing BC Biocarbon technology, seeing carbon removal credits offered to the voluntary market [264,265].

The CARBONITY project, inaugurated in 2025, is a partnership between technology provider AIREX Energy, utility expert SUEZ and a local mill operator. CARBONITY will initially produce 10,000t of biochar annually, while tripling production by the end of 2026 [266].

Moreover, production of biochar destined for the metallurgical sector is prominent. In 2018 Elkem Metal Canada announced investment into a biochar production facility in partnership with Canadian technology manufacturer Pyrovac. The project is aimed at producing 40,000t of biochar annually, to replace its fossil coal consumption in its ferrosilicon production [267].

Other such projects are led by Canadian technology provider CHAR Technologies, with one active site and three others under construction [268,269], Evolys, a consortium of Rio Tinto and Aymium, who will replace fossil coal in local ilmenite production [270] and Infinite Carbon with pilot manufacturing for biochar destined for the steel industry [271].

Canada boasts a number of small-scale and mobile producers as well. Canadian producers include Bioburn Pro as well as Tigercat, who's portable carburizer allows for on-site carburization of wood-waste and debris [272,273].

9.2.3 Applications

Canada has a number of projects ongoing for metallurgical application, most prominently the projects by Elkem Metals Canada and Evolys, replacing fossilized coal in for metallurgic production mentioned above.

There are a number of producers targeting soil and agricultural markets, including Titan Biochar and BC Biocarbon, with their soil amendment products [274,275].

Activated carbon applications is a market frequently mentioned. CHAR Technologies has developed a product they call SulfaCHAR, which has been engineered to replace fossil coal as an effective filter for biogas production. The used biochar can then be re-used in creating a sulphur-rich soil amendment fertilizer as a secondary application [276]. Moreover, Titan Clean Energy Products also brings a number of activated charcoal products to market for air and water filtration as well as niche markets like cat litter [277].

9.2.4 Research and development

Universities involved in biochar research include the University of Saskatchewan, University of Alberta and University of Laval [278–282].

Natural Resources Canada has invested in numerous biochar projects in its CanmetENERGY program from 2023 to 2028. Examples include the *Bioenergy for Decarbonization of Heavy Industry*, focusing on integrating biochar as a defossilisation material in both steel and cement production. Moreover, this project participates in international standard development for biochar (ISO TC238) [283]. The *Integrated Biocarbon Sequestration Pathways for Negative Emissions Technologies* project focuses on reassessing current and emerging biomass conversion methods, characterization and assessment of biochars and national quantification of negative emissions potential in Canada [284]. Lastly, *Biofuels for Industry and Transportation Net Zero* is working to advance biomass conversion with pyrolysis technology to develop bio-based solutions for industry and transportation. The project explores the creation of biocrude, biochar and energy from residual lignocellulosic biomass [285].

Federal institutions are also interested in soil-based applications, with Agriculture and Agri-Food Canada (AAFC) conducting research on the effects of biochar in its Agricultural Climate Solutions Living Labs program [286,287]. Projects include exploring poultry manure bio-digestate with biochar as soil amendments [288] and effects of biochar as an additive in horticulture plants and soil health [289].

9.2.5 Policy, frameworks, and national strategies

Canada has implemented several carbon negative policies throughout its various sectors, including agriculture, infrastructure, energy and industry, through both direct and multi-sector policies, mainly in the form of funding programs. The most actionable policy for CDR is the GHG Offset Credit System, a trading platform where credits are created by registered avoided emissions or CDR. The development of a DAC protocol is ongoing, while a protocol is being considered for BECCS [263]. Implemented carbon removal policies have been limited to funding programs, mainly targeted towards agriculture and multi-sector approaches [290].

Carbon pricing in Canada can be traced all the way back to 2007, today seeing various mandatory carbon pollution pricing systems adopted both at the federal and provincial levels, with the federal system involving a large-emitter trading system, including an escalating carbon price for emitters [291]. The goal of the system was first to reduce emissions across the country, where industrial emitters in the system must meet an emissions intensity benchmark, or purchase credits to counterbalance extra emissions [263].

Currently, Canada does not boast any policy specifically targeting the production and/or use of biochar as a material of CDR technology, rather supporting through clean industry initiatives and funding programs. The federal government of Canada administers relevant industry and climate-based innovation funds where biochar projects can and have been support, including Natural Resources Canada's Investments in Forest Industry Transformation Program and Clean Fuels Program [258,292,293]. Moreover, provincial funding programs have also supported biochar production, such as Ontario's Forest Sector Investment and Innovation Program [294,295]. Based on federal research timelines (2023-2028), policy towards BCR could increase in Canada, as it may be assumed climate policies to date have focused on emissions reductions and in-setting rather than removals and off-setting [283–285].

9.2.6 Gaps, challenges, and opportunities

Gaps & Challenges

- The lack of biochar inclusion in Canada's policy framework is the country's biggest hurdle. Moreover, its slow implementation of regulatory CDR tools hinders investment in biochar production for carbon removals.
- If not used locally, biochar production site locations must be considered, as access to global markets other than the US will require shipping.
- Large energy infrastructure across the country does not create an advantageous market for decentralized bioenergy systems.

Opportunities

- Biomass availability is Canada's biggest opportunity with regards to biochar. Not only in volume, but because biochar presents a promising new market for biomass residues. For the forest industry, this is an opportunity for offtake markets for low-grade fibre which pulp and paper had previously taken. Demand for low-grade forest fibre can in-turn lead to more sustainable forest management across the country.
- Developing trade partnerships to send biochar to Europe, especially for high-volume industrial applications such as metallurgy. Canada's vast biomass resources, such as forestry residues, could adhere to strict product quality requirements which are common in metallurgical applications.
- Canada's steel production, mainly found in in-land provinces, could utilize biochar produced nearby, eliminating the need to ship biochar.
- Biochar production with poly-generation technology is an opportunity to provide Canada's rural communities with sustainable energy.
- Biochar in asphalt and construction materials is a low-hanging fruit for industrial-scale BCR deployment, especially with large infrastructure projects coming.

9.3 China

9.3.1 Overview

China is a large country totally 9.6 million km² and is one of the most populated countries in the world, with 1.4 billion inhabitants and a relatively high population density. Its land is diverse, being dry and arid in the north and west, subtropical conditions in the south. 56% of the country is agricultural land, predominantly permanent meadow and pasture (42%), arable land (12%), and a quarter of the country is forested.

Reported by IEA Bioenergy in 2024, only 3.3% of China's total energy consumption is supplied by bioenergy, mainly from solid biofuel consumption. The supply of solid biofuels is shifting in China. Residential heating made up nearly all of solid biofuel energy supply in 2010, however, electricity and commercial heat from solid biofuel have since supplied an equal share without net change from 2010 to 2022. At the same time fossil coal continues to increase and remains the dominant source of Chinese energy supply at roughly 61% of total supply [296,297].

China is the world's largest generator of agricultural residues and one of the most active geographies for thermochemical biomass conversion. Biochar activity is underpinned by vast feedstock availability (rice husk, wheat and corn straw, forestry offcuts, and municipal organics) and a decade of rapid deployment of pyrolysis and gasification systems. In practice, the industrial biochar market is still emergent relative to China's technical potential. Recent synthesis of literature places theoretical/maximum national capacity in the hundreds of millions of tonnes per year [298]. The near-term trajectory is shaped by three forces: (1) continued growth of biomass-to-energy projects that yield gasification char as a by-product; (2) selective build-out of larger, rice-husk-based pyrolysis lines along coastal grain corridors; and (3) tightening expectations on product quality and air-emissions control that will influence agricultural use.

9.3.2 Production

Feedstocks

Biomass production varies greatly throughout regions of China. For biochar production, crop residues dominate, notably rice husk, rice straw, wheat straw, and corn cobs. A study from 2024 found China produced 737.5 million tonnes of agricultural residues in 2020, with 82.3% of this total being utilized. Coastal provinces with dense rice processing (e.g., in the Yangtze River Delta and parts of the southeast) are particularly active for husk-based projects, while bamboo and forest residue char arises from the south of the country. Maize and wheat production dominate the north and northwestern regions [298]. Feedstock competition is rising in peri-urban regions, where residues are also sought for other, mainly energetic uses.

Technology

In contact with Dr. Genxing Pan of Nanjing Agriculture University, he shared that more than 80% of current tonnage is gasification char originating from biomass gasification plants designed for process heat and steam/electricity generation. This material increasingly finds outlets in construction materials, adsorbents, and soil blends where specifications allow. Slow-pyrolysis and carbonization systems—often batch or semi-continuous—are present in bamboo-rich hilly regions but account for a smaller industrial share. Intermediate and fast-pyrolysis units exist in niche deployments.

Technology providers include HaiQI Group who have numerous biomass gasifiers with targeted poly-generation outputs such as steam, heat and electricity, as well as mobile processing units [299].

Pyrogreen offers 11 different technologies in various size and outputs. Technologies include screw conveyor, rotary kiln and fixed-bed systems, offering various energy utilization methods. Their projects include a rice husk power plant in Myanmar with plants in construction in Taiwan and Indonesia [340].

Beston Group also provides the market with a number of technologies, with over 7,200 machine hours per year. The company produces equipment for continuous biomass processing as well as tire, oil and plastic treatment. Their technology is deployed around the world including in USA, Turkiye, South Africa, France, Colombia, Croatia, Korea and Indonesia, processing various feedstocks from olive pits, coconut shell, wood and straw [341].

There are a number of other technology providers as well, including but not limited to Henan Mingjie Environmental Equipment and Gemco Energy [342,343].

Scale and volumes

A paper by Xia et al [338] found China’s maximum potential for biochar production from 2018 figures was 145 Mt yr^{-1}. Per Dr. Genxing Pan, China’s installed equipment base and resource potential are vast, but realized, saleable biochar volumes remain modest compared to potential. Current industry estimates indicate ~0.7 Mt biochar produced in 2024-2025, with ~0.5 Mt expected in 2025, reflecting commissioning cycles and market absorption. This stark gap with theoretical capacity highlights a deployment and market-development constraint rather than a feedstock limit.

Several large ~150 t/day lines using rice husk are reported under build, with first power and biochar output expected over the next year. These projects are typically co-located with rice mills or agro-industrial clusters to reduce logistics costs and secure year-round feedstock. Along the eastern seaboard and lower-Yangtze corridor, operators report easier siting/permits where heat and steam can be monetized into industrial estates or district energy.

Like many large countries, one of China's biggest challenges of utilizing its biomass volumes is a geographical issue to match supply and demand. In provinces such as Yunnan, biomass production and supply does not synergize geographically with energy and large-scale biochar demand.

Project Examples

The Jianxing Tongao biochar project produces 10 tonnes of biochar daily from agricultural residues. Having worked with local governments, they claim to have secured 100,000 tonnes of biomass annually for their production. The company targets the agricultural sector as their offtake while selling carbon removal credits to the voluntary market [344].

It is noted biochar pyrolysis pilot plants are primarily located in Shenyang, Wuhan, Inner Mongolia, Heilongjiang, Henan, Anhui, and Guizhou. The extent of projects is expected to be much larger in both number and scale as those provided in this section, as well as utilizing a number of feedstocks, including bamboo and forestry residues [345]. However, limited information was available through the research.

9.3.3 Applications

Agriculture and soils

Agricultural application remains the most visible end-use in domestic discourse, but growth is moderated by conservative agronomic practice and varying provincial rules on biochar quality. Where adopted, biochar is blended into compound fertilizers, pelleted for orchards/vegetables, or applied to saline/alkaline improvement projects. Demonstrations cite fertilizer substitution and water-holding gains, though farmer-level uptake depends on price, logistics to the field, and confidence in quality standards. Moreover, China's compound fertilizer enterprises are rapidly developing "biochar-based fertilizers" and "biochar-based slow-release fertilizers", which have become major growth drivers.

Large-scale pilots using biochar for saline–alkali soil remediation have been implemented in Shandong and Jilin.

Barriers of biochar in agricultural systems can also be traced to regulation, with China's agricultural standards are very cautious to heavy metal, pH and electric conductivity in soils limits biochar's deployment. Another barrier noted was that armers focus more on economic benefits and improved fertilizer efficiency rather than carbon sequestration value.

Material Applications

A rapidly expanding outlet for gasification-derived char is cement, asphalt, and concrete additives as well as polymer and asphalt modifiers. Material applications are attractive because they can absorb heterogeneous char streams, are less sensitive to agronomic risk, and fit industrial customers' decarbonization goals, which aligns with the policy direction of high-quality solid waste utilization in China. Several municipal pilots are testing char-modified asphalt to improve rutting resistance and extend pavement life.

Environmental uses

Activated and engineered chars have matured greatly in China's industrial sector, being used for odor control, water polishing, and heavy-metal adsorption in industrial and municipal settings. These markets value consistent particle size distribution, ash content, and iodine number, favouring higher-spec char and post-activation. Moreover, large number of application cases of biochar in China, such as industrial wastewater treatment, mine remediation, and landfill leachate conditioning.

Animal husbandry and organics management

Smaller volumes flow into litter/bedding, manure management, and composting to reduce ammonia and improve nutrient retention, particularly in intensive livestock provinces. Co-composting with biochar is promoted in some waste-management programs to stabilize organics.

9.3.4 Research and development

China's academic and applied biochar research pipeline is extensive. National labs and university consortia publish at very high rates on pyrolysis fundamentals, biochar characterization, and field agronomy. Priority themes include: (1) scaling intermediate/slow-pyrolysis for stable-carbon yields; (2) gasification char upgrading for materials applications; (3) MRV methods for carbon storage accounting; and (4) soil-system trials linking biochar to nitrogen-use efficiency and saline-alkali soil rehabilitation. Collaboration between soil science groups and industrial partners is common, with several "college–industry" alliances translating lab findings into fertilizer formulations and remediation products. China also exports pyrolysis technology and know-how, particularly to Southeast Asia.

Key institutes include, but are not limited to, the Nanjing Agriculture University, Zhejiang University of Science & Technology and Shenyang Agricultural University, the latter having a Biocharcoal Engineering Technology Research Laboratory.

9.3.5 Policy, frameworks, and national strategies

Biochar is framed within broader carbon-neutrality and rural revitalization agendas, and within waste-to-resource policies that favour recovery of agricultural and forestry residues. Biomass power and cogeneration programs indirectly support biochar via gasification deployment, though incentives primarily target energy output.

Standards and permitting

A number of standards have been developed in China, particularly for biochar application in various soil applicants, ranging from fertilizer applications, applications for specific crops as well for various biochar characteristics, such as heavy metals [346].

Two issues shape near-term growth for agricultural use: (1) product standards for biochar (quality parameters, contaminants) and (2) tail-gas/air-emissions control, particularly for small rural plants.

Carbon markets

Domestic carbon policy is evolving. While methodologies for biochar-based carbon removal exist internationally, alignment with domestic certification/crediting pathways is still maturing. Some developers sell into export-oriented voluntary markets; others pair char utilization with enterprise decarbonization goals (e.g., fossil-carbon substitution in metallurgical and building products) rather than explicit removal crediting.

Waste and biomass policy are also relevant. Access to residues depends on agricultural burning bans, straw collection programs, and municipal organic-waste rules. Provinces with strong straw collection logistics and rice-mill clusters support higher load factors at pyrolysis plants, while mountainous areas rely on smaller distributed units processing bamboo and mixed residues.

9.3.6 Gaps, challenges, and opportunities

Gaps & challenges

- Deployment gap: Realized output (~0.5–0.7 Mt) is a tiny fraction of technical capacity, reflecting bottlenecks in permitting, market development, and project finance.
- Quality and compliance: Variable char quality and uneven enforcement of air-emissions standards (tail-gas control) constrain agricultural channels and public acceptance in rural areas.
- Logistics & seasonality: Residue collection and densification remain costly outside of integrated agro-industrial hubs; moisture and seasonality complicate year-round operations.
- Market education: Agronomic benefits are context-specific; growers need local trials, extension support, and clear guidance on use rates and economics.
- Data transparency: Public, plant-level production statistics are limited; inconsistent definitions (gasification char vs. pyrolysis biochar) hinder market sizing and comparability.

Opportunities

- Industrial materials pull: Cement, asphalt, brick, polymers, and metallurgical uses can absorb gasification char at scale while contributing to industrial decarbonization.

- Co-location with heat users: Embedding plants in industrial parks and food-processing zones monetizes heat/steam and improves project economics.
- Retro-fitting existing power plants: The conversion of coal to biomass pyrolysis plants would be an effective way to reduce fossil-sourced GHG emissions while growing renewable energy and biochar supplies.
- Rice-husk corridors: New 150 t/day lines near mills can anchor reliable feedstock chains; coastal provinces with efficient logistics are positioned for early scale.
- Standardization and MRV: Advancing national product standards, emissions control guidance, and MRV for carbon storage will unlock agricultural applications and enable participation in high-integrity carbon markets.
- Mobile & modular units: For remote farming areas such as Yunnan Province, mobile pyrolysis offers landscape-management and air-quality co-benefits by displacing open burning, even if volumes are smaller.

9.4 European Union & Switzerland

9.4.1 Overview

The European Union (EU) is a political and economic union of 27 states in Europe. The EU has a population of over 447 million and makes up an area of 4.0 million km² with diverse climates; temperate maritime in the southwest, mediterranean in the south, continental climates in central Europe and boreal climates in the north. 41% of lands are forested, 40% agricultural lands including permanent grasslands and croplands. In 2022, renewables made up 18% of the EU's final energy consumption, with bioenergy making up >60% of this share (11.1% of total) [347,348].

Switzerland is a mountainous country located in the middle of Europe totalling 39.6 thousand km² and a relatively high population density of 222 persons per km². The Swiss climate is temperate with a third of the country being forested, and a little over a third being crop and permanent meadow and pasture. From an IEA report in 2024, Switzerland depends largely on fossil (48.6%) and nuclear energy (27.8%), with bioenergy contributing 8.8% of the country's energy supply. It is not a member of the EU, nor member of EEA [349]. Switzerland was included in this section due to the strong synergies of activities within the EU and general geographic location.

From a biomass perspective, the EU largely uses primary and secondary woody biomass for its production (69%), with primary and secondary agricultural biomass (18%) and tertiary biomass and biowaste (i.e., recycled vegetable oil, sewage sludge, etc.) also being utilized. Despite having a net import dependency of fuel for bioenergy production (<5%), bioenergy is reported by the IEA to be a major contributor to energy security, as EU's high dependency on fossil fuels also has a high import dependency [347]. Translating this to tonnages, in 2022, the EU used 317 million tonnes dry matter (Mtdm) biomass for bioenergy production. Meanwhile, 260 Mtdm of bio-based materials contributed to industrial material use, 95% of which being wood-based products [350].

Although these figures do not directly translate the potential for biochar-bioenergy polygeneration, they do represent preexisting use of biomass in the EU. It also suggests an adopted culture in supporting a bioeconomy which efficiently and competitively utilizes biomass. Moreover, EU biomass production and use is projected to grow roughly 20% by 2045 [351]. In such a competitive market, it is clear the prioritization of biomass use is a major factor in the scaling of biochar production and use in Europe.

Associations

Driving the discussion in Europe is Biochar Europe (BCE), an industry association made up of over 130 member organisations from both industry and scientific actors. BCE supports the broad application of biochar to drive defossilization, enhance product quality, boost agricultural resilience and mitigate climate change through policy and regulatory intervention in the EU. In addition to their policy interventions, BCE produces an annual biochar market report for Europe [352].

A number of national and regional associations are also established, including German Biochar, Italian Biochar Association, Association Technique Energie Environnement (France), ÖBIKA (Austria), CHARnet (Switzerland), V4 Biochar Platform (Poland, Czechia, Slovakia, Hungary), Hellenic Biomass Association (Greece), Swedish Biochar Innovation Cluster and The Bioenergy Association of Finland.

9.4.2 Production

Technology

It is estimated Europe currently has 30 pyrolysis technology providers. Europe's fleet of technologies vary in design, size, feedstock and resulting product, whether to prioritize biochar, syngas heat/energy and synthetic oil production. Moreover, technologies vary in maturity, with market champions producing at TRL8 or TRL9, some of these providers have installed dozens of systems. Other technology providers are not as developed and are at TRL6 or TRL7, thus presenting a diverse market. Example technology providers include SYNCRAFT, Pyreg, AquaGreen, EQTECH, CarboForce, Next Generation Elements, Xylergy and BiokW.

Business models

Many biochar production sites in Europe are focused primarily on energy production and biochar and syngas as the byproducts. Energy utilization is essential in a sustainable biochar business model due to high labor, regulatory and biomass costs in Europe, compared to other global markets. Excess heat and electricity from pyrolysis plants have been proven to support decentralized energy grids while being coupled with ORC turbines and gas engines. Examples are gas engines from Austrian-based INNIO Jenbacher, as well as ORC Turbine technologies from DÜRR and ElectraTherm.

Production business models vary in Europe and include technology & equipment providers, plant design and operate, plant operators, and biochar product producers. A recent trend observed by Biochar Europe is a growing number of European companies broadening their business models to being project developers who later own and operate the biochar plants. This can provide benefits such as more central biomass sourcing and biochar sales. Moreover, there are also project developers based in Europe with focus in developing projects in the global south.

Production Capacity

Europe sees the largest number of biochar projects dedicated to BCR globally, with 203 plants installed and 185 plants in operation. In 2024 alone, 33 biochar plants dedicated to BCR were installed and commissioned, with 46 projects under construction or contract for commission in 2025. These projects vary in size of production, goal (energy vs biochar production), feedstock and location within continental Europe, including Norway and Switzerland.

In 2024, Europe's production capacity dedicated to BCR grew to 84,000 t, resulting in 55,000 t biochar dedicated to BCR produced. This represented an equivalent to 150,000 t CO_{2equ}, a 12% increase from 2023.

BCR can only be considered as one of three markets for biochar/charcoal. There is a long-established charcoal market with its primary destination to the barbecue market, as well as an increasing trend in demand from the metallurgic sector. In 2024, Europe's charcoal production capacity reached 284,000 t. Together, European biochar dedicated to BCR and charcoal production capacity combined for a total of 324,000 t. Current markets for Europe's biochar can be simplified to traditional barbeque charcoal, biochar to the metallurgical sector and used in construction materials and agriculture, both for their climate service and utilisation of material properties.

About 70% of biochar dedicated to BCR was produced by 3 regions: Nordics: 31%, Germany: 25%, Austria & Switzerland: 15%, Other Countries: 29% [352].

Project Examples

Sweden: Stockholm Urban Biochar Initiative

By 2020 the initiative produced 7,000 metric tonnes of biochar across five planned biochar plants processing green waste to produce biochar and renewable energy. It also generated 25,000 MWh of heat annually (enough for 400 apartments) and created the world's first urban carbon sink using biochar. The project has installed 300 new urban plant beds per year using biochar. 1,500 Stockholm residents had collected biochar for personal use. The project has been a lighthouse in demonstrating how cities can integrate biochar into waste management and district heating, turning urban green waste into a climate solution.

Sweden: Ecoera

Ecoera is a pioneering Swedish biochar company focused on carbon removal and sustainable agriculture. Awarded WWF Climate Solver status for climate innovation. Ecoera developed the world's first biochar-only carbon removal platform, starting with Sweden's first large-scale biochar application in 2009. Their facility in Hammenhög, Sweden, is among the largest biochar production sites in the EU, with proven industrial-scale carbon removal capacity of 6,500 tonnes of biochar per year.

The facility uses a variety of organic residues—including seed production waste, park and garden waste, sludge, algae, and seaweed. Biomass is carbonized via pyrolysis, producing biochar, syngas, and heat. The heat is utilized and the biochar is returned to agricultural soils as a stable carbon sink. Their biochar is certified under the strict European Biochar Certificate (EBC).

Finland: Carbofex

Carbofex Ltd, based in Nokia, Finland, was founded in 2016. The company specializes in continuous pyrolysis technology for converting biomass into biochar, pyrolysis oil, and renewable energy. Their demo plant uses a continuously operating, indirectly heated screw reactor that carbonizes biomass at 650–900°C and produces 1000 tonnes of biochar/year and 600 tonnes of bio-oil along with 10,000 MWh of clean energy (used in district heating networks). It has captured nearly 10 000 tonnes of CO_2 since 2017. The system can process a wide range of biomass, including wood chips, agricultural residues (straw, hulls, olive pits, coconut shells) and industrial byproducts from forestry and agriculture.

Austria: Sonnenerde

The biochar facility at Sonnenerde GmbH in Riedlingsdorf, Austria has been producing biochar since 2012, making it one of the first continuously operating biochar plants in Europe. The facility uses Pyreg500 pyrolysis technology, which ensures clean production by eliminating carcinogenic polycyclic aromatic hydrocarbons (PAHs) during the process. In April 2025, Sonnenerde inaugurated a new carbonization facility (KOHLOSS) which is a novel integration of biochar production and sewage sludge drying, built around the PyroDry®5000 system. Biochar Output is prospected to be up to 3,000 tonnes/year up from current annual capacity of ~1,000 tonnes of biochar. Feedstock is agricultural residues like grain husks, sunflower pods, spelt husks, and cellulose fibers. Applications are in soil improvement and composting in organic farming. Certification is under the European Biochar Certificate (EBC) and verified carbon sink certificates are obtained via Puro.earth.

Switzerland: H2 Glovelier Plant

The largest biochar production facility in Switzerland is being built in Glovelier, Jura. Via Hynoca® technology – a biomass thermolysis and gasification process – biochar is produced from local wood industry by-products and low-grade wood at a rate of 450 tonnes/year, although the main goal is hydrogen output. Biochar is a by-product of hydrogen and electricity production, used for compost enrichment and soil amendment. Each kg of hydrogen produced results in a net negative carbon balance (approx. -12 kg CO_2 per kg H_2), thanks to carbon sequestration in biochar and the hydrogen replacing fossil energy sources.

France: Carbonex

Three facilities in France, all using the same cyclic proprietary technology, make up to 50,000 tonnes of biocarbon (biochar and charcoal) per year from woodchips and forest thinnings. The biochar is used for agriculture, industry (concrete) and carbon removal. Electricity (up to 5 MW) is generated to power 20,000 homes. Carbonex's biochar production removes about 1,000 tonnes of CO_2 per year and is certified by EBC-Agro and EBC-BasicMaterials (European Biochar Certificate).

Netherlands: Power 4 Sustainability

The project uses woody bio-based material from local felling and pruning, maintenance and thinnings, in support of sustainable forest management, to up-cycle residues to produce high-quality projects. The project will be in operation in 2027, where P4S is targeting its biochar to support supply chains for agricultural products , the food industry and activated carbon. The project is certified through Puro.earth.

9.4.3 Applications

Europe is the region most invested in biochar applications beyond soil and agricultural applications. Drivers of such development are undoubtedly strong EU climate policy, including the early adoption of its Emissions Trading System (ETS) and the more recent emergence of the biochar's inclusion in the Carbon Removal and Carbon Farming Regulation (CRCF), creating a path towards regulated emissions trading and BCR as a supplementary tool. These regulatory pressures and tools have made Europe central to some of the most groundbreaking research and development programs, public and private investment and commercial commitments to biochar.

Construction Material

Biochar in cement, concrete and asphalt is a fast-growing application for biochar, largely driven by the CDR benefit to adding biochar to these materials. However, pioneering companies in this field such as CarStorCon and ecoLocked are not only finding climate benefits, but material benefits to biochar as a component in cementitious materials, each having delivered numerous projects over the last years. This is translating to real interest in the construction sector from companies such as STRABAG and building material producer Holcim. Furthermore, biochar in clay materials are also being explored by researchers and companies such as Natürlich Bauen.

Plastics & Polymers

Belgian company Carboganic is aiming to defossilise the plastics industry by replacing fossil carbon in polymer production. Their pioneering includes successful trials in 3-D printing with their polymer technology, creating opportunity for more sustainable products for several manufacturing sectors.

Steel & Metallurgy

Biochar application in metallurgy as an alternative to fossil carbon has seen a recent spike in interest from Europe's metal producers, especially considering upcoming free-allowances being lifted in the EU ETS, putting even more cost of production pressure on heavy-emitters in Europea's industrial sector. Several European biochar producers are targeting the metallurgic sector with their products, including Swedish-based company Envigas and Procarbon. Moreover, agglomeration technology providers, such as HÄNDLE, are beginning to offer machines specifically for biochar products.

Early movers in the metallurgic sector who have invested in integrating biochar into their value chains include Outokumpu, Europe's largest producer of stainless steel, who have made a €40 million investment to produce and use 15,000 tonnes of biochar annually. Swedish metal powder producer Höganäs have also announced operations to replace 20% of their fossil carbon supply with biochar by 2026. Austria's voestalpine Stahl has been conducting trials on biochar's application in their electric arc furnace.

Soil and Agriculture

Although it is unknown how much biochar is being applied to soils in the EU, the market is seeing more biochar-based products coming to market. Examples of companies pioneering biochar-based agriculture products include Sonnenerde, Sylva Fertilis, Skänefrö and Inkoh AG. Moreover, a number of livestock feed products on the European market from providers such as Carbuna and CharLine.

9.4.4 Research and development

Europe boasts several public and private institutions with significant capacity in biochar research and development. Interests vary from biochar and energy production, permanence, various applications and standardization. Please see the following list as a few examples demonstrating the variety of capacity throughout the EU and Switzerland:

Germany: Frauenhofer ISE & UMSICHT

Fraunhofer's ISE has a strong focus of biochar as a negative emissions technology, particularly biochar and pyrolysis in applied, systematic solutions. Their UMSICHT division develops plants and processes, production methods of biochar and offers scientific support along the entire biochar value chain, from feedstock to production and applications.

Austria: Bioenergy and Sustainable Technologies (BEST)

BEST uses thermochemical, biochemical and syngas technologies for the development of biomass-, residues- and waste-based biorefineries to produce green alternative products and energy. BEST is a part of the Austrian COMET Competence Centres (K1) which is managed by the publicly funded Austrian Research Promotion Agency (FFG).

Czechia: University of Chemistry and Technology Prague (UCT Prague)

UCT Prague explores various energy and material utilization of biomass, alternative fuels and bio-wastes. Their interests in biochar vary and include the effects of pyrolysis on sewage sludge and complex chemicals such as PFAS.

Italy: Re-CORD

Re-CORD is a private-public nonprofit R&D organization formed in 2010 focusing on the fields renewable energies, biomass, bioenergy and bioeconomy. Biochar, activated carbon and production processes are within their core research focus, having worked on a number of EU, national and self-funded research projects.

Poland: Institute for Chemical Processing of Coal (ITPE)

Although ITPE’s primary focus is on fossil coal, the Institute has shifted its focus to include biogenic alternatives to traditional coke. Their interest in biocoke primarily services for alternative use in the metallurgical sector.

Sweden: Swedish University of Agriculture (SLU)

SLU’s Biochar network is a research group with diverse aims across several fields of research pertinent to biochar and agriculture. Focus includes projects both in Sweden and abroad, bringing together various SLU departments including topics such as forest management, energy and technology, aquatic science and assessment and more.

Denmark: Technical University of Denmark (DTU)

DTU’s Department of Chemical and Biochemical Engineering investigates biochar’s interaction with the environment, pyrolysis and biochar production, especially within their Combustion and Harmful Emission Control Research Centre.

Netherlands: Wangeningen University

Wageningen University conducts various studies in the field of biochar, ranging from local applications and impacts of biochar in soils, biochar physical properties, and economic analyses.

Switzerland: Ithaka Institute of Carbon Intelligence

The Institute is renowned for its expertise in the production, post-production treatment, and application of biochar. Ithaka established the European Biochar Certificate and developed the first C-sink standards, including those for biochar, enhanced weathering, trees, and construction materials.

9.4.5 Policy, frameworks, and national strategies

European Union

In recent year several EU legislations support and regulate the use of biochar. Biochar is regulated by a number of bodies, including the EU’s regulation on the registration, evaluation, authorisation and restriction of chemicals (REACH), a basis of regulating product registration. Moreover, major files which support biochar include the Fertilizing Products Regulation as a component material for fertilizers, allowing biochar to obtain a CE label [353] and the Renewable Energy Directive, which upholds EU biomass sustainability standards and utilization for bioenergy use of biomass [354].

However, maybe the most enticing regulation for biochar in the EU is the CRCF. Published by the EU in 2024, the CRCF is the first EU-wide voluntary framework for certifying carbon removals, carbon farming and carbon storage for products in Europe, including biochar. The goal of the regulation is to facilitate the uptake of high-quality carbon removals to support the achievement of EU climate commitments, aiming to create trust in carbon removals through effective requirements on monitoring, liability and ensuring quality standards. Finally, it aims to encourage the generation, trade and use of carbon removal units [355,356].

Despite this progress much policy integration for biochar remains, particularly for sector-specific policies and regulations, to realize the extent of benefits biochar and pyrolysis can provide to Europe. This includes, but is not limited to, biochar use in cementitious products, pyrolysis' use for sewage sludge in wastewater treatment as well as national zoning and licensing laws for biochar production projects.

Beyond legislation, the EU has a track record of support biochar projects, providing funding for a number of biochar projects through channels like the EU LIFE program [357], Horizon Europe [358] and Innovation Fund [359]. However, funding has been targeted and project based, with no broad announcements or funding for the biochar industry in any aspect, whether it be production, application/market development or system integration.

National Strategies

At the EU level, there is no dedicated strategy for biochar integration into the economy. However, there are efforts such as the Bioeconomy Strategy do include biorefineries within their scope. Funding in the EU is also quite limited for the biochar industry. Recently, Arbion Industries (formerly Vow Green Metals) won EU innovation Fund funding in 2025. They are, however, based in Norwayand thereby outside the EU [360].

Delivering perhaps the largest national investment in biochar globally, Denmark announced a €1.35 billion subsidy program for pyrolysis-based biochar production over a timeline of 2024 to 2045. The investment is in line with a national climate target, estimated to reduce GHG emissions by 1.8m tonnes of CO_{2equ} by 2030 [361]. In addition, the Danes are supporting their investment by incubating collaboration amongst its government by creating the Green Tripartite, involving agricultural, conservation and industry stakeholders [362].

In Switzerland, a number of policies have integrated biochar, particularly regulations. These include the Fertiliser Ordinance, the Chemical Risk Reduction Ordinance and the Ordinance on Air Pollution Control [363–365].

9.4.6 Gaps, challenges, and opportunities

Gaps & Challenges

- Competition for biomass may be one of the biggest challenges for biochar in Europe, especially to meet the scale of demand from industries such as construction and metallurgy sectors.
- A lack of investment from EU member-states to support biochar projects hinders further integration of biochar production and application. Both as a competitive edge to access feedstock, but to also create supported off-take markets.

Opportunities

Strong EU climate policy, coupled with developments in the CRCF, set the scene for biochar to realize its climate-service as a carbon removal credit, in addition to its material benefits. This will be a catalyst to grow biochar production and use.

- Integration of biochar as a CDR method coupled with the tightening of free allowances within the EU ETS is an excellent demand opportunity to quickly scale. Especially for sectors with material and in-setting benefits, such as construction materials and metal production.
- Biochar in soils to support soil health, especially when soil health is becoming a more pressing priority to EU states.
- Although competition for biomass is high, the culture of biomass utilisation is strong in Europe. Further improvements to utilize biomass can be built upon to maximize sourcing without needing to intensify harvesting.
- Europe's bioenergy experience creates a strong environment for decentralized production of biochar and easily integrated utilization for heat/electricity by-products.

9.5 Japan

9.5.1 Overview

Japan is an island nation totalling 365 thousand km² with a population of 125.1 million residents and a high population density. The country is very mountainous, with a limited area of flat land. Only 12% of Japan is considered agricultural lands, mainly dedicated to rice production, while forested area covers over two-thirds of the country.

Fossil fuels make up the majority of Japan's total energy production. Renewable energy supply is rising in Japan, however mainly from hydropower and solar. The use of bioenergy has as well, particularly from the use of solid biofuels for heat & electricity production, however very modestly, making up only 2.7% of total energy supply in 2022. The IEA states biomass supply as a challenge in growing bioenergy production, and that R&D projects in biomass utilization, such as municipal solid waste, can be an opportunity for the country. This can reflect directly to the potential production of biochar in Japan [366].

In line with biochar, Japan presents a limited area for biomass sourcing, in comparison to many other nations. However, the integration and call for biomass sourcing and utilization in bioenergy is a good reflection of the interest and current biochar activity today.

Representing biochar interests in Japan is the Japan Biochar Association (JBA), which was established in 2009. Their work is embedded in the promotion and utilization of biochar and its properties in support of environmental restoration, working collaboratively around the globe. They state biochar has been part of research in Japan for many years, even being recognized as a soil improvement material by the Ministry of Agriculture, Forestry and Fisheries in 1986. Over more than 30 years, Japan has developed a very mature knowledge base [367]. Researchers and applicators in Japan have been accumulating their understanding of biochar in both study and practice, going beyond initial findings of agricultural applications to now carbonizing technology, architecture and solutions for environmental problems. Moreover, their website boasts biochar standards for carbon storage and guidelines for soil improvement applications, which are used as part of monitoring methodology in Japan's J-Scheme [368].

In addition, biochar in Japan is supported by the Japan Biochar Research Center (JBRC). Established in 2022 from Ritsumeikan University, JBRC was founded to promote the research and dissemination of BCR. Moreover, JBRC founded the Japan Biochar Consortium (JBC) to bring together private companies, local government and researchers to collaborate on advancing biochar research, social implementation and dissemination. Today the JBC holds 149 members between organizations and individuals. Together with JBRC, they engage Japanese actors through hosting symposiums, workshops, study groups and hosting [369].

With the JBRC, JBC & JBA all driving the discussion today, it must be mentioned that body's representing biochar and charcoal in Japan date back as far as 2002, finding sources referencing a body called the Association of the New Use of Charcoal in Japan [370], demonstrating a collected interest into the capabilities of biochar in Japan.

9.5.2 Production

Biochar production for intended use in Japan can be dated back hundreds of years, with references in an Encyclopaedia of farming published in 1697. Today, feedstocks of focus for biochar applications in agriculture are wood, bamboo, and plant shells including rice husk, soybean pod and corn cobs. However, the market can be classified mainly by rice husk biochar producers, and woody biomass biochar producers, primarily as a co-product of bioenergy production.

JBA classifies biochar products into three categories, primarily based on products derived from variable temperature applications; white charcoal (≥900°C), black charcoal (500°C - 650°C), rice husk biochar (350°C - 500°C) and Burn & Off charcoal (extinguish and water application for cooling) [371].

A major source of biomass in Japan is rice husk. Once commonly burned, its prohibition creates opportunity for biochar production in Japan, with Japan alone producing over 2 million tonnes of rice husk annually [372]. In response, the New Energy and Industrial Technology Development Organization’s (NEDO) Green Innovation Fund, in collaboration with Yanmar Energy System and JA Gifu (Gifu Agricultural Cooperative) launched a pilot rice husk biochar production system in 2025. Over a six-year period (ending 2031) the project aims to reduce the cost of biochar production in Japan while conducting agriculture field trials in over 50 regions in Japan. The biochar will be enhanced with microorganisms to further promote positive soil and plant effects. The project targets an annual biochar output of 120 tonnes, and plans to expand after 2031 to produce over 10,000 tonnes annually [373]. Rice husk biochar represents a particularly important pathway [367].

Another notable project is the Shingu Forest Energy which was commissioned in 2020, utilizing a Syncraft pyrolysis unit coupled with a Jenbacher engine for electricity production. The site utilizes roughly 20,000 tonnes of woody biomass annually, producing 1,500 tonnes of biochar. The project is setting aim at growing the BCR market in Japan by developing a environmentally-friendly construction materials which incorporate biochar [374,375].

Other active industrial actors include PROS Co. Ltd., who are allegedly one of Japan’s largest rice husk biochar producers [376]. Nippon Tan Co. Ltd., who states are developing their own technology but no confirmation of current production, as well as Hatsutory Co. Ltd., who produce biochar from underutilized materials such as driftwood and felled trees, and they sell kilns [377,378]. Finally, Sinanen Facilities Co. Ltd., announced its strategic move to the carbonization business with goals of replacing fossil coal with biochar in the steel and coal-fired powerplant industries. There are no updates at this time whether production has begun [379].

Technology Providers

Since 2019, Yanmar Energy System has been developing its gasification power generation system, with the NEDO funded project mentioned above as one of, if not the company's first attempt at its product's commercialization. Although limited information is available about the technology, its furnace is known to have a heat capacity of 800ºC - 1000ºC and one unit is capable of processing 400 tonnes of rice husk annually [372].

Tromso Co., Ltd also provides the market with their continuous biochar production equipment, equipped with a screw to pyrolyze small biomass such as rice husk, rice straw and peanut shells [380].

9.5.3 Applications

Application focus in Japan is highly centred around biochar in soil and agricultural applications, as these are the mentioned focus areas of interest groups JBA and JBC. A particular strength of the Japanese context is the development of detailed application guidelines [367]. More specifically, the JBA's *Application guideline of biochar for agriculture* includes 8 principles of biochar applications cover seedling, various field, pot and hydroponic applications, providing application guidelines for crops such as paddy rice, soya bean, corn, leafy vegetables, fruits, vegetables, trees, flowers and compost production. Rice husk charcoal has long been used in rice farming as a soil improvement material [371].

Companies like TOWING are taking a value-added approach to biochar in soils. TOWING produces their biochar product *Soratan,* which is a fertilizing additive where microorganisms are added to biochar to enhance soil environments [381].

While Japan demonstrated a high level of maturity in knowledge development, agricultural application, and methodological frameworks, the scale of market activity is not clear nor seems to be at large scales. Japan's interest in biochar and charcoal applications has been explored since the early 2000's. In a paper by Ogawa and Okimori [370], the authors reference a market analysis of new use purposes of charcoal in 2002, where agricultural applications were the majority (27%), conditioning of humidity (23%), livestock industries (8%) and water treatment (4%) also mentioned.

An interesting product on the Japanese market is COOL VEGE as part of the Carbon Minus Project. COOL VEGE is an eco-brand for produce cultivated with biochar in rural Japan, with the project aimed at maintaining food production, revitalizing rural economy and preservice the natural environment, all while reducing emissions [382].

Despite the focus on agriculture, Japan has a strong steel industry, which is actively researching possible decarbonisation pathways. As an example, Nippon Steel is aiming to achieve carbon neutrality by 2050. Even though not the main decarbonisation pathway for Japan's blast furnaces, biochar is actively being researched as a carbon carrier for the country's metal industry [383].

9.5.4 Research and development

At the forefront of biochar activity in academia is Ritsumeikan University (RU), which hosts the JBRC and JBC. RU began research on biochar in 2019, later obtaining government support to continue its carbon removal endeavours, leading to the establishing of JBRC in 2022. JBCR's research is centred in natural sciences and social sciences to understand biochar's environmental functions and climatic impact, and how these technologies are applied and integrated in the real world. JBRC also coordinates with other universities and other institutes on biochar production, characterization and analytical methods for BCR quantification.

Japan International Research Centre for Agricultural Sciences is a public administered institute also focusing on biochar, having produced a number of biochar publications on projects in greater Asia and the global south.

Lastly, it must be noted Japan has a reputable history of in-depth efforts analysing biochar's socio-economic integration. The Carbon Minus project, as mentioned above, was analysed by researchers in 2010 working to understand the brand's perception on its local demographic but also dove into the idea of connecting rural and urban environments and valorising environmental and climate services pertinent to biochar integration in agriculture [384].

9.5.5 Policy, frameworks, and national strategies

Japan is among the more advanced countries in terms of integrating biochar into policy frameworks [367,385]. In 2020, Japan announced its aim to be carbon neutral by 2050. As a way to drive down emissions, Japan developed its J-Scheme. J-Scheme is a mechanism for administering BCR credits through its regulatory lever, Tool for CO_2 Removal from the Atmosphere. The J-Scheme accepts stock refractory carbon in mineral soil by adding biochar to cropland and/or grassland. The methodology's eligibility includes application of biochar in line with Japan's cropland regulations; product characteristics, specifically a carbon content and fraction with a minimum durability of 100 years, or, production characteristics including made from certifiable feedstocks/temperature that make such default values applicable [386].

The J-Scheme's credit volume calculation approach is:

$$\text{CO}_2\text{ stock} = (\text{Added biochar volume x Organic carbon content x Fraction of biochar carbon x } 44/12) \\ - \text{CO}_2\text{ emissions resulted from biochar production and transportation}$$

Finally, there is a set of 3 monitoring methodologies including (1) Measuring the degree of refinement (electric conductivity) by a charcoal refinement meter, etc.; (2) Measuring the organic carbon content at an industrial experimental station, etc.; (3) Measuring the organic carbon content, being based on the JBA's specification on the measurement of biochar for carbon stocks in soil [386].

The J-Scheme appears to have other methodologies beneficial for biochar production, including methodologies for renewable heat and electricity generation [386].

Moreover, in response to setting aim at carbon-neutrality by 2050, Japan launched a 2 trillion Yen (€11B) fund as part of NEDO to drive green innovation projects in the country. Launched in 2020, this includes support for R&D projects, demonstrations, and social implementation projects for up to 10 years to companies that commit to ambitious goals [387].

9.5.6 Gaps, challenges, and opportunities

Gaps & Challenges

- With northern Japan experiencing harsher winters than southern regions of Asia, it is generally limited to one harvest of rice per year, reducing its availability of rice husk in comparison to neighbouring regions [367]. Nonetheless, the annual production of 2 Mt is significant for local production and use.
- A lack of biomass diversity may limit the variety of capability biochar can provide from local feedstocks.

Opportunities

- Biochar recognized as a biochar carbon removal methodology is a foundational building block for further deployment. Japan must further invest in pyrolysis technologies to improve biochar's deployment.
- Integrating more applications where biochar can be a tool for carbon sequestration and emissions avoidance, including biochar in cementitious materials and replacement for fossil coal.
- Considering Japan's high population density, sewage sludge pyrolysis may be an effective source of nutrient circularity, energy production and further spread of harmful chemicals.
- Japan has a high degree of capacity in understanding rice husk biochar. This knowledge could be shared through international collaboration in other rice producing countries. This could not only help rice crop yields and crop residue management, but allow other regions to prosper from carbon removal credits.

9.6 Norway

9.6.1 Overview

Norway, with a population of 5.6 million people, has a relatively large and diverse landmass (384 483 km^2) which can be divided into developed areas (2%), boreal forests (37%), low vegetation areas such as marshlands, tundra and alpine regions (38%), unvegetated rock and gravel areas (7%), and agricultural areas (4%) [388]. In addition, Norway has a long coastline (102 936 km) with a significant marine biomass production [389]. Annual extraction of biomass amounts to about 15 million tonnes [390]. At present, biomass is used in food, fodder, and materials production, in addition to energy provision. The latter is mainly associated with industry, and domestic and district heating from wood, wood chips from forestry, and household waste (in the case of district heating). However, Norway is a highly electrified country with limited district heating infrastructure compared to its Nordic neighbours [391]. Biogas production from sewage sludge, food waste and manure is rapidly developing, but most of the country's biomass potential stems from the forestry sector, together with more limited contributions from agricultural and aquaculture residues. Most of this potential is untapped, as actual energy production from biomass is about 18 TWh annually [392], with the current potential being more than double that amount [393]. In Norway, a comparably small share of the land area is used for agriculture. Norway has a strong metallurgical sector with several large companies producing silicon, ferro-silicon, manganese alloys, aluminium and other metal products.

Associations

Norsk Biokullnettverk (Norwegian Biochar Network) is a member association who brings together around 30 biochar actors from all aspects of the Norwegian biochar value chain. The association works to promote biochar in Norway's circular bioeconomy to support climate efforts and to ensure Norway is a leader in biochar use and production.

The *Nordic Biochar Network* (NBN) is a Norway-based network targeting mainly the Nordics. The network's goal is to increase awareness of biochar and promote collaboration and knowledge exchange across Northern Europe. The network has about 500 members from academia and industry as well as private people. The network's main activities include the organization of dissemination activities like open workshops and webinars.

9.6.2 Production

Norway has begun establishing industrial-scale biochar production facilities, utilizing its forest residues, logging by-products and waste wood as the main feedstocks. There are currently eight biochar production sites in Norway.

These sites include OBIO at Rudshøgda, operating two BIOMACON units with a combined production capacity of 750 t/year. The company produces EBC-certified biochar, and targets mainly soil amendment and animal fodder. Surplus heat is used to heat a nearby slaughterhouse [394].

The city of Sandnes (and their intermunicipal cooperation (IMC) company, IVAR) on the western coast of Norway also owns and operates two BIOMACON units, together producing around 400 tonnes biochar per year. One focus so far has been urban applications of biochar [395].

Other biochar producers in Norway include ØRAS (another IMC) [396], Trøndelag Fylkeskommune [397], and WAI Environmental Solutions [398].

Due to its strong metallurgical sector, Norway has several companies targeting the production of biochar for the metal industry. Arbion (formerly VOW Green Metals) is currently starting up their biochar production in Follum, with an output of 25 000 tonnes of biochar agglomerates [399]. Cruda (involving Standard Bio) is also establishing a biochar production facility with a capacity of 10 000 tonnes of biochar agglomerates [400]. Both companies have recently received European funding to support ongoing and future projects [401,402].

Beyonder, a battery cell and module producer, is working on utilizing biochar from sawdust for battery cell production [403].

Technology Providers

With VOW ASA, Norway has a noteworthy biochar technology provider. The company has acquired the French technology provider ETIA and their electrically-driven pyrolysis technology (Biogreen). Furthermore, VOW can also supply pyrolysis technologies via its subsidiaries C.H.Evensen (large scale gas driven and/or electrically driven) and Scanship (compact systems for pyrolysis of sludge and waste on cruise ships) [404].

9.6.3 Applications

Currently, the main biochar applications in Norway include metallurgy and feed additives. The largest national production sites and suppliers are focused on either one of these two applications. At present these two markets are the only ones that find the use of significant quantities of biochar affordable. Among these two, biochar for metallurgy is expected to fuel the largest demand for biochar by far. Other notable applications include biochar for composting and soil improvement, but at present implementation is not considered cost effective at scale. Notable metallurgical companies in Norway that are researching and testing the substitution of fossil coal with biochar include Elkem, Eramet, Alcoa, Wacker, and Hydro.

9.6.4 Research and development

There is a strong academic research presence in Norway, which features internationally acclaimed researchers and projects. Main areas of focus have been biochar carbon storage, production and properties, agricultural soil improvement, environmental remediation. The main research arenas in Norway include

- *SINTEF Energy Research*, focusses on biochar production from various feedstocks, including pretreatment and upgrading, product characterization, by-product valorization, and emissions testing.
- *Norwegian University of Life Sciences (NMBU)*, who works on agricultural applications in the global south, biochar production from waste biomass and soil restoration and remediation.
- *Norwegian Institute of Bioeconomy (NIBIO),* who focusses on biochar for agricultural and forestry applications, with focus on carbon permanence and sustainable farming practices including fertilizer optimization
- *Norwegian Geotechnical Institute (NGI)*, working on biochar for environmental remediation and fate of contaminants and emissions from the pyrolysis process.
- *Norwegian University of Science and Technology (NTNU),* who works on life cycle assessment of biochar-based value chains.

9.6.5 Policy, frameworks, and national strategies

Norway has taken a leading role in developing carbon capture and storage (CCS), investing heavily in projects such as Longship and the Northern Lights storage site in the North Sea. These initiatives are central to Norway's strategy for addressing emissions from hard-to-abate industries like cement, waste-to-energy, and metallurgy. Supported by significant public funding and clear policy frameworks, CCS represents a cornerstone of the country's industrial decarbonisation pathway [405,406].

Alongside this, biochar offers a complementary approach to long-term carbon removal. Produced from forestry and agricultural residues, biochar stores carbon in a stable form while providing co-benefits such as improved soil health and resource efficiency. Norwegian research institutes and companies have developed promising biochar applications, and small-scale commercial plants are now in operation.

However, policy support and visibility for biochar remain limited compared to CCS. While large-scale capture and storage projects have benefited from substantial national funding, biochar initiatives are mostly supported through smaller innovation and regional programs. This difference reflects the early emphasis on industrial CCS infrastructure and the more recent emergence of nature-based and distributed CDR solutions such as biochar.

Some noteworthy policy documents and funding mechanisms include:

- Climate targets: Norway's *Climate Action Plan (2021–2030)* and long-term 2050 strategy include measures to increase CO_2 removals alongside emission reductions [407].
- Klimakur 2030: Biochar was identified as a cost-effective mitigation measure, with an estimated potential of about 0.8 Mt CO_2 per year by 2030 using sustainable biomass sources [408].

- Agriculture sector plan: The climate agreement between the government and the agricultural sector highlights opportunities for soil carbon storage and sustainable use of residues, including biochar [409].
- EU alignment: As part of the European Economic Area, Norway follows the EU's *Carbon Removal Certification Framework (CRCF)*, which explicitly recognises biochar carbon removal (BCR) as a quantifiable pathway.
- National guidance: The Norwegian Environment Agency's measure sheet "J07 Biokull" proposes increasing the use of biochar in agriculture, aiming for about 30 000 tonnes by 2035 [410].
- Funding programmes: Biochar activities are currently supported through instruments such as Enova, CLIMIT, and Regional Research Funds, often at pilot or demonstration scale. In addition, the use of biochar by Norwegian farmers is subsidized by the Regional Environmental Program (Regionalt miljøprogram - RMP) in several counties, currently capped at 4 tonnes dry biochar per farm per year.

9.6.6 Gaps, challenges, and opportunities

Gaps & Challenges

- Limited policy recognition: Biochar is not yet fully integrated into Norway's climate accounting framework or its greenhouse gas inventory, which limits incentives for deployment compared with CCS.
- Fragmented support mechanisms: Current funding is spread across small innovation programmes, with few long-term instruments for large-scale production, certification, and market development.

Opportunities

- Metallurgical industry as a driver: Norway's strong metal sector—especially in ferroalloy and silicon production—offers a natural market for biochar. Replacing fossil coal with biochar can significantly reduce process emissions while supporting domestic value chains based on forest residues.
- Synergies with CCS: Biochar and CCS are not competing but complementary measures. CCS targets large industrial point sources, while biochar can deliver distributed, land-based removals. In the longer term, hybrid systems combining biochar production, BECCS, and CO_2 utilisation could expand Norway's carbon management capacity and strengthen its position in negative emissions technologies.
- Aquaculture as a future driver: The large aquaculture industry has started exploring pyrolysis and biochar production both for valorizing by-products as well as a more sustainable waste handling strategy.

9.7 Saudi Arabia

9.7.1 Overview

Saudi Arabia is country located on the Arabian Peninsula spanning a total area of 2.15 million km² lying in the tropical and subtropical desert region. The country has a population of roughly 35 million inhabitants. Its landmass has mountains to the west, large desert areas in its interior with coastal regions of oases in the east. Nearly all of the country is considered arid with high temperatures in summer and close to freezing winters, seldom seeing rainfall or cloud cover.

Even under such arid and extreme growing conditions, Saudi Arabia produces crops such as cereals, wheat and vegetables, and are large producers of palm and dates [411]. Date production specifically has been a targeted export to diversify the country's gross domestic product (GDP), with over 37 million palm trees today [412].

However, the primary resource is the country's vast oil reserves, which are 4th largest in the world. Oil made up 63.8% of the country's energy supply in 2023, with natural gas making up 36.1%. The remaining 0.1% was covered by renewables [413].

Under these conditions, it is clear energy production is not a driver of biochar production, however, with large investments and initiatives in Saudi Arabia to afforest and diversify the economy through bioresources, opportunity is ample in Saudi Arabia.

There is no dedicated biochar association in Saudi Arabia, outside of research.

9.7.2 Production

A promising Saudi-based start-up is Terraxy, who produces biochar from chicken manure, of which currently all 400,000 tonnes produced in Saudi Arabia ends up in landfill. Their CarboSoil solution is tied to contribute to the country's 10 billion trees initiative, which aims to rehabilitate over 74 million hectares of lands [414]. Their pilot plant produced 150 tonnes of CarboSoil In 2023-24, which the company claims is ready to scale [415,416].

Moreover, The National Centre for Palm and Dates and the Ministry of Environment , Water, and Agriculture have collaborated to produce biochar from palm waste. The breakthrough is targeted at supporting water retention for crop production, to utilize agricultural waste while creating an economic opportunity around the country's palm and date industry [417].

No data is available on the scale, or projected scale, of biochar production.

9.7.3 Applications

The Saudi Green Initiative (SGI) plans to green the Saudi landscape, including cities and deserted areas. Tree-planting initiatives will be rolled out over several years, with more than 600 million trees and shrubs expected to be planted by 2030. The effort will be expanded to plant 10 billion trees in support of sustainability targets. These targets have spurred biochar awareness and applications in soil amendment for water and nutrient retention in sandy soils. An example project is the Green Riyadh Program. The program aims to plant 7.5 million trees throughout the city of Riyadh to increase its urban and residential green space from 1.5% to 9% [418]. A joint venture between Saudi company Eco Tadweer and American based Strategic Environmental & Energy Resources (SEER) developed a partnership to develop an understanding of the effects biochar has on urban tree planting initiatives in Riyadh. The joint venture entered a partnership with American company Biochar Now, who has developed a pH adjusted biochar to cater best to Saudi soil conditions from their kiln-based biochar [419]. Biochar Now uses a kiln-based technology, however it is not known where the biochar is produced for this project [420].

Furthermore, biochar is found to be very impactful in local plant production, reducing metal concentration in dates, improving growth rates of wheat and lettuce by more than 70% and 51% respectively.

9.7.4 Research and development

Research Institutes

Initiated in 2011, the Saudi Biochar Research Group (SBRG) is one of Saudi Arabia's most prominent biochar initiatives. Based in the College of Food and Agriculture Sciences at King Saud University, SBRG is teamed by researchers, professors and students work on a number of facets of biochar and pyrolysis in lab and applied research settings. This includes multi-disciplinary aspects of pyrolysis and biochar production from various waste materials and biomass at residential and industrial scales, most predominantly date palm tree residues. Their strengths and expertise revolve around proximity analysis, elemental analysis, chemical analysis and physical structural analysis of biochar. Moreover, their applications of interest include soil amendments, composite materials, environmental remediation and climate mitigation [421]. The group has been featured in 35 journals around the world. In correspondence with SBRG founder Prof. Mohammad Ibrahim Al-Wabel, the SBRG's current focus is the development of standards for biochar in Saudi Arabia.

9.7.5 Policy, frameworks, and national strategies

Saudi Vision 2030 [422] is an umbrella initiative under themes of creating a vibrant society, thriving economy and an ambitious nation. The key objectives of Saudi Vision 2030 are to reduce carbon emissions by 278 million tonnes annually, plant 10 billion trees to rehabilitate 40 million hectares over a span of decades, and to designate 30% of the country's land and sea by 2030. These goals are in place to enhance environmental wellbeing and to drive and diversify a more circular economy [421,422]. Vision 2030 also includes aims of carbon emission reduction and reforestation [423].

Although no evidence was found for biochar in Saudi policy or frameworks, active biochar projects with strong ties to government departments, ministries and universities is a positive sign of national support for biochar's social adoption and could accelerate implementation. No CDR frameworks were noted, however interest in emissions reduction is clearly stated in SV2030.

9.7.6 Gaps, challenges, and opportunities

Gaps & Challenges

- Although adoption of renewable energy is underway since 2022, sources are primarily from wind and solar. This creates an even more competitive energy market for bioenergy as a co-product of biochar production, reducing overall gain from production.
- With only recent deployment of planting initiatives, crops may take time before enough residues are produced to support large-scale biochar production to further support planting initiatives and soil quality.

Opportunities

- Afforestation projects stemming from SV2030 are one of the biggest application opportunities for biochar. Biochar's deployment has an impactful capability to improve growing conditions, reduce resource consumption, while provided a further CDR benefit. Moreover, a circular framework is very implementable when utilizing corresponding biomass wastes and residues.
- Establishment of the SBRG provides capacity to strategically deploy biochar production and applications.
- As producing biochar standards is a focus of the SBRG, collaboration with states who have developed agricultural standards would be an effective move. Even where soil conditions may not share similar characteristics, frameworks and BCR integration to carbon removals may be key topics of benefit. In turn, it may be advantageous to then pass that knowledge capacity on to neighbouring country's with similar environmental conditions.

9.8 United Kingdom

9.8.1 Overview

The United Kingdom is located in northwestern Europe, incorporating the island of Great Britain and the northeastern portion of the island of Ireland, making up an area of 242 thousand km². 68 million people make up the country with a population density of 282 people per km². Its land use is predominantly agricultural land (72%) which is mainly permanent meadow and pasture. 25% is arable land while forests make up less than 14%. The UK has a temperate climate.

In 2022, bioenergy contributed to 8.4% of the country's energy supply, with an import dependency of 30%. Solid biomass has grown steadily over the past decade, mainly going to power production in converted coal power plants, making up 11% of electricity consumption and a modest 5.5% of fuel and heat consumption. Heat and fuel consumption is largely dominated by fossil fuels, making up over 90% of all heat and fuel consumption [424].

Lefebvre et. al [425] estimate UK biomass availability at ~32 Mt annually which is larger than the UK government's projection, while the Independent Review of Greenhouse Gas Removals [426] published for the UK government in October 2025, states 13-25 Mt of available biomass. It must be noted large discrepancies for available biomass stem from the fact that the limited domestic supply and the reliance of imports for the planned bioenergy expansion create large uncertainties for future supply availability in different scenarios, coupled with variability in which biomasses are considered in the scope of studies. However, in a letter from biochar experts from CO2RE and the Biochar Demonstrator, the authors estimate a potential of 2 Mt of available biomass feedstock for biochar production [427].

Biochar is of the fastest growing and implemented CDR technology in the UK. The UK State of Carbon Dioxide Removal report for 2025 tallies 35 active biochar companies in the UK, making it the highest count of any CDR technology [428]. Despite the rapid growing sector, biochar is not represented by a biochar association in the UK. However, groups like Carbon Gap represent BCR, as a near-commercial carbon removal methodology, where they have made calls upon the UK government to adopt new implemented standards for BCR [429].

9.8.2 Production

Key production sites include those funded by the UK's Department of Energy Security and Net Zero (DESNZ) and Direct Air Capture and GGR Innovation Competition. The successfully funded projects include Black Bull Biochar, Invica Industries, Lapwing Energy, Ricardo and Mersey Biochar [427]. The projects vary in scale, use of heat/energy, and the type of feedstock used. Most are targeting agricultural and carbon removal applications however, even including farm-based production by Lapwing Energy. Invica Industry's E-Coke branch is producing biochar as an alternative for fossil carbon industrial processes [430].

Ricardo's Bioccus project stands out, as they have combined their carbon capture system with UK company Woodtek's pyrolysis technology, and hot air turbine technology to process forestry waste. The system maximizes feedstock through by producing biochar, delivering excess heat to up to 300 local homes and businesses while capturing any CO_2 that would be emitted during the process. Ricardo wishes to deliver the captured CO_2 to local food and beverage manufacturers and to produce biochar which is eligible for CDR credits, thus maximizing its climate impact [431].

Other notable production facilities include Brodie Biomass, which is a farm-based production utilizing local wood and Carbon Hill Limited, which has been active since 2022, producing biochar for on-farm uses and compost blending [432,433]. Perhaps the largest biochar production plant in the UK was announced in 2024 by A Healthier Earth. Their site in Royal Wooton Basset plans to produce 9,000 tonnes of biochar annually, capturing 17,000 tonnes of CO_2 annually by processing locally sourced organic waste which otherwise would have been destined for landfill or incineration [434].

There is no total production known in the UK.

9.8.3 Applications

A number of projects are underway to support market development. Carbon Cell [435] is startup producing biochar-based foam to replace polymer-based foams. Carbogenics [436] produces biochar from difficult recycle organic waste and wastewater screenings, with their biochar targeting anaerobic digestion. Biochar Innovations [437] is also a start-up producing biochar-based products such as carbon negative fertilizers.

9.8.4 Research and development

Innovation in GGRs in the UK is being driven by academic research and the private sector, and has been supported by public innovation funding. The UK government has invested £100 million in research and innovation for GGRs:

- DESNZ recognises the potential benefits of biochar and has been taking active steps to address critical evidence gaps. Funded by DESNZ, phase one of the DAC and GGR Innovation Competition delivered 22 feasibility studies across DAC, BECCS, enhanced weathering, and biochar, while phase two awarded over £49 million of government funding to 14 of the most promising demonstration projects. Five biochar production projects were funded by the DAC and GGR Innovation Competition – the examples listed in section 9.8.2 represent a £19 million investment.
- UK Research and Innovation (UKRI), through its Strategic Priorities Fund (SPF), has invested £31.5 million in the Greenhouse Gas Removal Demonstrators (GGR-D) program and its coordinating CO2RE hub based at Oxford University, which includes a biochar demonstrator project among four other GGR demonstrators. As well as testing and

piloting a suite of GGR approaches at sites around the UK, the program has conducted vital cross-cutting research to support sustainable routes to large-scale removal of atmospheric greenhouse gases.

- The Live Labs 2 project is developing new materials for decarbonising roads in the UK, including biochar. The project is backed by £30 million in government funding from the Department for Transport (DfT) [438].

A number of prominent research institutes are involved in biochar research, development and innovation, focusing on its production, characterisation, and application:

- The University of Edinburgh's UK Biochar Research Centre – Pyrolysis Pilot Plant and analysis facility is currently involved in the C-Sink project (EU Horizon) to develop standard methodologies for land-based carbon removal technologies including biochar (C-Sink Project).
- The University of Nottingham, leads the biochar demonstrator project, in conjunction with Bangor University, the University of Leeds, the UK Centre for Ecology and Hydrology, Scottish Universities Environmental Research Centre, and Forest Research, actively trialling biochar application to agricultural soils.
- Aston University has a fast pyrolysis pilot plant and energy focus. The university hosts the Biochar CleanTechAccelerator Program to identify novel application areas for biochar.
- The UK Centre for Ecology and Hydrology and Scotland's Rural College (SRUC) have an active program for soil remediation in the River Wye Catchment area, partnering with Black Bull Biochar and funded by Defra's Farming Innovation Programme's Nutrient Management Competition.

Other notable & novel projects include the Live Labs 2 project developing new materials for decarbonising roads in the UK, including the use of biochar. The project is backed by £30 million in government funding [438]. CO2RE is a large national research program developing the CO_2RE Evaluation Framework, a science-based framework for the sustainable scale-up of carbon dioxide removal, policy and governance focused [439]. Finally, the Biochar Demonstrator is research program co-funding the establishment of 5 start-up companies to obtain real world data on biochar production, deployment, and societal integration [440].

9.8.5 Policy, frameworks, and national strategies

In June 2019, with the Climate Change Act 2008 (2050 Target Amendment) Order 2019, the UK Government committed to a 100% reduction of greenhouse gas emissions by 2050 compared with 1990 levels (2045 in Scotland). This is referred to as the net zero target. The Climate Change Act requires the UK government to set legally-binding "carbon budgets" (caps on UK greenhouse gas emissions over five-year periods) which must be met by government policies. Moreover, removals are prominent in the country's Carbon Budgets and Growth

Delivery Plan, which has set a goal of 0.7 million tonnes per year of engineered removals by 2030, increasing to 21.8 million tonnes per year by 2035 [441].

The UK's Climate Change Committee (CCC), an independent, statutory body also established under the Climate Change Act, advises government on carbon budgets and emissions targets and reports to the UK Parliament on progress. In February 2025, the CCC published its advice to the UK government on the Seventh Carbon Budget (CB7 - the period 2038 – 2042) [442]. The report stated that there had been no engineered removals (which includes biochar) recorded prior to report publication in the UK aside from small-scale testing. However, the CCC's Balanced Pathway modelled 21.3 $MtCO_2e$ of engineered removals per year by 2040 (within the CB7 period) , increasing to 35.8 $MtCO_2e$ of engineered removals per year by 2050. These are stated as a necessity to offset residual emissions from hard to abate sectors (predominantly aviation). The CCC estimates that, in 2040, 89% of these removals will stem from BECCS, 9% from direct air capture, and 3% from enhanced weathering and biochar combined. Research efforts by CO_2RE and sustainability consultancy ERM cited in the UK's recent Independent Review of Greenhouse Gas Removals estimates that biochar sequestration costs could be as low as £20/tCO_2 or as high as £1171/tCO_2 in 2030, depending on the feedstock used.

The UK's Biomass Strategy is also relevant. The UK only supplies 66% of its current biomass demand domestically. Models predict that domestic supply will not grow considerably until 2050 and growth in biomass use will rely on imports. One area of available current and future biomass is identified as digested sewage sludge which is currently applied to agricultural land (86%, 3.5 million tonnes annually) but poses environmental obstacles especially out of growing seasons. There is a general focus on energy security and BECCS in terms of biomass utilisation with no mention of biochar [443].

9.8.6 Gaps, challenges, and opportunities

Gaps & Challenges

- The classification of biochar as a waste material under UK law is a barrier to the production and deployment of biochar in the UK. Biochar is classified as a waste material under current UK law as it is commonly produced from biomass that is actively discarded from or not intended for further use in other processes or is an industrial by-product of pyrolysis for other purposes (e.g., generation of heat or alternative co-products) [444]. The only way to avoid classification of biochar as waste is to produce it from purpose-grown biomass or feedstocks specifically designated as non-waste materials. Some waste regulation does permit the use of untreated forestry and agricultural residues as feedstocks for biochar production, but places limits on storage quantities, and production and application rates. For other wastes, permits can be granted on a case-by-case basis, but decisions must be taken for each new site.

- The Independent Review of GGR indicated that, while the UK government has made progress in supporting GGRs, particularly in recent years, policy uncertainty remains a significant barrier. For biochar, this may be exacerbated by a perceived policy focus on BECCS, Energy from Waste and DACCS. While recognising the significant advances in understanding of the long-term efficacy, stability and impacts of biochar deployment, the Independent Review of GGR acknowledged remaining uncertainties for topics such as biomass strategies and plans for small-scale biomass sites.
- As in many countries, cost factors are a challenge for biochar integration, particularly regarding creating competitive and attractive biochar price despite high capital costs, lack of scalable MRV and feedstock pricing. Scaling, let along sustaining operations under conditions creates a difficult scenario for biochar projects to succeed financially.

Opportunities

- One area of increasing interest is the wastewater treatment sector which urgently requires additional treatment options for sewage sludge and remains highly active in research on biochar technology. While this presents an opportunity due to the size of the sector and favourable economics, the lack of regulation currently prohibits large scale deployments.
- Biochar was demonstrated in the Independent Review of GGR as a more cost-effective CDR method in comparison to other CDR methods. This acknowledgement may be unlock financing and funding opportunities as one of the cheapest options to achieve CDR [443].
- Transitioning the UK away from incineration to poly-generation biochar production would mean the country could prosper from more additionality from its electricity production. Moreover, projects like the Ricardo case model, shared in section 10.2, emphasizes the level of local expertise and ingenuity to maximize climate impact through the country's bioenergy resources.

9.9 United States of America

9.9.1 Overview

The United States of America (US) has a total land area of 9.15 million km² with a population density of 26 persons per km². One third of its land is considered forested while 45% of the country is agricultural land, with 28% permanent meadow and pasture and 17% considered arable land. The remainder is considered urban, bare rock or desert lands.

The IEA estimates that in 2022, roughly 4.3% of the country's energy supply and 10% of heat supply derived from solid biomass sources. Biomass is sourced domestically, with the main share of bioenergy contributing to heat for industry [445].

Associations

The US Biochar Initiative (USBI) works to advance the production of biochar in industrial, agricultural and infrastructure markets to reduce biomass waste, grow the economy and mitigate climate change. USBI focuses their efforts on biochar markets, education and outreach, research and innovation, climate and sustainability and building the biochar community in the US, being host of the North American Biochar Conference [446].

The USBC is an industry trade association of various actors in the biochar value chain to share a unified voice advocating for developing markets, policy and economic conditions for biochar industry growth in the US [447]. Today, USBC is comprised of nearly 30 member organisations.

9.9.2 Production

With such vast forest and agricultural areas, biomass can be considered plentiful in the US. In parallel, a strong economy promotes primary and secondary use of biomass utilization. However, in discussions with Myles Gray of the USBI, he explained biomass residues and wastes are often under- or unutilized resources, with these resources often considered a high waste disposal cost. This is enhanced by trends in the forest industry away from the use of low-grade wood which previously would have been utilized by pulp and paper.

Finding success in the American biochar market means producers must utilize all products from their production line, stressing that high labour costs and high regulatory costs create a market where production costs are higher than in less developed global markets.

In addition, it was noted that beyond the 3 common markets in biochar production, waste management tipping fees can be an additional source of income. He explains many companies face high waste disposal costs for biomass which they cannot utilize downstream from their processes. Biochar production is advantageous in such a market environment as it not only utilizes these wastes and residues but reduces costs upstream in the value chain.

Technology Providers

Pyrolysis technology providers have a great variance in the US. According to USBI's Directories, an estimated 37 technology providers are operating in the country, which can be categorized as 21 small scale pyrolysis & gasification, kiln/firebox and mobile carbonization providers producing 200-1,000 tonnes annually, 6 medium scale industrial pyrolysis & gasification providers producing 1,000 - 10,000 tonnes annually, and 10 large scale industrial pyrolysis & gasification providers producing at 10,000-100,000 tonnes annually [446].

Beyond scale, these technologies vary based on their targeted feedstock and offtake market whether biochar, bio-oil or energy production as well as general technological approach.

Biochar Production

USBI's directory presents a number (50+) of US-based producers located across the country, however it is unclear how many of these producers are actively providing biochar to the market today. In the USBI's Global Status Report Survey, North America as a continent (Canada, Mexico, United States) produced an estimated 169,564 tonnes of biochar in 2023, with roughly 75% of that production coming from stationary auger or rotary kiln technologies from large scale producers (10,000 tonnes or more annually). It must also be noted that a number of production sites at micro-, small and medium scales are active in the US. Interestingly, their survey also found that over 70% of North American biochar production was not associated to carbon removal credits [448].

Other actors

The USBI directory also highlights several American laboratories (3) and regional biochar associations and groups (8), demonstrating an established and growing sector in the country beyond its national association.

Notable projects

One of the largest planned biochar production facilities in the globe, steel producer Steel Dynamics Inc. (SDI) announced its joint venture with technology provider and operator Aymium, launching the SDI Biocarbon Solutions production facility located in Columbus, Mississippi. The facility will replace fossil coal with biochar SDI's electric arc furnaces to reduce the company's GHG emissions. The facility's initial production is expected to produce over 160,000 tonnes per year and are expected to begin in 2026 [449].

9.9.3 Applications

Agricultural applications are currently the most popular product applications of biochar in the US. In discussions with Myles Gray of USBI, an area of focus has been high-rate of application soil amendment, estimated 1 to 5 tonnes per acre of application within the USA. To support agricultural applications, USBI has been working to promote biochar in US's Department of Agriculture (USDA) frameworks to make application more lucrative and adoptable for farmers. Targeted crops include value-added products such as potatoes. Other agricultural focuses include powdered biochar in nitrogen fertilizers as well as potting media and horticultural substrate.

Other applications of focus for USBI include removing national regulatory barriers for biochar use in cement and concrete, biochar integration storm water management guides, as well as urban application manuals for cities and homeowners.

9.9.4 Research & Development

A number of universities in the US have conducted research on most aspects of biochar, with a large emphasis on biochar research in soils and agriculture systems. One of the most prominent institutes includes the Lehmann Lab at the College of Agriculture and Life Sciences at Cornell University. The Lehmann Lab works to grow understandings of biochar in various soil ecosystems, including its behavior in soils, effects on plant growth, microbial composition and LCA of GHG or water quality and economics. The group is very active today, with over 300 publications and over 100,000 citations in peer-reviewed literature [450].

The Bioeconomy Institute at Iowa State University must also be mentioned, as their research in various aspects of biochar and pyrolysis are leading in the US. Their focuses include carbon negative economy, agricultural applications as well as research in pyrolysis oil applications and pyrolysis and gasification. In addition, they collaborate on agricultural applications in the incorporating partners universities such as Stanford University, University of California Berkely and Indiana University [451].

Government research departments include the USDA's Climate Hub, Agricultural Research Services and Forest Service [452,453].

9.9.5 Policy, frameworks, and national strategies

Climate policy has been deprioritized by the current US Administration, however that does not seem to impact biochar's momentum in the US. The utilization of American biomass in local economy is very much in line with recent "America First" initiatives, while the utilization rather than waste of biomass supports rural economies [454].

The USBC is driving the biochar discussion in US policy. Their strategic initiatives include expanding tax incentives to include biochar, better inclusion of biochar and pyrolysis in regulatory frameworks and key bills and developing capacity, understanding and a roadmap for biochar in key federal departments. At the state level, California and New York are avid leaders in the CDR discussion, particularly in California's CDR Purchase Program and New York's Empire State Carbon Farming Act [455].

Furthermore, there is work being done to influence the Environmental Protection Agency to create a permitting and regulatory lane for pyrolysis and gasification plants to differentiate from incineration plants. This regulatory differentiation is the basis for the presumed benefits to air quality pyrolysis and gasification present to the market over incineration of materials [454].

9.9.6 Gaps, challenges, and opportunities

Gaps & Challenges

- Low energy prices pose a challenging loss of revenue for biochar production, further putting pressure to recovering costs of production to material and BCR revenues.
- Lack of government support on climate change services, such as carbon removals, hinders investment and adoption of BCR in the US. This will impact the construction sector specifically, where it will take individual initiative to drive interest and growth for biochar's integration.

Opportunities

- Cheap and abundant biomass is the biggest opportunity in the US. This is a considerable asset and basis for a US biochar industry, especially if producers are able to collect tipping fees from feedstock providers.
- Positive engagement on agricultural benefits is beneficial to biochar integration in US agricultural systems.
- Development of biochar standards in government legislation and frameworks will drive biochar use cases.
- Despite the US energy market being competitive for bioenergy, the decentralized nature of biochar production could prove beneficial with energy by-product utilized in adjacent rural industry.

9.10 Other countries

9.10.1 South America

Bolivia: Exomad Green
Currently the world's largest biochar producer, Exomad Green's facilities in Guarayos Region, Bolivia process forestry residues into 50,000+ tonnes of biochar annually to sequester 120,000+ tonnes CO_2 effectively. When completed (Phase 2, expected 2027), this facility will have 16 biochar reactors, capable of removing up to 320,000 tonnes of CO_2 and producing 128,000 tonnes of biochar annually. Exomad Green's broader goal is to remove 800,000 tonnes of CO_2 by 2027 across multiple sites, certified under Puro.earth for their carbon credits. Partnering with agricultural communities provides soil enhancement. By integrating biochar into agricultural practices, they attempt to enhance food security, restore degraded soils, and support local economies [456].

Their field studies show how biochar i) boosts sorghum growth in drought-prone Yacuiba, Bolivia; ii) increases soybean yields, even in low rainfall conditions in La Rivera, Bolivia; iii) influences corn and beans in controlled plots, evaluating the impact of biochar on crop production by comparing four treatments: a control (no application), biochar alone, biochar with fertilizer, and biochar with both fertilizer and microorganisms.

Colombia: Biodiversal Coffee Project
Biodiversal is a Colombia-based regenerative agriculture company working with smallholder coffee farmers to promote more sustainable farming practices. The aim of the project is to turn coffee tree pruning into biochar. With Planboo's dMRV technology, the entire process is tracked and measured, generating robust carbon credits for 200,000 t CO_2 removed by 2030 (100,000 tonnes of biochar applied by 2030). Revenue from these carbon credits funds the project's growth and directly supports farmers through cash stipends. Farmers also keep all the biochar they produce to improve soil health and reduce reliance on chemical fertilisers [457].

Brazil: Coffee Project
French green tech company NetZero and global coffee giant ECOM have embarked on a partnership to introduce large-scale biochar use in coffee cultivation. The partnership's immediate goal is to establish an industrial-grade biochar factory in Machado, Brazil, a major coffee production hub. The facility plans to produce 4,000 tonnes of biochar annually, enabling the direct removal of over 6,000 tonnes of carbon emissions from the atmosphere [458].

Brazil: Aperam Energia
Metallurgical company Aperam BioEnergia has been producing charcoal for its steel production site in Brazil for over a decade, deriving from the company's 100,000 hectare eucalyptus forest. The use of biogenic carbon has eliminated the use of fossil coke from its supply chain [459].

Nicaragua: Coffee Project

The aim of this project is advancing climate resilience in Nicaraguan coffee supply chains by converting farm wood residues into biochar. This biochar is used to enrich coffee pulp compost, which then replaces synthetic fertilizers in coffee nurseries, improving seedling survival and soil health. The biochar-enriched compost acts as a natural soil amendment, improving water retention and fertility, which boosts crop yields and seedling survival rates. Farmers gain a new income stream from selling wood waste for biochar production and benefit from improved crop yields and reduced costs from better tree health [460].

9.10.2 Africa

Tanzania: Enhanced Livelihoods through Commercial Agricultural Production (ELCAP)

The ELCAP project (Enhanced Livelihoods through Commercial Agricultural Production) in Tanzania is a major initiative led by the Strømme Foundation, with funding from NORAD and in partnership with organizations such as Amani Girls Organization (AGO), the Norwegian Geotechnical Institute (NGI), the Norwegian University of Life Sciences (NMBU), Returkraft, Engineers Without Borders (EWB), and Climate Smart Farming Solutions (CSFS). Location is the semi-arid Singida region, Tanzania (with activities in Manyoni, Ikungi, and Iramba districts.

Overall goal is to sustainably improve the livelihoods of smallholder farmers, their households, and other value-chain stakeholders through novel biochar formulation value chains, market linkages and private sector partnerships. The project developed and promoted the use of biochar as a way to add value to agricultural production and support environmental sustainability. The biochar is made from sunflower stems, maize cobs and agroforestry prunings. The biochar is produced on-farm by farmer collectives using the Kon-Tiki kiln technique, a low-cost, farmer-friendly method for making high-quality biochar (see chapter 6). Crops include maize, sunflower, sorghum, and pigeon peas. Facilitating connections between farmers and markets, including private sector actors, to ensure that increased production leads to improved incomes.

The project is one of the largest in the world in terms of numbers of participants (over 6 000 farmers have been trained in 1-2 tonnes of biochar each per year with flame curtain kilns, sequestering 12 000-24 000 tCO_2 removed/year) and has led to significant (30-50%) increases in crop yields for participating farmers through the introduction of new technologies and training [461].

Ghana: Tachibana Cocoa Project

Traditionally, after harvesting cacao beans, farmers either burn or leave the cacao pods on their farms, which can lead to the growth of fungi that damage crops, release harmful emissions, and attract disease-carrying mosquitoes. To tackle these issues Tachibana and Planboo incentivise farmers to turn their cacao pods into biochar instead. This approach not only prevents fungal development but also transforms agricultural waste into valuable biochar, improving soil health and removing carbon. Joined by even more cacao farmers in the coming years, this project is on a path to scale up and remove 18,000 tonnes of carbon by 2030 [462].

Ghana: Cacao Biochar Project

The Ithaka Institute's Ghana biochar project is a pioneering effort to transform cocoa farming into a climate-positive, more productive, and resilient system—using farmer-friendly biochar production and innovative application methods. It is a large-scale (3000 farmers) demonstration and research initiative focused on improving cocoa farming systems and soil health in Ghana, while also creating a significant carbon sink to help mitigate climate change. Main focus is to improve yields and crop health in cocoa agroforestry systems, which often suffer from degraded and acidic soils, turn cocoa farms into carbon sinks by applying biochar-based fertilization and demonstrate and document the agronomic and climate benefits of biochar for decision-makers.

Part of the biochar is made from cocoa shells at milling sites. Another part is produced on-farm by farmers using the Kon-Tiki kiln technique. Biochar is mixed with water-dissolved fertilizer and the slurry is injected with compressed air 20–40 cm deep into the root zone of each cocoa tree, distributing the biochar-fertilizer mix in a 0.5–1 m diameter area around the roots. At least 20% higher yields are expected, with up to 50% possible based on experience with other tropical crops.

The project is designed as a model for other tropical farming systems and is intended to provide robust data for scaling up biochar use in Ghana and beyond. The Ithaka Institute collaborates with other organizations and projects in Ghana, such as distributed smallholder biochar production using locally adapted pyrolysis units ("Kon-Tiki" flame curtain kilns), which are being rolled out to hundreds of villages. These efforts are improving soil fertility, reducing emissions, and empowering women and smallholder farmers [463].

Ghana: Bonding over Biochar Project

Bonding over supports small-scale cacao farmers in Oti, Ghana, turn waste cacao pod husks into biochar. With innovative kilns specifically designed for cacao waste, they've managed 94% methane reduction and enabled safer, healthier working conditions for operators of their projects. The carbon-rich, soil-nurturing biochar produced is mixed with compost or manure and returned to nearby fields, keeping the agronomic benefits close to the communities that create it. Carbon finance for 41,000 tCO_2 removed/ year (24,000 tonnes biochar applied/ year) is obtained from Carbon Standards International (CSI) [464].

Kenya: NARA Kenya Community Drylands Project

Decades of conflict have made Turkana home to one of Africa's largest refugee communities. Criou and Planboo are joining forces with local communities to regenerate the land. As the world's first refugee-led carbon project, it is turning encroaching bush into biochar and applying agroforestry techniques to transform depleted soils into fertile farmland. Each tonne of carbon removed (Carbon removal potential of 100,000 tCO_2 removed by 2030) is tracked and verified through Planboo's MRVin platform, generating high-integrity credits and new income streams for refugees and local communities participating in the project [465].

Namibia: Farm Gai Kaisa Biochar Project

The aim of this project is to sustainably harvest excessive encroaching acacia bush to produce biochar (Carbon removal potential: 329,000 tCO_2 removed by 2030 via 164,000 tonnes of biochar and certified by Puro). This approach not only helps restore the Savannah but also improves agricultural productivity. By applying biochar to soil, we enhance its health, boost crop yields, and build climate resilience—creating benefits that extend from the land to the communities who rely on it [466].

Zambia: Cotton Biochar Project

Cotton farming is an essential livelihood for over 300,000 smallholder farmers in Zambia, Southern Africa. But with a heavy reliance on rainfall coupled limited resources to adapt, they are especially vulnerable to climate change. In recent years, extreme droughts and unpredictable weather have depleted the soil, making it harder to grow crops and earn a living. As a result, cotton production has dropped by 50% since 2012, reaching its lowest level in decades. Cotton farmers are trained to turn cotton stalks into biochar (Carbon removal potential: 66,000 tCO_2 removed by 2030, certified by CSI), enriching their soil and improve crop quality [467].

9.10.3 Asia

Thailand: WongPhai Bamboo project

WongPhai is a community-driven initiative in rural Thailand that promotes bamboo cultivation and utilisation. Traditionally, bamboo offcuts were collected and burned, generating significant pollution. Planboo and WongPhai joined forces in 2023 to transform bamboo remnants into biochar, effectively removing CO_2 from the atmosphere. The biochar further improves soil quality and increases crop yields in neighbouring farmlands, while also being used in septic ponds on pig farms to enhance air quality and reduce methane emissions. The impact is intended to extend beyond environmental impact; committed to fostering local economic growth. By leveraging carbon finance, we are setting the stage for scalable biochar initiatives that address climate change and provide substantial benefits to the community. The carbon removal potential is 36,500 tonnes CO_2 removed by 2030. Certification of the carbon stored is through the Carbon Standards International (CSI) platform [468].

9.10.3.1 India

Overview

India is located in southern Asia spanning an area of 2.97 million km² with the world's second largest population, at 1.3 billion inhabitants. India has the largest agricultural economy int he world [469]. Moreover, as the world's third largest energy consumer, India faces a growing energy demand in parallel with its growing economy. It relies heavily on imported fossil fuels, leaving its energy security vulnerable. 22% of its total energy supply comes from renewables, of which 85% derived from bioenergy, mainly for residential heating. This type of residential heating, though, is quickly being replaced by oil and gas [470].

Both India's energy and agricultural sectors play a key role biochar's massive potential in the country. High population density and fossil fuel use, as well as the burning agricultural residue have contributed to air quality related health concerns, which accounted for nearly 18% of all annual deaths in 2019 [471]. Utilizing pyrolysis as an alternative to burning, and the utilization of sewage sludge present great opportunities for bioenergy and biochar production in India. The IEA [472] projects India to be the fastest growing bioenergy market in the world between 2023 and 2030, however warns phasing out of traditional bioenergy, feedstock management, coordination and GHG standards as supportive measures to succeed.

Associations

Carbon Removal India Alliance (CRIA) is a member-based organization dedicated to catalyzing and supporting the growth of carbon removals in India, striving to make India a global leader in CDR. The only organization of its kind in India, CRIA is developing a CDR network, conducting research, supporting knowledge transfer, as well as engaging at the international level. In speaking with Srishti Singh of CRIA, biochar is a big part and growing discussion of the carbon removal discussion in its membership and broader India [473].

Production

Crop Residue Management

One of India's most harmful and challenging agricultural hurdles is crop residue management. An estimated 100 million tonnes of crop residues are produced annually, mainly from rice paddy, and 80% of all burning is concentrated in the months of October and December. Not only does crop residue burning contribute to poor air quality and health conditions, it also depletes soil organic matter and is largely an unsustainable, counterproductive practice. Now banned, India faces a lack of implementation of the ban, leading to a lack of action. Pyrolysis and biochar are beginning to shift this narrative for the better in India.

Technology

APChemi and Ankur Scientific are companies producing pyrolysis and gasification plants. Both companies claim their products manage an array of feedstocks from biogenic forest and agricultural residues and sewage sludge, as well as non-organic materials such as tires and plastics.

Artisanal Production

The first being farmers producing and utilizing their own biochar with kiln technology, sometimes obtaining artisanal biochar certification to obtain BCR credits on the voluntary market. Drivers of artisanal production are burn-free crop residue management, access to BCR credits and soil quality improvement from biochar soil applications.

However, artisanal producers are often challenged by their capacity to convert their residues from biomass to biochar. Pyrolysis can be a time-intensive process and one difficult to scale as an individual farmer. If farmers have another job or lack of farmhands, they may lack capacity needed to produce biochar.

Artisanal projects are also achieving other biomass management goals. Varaha leads artisanal biochar projects in India, utilizing invasive *Prosopis juliflora* in the regions of Gujarat and Rajasthan for biochar production using KonTiki kilns since 2023. The project has removed 5,000 tonnes of carbon from the atmosphere by providing the biochar to farmers for field application [474]. Other businesses facilitating biochar projects in India include Carboneers and Circonomy [475,476].

Industrial Production

The second common production avenue is industrial production. Pyrolysis plant operators source biomass from local farmers free of charge, process the material and later return biochar back to farmers to apply to their fields at no cost. Although it does not drive an initial revenue, plant operators collect the corresponding carbon removal credits as revenue. Although this is the most common industrial model, there are biomass aggregators where producers purchase biomass.

Takachar Portable Biochar Technology

Takachar is an award-winning (Earthshot Prize and the XPRIZE Carbon Removal Milestone Award) Indian startup (with MIT roots) that has developed portable, small-scale biochar reactors designed to tackle the massive problem of crop residue burning in India and other regions. They aim at smallholder farmers, converting agricultural waste into biochar. Takachar's technology reduces smoke emissions by up to 98% compared to open burning [477]. Using Takachar's fertilizer blends, farmers have seen 20–30% increases in crop yields and up to 30% higher net income. The technology is also being used in India, Kenya, and the United States, with support from organizations like the World Food Programme.

Mash Makes:

Mash Makes is an Indo-Danish company producing biochar in India, targeting agricultural wastes and residues. The company's facility in Udupi pyrolyzes cashew waste, having produced over 7,000 tonnes of biochar from their three pyrolysis units. The site also employs 125 people. Their target applications include biochar as a biofuel for hard-to-abate industries such as shipping and heavy industry. They also have their biochar applied to fields across India, utilizing carbon removal credits as well [478].

Applications

Agricultural applications are most popular and prevalent in India. This is driven primarily by the impact of material benefits farmers experience with their crops. Although a largely beneficial material for local farms, CRIA explained much work lies in communicating these benefits, where the material is still very new and not fully understood by farmers.

Research and development

A number of universities are researching biochar in a number of facets. Noted research institutes include the Indian Institute of Technology (IIT). IIT's Roorkee campus houses the Biomass and Biochar Research Laboratory, focusing on thermochemical conversion of biomass, biochar applications including climate, adsorption and agricultural services and corresponding systematic frameworks [479]. Their campus in Guwahati has recently published their findings in biochar's effectiveness as an adsorbent in treating industrial wastewater [480]. The Indian Institute of Science's Material Engineering Research, Innovation and Application Lab (MatERIAL) Group has explored biochar's application in cementitious materials, having published a number of papers [481–483]. It is unclear the extent of the group's activity today.

Policy, Frameworks & National Strategies

Although there are no policies, roadmaps or funding sources explicitly reference biochar, India's government has several initiatives indirectly supporting biochar. Biochar is highly in-line with national strategies such as the National Mission on Sustainable Agriculture and the Central Sector Scheme on Crop Residue Management, laying the groundwork for future investment and growth of India's biochar sector.

Excitingly, biochar is recognized by the Bureau of Energy Efficiency as an acceptable methodology, allowing for biochar's acceptance in India's Carbon Credit Trading Scheme (CCTS). CCTS is India's cap-and-trade framework for listed large-emitters to offset their emissions. This further enhances government interest and support for the sector, while contributing an additional CDR tool to already utilized voluntary markets [484]. According to CRIA, India's BCR market within its CCTS is expected launch in March 2026.

9.10.3.2 New Zealand

Overview

New Zealand is a Pacific island nation with a land mass of 263 thousand km^2 and a population of 5.3 million people, translating to a low population density. Its land use is divided 40% agricultural land, mainly permanent meadow and pasture, and 38% forested land, mainly naturally regenerative. It has a predominantly temperate maritime climate [485].

New Zealand has a high renewable energy contribution to its total energy consumption, however only 7% of its energy comes from bioenergy. 90% of this share is from solid biomass going mainly to the industrial sector, with a smaller share to power production and residential heat. The country does plan to increase bioenergy's contribution to electricity production to 12-14% by 2035. In addition, New Zealand has committed to reducing net emissions of most GHG to zero by 2050, including a target to make all electricity production renewable by 2050, identifying its pulp and paper industry as key to its bioenergy future [485,486]. This is a very good opportunity for pyrolysis and biochar production to be integrated.

Associations

Representing biochar in New Zealand are ANZBIG and Biochar Network New Zealand (BNNZ), where the organizations are open about their mutual support and collaboration for each other. BNNZ is a member-led society dedicated to promoting and supporting awareness, understanding and acceptance of biochar in New Zealand, striving for initiatives where biochar production and applications contribution to the country's emissions reductions.

Production

Feedstock

A 2020 study by the Hedley et al. [487] identified forest residues; wood processing residues; agricultural residues, mainly orchard, stover, straws and animal reserves; processing residues like peelings and juicing marc; and municipal wastes such as yard and food waste and sewage sludge as key biomass sources for biochar production.

Producers & Actors

A number of actors using pyrolysis technology to produce biochar. The Green Circle utilizes forest and agricultural residues, such as pine and grape marc, to produce biochar, heat and carbon credits. The company is also invested in how its product is utilized, collaborating with local vineyards to explore their products' effectiveness in viticulture [488].

Southland Carbon is another example, bringing biochar and wood vinegar to the market. Their biochar is targeted for agricultural applications, including soil amendment, food production and livestock feed while their wood vinegar can be used as a pesticide, fertilizer, composter booster and/or seed germinator [489].

Other actors include consultants like Epic Char, who enable biochar primary producers to bring biochar to market in a productive manner, working closely with German pyrolysis manufacturer Pyreg, and market actors to deliver successful biochar projects [490]. Verum Group, a scientific monitoring, analysis and testing consultancy offers their laboratory services for biochar analysis [491].

Application

Agricultural applications are the focus in New Zealand and although limited information is available on its application beyond small projects, interest in biochar is growing in New Zealand's agricultural sector. Zespri, producer of one of the country's most commonly known products, kiwi fruit, has been trialling biochar's effectiveness in fruit production. It was noted from Zespri that interest in biochar exists in New Zealand, however a lack of producers make the market price an issue, limiting its adoption [492].

At the community level, The Good Carbon Farm connects with school and community gardens as well as conservation projects restoring native landscapes who are interested in biochar. They work to collect biomass, produce biochar and later donate the material to the cause [493].

Research & Development

One of the most comprehensive biochar research output in New Zealand is Ag Emissions Centre's study by Hedley et al. [487]. Their review focuses on biochar's potential role to reduce net GHG emissions in NZ agriculture, covering LCA, economic feasibility and proposed GHG accounting methodologies. The study suggests a mixture of small-scale, portable and medium-scale pyrolysis operations for productions adjacent to orchards, to utilize horticulture and vegetable production residues and as a source of heat from municipal wastes which normally incur a tipping fee for treatment. Moreover, the authors concluded biochar production should be a tool in forest, farm and waste industry GHG budgets and recommended a series of research topics NZ should pursue.

Today, it is unclear to what degree research institutes are invested in biochar in New Zealand, however a number of institutes are noted to have conducted biochar research since the early 2010s.

The Bioeconomy Science Institute's Landcare Research Group has a recent publication on biochar's incorporation in soils [494].

Massey University has been involved in biochar research, even hosting the New Zealand Biochar Research Center. It's unclear if NZBRC remains established, as information online is limited while relevant sources are dated to the 2010s.

The New Zealand government has supported biochar research, including a 2021 review of biochar as methodology in reducing GHG emission in New Zealand's agriculture.

Policy, Frameworks and National Strategies

As noted above, the New Zealand government has funded biochar research in the past however, it appears biochar research has not translated into NZ policy in sectors such as agriculture.

On the climate action front, New Zealand has established its Emissions Trading System, covering the sectors of forestry, waste, synthetic gases, industrial processes, liquid fossil fuels and stationary energy. The most relevant activity to biochar in the Carbon Removals Strategy is under biological processes, predominantly forestry, which states wood products are an accepted removal methodology however, it does not explicitly state biochar [495]. The other activities included are DACCS and reversing GHG emissions from drained organic soils. In 2023, forestry was the only recognized carbon removal activity [496]. No relevant update to newly considered carbon removal methodologies were noted.

10. Summary and recommendations

The production and use of biochar in the countries and regions discussed above vary greatly, although the common challenge felt across the globe is limited off-take markets. In order for biochar to scale across the globe, commitment to utilize biochar must come from various market which can use biochar. To support this, strong commitments and policy language supporting biochar is recommended to national states.

Recognition of BCR at the National level

This is the first step toward unlocking Biochar Carbon Removal (BCR) markets at the national level. Early movers such as the EU and Japan have begun establishing frameworks that recognize biochar as a credible carbon removal pathway. But significant work remains—not only within EU Member States, but globally—to translate high-level recognition into functioning, investable markets.

Enabling BCR markets is more complex than climate policy alone. It requires regulatory alignment across multiple domains: recognition of pyrolysis technology in zoning and permitting frameworks; acceptance of biochar within agricultural, soil, and materials regulations; and adaptation of sector-specific rules that determine how and where biochar can be produced, traded, and applied.

Climate policy is the essential starting point. Clear recognition of BCR within national climate strategies creates the signal that can trigger the necessary adjustments in permitting, product standards, and market regulation—ultimately enabling deployment at scale.

Alignment within National Land & Biomass Strategies

Moreover, biomass markets and resource management systems can largely dictate how biochar can be produced and scaled. For instance, countries like Australia, India and USA appear to have pathways to scaling production, where biochar provides a solution to managing residual and waste biomass systems. In contrast, continental Europe biomass markets experience higher prices, competition and high biomass utilization, while also having the highest demand for biochar. Recent advancements in biorefinery technology are revolutionizing how economies can utilize biomass residuals in a way which support local and regional economics, in-line with national, social, economic and environmental targets. In these regards it is recommended countries recognize pyrolysis refineries and biochar within their national biomass and land use strategies as off-take markets for residual biomass. Planned and strategic allocation of biomass for biochar is the basis for developing both domestic and global market development, while reinforcing the opportunity to maximize biomass utilization and climate impact.

Support for inter-nation collaboration

To progress biochar's implementation and success as a climate solution, nation states must work to collaborate and share findings on breakthroughs for systematic integration of biochar as a climate, biomass management and decarbonization solution, it is recommended dialogue and collaboration are shared amongst countries

Ensure safety, but enabled handling, shipping and storage

Safe handling, storage and shipping of biochar, especially in bulk quantities due to risk of self-ignition, remains a challenge for developing a global biochar market. One area in particular is marine shipping, which experienced 68 biochar fires between 2015 and 2022. As IMO is an international body supported by national authorities, it is recommended countries engage with IMO to determine best-path-forward which reduces special provisions for biochar transportation while ensuring safe and risk-free transportation.

Funding and support for biochar developments

An essential component to realize biochar projects at both scale and multitude of projects is public funding. It is recommended biochar funding programs become developed at the national level for all facets of biochar (R&D, project development, application development, etc.) tailored to achieve national goals and targets. In addition to direct funding and grants, public procurement for biochar projects presents an interesting pathway for decision makers as they can enable public projects which align with public goals, while supporting industry to scale and deploy technology.

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