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Local Biochar Use for Sustainable Agriculture in Asia

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Green Asia

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Abbreviation list

amoA	ammonia monooxygenase subunit A gene
ARR	afforestation, reforestation and restoration
AWC	available water content
CCS	carbon capture and storage
CDR	carbon dioxide removal
CEC	cation exchange capacity
Corg	organic carbon
CSI	Carbon Standard International
EBC	European Biochar Certificate
FEAST	Lifeworlds of Sustainable Food Consumption and Production: Agrifood Systems in Transition
GHG	greenhouse gas
Gt	gigaton
IBI	International Biochar Initiative
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
JBA	Japan Biochar Association
JIS	Japanese Industrial Standard
K_{sat}	saturated hydraulic conductivity
LCA	life cycle assessment
MWD	mean weight diameter
NDC	nationally determined contribution
PAHs	polycyclic aromatic hydrocarbons
SNS	social networking sites
SOM	soil organic matter
SSA	specific surface area
tC	tonne of carbon
TCFD	Task Force on Climate-related Financial Disclosure
tCO_2e	tonne of CO_2 equivalent
t-d.m.	tonne of dry matter
TGO	Thailand Greenhouse Gas Management Organization
TNFD	Taskforce on Nature-related Financial Disclosures
w/w	weight by weight

Abstract

Biochar is a solid material derived from the thermochemical conversion of biomass such as wood, grass, and livestock manure under limited oxygen conditions. Biochar has received increasing attention due to its potential to improve the soil environment and mitigate climate change through carbon dioxide removal. When applied to mineral soils, biochar can enhance soil fertility and moderately increase soil pH in acidic soils, offering a promising approach to sustainable agriculture. However, its application requires consideration of the soil pH and adherence to safety regulations.

The beneficial properties of biochar, including its high specific surface area, cation exchange capacity, and nutrient content, depend on the feedstock and pyrolysis methods. Wood-based biochar generally has a higher carbon content, whereas manure-based biochar tends to provide more plant-available nutrients. Its porous structure provides habitats and retains nutrients for soil microorganisms, which play a crucial role in nutrient cycling and the maintenance of soil ecosystems.

To streamline estimating soil carbon sequestration using biochar, a new method using proximate analysis based on the Japanese Industrial Standard (JIS) M 8812 was developed. This method estimates the pyrolysis temperature and carbon sequestration potential by analyzing the volatile matter and fixed carbon content. However, biochar production processes, including feedstock collection, pyrolysis, and transportation, often rely on fossil fuels and electricity. Therefore, assessing the net environmental impact, including associated CO_2 emissions, using life cycle assessment is necessary to ensure the role of biochar in achieving carbon neutrality.

Effective biochar production requires pyrolysis temperatures exceeding 350 °C and careful management of gases and smoke emissions. Given the seasonal and dispersed availability of local unused biomass, selecting appropriate pyrolysis systems is essential for maintaining economic feasibility and avoiding overinvestment. In the Asia–Monsoon region, cereal crop residues, particularly rice husk, and straw, are the most abundant feedstocks, followed by perennial crops such as sugarcane. The annual biochar production potential is estimated at 700 million tonnes, accounting for approximately 3.7% of the region's total greenhouse gas emissions in CO_2 equivalents.

Biochar application rates should account for the diverse soil conditions across Asia. Due to its low nitrogen content compared to phosphorous and potassium, supplementing biochar with nitrogen sources, such as manure or compost, is recommended. Although biochar generally meets the safety thresholds for heavy metals, PAHs, and dioxins, biochar derived from sludge and animal waste may require additional attention because of its potentially higher heavy metal content in some cases. Fresh biochar in soil can reduce the efficacy of herbicides and pesticides. Further research is necessary to understand its long-term interactions with soil and plants in agricultural systems, and especially how biochar properties affect root remediation potential and microbial nutrient cycling.

Robust policy frameworks and incentives are essential to promote the implementation of biochar. These include subsidies for carbon removal and credits related to the amount of carbon removed. Japan has been at the forefront in this area, with its Ministry of Agriculture, Forestry and Fisheries offering subsidies to support biochar production and application. Socio-economic systems that balance short-term economic profitability with long-term sustainability, such as the COOL VEGE® eco-brand initiative launched in 2008 in Kameoka City, Kyoto Prefecture, are effective models for advancing biochar adoption.

By addressing these challenges and integrating biochar into agricultural practices, its potential for enhancing soil environment, contributing to sustainable agriculture, and mitigating climate change can be further realized.

1: Introduction and overview of biochar

1.1: Background and implications of biochar use for soil amendment and carbon removal

Biochar is a versatile and effective tool for improving the soil environment, increasing agricultural productivity, and contributing to environmental sustainability. However, its effectiveness depends on the properties of the biochar itself, as well as soil, climatic conditions, and management practices. References to soil improvement using charcoal and ash can be found in Japan's oldest agricultural book, *Nogyo Zensho*, published in 1697 during the Genroku era. Records of charcoal use in agriculture date back 150 years in Europe (Schmidt et al. 2021). The modern world recognized the agricultural and carbon sequestration benefits of biochar when the fertile and long-lasting Terra Preta ("Dark Earth") soils of the Amazon Basin were rich in ancient human-made charcoal (Lehmann and Joseph 2009). Although charcoal has a long history of use, it has regained attention as biochar. Biochar is not a new category of charcoal but rather a term used when charcoal is used for environmental improvement purposes.

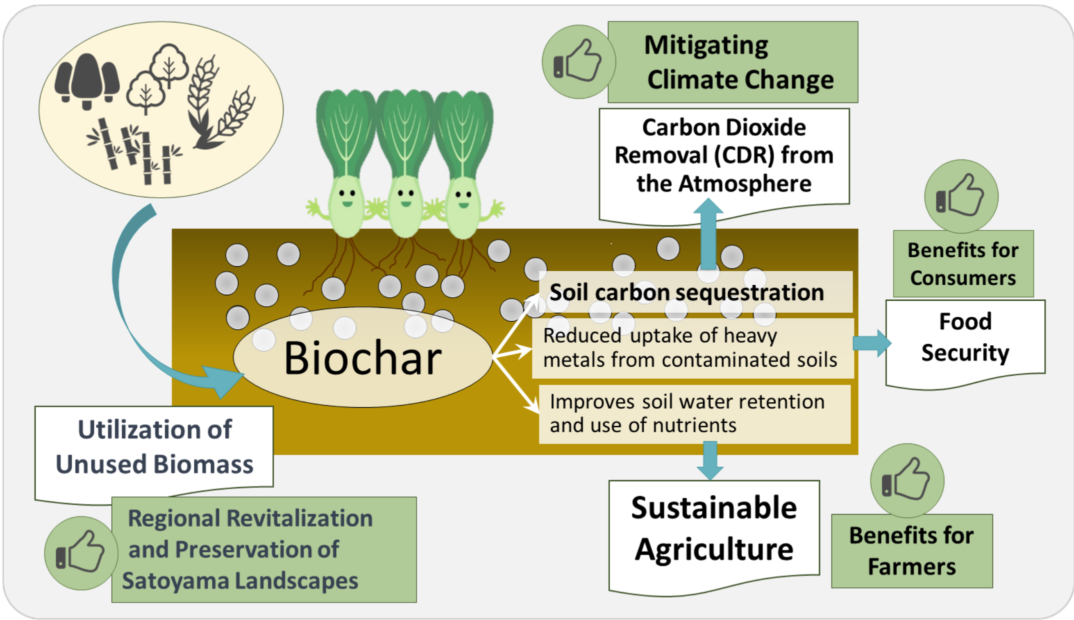


Figure 1.1. Unlocking the power of biochar for mitigating climate change with co-benefits in soil improvement and in the regional economy. Adapted from Kishimoto-Mo (2018).

Academic interest in biochar has increased substantially. More than 17,000 research articles were published in 2021, representing a substantial increase from approximately 100 in 2010. These comprehensive studies, including meta-analyses, have shed light on the diverse functionalities of biochar (Blanco-Canqui 2021; Schmidt et al. 2021; Xia et al. 2023; Refer to Section 2 for more details). This has highlighted the considerable potential of biochar to enhance global soil carbon storage and improve soil quality. Originally recognized for its efficacy in soil improvement, the use of biochar has been re-evaluated and has become increasingly recognized as a promising carbon dioxide removal (CDR) technology for contributing to climate change mitigation and supporting food security (Figure 1.1).

To achieve a carbon-neutral society by 2050, as called for in the Paris Agreement (COP21), it is essential to use CDR technologies to offset any remaining emissions despite reduction efforts (Woolf et al. 2021). CDR refers to processes that remove CO_2 and other greenhouse gases (GHGs) from the atmosphere, effectively achieving negative emissions in contrast to emissions (Refer to Section 3.1 for more details). There are two main types of CDR, that is, enhancing natural processes that capture carbon, such as increased uptake by trees and soil, and enhancing chemical processes, such as direct air capture and underground storage. These methods are at various stages of development, with some remaining conceptual phases.

Afforestation and reforestation, soil carbon sequestration, and biochar use are the three nature-based CDR options that have co-benefits. Among these, biochar use has the potential to help achieve net-zero emissions in agriculture (Shrestha et al. 2023). In 2019, the agricultural sector contributed 16% of the global emissions (57.4 Gt CO_2 equivalent), including emissions from livestock, agricultural soils, and rice cultivation (Olivier & Peters 2020). To achieve net-zero emissions in agriculture, efforts to reduce emissions must be complemented by CDR technologies such as the incorporation of biochar into agricultural soils. The biochar approach involves capturing atmospheric carbon within plant materials and converting it through pyrolysis into a resilient soil amendment that is resistant to microbial degradation. The global potential for CO_2 sequestration using biochar is estimated to range from 0.5 to 2.3 Gt CO_2 equivalent annually (Fuss et al. 2018). Biochar is a CDR technology that can be conducted cost-effectively and at a sufficient scale to make a difference (Woolf et al. 2021).

However, using biochar as a CDR option on a scale sufficient for a substantial impact is contingent on the concentration of spare biomass resources, cost-effective collection, preparation, biochar production, and the relative benefits derived. Although abundant spare biomass resources exist, they are often thinly distributed across extensive land areas, necessitating substantial effort and expense for collection and use. Therefore, cost-effective production of biochar of consistent quality remains a critical hurdle to expanding its use. The development of economically sustainable business models and financial support is essential for this endeavor.

1.2: Definition and characteristics of biochar

Biochar is a solid material obtained from the thermochemical conversion of biomass under oxygen-restricted conditions. It can be used for any purpose and does not involve rapid mineralization of CO_2. Biochar is commonly used for soil improvement and the long-term storage of stable carbon (Shackley et al. 2016; Figure 1.2).

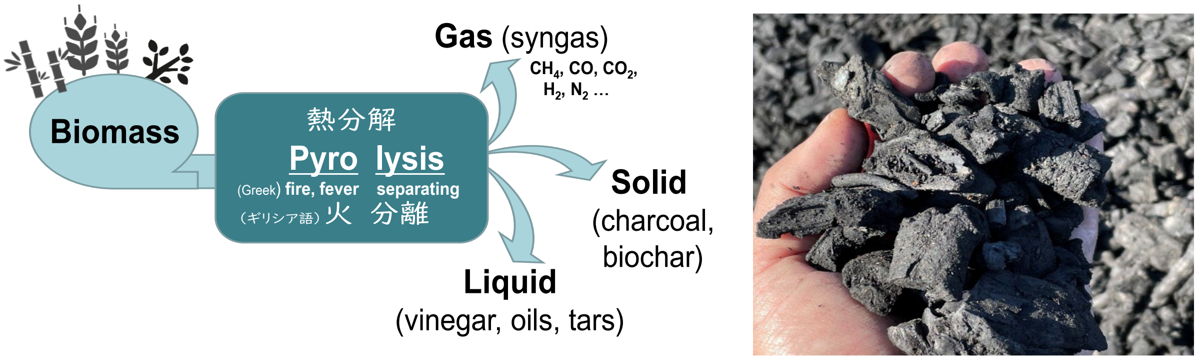


Figure 1.2. Biochar is a solid material generated through pyrolysis and designed to be used for environmental management (Kishimoto-Mo and Shibata 2023).

In the IPCC 2019 Refinement, with the aim of estimating carbon sequestration through biochar additions to mineral soil, biochar is defined as a solid material generated by heating biomass to a temperature exceeding 350°C under controlled and limited oxidant concentrations to prevent combustion (Ogle et al. 2019). These processes are categorized as pyrolysis (excluding oxidants) or gasification (involving low oxidant concentrations to produce syngas). Torrefaction and hydrothermal carbonization (liquefaction) are not considered in this estimation because they do not yield solid products that exhibit significantly greater persistence in soil than the original organic feedstock (Woolf et al. 2021). This technical report adheres to the definitions of biochar as outlined in the IPCC 2019 Refinement, unless explicitly specified otherwise.

Schmidt et al. (2021) reviewed 26 meta-analyses with more than 1500 publications and consistently demonstrated the overall positive impact of biochar use on parameters such as crop yield, root biomass, and water use efficiency (Table 4.5 in Section 4.3). No consistent negative agronomic or environmental effects were observed for any of the evaluated parameters. Biochar application in agriculture must adhere to safety regulations and requirements established by national and/or regional authorities. In the absence of specific regulations, biochar standards or certifications such as those provided by the International Biochar Initiative or the European Biochar Certificate can be used as benchmarks. The biochar discussed in this technical report is expected to comply with the health and safety regulations and meet the specified requirements of national and/or regional regulations.

1.3: Objectives and scope of the technical report

Japan's extensive experience in using biochar in agriculture encompasses its historical applications, lessons learned, and potential for modern and sustainable farming. In Japan, the rapid economic growth in the 1970s led to a decline in charcoal consumption, prompting the exploration of new charcoal applications (Ogawa and Okimori 2010). Research on the use of woody biochar in agriculture began in the 1970s, and it was recognized as a soil improvement material under the Soil Fertility Enhancement Act Enforcement Order of 1984 (Law No. 299 of 1984; last amendment, Law No. 306 of 1996). By the late 1990s and the 2000s, non-fuelwood charcoal production reached 40,000 t annually, with 27% dedicated to agricultural use (Ogawa and Okimori 2010). This technical report aims to illuminate the best practices and general guidance derived from Japan's rich history in this field while incorporating recent reviews from researchers worldwide on the use of biochar in agriculture and offering valuable insights for a global audience seeking innovative and sustainable agricultural solutions.

This technical report is designed to explore the use of biochar, focusing on its practical applications in CDR while also discussing its co-benefits for environmentally sustainable agriculture. The goal is to create an informative report that shares insights into biochar use techniques and their potential for encouraging regional development, with a specific focus on Asian countries.

The primary audience for this technical report includes researchers, policymakers, extension workers, development practitioners, and farmers in the Asia–Monsoon region. However, its content, perspectives, and length have been tailored to make it a valuable resource for regional policymakers entrusted with formulating and implementing agricultural and environmental policies that simultaneously promote regional development and reduce CO_2 emissions.

2: Soil improvement with biochar

Biochar can be produced from a variety of feedstocks, including wood, bamboo, pruned branches from fruit trees, husks, and waste biomass such as poultry litter and sludge. Wood-based biochars typically have higher carbon content but lower plant-available nutrients, whereas manure-based biochars tend to exhibit the opposite trend. Grass-derived biochars are generally between woody and manure biochars (Ippolito et al. 2015). The diverse properties of biochar, such as its large specific surface area, high cation exchange capacity, and substantial nutrient content, can improve the soil environment and fertility (Beusch 2021). These beneficial chemical, physical, and biological properties of biochar are illustrated in Figure 2.1.

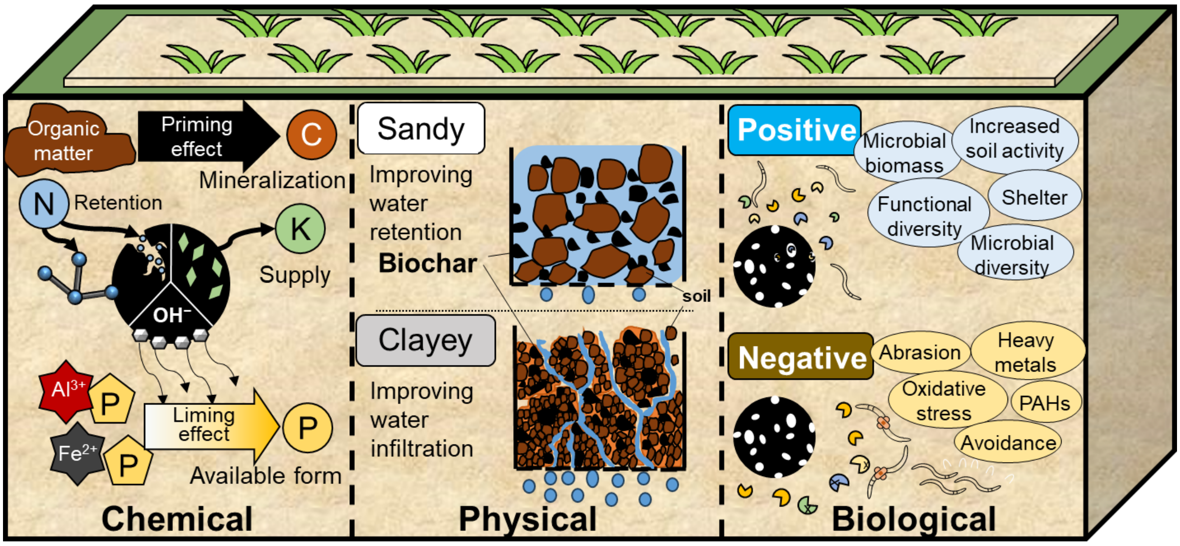


Figure 2.1. The comprehensive chemical, physical, and biological properties of biochar

2.1: Effects of biochar on soil fertility and nutrient management

2.1.1: Effect of biochar on soil fertility

The soil amendment effects of biochar vary widely depending on biochar feedstocks and soil types to which it is applied (Ji et al. 2022). Application to acidic soils can moderately increase soil pH, making the soil suitable for crop production, while application to alkaline soils can cause an excessive increase in soil pH, which can have adverse effects. In addition, differences in biochar characteristics should be considered, as different biochar feedstocks show remarkable variations in their pore structures, chemical compositions, and nutrient contents (Mukome et al. 2013).

Biochar soil application affects the mineralization rate of native soil organic matter (SOM) through a so-called priming effect (Rasul et al. 2022). Both positive (i.e., acceleration of mineralization) and negative (i.e., inhibition of mineralization) effects have been reported for the priming effect of biochar. A meta-analysis reported an increase in carbon mineralization (+15%) after biochar application as evidence of a positive priming effect over a relatively short period of time (Maestrini et al. 2015). In another meta-analysis, a negative priming effect (–8.6%) was observed over six months after biochar application (Wang et al. 2016). These contradictory results may reflect the involvement of several factors in the biochar-induced priming effect, such as the soil chemical structure of SOM, microbial community composition, and nutrient availability, as well as biochar pyrolysis temperatures, feedstock type, and other factors. The priming effect of biochar additions, particularly in mineral soils, is expected to be more negative over several years but is conservatively not included in current biochar soil carbon sequestration accounting methodologies (Woolf et al. 2021). Biochar applied to organic (e.g., Histosols) or forest soils with an organic horizon was excluded because of the potential for positive priming (Woolf et al. 2021).

Biochar also has a high specific surface area due to the presence of many micropores on its surface (Akhil et al. 2021) and a high amount of oxygen-containing surface functional groups such as hydroxyl (–OH) and carboxyl (–COOH) groups, making its surface negatively charged and leading to a high cation exchange capacity (Murtaza et al. 2022; Suliman et al. 2016). Consequently, nutrients in fertilizer such as ammonium-nitrogen (NH_4^+-N) and nitrate-nitrogen (NO_3^--N) applied to the soil are sorbed on the biochar surface by various mechanisms (e.g., pore filling, cation exchange, electrostatic interaction, and surface complexation), leading to extended nutrient residence time in the soil and significantly reducing ammonia (NH_3) volatilization from the soil surface and NO_3^--N leaching to underground water (Rubin et al. 2020; Sun et al. 2017). Sha et al. (2019) reported that when biochar was co-applied with urea or organic fertilizers (<200 kg N ha^{-1}), NH_3 volatilization was significantly reduced (–18.6% and –28.7%, respectively). According to a meta-analysis by Borchard et al. (2019), NO_3^--N leaching decreased by 26–32% after biochar application. Biochar affects the inorganic nitrogen dynamics. While some studies have reported that biochar application increases gross nitrification rates in forest soils (~ 66%) and arable soils (10–69%) (Ball et al. 2010; Nelissen et al. 2012), other studies have found no effects in experiments conducted on grassland and arable soils (Cheng et al. 2012; DeLuca et al. 2006).

Biochar also mitigates soil acidity. In general, biochar is alkaline (pH>7) because of the large amount of minerals in the feedstock before pyrolysis, which remain as ash after pyrolysis (Roberts et al. 2015). Therefore, it has a strong liming effect, especially when applied to acidic soils, and this change in pH has a strong impact on nutrient solubility in the soil and availability to crops. Phosphorus in the soil combines mainly with iron (Fe^{2+}) and aluminum (Al^{3+}) ions under acidic conditions and becomes an insoluble fraction. Meanwhile, when the soil pH is neutral, phosphorus changes to a crop-available soluble fraction (Hong and Lu 2018).

Biochar directly releases nutrients into the soil. Potassium (K^+) in biochar generally remains in crop-available forms (ash or soluble salts), especially when produced using woody feedstocks, such as bamboo (Hien et al. 2021; Karim et al. 2017). This form of K^+ is released slowly into the soil and is taken up by the crops. Biochar also contains other micronutrients, such as iron, zinc, manganese, and copper, depending on the feedstock and production method, that can be supplied to the soil as well (El-Naggar et al. 2019).

2.1.2: Effects of biochar on nutrient management

The systematic review of 26 global meta-analyses (Schmidt et al. 2021) indicated that when compared to a control, biochar alone increased plant productivity by 16 ± 1.3% and crop yield by 13 ± 2%, while biochar + fertilizer increased crop yield by 10 ± 4.6% (Refer to Table 4.5 in Section 4.3). The high plant or crop productivity was likely due to the priming effect of biochar on SOM and its ability to retain, solubilize, and provide crop nutrients, thus significantly increasing crop nutrient absorption compared to the control. Other benefits of biochar include the removal of pesticides, polycyclic aromatic hydrocarbons (PAHs), and other organic contaminants in soil and the immobilization of heavy metals, which can efficiently and environmentally reduce toxic stress and bioavailability to crops and microbes (Ji et al. 2022).

Therefore, by improving soil nutrient availability and fertility, biochar can improve crop growth and productivity. However, it is essential to evaluate the specific effects of biochar on soil nutrients through field experiments, considering the different climatic conditions and soil properties in different regions.

2.2: Effects of biochar on soil structure and hydraulic properties

2.2.1: Effects of biochar on soil structure

High soil aggregate stability is widely viewed as an indicator of a suitable soil structure, and both factors are important for supporting soil fertility and hydraulic properties (Bhat et al. 2022; Bronick and Lal 2005). When biochar is applied to soil, biogenically excreted organic matter can bind soil particles together, thereby improving aggregate stability (Guhra et al. 2022) and promoting soil microbial activity (Liang et al. 2010; Zhang et al. 2021). In a meta-analysis by Omondi et al. (2016), biochar application increased aggregate stability by up to 8.2%, on average. However, the effects of biochar on aggregate stability depend on the soil type. The mean weight diameter, an indicator of aggregate stability, significantly improved by 7.5% and 20.7% in fine- and medium-textured soils, respectively, but not in coarse-textured soils with biochar application (Omondi et al. 2016).

2.2.2: Effects of biochar on soil hydraulic properties

Biochar can improve water retention and hydraulic conductivity in soil because of changes in the soil pore size (Edeh et al. 2020). Available water content (AWC) is a key parameter for soil water retention. According to metadata, biochar application has positive effects on AWC in sandy soils, with a 32.9% increase compared with the control (Edeh et al. 2020). Biochar application improves AWC by decreasing the average pore size in coarse-textured soils because smaller biochar particles can fill large pores in the soil (Liu et al. 2017). However, biochar application to sandy soils reduces water infiltration (Bhat et al. 2022). The saturated hydraulic conductivity (K_{sat}) is a widely used measure of water infiltration. A meta-analysis indicated that biochar application reduced soil K_{sat} by 64.6% on average (Edeh et al. 2020), potentially because the porous structure and small size of biochar can block soil micropores, thus decreasing water infiltration (Bhat et al. 2022).

However, biochar application to clayey soils improves water retention and infiltration to varying degrees. Compared with sandy soils, the effect of biochar on water retention in clayey soils was lower, with an average 9.1% increase in AWC (Edeh et al. 2020). Pristine clayey soils have higher water retention than sandy soils because of the clay particles' large surface area (Hussain and Ravi 2021). Therefore, biochar has less impact on water retention in clayey soils. However, the application of biochar to clayey soils can improve water infiltration. Edeh et al. (2020) reported a 28% increase in K_{sat} for clayey soils. Biochar can increase the number of macropores in the soil owing to soil aggregation (Guhra et al. 2022; Obia et al. 2018), allowing for the rapid movement of water and improving water infiltration (Edeh et al. 2020).

2.3: Effects of biochar on soil microbial communities and meso/macrofauna

2.3.1: Effects of biochar on soil microbial communities

Soil microorganisms play a crucial role in maintaining soil ecosystems by solubilizing nutrients, regulating nutrient cycling, and acting as a buffer against various stresses, that is, drought and pollution, among other beneficial roles. Biochar application improves soil biological properties directly and indirectly (e.g., Gruss et al. 2019; Sheng and Zhu 2018; Xu et al. 2020). Biochar can act as a direct resource for soil microbes because it contains a small fraction of labile carbon, such as volatile matter, ash, and mineral nutrients for growth. The porous structure of biochar protects and shelters the microorganisms from predation. Therefore, soil microbes can colonize biochar particles and use the biochar as a habitat. However, these direct effects are rather short-lived, as resources are depleted and the porous structure collapses over time in the soil (Dai et al. 2021). Biochar indirectly influences soil microbial communities by increasing water retention and altering the soil chemistry. The surface functional groups and porous structure of biochar can retain nutrients and resources that would otherwise be lost through leaching, erosion, and volatilization. These increases in the bioavailability of resources allow for more efficient use by soil microorganisms, thus promoting their growth (Dai et al. 2021; Sun et al. 2019).

The soil pH is a key driver of bacterial and fungal growth. Like plants, the ideal pH range for most soil microbial growth is 5.5–6.5, with bacteria and fungi favoring more neutral and acidic pH, respectively (Msimbira and Smith 2020). Because biochar is typically alkaline, regardless of the derivative raw material or pyrolysis method, biochar application often results in an elevated soil pH. This property of biochar is beneficial for acidic soils (Dai et al. 2021). Sheng and Zhu (2018) reported that biochar application promotes bacterial diversity in acidic soils. Meanwhile, in alkaline soils, it has either a detrimental or no effect on bacterial diversity. A meta-analysis of the effect of biochar on soil microorganisms showed that microbial growth was more pronounced with biochar produced at low pyrolysis temperatures (e.g., ≤ 350 °C) when applied to acidic soils (Zhang et al. 2018). This was confirmed by another meta-analysis, which also found that increased arbuscular mycorrhizal fungal abundance, increased microbial biomass carbon, and functional richness from biochar application were diminished at higher soil pH (Xu et al. 2020). The effects of biochar on soil microorganisms are most pronounced in heavily weathered soils, which are often associated with a low soil pH.

2.3.2: Effects of biochar on meso- and macrofauna

There are concerns that biochar may be toxic or damage soil fauna. Earthworms have exhibited avoidance behavior, stunted development, and physical damage in response to rice husk or wheat straw biochar at application rates of ≥ 10% w/w (200 t ha^{-1}) due to external and internal abrasion caused by biochar (Elliston and Oliver 2020). Similarly, earthworms exhibited avoidance behavior in response to biochar derived from spent coffee grounds applied at 5% w/w (100 t ha^{-1}), owing to a shift toward a sandier soil texture, which the earthworms tended to avoid. Earthworm muscle tissue showed signs of oxidative stress with biochar application (Sanchez-Hernandez et al. 2019). However, at biochar application rates ≤ 2.5% w/w (50 t ha^{-1}), earthworm and biochar application had interactive effects, increasing soil enzyme activities and earthworm gut multifunctionality while showing no significant earthworm avoidance behavior or stunted development (Jin et al. 2022; Sanchez-Hernandez et al. 2019).

Biochar can promote meso-and macrofaunal abundance in soil. A field study conducted in Poland showed that wood-chip biochar (produced at 300 °C) applied at 50 t ha^{-1} increased the average abundance of mites and springtails from 42.6 to 65.1 and 8.1 to 27.6 individuals, respectively, in an oilseed rape field compared to no biochar application (Gruss et al. 2019). The biochar used in this study was free of PAHs and other toxins. Soil meso- and macrofauna have not been as extensively studied as soil microorganisms. There are still many unknown aspects, including the potential chronic effects of biochar and shifts in trophic interactions resulting from biochar application.

2.4: Biochar application in Asia

In the Asia–Monsoon region, monsoon winds from the sea cause a rainy season with heavy rainfall in summer, resulting in NO_3^--N leaching from the soil due to the large amount of precipitation (Huang et al. 2011). Because the soils in the region tend to be acidic, phosphorus fixation is likely to occur. The use of biochar in these areas is expected to reduce NO_3^--N leaching from the soil and solubilize phosphorus in the soil. Because SOM runoff occurs in areas with heavy rainfall (Major et al. 2010), the SOM accumulation effect of biochar application can help maintain and improve soil fertility.

Asia has many deserts, including the Gobi, Karakum, and Kyzylkum Deserts. Desert soils have poor aggregate stability and water retention (Fu et al. 2021). Biochar application increased water retention by 15% in desert soils (Shao et al. 2023). The effects of biochar on the hydraulic characteristics are dependent on the soil texture. However, soil structure can be improved by selecting the appropriate biochar for each soil type.

Rice is one of the most abundant crops in Asia, and one of the major issues in rice paddy fields is the loss of nitrogen through ammonia volatilization. A study conducted in China showed that the application of rice straw biochar to paddy fields reduced ammonia volatilization and promoted rice growth (Sun et al. 2019). Biochar application increased *amoA* gene abundance, a marker of ammonia-oxidizing microbes, thus increasing NH_4^+ oxidation. This decreased the NH_4^+ concentration in the surface water and decreased nitrogen loss through volatilization. A potential factor contributing to the stimulation of ammonia-oxidizing microbes by biochar application is the increase in pH from mildly acidic to near-neutral, which is ideal for the growth of these microbes (Sun et al. 2019).

2.5: Emerging trends and future directions in biochar research

A scientometric review of biochar research trends from 1998 to 2018 showed a rapid increase in the number of publications since 2010 (Wu et al. 2019). Between 2011 and 2015, key topics included biochar production and biochar and global climate change. From 2016 to 2018, the focus shifted to biochar and composting, highlighting the importance of mixing biochar with nitrogen sources for optimal application in agriculture. Recent studies have explored updated reactors, energy production technologies, and modified biochar for environmental remediation.

There are still knowledge gaps in understanding the long-term biochar–soil–plant interactions in the field, including their impact on crop yields, greenhouse gas reduction, priming effects, and the effects of repeated biochar application in situ (Joseph et al. 2021). Biochar can be customized for specific applications through careful selection of the feedstock. However, there are concerns regarding the long-term effects of continuously reapplying biochar on the capture and release of heavy metals from the soil, especially when the feedstock originates from outside the local biomass system, such as waste treatment residues. Further research is needed to fully understand the co-benefits of biochar application, particularly how biochar properties affect root remediation potential and microbial nutrient cycling, and to develop optimal formulations to improve nutrient use efficiency. This necessitates well-designed, long-term field experiments with measurable variables related to the physical and chemical properties of biochar. Therefore, standardizing biochar analysis methodologies, including pretreatment protocols, is essential.

Combining biochar with mineral and/or organic fertilizers is likely to enhance nutrient use efficiency and prove to be cost-effective by integrating biochar with farming operations (Joseph and Taylor 2024). Further field trials are needed to assess the nutrient performance and potential reductions in greenhouse gas emissions (Melo et al. 2022).

In the context of the carbon credit certification scheme for biochar, quantifying biochar carbon sequestration and the associated greenhouse gas emissions due to biochar production and application is crucial (Section 3.3). However, there are limited case studies evaluating the emission factors for CH_4, N_2O, and NOx during the biochar production process (Cornelissen et al. 2016), especially for Asian-specific feedstocks and methods, such as flame-curtain kilns, for farmer-scale biochar production. Therefore, there is an urgent need to accumulate more case studies and conduct meta-analyses within this context.

3: Carbon neutrality and biochar

3.1: Biochar as a carbon dioxide removal (CDR) technology

Lehmann et al. (2021) thoroughly reviewed the use of biochar as a soil amendment to reduce GHG emissions and achieve CDR. To achieve net-zero carbon emissions, cost-effective and scalable CDR technologies, including the use of biochar, are crucial. Table 3.1 summarizes the six promising CDR options. Every possible solution must be considered to prevent the worst impacts of climate change. Optimizing the synergy between different technologies, that is, determining the best mix is essential when considering factors such as scale, cost-effectiveness, and resource sustainability. In cases

Table 3.1 Six promising carbon dioxide removal (CDR) technologies (adapted from Minx et al. 2018)

CDR method	CO_2 capture	Storage medium	Description
Afforestation & Reforestation (AR)	Photosynthesis	Biomass	Trees remove CO_2 from the atmosphere. Carbon can be bound in the medium to long term by material use of the biomass.
Soil carbon sequestration (SCS)	Photosynthesis	Soil	Plants/Crops remove CO_2 from the atmosphere. Increase the carbon content of soils (humus) through agriculture practice such as green manure, cover crop, organic farming, no-tillage, agroforestry etc.
Biochar (BC)	Photosynthesis	Soil	Plants/Crops remove CO_2 from the atmosphere. Through pyrolysis, the carbon stored in the plants can be bound in the long term in the soil.
Bioenergy with carbon capture & storage (BECCS)	Photosynthesis	Geological reservoirs	Plants remove CO_2 from the atmosphere. The biomass is used to produce energy, the CO_2 is separated and stored underground.
Direct air capture (DACCS)	Chemistry	Geological reservoirs	CO_2 is extracted from the ambient air with filters or in chemical processes and stored underground.
Enhanced weathering (EW)	Geochemistry	Minerals	Rock is crushed and exposed to natural weathering/mineralization. The weathering process removed CO_2 from the atmosphere, the carbon is firmly bound in the form of carbonates.

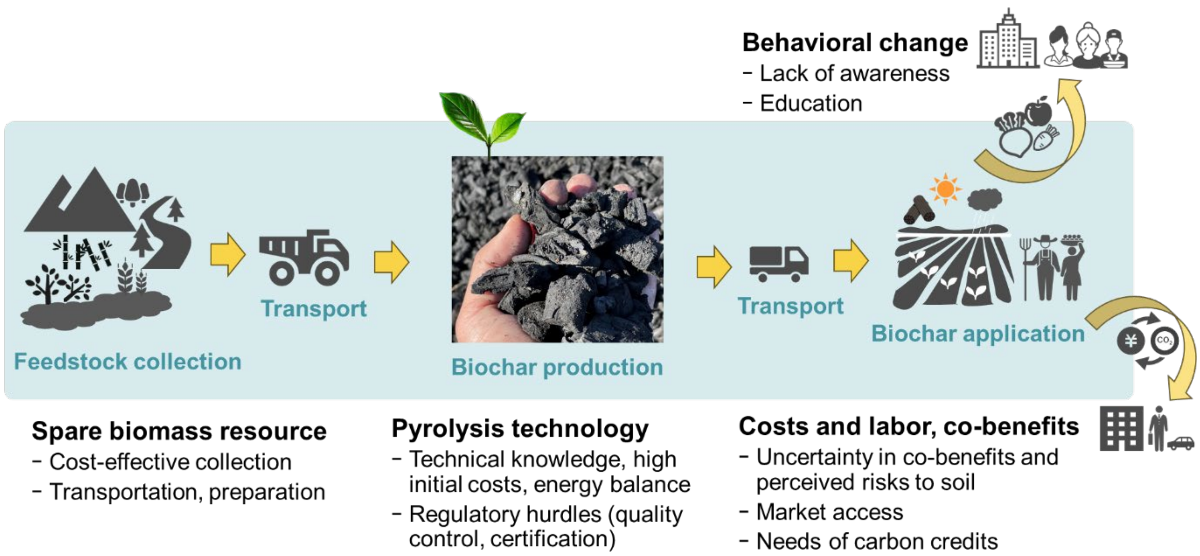


Figure 3.1 Barriers to biochar implementation for mitigating climate change.

where there is competition for resources among technologies, regional-scale optimization is the best approach.

There are several barriers to biochar implementation for mitigating climate change, including feedstock collection, production, and application. These barriers involve technical, cost-efficiency, and social transition issues, as illustrated in Figure 3.1. Overcoming the barriers to biochar implementation requires a combination of research, education, incentives, and support policies. Subsidies, carbon credits, and eco-branding are schemes that may promote the use of biochar. See Section 5 for further discussions on these topics.

3.2: Estimation of soil carbon sequestration through biochar

The IPCC 2019 Refinement provides a methodology for estimating carbon stock changes in mineral soils associated with biochar amendments (Ogle et al., 2019). The estimation equation is as follows:

$$\Delta BC_{\text{mineral}} = \sum_{p} (BC_{\text{TOT}} \times F_{\text{c}} \times F_{\text{perm}}), \text{ .... (Eq. 1)}$$

where $\Delta BC_{\text{mineral}}$ is the total carbon stock change due to biochar application (t-C yr^{-1}), BC_{TOT} is the mass of biochar applied (t-d.m. yr^{-1}), F_{c} is the fraction of biochar organic carbon content for biochar type p (t-C t-d.m.$^{-1}$), and F_{perm} is the fraction of biochar carbon that remains after 100 years for biochar type p (t-C t-C^{-1}). The default values of F_C and F_{perm} in the IPCC 2019 Refinement (Appendix 4, Chapter 2, Volume 4, refers to Ogle et al., 2019) vary with feedstock and pyrolysis/gasification temperature, with F_{perm} changing at three pyrolysis temperature levels (350–450 °C, 450–600 °C and ≧600 °C). Woolf et al. (2021) developed more precise models, as shown in Appendix 4, encouraging countries to update their calculations.

In Japan, the default values of F_{c} and F_{perm} were established based on the IPCC 2019 Refinement and Supporting Scientific Research (J-Credit Scheme 2023), as shown in Table 3.2. Wood-based biochars such as *Hakutan* (hard charcoal), *Kokutan* (soft charcoal), *Ogatan* (sawdust coal), *Funtan* (fine coal), and bamboo biochar are documented in Japan's National Greenhouse Inventory Report and the J-Credit Scheme. Domestic products and other types of biochar are eligible for use under the J-Credit Scheme. Japan has reported biochar amendments since the 2020 submission of its national GHG inventory, with 5.02 thousand tons of CO_2 reported for fiscal year 2018 and 5.56 thousand tons for fiscal year 2019 (Kishimoto-Mo, 2022). On June 30, 2022, the J-Credit Scheme officially certified carbon credits for the first time, totaling 247 t-CO_2 (Kishimoto-Mo and Shibata, 2023).

Table 3.2 Biochar types and variables used for carbon sequestration estimation in Inventory reporting and J-Credit Scheme.

Category	Feedstock type	F_c	F_{perm}
Biochar for inventory reporting	Hard charcoal (*Hakutan*)	0.77	0.89
	Soft charcoal (*Kokutan*)	0.77	0.89
	Sawdust coal (*Ogatan*)	0.77	0.89
	Fine coal (*Funtan*)	0.77	0.8
	Bamboo biochar	0.778	0.65
Domestically produced and other biochar	Animal manure	0.38 / 0.09*	0.65
	Wood	0.77 / 0.52*	0.65
	Herbaceous	0.65 / 0.28*	0.65
	Rice husk and rice straw	0.49 / 0.13*	0.65
	**Nut shells, pits and stones	0.74 / 0.40*	0.65
	Biosolids (paper/sewage sludge)	0.35 / 0.07*	0.65
	*Gasification **Including coffee residues		

Source: J-Credit AG-004 (Ver2.1) biochar methodology eligibility as of April 2024. https://japancredit.go.jp/pdf/methodology/AG-004_v2.1.pdf

Japan has traditionally evaluated biochar properties using proximate analysis based on Japanese Industrial Standard (JIS) M 8812. This measures fixed carbon (FC), volatile matter (VM), ash, and moisture. A protocol was established to convert the JIS parameters to the IPCC variables F_C and F_{perm} for woody and bamboo biochars (Kurimoto et al. 2024). Through a proximate analysis, the pyrolysis temperature, F_C, and F_{perm} were estimated from the VM/FC ratios (Figure 3.2). This conversion protocol is also applicable to biochar made from other feedstocks, enhancing national greenhouse gas inventories and promoting the use of carbon dioxide removal (Kurimoto et al. 2024).

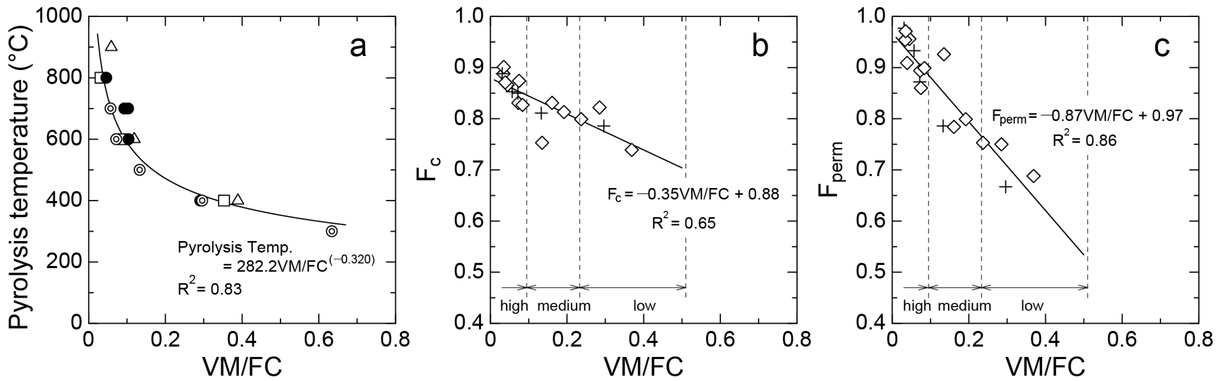


Figure 3.2. Estimation of (a) pyrolysis temperature, (b) biochar organic carbon content (F_C), and (c) the fraction of biochar carbon remaining in soil after 100 years (F_{perm}) based on proximate analysis values (VM/FC) of bamboo biochar (Adapted from Kurimoto et al. 2019; 2020).

Figure 3.3 illustrates the correlation between FC and the product of F_C and F_{perm} ($F_C \times F_{perm}$) with an exponential function derived from woody and bamboo biochars (Kurimoto et al. 2024). This approach allows the direct assessment of carbon sequestration by biochar using FC and the amount of biochar applied to soils using Eq. 2, as shown below:

$\Delta BC_{\text{mineral}} = \sum_p \left(BC_{\text{TOT}} \times 0.136e^{0.0192FC}\right)$ .... (Eq. 2)

The current approach using Eq. 2 applies only to biochar produced via pyrolysis, with torrefaction and hydrothermal carbonization not considered, as discussed in Section 1.2. There is a need to adjust Eq. 2 to account for biochar with high ash content and biochar derived from gasification processes.

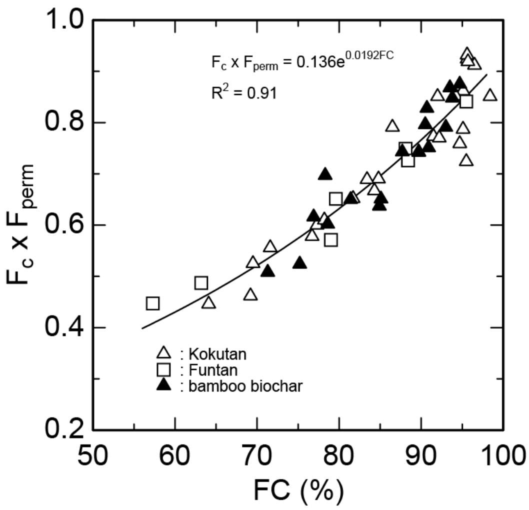


Figure 3.3. Relationship between FC and the product of F_c and F_{perm}. F_{perm} is calculated at a soil temperature of 14.9 °C (Adapted from Kurimoto et al. 2024).

3.3: Considerations of life cycle assessment for biochar practices

Applying biochar to farmland involves obtaining biomass (feedstock), performing pyrolysis, and transporting the biochar if the locations for feedstock collection, pyrolysis, and farmland are applied. These processes often rely on fossil fuels and electricity, leading to environmental impacts such as CO_2 emissions (Figure 3.4). Therefore, it is crucial to understand and minimize these environmental loads when applying biochar to farmlands. Assessing GHG emissions is essential because they can offset the carbon sequestration benefits of biochar, making proper assessment imperative.

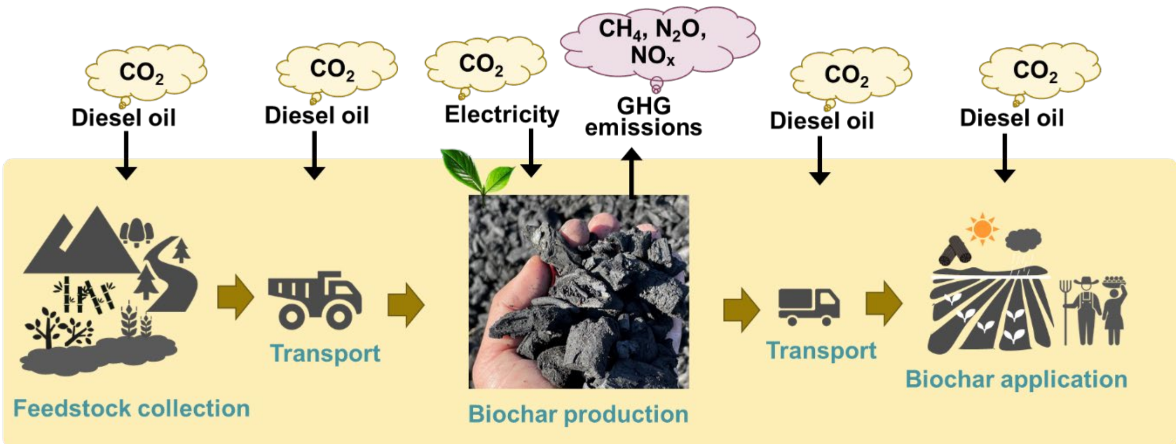


Figure 3.4. Greenhouse gas (GHG) and fugitive emissions throughout the biochar life cycle.

Life cycle assessment (LCA) is a methodology used to quantify the environmental impact of raw material extraction on product manufacturing, use, and disposal (ISO 2006). The procedures for conducting LCA based on ISO 14040:2006 are outlined in Figure 3.5. The process of conducting LCA for the biochar produced from rice husks is shown (Figure 3.6).

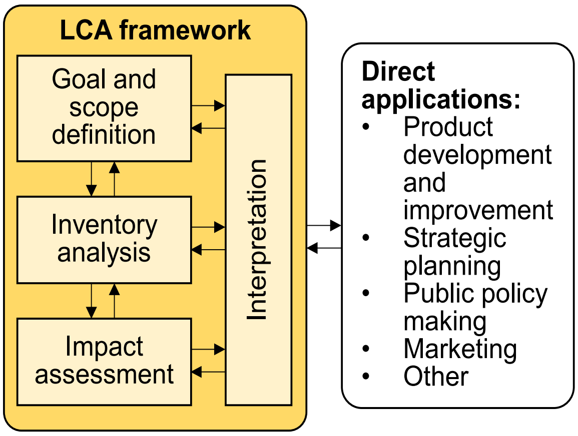


Figure 3.5. Stages of an LCA (ISO 2006).

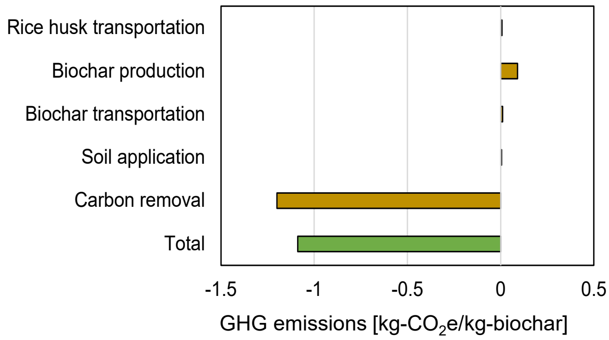


Figure 3.6. Example of GHG emissions through the biochar life cycle (Nakano et al. unpublished).

(1) Goal and scope definition: This phase defines the purpose and scope of the study. The purpose of this LCA was to quantify the GHG reduction effects of applying biochar to farmlands. LCA can be used to assess various environmental aspects such as resource consumption and ecological toxicity. It is crucial to define the system boundaries that outline the scope of the LCA, typically covering the entire process from feedstock production and biochar production to farmland application. However, when biochar is produced from agricultural residues, such as rice husks, investigations often begin when biomass is generated.

(2) Inventory analysis: This phase involves detailing the inputs and outputs of each process, such as feedstock collection and biochar production. Data collection includes information, such as the 4 kg of rice husk required to produce 1 kg of biochar, requiring 0.02 kWh of electricity. Using these data, emission factors (e.g., 0.62 kg-CO_2/kWh) were applied to calculate the CO_2 emissions associated with electricity consumption. The amount of carbon removed, depending on the biochar quality, was calculated. Data on fugitive emissions, such as CH_4, NOx, and CO, during biochar production were also collected.

(3) Impact assessment: This phase evaluates the impacts on environmental impact categories. In this case study, with a focus on climate change, the impact of each GHG was converted into CO_2 equivalent amounts and aggregated. During biochar production in a flame curtain kiln (see Section 4.1), significant amounts of CH_4 may be released. Because CH_4 has a global warming potential (GWP) 27 times greater than that of CO_2, its emissions were multiplied by 27 to convert them into CO_2 equivalents (Forster et al. 2021). The results are shown in Figure 3.6.

(4) Interpretation: This phase involves analyzing the results and, if necessary, conducting a sensitivity analysis. The carbon removal effect of biochar was more substantial than the GHG emissions associated with its production. This net difference can be considered the GHG removal effect of biochar throughout its life cycle.

4: Best practices and general guidance

4.1: Recommendations for biochar production technologies

The pyrolysis of biomass is a thermochemical process that generates gases, liquids, and solids. The proportions of these products are determined by temperature and cooling methods. When the solid components are prioritized, managing the gases and smoke released during carbonization is critical. Common approaches include direct combustion for heat recovery, gasification for electricity generation, and liquefaction for wood vinegar and tar recovery.

Biomass thermochemical conversion systems are generally classified into continuous and batch types, and can be further categorized based on the following criteria:

- **Heat source supply:** internal heating, external heating, hydrothermal, or hybrid types
- **Air tightness:** oxic (open flame curtain method), anoxic (no or limited oxygen is admitted to the reactor), or semi-anoxic (common in continuous systems)
- **Pyrolysis temperature:** below 300 °C (semi-char), 300–450 °C (low), 450–600 °C (medium), 600–800 °C (high), above 800 °C (e.g. hard charcoal "*Hakutan*")

Table 4.1 outlines biomass thermochemical conversion technologies with a primary emphasis on solid products. The biochar used for environmental improvement and carbon sequestration requires a pyrolysis temperature exceeding 350 °C (Section 1.2).

Table 4.1 Biomass thermochemical conversion technologies for biochar compared to charcoal and bio-oil (modified from Brown et al. 2024)

Thermo-chemical conversion	Tempera-ture (°c)	Other defining parameters	Production				Major intended products
			Solid	Gas	Liquid		
					Water soluble	Oil soluble	
Carbonization	180-1200	Air tightness, residence time, raw materials	10-35% Solid product	20-75% H_2O, CO_2,NOx, CO, CH_4, H_2, etc.	15-45% Wood vinegar, alcohol etc.	5-15% Tar, phenols, pitch, etc.	Charcoal for fuel, moisture regulating, deodorizing and industrial reducing agents.
Pyrolysis (for bio-oil)	400-700	Heating rate, residence time, particle size, gas flow rates	10-25% Solid product	20-40% H_2O, low-boiling volatile gases	40-70% Wood vinegar, alcohol etc.	40-70% Tar, phenols, Pitch, etc.	Bio-oil, chemical products such as pest repellents, animal repellents, surfactants, and fuels
Pyrolysis (for biochar)	350-900	Air tightness, residence time, heating rate, particle size, gas flow rates	20-50% Solid product	20-75% Combusted or for heat recovery if not liquified.	15-35% Wood vinegar, alcohol etc.	5-15% Tar, phenols, pitch, etc.	Biochar, soil amendment, carbon sequestration, and soil remediation
Gasification	500-1500	Oxidizing media, equivalence ratio, machinery type, raw materials	5-15% Solid byproduct	25-95% CO,CH_4, C_2H_4,H_2, etc.	5-60% Cooled by temperature range for liquefaction according to its application.		Syngas, gaseous fuel for heat and power, and gas to liquid. Solid byproduct for biochar.

Biochar production technologies are diverse and depend on the type, moisture content, and volume of biomass feedstock.

Locally unused biomass is commonly used for biochar production. It is often scattered across large areas in small amounts and may be seasonal. Therefore, the careful selection of pyrolysis systems that match the available biomass supply is essential to avoid overinvestment and ensure economic sustainability.

In Japan, traditional charcoal kilns have been used for centuries mainly to produce fuel charcoal. These kilns are categorized into two types: hard charcoal from "*Hakutan*" kilns operating at 1000–1200 °C and soft charcoal "*Kokutan*" kilns operating at 400–900 °C. During production, small charcoal pieces and powder known as fine coal "*Funtan*" that cannot be sold as fuel are repurposed as soil amendments for agriculture. *Hakutan*, *Kokutan,* and *Funtan* are included in Japan's national GHG inventory for reporting soil carbon stock changes with biochar amendment (see Table 3.2 in Section 3.2).

In orchard and bamboo grove management, biomass-like pruned branches and bamboo are often produced in large quantities. These can be easily pyrolyzed on-site using portable kilns such as the Moki-Kon-Tiki flame-curtain kiln (Figure 4.1). The kiln can be operated by sequentially adding biomass, with the combustion of the emitted gases creating a flame curtain at the top, resulting in an oxygen-deficient environment at the bottom for pyrolysis. The biomass can be continuously added through the flame until the kiln is full. The gases and smoke released from the pyrolysis zone are captured and combusted in the flame zone to obtain cleaner emissions (Figure 4.1A). This kiln is well suited for thicker materials such as bamboo and pruned branches of 1–4 cm in diameter. However, it is less effective for granular materials such as rice husks because of limited

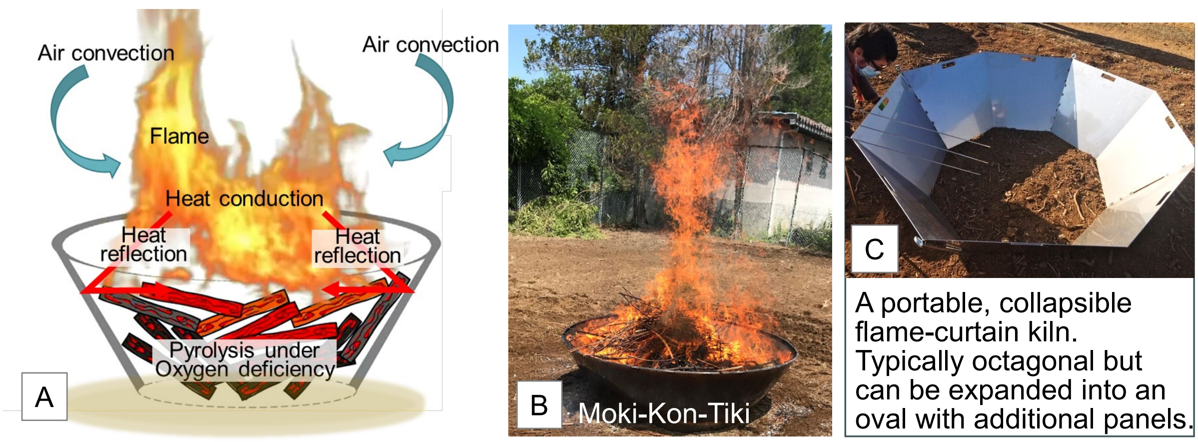


Figure 4.1 Schematic diagram explaining the principle of open-type portable flame-curtain kilns to produce biochar (adapted from Oo et al. 2018).

airflow. Originally developed in Japan, Moki-Kon-Tiki gained recognition in 2009 and has since become a major biochar-production device, adapted and improved in over 50 countries (McGreevy et al. 2016).

In the rice-growing areas of Asia, rice husks are readily available biomass sources collected from local mills. They are typically pyrolyzed using continuous systems, often rotary kilns (Photo 4.1A), designed to match specific feedstock and quality. A key challenge in relying on a single biomass source is the risk of reduced operational efficiency owing to seasonal availability, which complicates equipment depreciation. When government subsidies are used, only the self-funded portion is subject to depreciation, which can result in an insufficient maintenance budget. Therefore, careful consideration of the appropriate scale of the pyrolysis equipment is crucial.

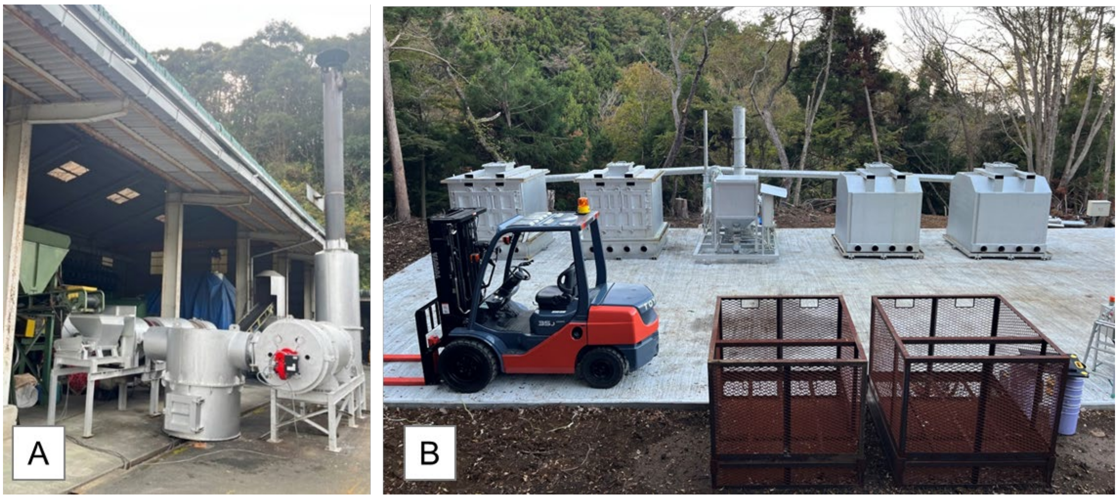


Photo 4.1 Continuous rotary kiln (A), and mobile anoxic pyrolysis units (B). Photo credits: (A) Soil Farm Co. Ltd., and (B) Takatsuki Biochar Energy Lab.

Recently, pyrolysis systems, such as mobile anoxic pyrolysis units (Photo 4.1B), have gained attention. The system operates at 600–700 °C and multiple units can be connected to handle different biomass quantities. By replacing the internal baskets, the system can adapt to different feedstocks with distinct shapes, such as bamboo and rice husk.

4.2: Sustainable sourcing of biochar feedstocks in Asia

Many countries in Asia, particularly in Southeast and South Asia, are situated in humid tropics that support a wide diversity of plant taxa. However, the expansion of large-scale farms and monocultural reforestation areas has been driven by economic demand. Table 4.2 lists the crop species and their parts prevalent in 28 countries in the Asia–Monsoon region that could be sustainable biochar feedstocks.

Table 4.2. Selected crops in the Asia–Monsoon region that could serve as feedstocks for biochar production.

Category	Crops with their parts available for biochar
Cereal	Rice (husk, straw), Wheat (straw), Maize (Stalk, Cob, Husk), Sorghum (straw)
Beans	Ground nuts (Straw, Husk/Shell), Peas (straw), Pigeon peas (straw), Soybean (Straw, Pods)
Perennial crops	Sugarcane (top, leaves, bagasse), Banana (above ground biomass)
Woody crops/fruits	Cassava (stalks, peelings), Coffee (beans husk), Cashew nuts (shell), Cocoa (beans shell)
Palms	Coconuts (Shell), Oil palm (fruit fiber, shell, bunch)
Woods*1	Pulpwood, round, split (residues at factory); Wood chips & particles; Wood residues
*1 : The terms of wood parts are derived from the item of FAOSTAT (2023 Sep) and defined by FAOSTAT (2016).	

To estimate biochar production potential, the author used the following data sources and conditions. Crop production data were sourced from FAOSTAT (August 2023) and forestry production data from FAOSTAT (September 2023), with product definitions based on FAO Crop Statistics (2024) and FAOSTAT (2016). The crop parts and coefficients for estimating the residue amounts were based on Lefebvre et al. (2023). To estimate carbon removal after 100 years through biochar, the permanence coefficient F_{perm} from Woolf et al. (2021) was used, applying values of 0.71 for East Asia and 0.64 for Southeast/South Asia, with medium pyrolysis temperatures (450–600 °C). These were adjusted for soil temperatures of 15 °C for East Asia and 25 °C for Southeast/South Asia, based on Haque et al. (2023).

Photo 4.2. Rice husks are generated in large quantities. (Cambodia)

Table 4.3 outlines the production and residue estimates, with cereal crop residues being the most abundant, particularly rice, which is widely cultivated in this region. Rice residues include husks (Photo 4.2) and straw is generated in large quantities. Maize is grown in all three regions, with residues consisting of stems, cobs, and sheaths. Wheat is produced in both East and South Asia. Perennial crops grown on large-scale corporate farms, such as sugarcane, are the second most important feedstocks following cereals. Sugarcane residues consist of bagasse, long leaves, and tops that remain after sap extraction. Palm trees, including both coconut and oil palms, are also abundant in the region. Oil palms, which are particularly prevalent on large-scale corporate farms, produce numerous small fruits with the outer shells becoming a residue. Legumes such as groundnuts and soybeans are cultivated across all regions with residues, including

Table 4.3. Potential biomass and residues available from agriculture/forestry in the Asia–Monsoon region

Region	Agriculture					Forestry	
	Cereal	Beans	Perennial crops	Woody crops/fruits	Palms	Woods	
	Production (1000 t)						Total
East Asia	635,831	46,557	122,049	5,075	1,084	32,995	**843,591**
Southeast Asia	236,296	3,952	180,187	76,347	398,902	15,963	**911,646**
South Asia	467,161	33,866	503,076	8,010	16,688	243	**1,029,044**
Subtotal	**1,339,287**	**84,374**	**805,312**	**89,432**	**416,674**	**49,201**	**2,784,281**
	Residues (1000 t)						Total
East Asia	977,120	106,500	40,120	3,219	495	14,137	**1,141,770**
Southeast Asia	447,243	8,282	59,222	51,982	176,447	2,989	**746,164**
South Asia	732,657	77,105	166,642	6,098	8,100	23	**1,020,626**
Subtotal	**2,187,020**	**191,886**	**265,984**	**61,300**	**185,042**	**17,329**	**2,908,560**

stems and pods. Cassava is the most abundant woody crop, with residues consisting of stems and peeled bark. Coffee, cashew nuts, and cocoa are luxury commercial crops with varying production levels across the Asia–Monsoon region and their residues include the outer shells of the fruits.

Recently, large-scale afforestation by corporations has increased in Asia's forestry sector. Although pulp and paper production remains the primary application, timber use is also growing. Although timber is still harvested from natural forests, waste materials from these forests are excluded from biochar feedstock. Most wood used for pulp and paper production in Asia comes from plantations, waste materials from afforestation sites (Photo 4.3), and processing factories, now used as feedstock for biochar production.

Photo 4.3. Logging in large-scale afforestation areas for pulp and paper production (Indonesia).

In addition to agricultural and forestry residues, bamboo groves, and livestock waste, which are both specific to Asia, offer further biochar production potential. The Asia–Monsoon region has a long history of charcoal production for fuel, with an annual output of approximately 8 million tonnes, indicating a foundational, although rudimentary, capacity for pyrolysis techniques.

Table 4.4 details the biochar production potential from these agricultural and forestry residues, along with their CO_2 equivalent values. In the Asia–Monsoon region, the biochar production capacity is estimated at 700 million tonnes, with the CO_2 equivalent averaging 3.7% of total GHG emissions and reaching up to 7.9% in Southeast Asia. While the region holds substantial biomass potential, actual availability and distribution vary significantly, requiring careful consideration for effective resource planning.

Table 4.4. Biochar potential from agriculture and forestry biomass residues in the Asia-Monsoon region.

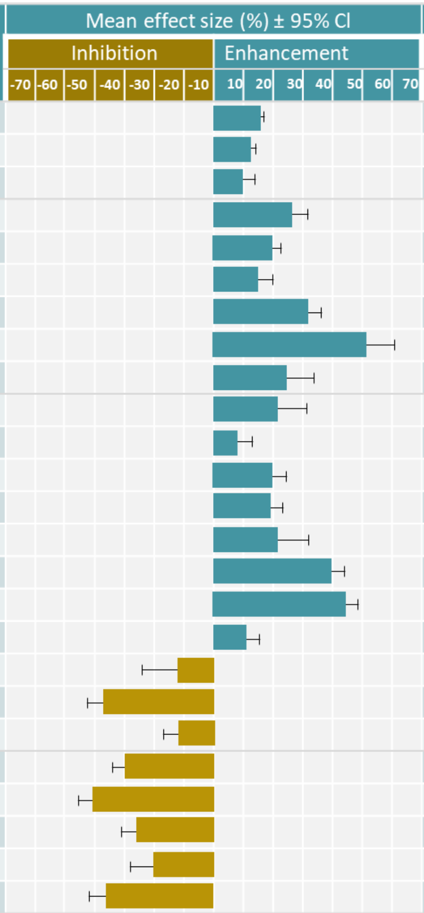
Region	Agriculture					Forestry	Biochar Total
	Cereal	Beans	Perennial crops	Woody crops/fruits	Palms	Woods	
	Biochar (1000 t)						(1000 t)
East Asia	224,280	6,119	10,030	799	124	3,579	**273,090**
Southeast Asia	111,811	1,505	14,805	12,907	44,112	747	**185,887**
South Asia	190,664	9,881	41,660	1,516	2,025	6	**245,753**
Subtotal	**546,755**	**25,665**	**66,496**	**15,222**	**46,260**	**4,332**	**704,730**
	CO_2 removal by biochar (1000 tCO_2e)						Total biochar CO_2 removal (1000 tCO_2e)
East Asia	373,692	24,533	16,758	1,372	218	7,548	**424,121**
Southeast Asia	134,170	519	22,322	19,991	69,933	1,421	**250,167**
South Asia	239,099	15,303	62,693	2,349	3,244	11	**322,699**
Subtotal	**746,961**	**42,166**	**101,773**	**23,712**	**73,395**	**8,980**	**996,987**

4.3: Optimal application rates and methods for different soil types and crops

Determining the optimal biochar application rate requires a strategic approach to maximize co-benefits, such as increased soil carbon, improved soil environment, and enhanced or maintained crop productivity (Schmidt et al. 2021), while minimizing potential environmental risks (Brtnicky et al. 2021; Shem et al. 2019; Wang et al. 2019). The co-benefits of biochar application are influenced by various factors, including biochar feedstock, pyrolysis temperature and duration, soil type, crops, climate, and cropping management history (for details, refer to Section 2). Despite this complexity, 26 selected meta-analyses published since 2016 that investigated a multitude of soil properties and agronomic performance parameters impacted by biochar application showed compelling evidence of the overall beneficial effects of biochar on all investigated agronomic parameters (Table 4.5).

Table 4.5. Expected co-benefits of biochar application to agricultural soils with the mean effect size (%) investigated in the 26 reviewed meta-analyses (modified from Schmidt et al. 2021)

Co-benefits	Main Parameter	Citation
Biomass yield	Plant productivity	Dai et. al .(2020)
	Crop Yield	Jeffery et.al .(2017)
	Crop yield (BC+fertilizer)	Ye et.al.(2020)
Plant physiol., soil, roots	Photosynthetic rate	He et.al. (2020)
	Water use efficiency	Gao et.al.(2020)
	Plant available soil water	Omondi et.al. (2016)
	Root biomass	Xiang et.al .(2017)
	Root length	Xiang et.al. (2017)
	Numbers of root modules	Xiang et.al .(2017)
Environmental effects & soil biology	Soil microbial biomass C	Pockarel et. al. (2020)
	Total PLFA	Zhang et.al. (2018)
	Bacteria	Zhang et.al. (2018)
	Fungi	Zhang et.al. (2018)
	Soil microbial biomass N	Zhou et. al. (2017)
	Soil organic carbon	Bai et.al. (2019)
	Available P	Gao et.al.(2019)
	Plant N uptake	Liu et.al. (2018)
	NO_3^- leaching	Borchard et.al (2019)
	N_2O emission	Borchard et.al. (2019)
	N_2O emission field studies	Verhoeven et.al.(2017)
Soil remediation	Cd in plants	Peng et.al. (2018)
	Pb in plants	Peng et.al. (2018)
	Cu in plants	Peng et.al. (2018)
	Zn in plants	Peng et.al. (2018)
	Ni in plants	Peng et.al. (2018)



Given the highly diverse soils in Asia, it is crucial to consider regional variation when establishing application rates to maximize their co-benefits in agricultural soils. Rice, a staple food and primary crop in most regions, contributes to the dominance of rice paddies and clayey soils. Common landscape features, such as low terraces and alluvial fans, result in widespread alluvial soils, including Inceptisols and Cambisols. In areas without rice paddies, typical organic peatland soils such as Histosols are found. Meanwhile, Oxisols, Ferrasols, Ultisols, and Acrisols are characteristic of these regions and mountainous areas in Asia (Kyuma 2016). Recognizing and accounting for soil diversity is essential for understanding the impacts and potential co-benefits of applying biochar to agricultural soils.

The biochar application methods varied widely (Figure 4.2). Biochar generally contains less or even lacks nitrogen compared to phosphorous and potassium. Therefore, additional nitrogen sources, such as mixtures with manure or compost, are recommended when applying biochar to soils. On-farm experimentation is highly

Figure 4.2 General biochar application methods according to the application guidelines of the Japan Biochar Association and cases studies in Japan.

recommended to optimize the benefits of biochar, considering its resources and cost-effectiveness. Box 1 offers general guidelines for biochar application. However, these guidelines may not guarantee benefits to every farm. It is advisable to consult the existing application guidelines developed by biochar organizations worldwide, such as Major (2010), Aller et al. (2023), and Joseph and Taylor (2024). To increase crop productivity and tackle climate change, more data from well-designed, long-term field trials are required to confirm the effectiveness of biochar in different soils, climates, and soil management systems (Vijay et al. 2021).

The levels of heavy metals, PAHs, and dioxins in biochars are typically within safe limits for crops. Their availability is often less than 1% of the maximum tolerable risk for crops (Joseph and Taylor 2024). However, biochar derived from sludge and animal waste requires more attention because of its potentially higher heavy metal content (Shem et al. 2019; Wang et al. 2019). Fresh biochar in the soil can reduce the effectiveness of herbicides and pesticides (Joseph and Taylor 2024). The UK Biochar Research Centre (2012) proposed a Biochar Risk Assessment Framework to address the issues of soil and groundwater contamination, contaminant bioaccumulation, and food safety associated with biochar use. A biochar risk matrix was created to provide a safety framework (Marmiroli et al. 2022). The World Biochar Certificate (WBC) guidelines, which specify the limit values for heavy metals and organic contaminants, are currently under development (WBC 2023).

Box 1: Recommended biochar application methods and rates (JBA, 2018)

In 2018, the Japan Biochar Association (JBA) compiled guidelines on biochar application methods and rates for various purposes and crops (Box.1 Table). For instance, when seeding and nursing seedlings in pots and beds, a recommended biochar mixture of 20–40% in relation to the soil volume is advised. For a more comprehensive understanding, refer to the link provided in the table notes (Japan Biochar Association 2018).

According to the JBA application guidelines (Box.1 Table), excessive biochar application is common in Japan, where approximately 60% of the upland agricultural soils are Andosols and volcanic ash soils characterized by low bulk density (inherently highly porous), high permeability, and low pH. These unique soil characteristics often prevent biochar from inhibiting crop production, even with excessive application. For example, in a well-drained Andosol in Hokkaido with a potato-winter wheat-sugar beet-soybean rotation, the application of woody biochar at rates of 0, 10, 20, and 40 t ha^{-1} had no significant impact on yield, quality, or GHG emissions (Koga et al. 2017).

The JBA was founded on April 4, 2009, in response to discussions at the 2008 International Biochar Initiative (IBI) Conference in London. The use of biochar for soil improvement has a long history in Asian countries, with Japan initiating scientific research on its agricultural and forestry applications in the 1980s. Over the past 30 years, researchers and practitioners have accumulated significant knowledge regarding the use of biochar. The JBA actively shares insights on biochar in agriculture, forestry, and environmental solutions, including carbon sequestration, to mitigate climate change.

Box 1 Table Recommended biochar application methods and rates per the application guidelines of the Japan Biochar Association (2018).

	Purposes	Recommended application methods and rates
Application methods	Seeding/seedling nursing	20-40% of pot/bed soil volume
	Ridge/furrow application	10-20% of ridge/furrow soil volume (depth is the cultivated soil layer)
	Planting hole application	Mix 1-2 liters into a planting hole (30 cm diameter and 15 cm depth)
	Trench application	Mix 10- 30% in a 20 cm width and 15 cm deep trench before planting
	Overall application	Mix 10-40 cubic meters per hectare
	Surface broadcast	Remove soil from the root zone to just below the canopy, mix 10-30% with soil
	Pot Cultivation	Mix 10-30% in pot soil volume
Application rates for selected crops	Grains and legumes	• Rice: 20-40% in seedling cultivation soil; 10-40 cubic meters per hectra for paddy fields. • Soybeans, Corn: 10-20% in furrows; 30% in trenches (20cm width, 15cm depth).
	Leafy vegetables	• Spinach, Komatsuna (Japanese mustard spinach), Cabbage, Chinese Cabbage: Approximately 20%.
	Fruit-bearing vegetables	• Cucumber, Tomato, Eggplant: Mix 1-2 liters per planting hole. • Strawberry, Tomato: Hydroponics - up to 50%; Pot cultivation - around 30%; Open-field cultivation - 20% across the furrow.
	Root vegetables	• Sweet Potatoes, Potatoes: 10-20%. • Japanese radish, Carrot: 20% across furrows.
	Fruit trees and woody plant	• Japanese pear, Apple, Plum: 30% mixed under the canopy tip. • Pine: 50-100%.

This table summarizes the application guideline of biochar for agriculture from the Japan Biochar Association homepage. For a detailed description, please refer to the following link: https://biochar.jp/cms/wp-content/uploads/2019/11/Application-guideline-of-biochar-for-agriculture.pdf

5: Local implementation of biochar use in Asia

5.1: Incentives for promoting biochar implementation in Asia

In countries in the Asia–Monsoon region, including Japan, awareness of the United Nations Sustainable Development Goals (SDGs) has only recently begun to spread. Although there is a growing understanding of the society's role in reducing CO_2 emissions, the crucial concept of removing CO_2 from the atmosphere to achieve a net-zero carbon goal remains largely unrecognized. However, the role of biochar in carbon removal is still in the early stages of development.

Nevertheless, initiatives highlighting the potential of biochar to mitigate climate change are gradually emerging across Asia (Table 5.1). International NGOs and universities are leading sponsors of ongoing demonstration studies and small-scale projects. Currently, at least five standards— the Puro Standard, Carbon Standard International (CSI), Climate Action Reserve (CAR), Verified Carbon Standard (VCS), and Reverse Standard—allow biochar producers to issue carbon credits for trade in the voluntary carbon market (IBI and Hamerkop 2024). Biochar Life, an internationally active environmental company, received accreditation from CSI under the Global Artisan C-Sink program in Thailand for its biochar project activities (Table 5.1).

Table 5.1 Outline of some biochar projects in the Asia–Monsoon region

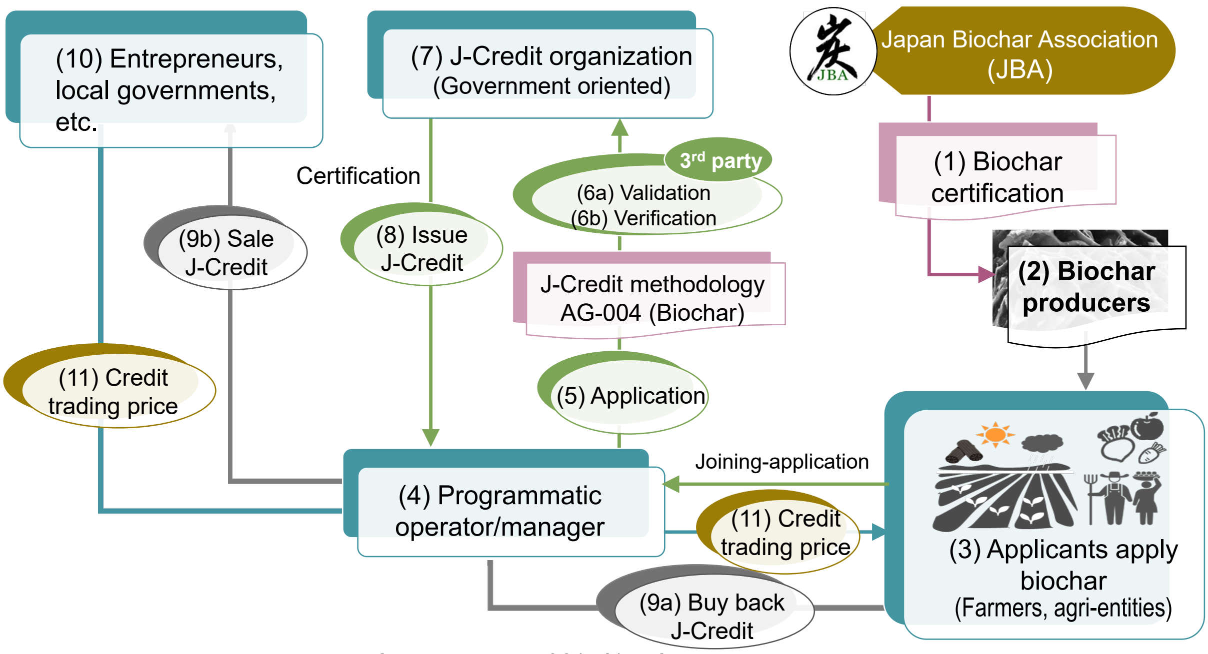
Entity/Institution	Activity	Reference
The NGO BambooPlus in Thailand	The group carbonizes a large amount of discarded bamboo residue and returns it to agricultural and bamboo forest areas. The group strives for quality standardization in carbonization process under the guidance of the International Biochar Initiative, and successfully obtained carbon credits for the biochar from Carbon Standard International certification. This has enabled the group to redistribute benefits to the villagers for improving their income.	International Biochar Initiative 2023
Biochar Life in Thailand and Indonesia	Biochar Life is an internationally active environmental company that is collaborating with C-sink to enhance the livelihoods of small-scale farmers and expand CDR initiatives through the certification of biochar carbon credits. They conduct training programs for small-scale farmers adopting simple and cost-effective carbonization methods and obtaining certification from C-sink.	CarbonFuture 2022
Environmental label "Carbon Footprint Product" in Thailand	This initiative, managed by the government via the Thailand Greenhouse Gas Management Organization, involves affixing a label to products that quantifies their carbon footprint. In the agricultural sector, this label is applied to rice. The presence of this label is associated with increased sales, prompting private companies to voluntarily pay registration fees to obtain the label.	TGO 2023
SAWA EcoSolutions	SAWA EcoSolutions (Puro.earth 2023) is a waste management company based in Singapore that has initiated a project in West Java, Indonesia, involving the carbonization of bagasse, a sugarcane byproduct generated in large quantities, to biochar. The produced biochar is used for agricultural soil improvement. Additionally, the biochar undergoes registration and certification for carbon credits through Puro.earth.	Puro.earth 2023

To advance biochar implementation, it is crucial that all stakeholders benefit from and are incentivized by the government's policy framework. This framework should provide benefits and incentives for feedstock suppliers, biochar producers, distributors, users including farmers and agricultural corporations, carbon credit creators, purchasers, and consumers to create a circular flow of incentives within the biochar value chain.

The key incentives in the policy framework include subsidies for carbon-removal initiatives and carbon credits tied to the amount of carbon removed. However, carbon removal efforts are typically limited to afforestation and forest management, and Japan is a notable exception for including biochar.

Substantial government subsidies are required to increase these incentives. In Japan, the Ministry of Agriculture, Forestry, and Fisheries (MAFF) offers subsidies to biochar producers who use agricultural and forestry residues (Agricultural Production Bureau 2024 Mar). Subsidies are available to farmers and agricultural corporations that apply biochar, supporting its use as a soil amendment to promote eco-friendly agriculture (Kishimoto-Mo and Shibata 2023).

Japan's J-Credit Scheme, administered by the central government, provides a mechanism for issuing biochar applications as carbon credits under the Tool for CO_2 Removal from the Atmosphere category, based on Methodology AG-004 Biochar addition to mineral soil



https://japancredit.go.jp/english/pdf/credit_english_001_41.pdf

Figure 5.1. Flow from J-Credit application and certification to sale for program-based biochar projects: Example from the Japan Cool Vege Association as program manager.

in cropland/grassland (J-Credit Scheme 2023). The methodology mandates proof of biochar quality, including a pyrolysis temperature exceeding 350 °C and associated CO_2 emissions calculations from feedstock collection, transportation, biochar production, and application (Section 3.3). Figure 5.1 illustrates the process flow from J-Credit application and certification to sale for program-based biochar projects, using as an example.

5.2: Designing the social implementation of biochar in Asia

To enhance the use of biochar for soil carbon sequestration, it is essential to design a socio-economic system that balances short-term profitability and long-term sustainability. Leading the way in real-world biochar-based carbon sequestration in agriculture is COOL VEGE®, an innovative eco-brand founded in 2008 in Kameoka City, Kyoto Prefecture, Japan (McGreevy and Shibata 2010). This has evolved into an Open Eco-Branding Concept that emphasizes the environmental value and incentivizes farmers through consumer recognition (Kishimoto-Mo and Shibata 2023). This concept allows for the open use and dissemination of eco-branding, thereby supporting the development of biochar-based eco-brands for agriculture. However, when eco-branding is used to add value to products, it is important to avoid overestimating the environmental value (EV) of certified carbon credits. Appropriate measures should be taken to ensure that EVs are not counted twice.

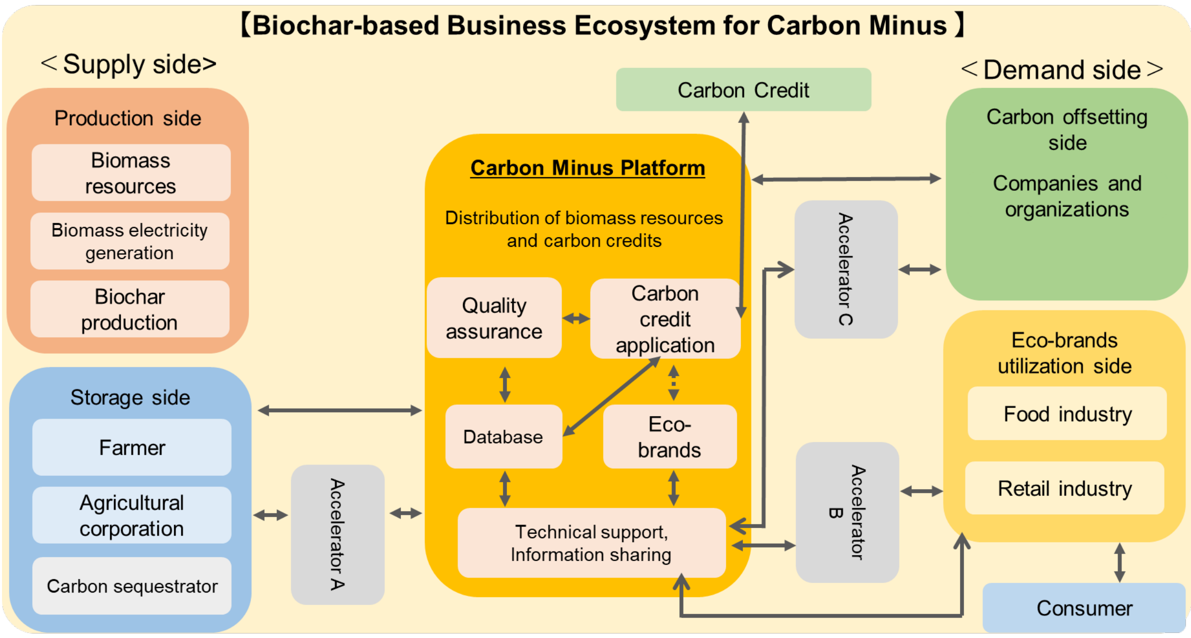


Figure 5.2. Platform and business ecosystem for carbon removal and storage with biochar. Adapted from Yoda (2025)

The successful social implementation of biochar requires cooperation among multiple stakeholders within a business ecosystem. The biochar carbon sequestration business ecosystem, shown in Figure 5.2, facilitates coordination among participants within the platform, including the following:

- **Supply Side**: This includes the production aspect, that is, producing or purchasing biochar and storage including applying biochar to farmland. Producers and applicators may not be the same entity.
- **Brand Use Side**: Food and beverage industries and retail businesses.
- **Carbon Offsetting Side**: Companies using J-Credits for carbon offsets.
- **Accelerators**: Entities supporting the activities of other participants/stakeholders.

The network's externalities, driven by synergistic increases in participants and stakeholders, and the potential for new combinations, drive business ecosystem growth.

The local implementation of biochar provides an economically viable method for carbon removal, contributing to decarbonization while offering co-benefits for soil improvement and food security, as detailed in Sections 2 and 3. As

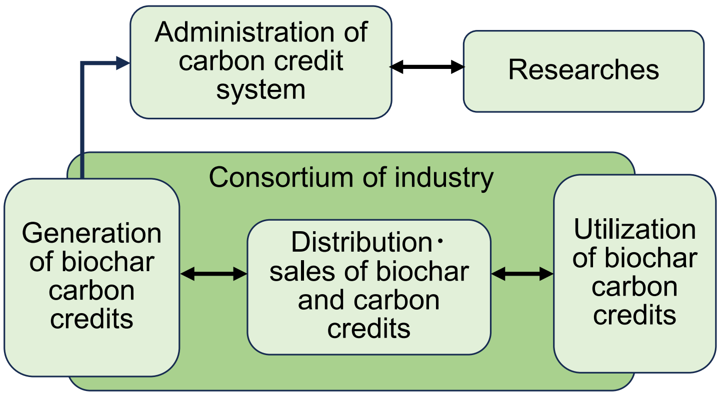


Figure 5.3. Diagram of organizations with various functions related to social implementation of biochar for carbon removal. Adapted from Yoda (2025)

Table 5.2. Examples of organizational structures based on various functions in Japan and Europe. Adapted from Yoda (2025)

Function	Japan	Europe
System administration	**Government** J-Credit Scheme (Management by METI, MOE, MAFF)	**Private sector** Carbon Standards International (CSI)
Research instiutition	NARO; Japan Biochar Research Center, Ritsumeikan University	Ithaka Institute for Carbon Strategies
Consortium of industries	Japan Biochar Consortium, Ritsumeikan University	The European Biochar Industry Consortium （EBI）
Distribution ・ sales	Japan Exchange Group Carbon EX Inc.	CarbonFuture GmbH
Notes:	**METI**: Ministry of Economy, Trade and Industry; **MOE**: Ministry of the Environment; **MAFF**: Ministry of Agriculture, Forestry and Fisheries; **NARO**: National Agriculture and Food Research Organization.	

shown in Figure 1.1, the biochar business ecosystem fosters a circular economy by efficiently using local unused biomass as a valuable resource and contributes to the preservation of the Satoyama landscape in the Asia–Monsoon region, such as Japan.

Locally generated carbon credits can be used globally, underscoring the innovative nature of this system. Figure 5.3 outlines practical case studies that emphasize the importance of collaboration across industries, governments, and academia.

Coordination with developed countries and regions is crucial for the successful implementation of biochar carbon removal. Table 5.2 outlines specific examples from Japan and Europe, where collaborations among industry, government, and academia are being developed.

5.3: Opportunities and barriers to biochar use in the Asian context

The vegetation in the Asia–Monsoon region, including East, Southeast, and South Asia, differs significantly from that of Europe and North America, with rapid growth rates (Table 4.3). Rice is the primary crop, and its growth varies with latitude. East Asian countries such as Japan typically harvest one crop per year, whereas tropical countries such as Indonesia and Thailand often harvest three crops per year. The abundant rice husk and straw produced in many of these countries are key feedstocks for biochar production. Therefore, it is crucial to establish a reliable system to ensure sustainable biochar production from rice husk and locally available feedstocks, along with standardized specifications and verification protocols. Developing a shared carbon credit market in the Asia–Monsoon region can further enhance trade and market potential.

It is essential to develop standards and verification methods for biochar produced from specific underused biomass in each country, such as coconut and oil palm husks, fruit tree husks, and pruned branches. Listing these biochar products on the proposed carbon credit market could not only activate the market but also contribute to regional sustainable agriculture and food self-sufficiency. To enable the widespread use of biochar in Asia, it is essential to cultivate a fundamental understanding of the technology and ensure its societal acceptance (Rogers 2003). The socioeconomic benefits of biochar are closely linked to its various applications among stakeholders, necessitating tailored knowledge dissemination and technology transfer.

One key challenge lies in engaging general consumers who may not purchase biochar directly but may benefit from related products, such as crops grown on biochar-applied farmlands. To reach these consumers effectively, communication approaches should leverage targeted media channels such as social networking sites (SNS), which are more impactful than traditional mass media. Biochar project websites and SNS accounts should focus on sharing accessible information, using visuals to engage residents, and conveying the benefits of biochar in an easy-to-understand manner (Photos 5.1). Involving the community in biochar-making events and offering hands-on experience, such as harvesting COOL VEGE® vegetables, can further strengthen stakeholder engagement.

Photo. 5.1 The events showing (A) citizens participating in bamboo biochar production, (B) students selling foods made from COOL VEGE® vegetables, and (C) citizens harvesting COOL VEGE® vegetables.

Advancing biochar implementation by expanding international markets, fostering socioeconomic benefits, and accelerating the effective local use of underused biomass in the Asia–Monsoon region offers an opportunity to shape a new societal model and, consequently, promote sustainable agriculture in Asia.

Author contribution statement

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- Lim Y.: Section 5.3
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