Global Biochar C-Sink Standard 4.0

Guidelines for the Certification of Biochar-Based Carbon Sinks

(also known as EBC Biochar C-Sink)

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Summary

The certification of carbon sinks (C-sinks) is a crucial step in scientifically grounded climate change mitigation. Reducing emissions and phasing out fossil carbon are essential to limit global warming. However, only carbon removal from the atmosphere can address the climatic impact of past industrial emissions.

The Global Biochar C-Sink Standard represents a significant advancement from the earlier European Biochar Certificate (EBC) C-Sink Standard, which was introduced as the first of its kind in 2020. Focusing on biochar-based carbon sinks, the EBC C-Sink Standard was the pioneering standard for negative emissions. The present new standard builds upon and enhances the initial framework, incorporating more comprehensive measures and methodologies for the calculation, tracking, and certification of biochar-based carbon sinks.

Key updates in the Global Biochar C-Sink Standard Version 4 include more advance carbon persistence analytics, methane offsetting, and the introduction biochar matrix providers as potential C-sink registration point.

The present standard ensures that every carbon unit sequestered through biochar application in an approved matrix is meticulously followed from its extraction from the atmosphere to its final storage or entry point to geology. The mandatory tracking system guarantees the integrity and transparent quantification of the carbon sinks.

Furthermore, the Global Biochar C-Sink Standard places a strong emphasis on accounting for all direct and indirect greenhouse gas emissions associated with biomass production, transportation, processing, storage, pyrolytic transformation, biochar handling and application, and monitoring of C-sink materials. By requiring these emissions to be fully offset before the C-sink can be registered, the standard ensures accurate representation of the climate impact of each Global Biochar C-Sink.

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Glossary

Biochar Processor	A company that uses certified biochar to produce biochar-based products (processed biochar) either through physical and/or chemical processing of the biochar (e.g., activation, granulation, or coating) or through blending it with other materials. A Biochar Processor must be EBC/WBC certified to register and label its products as EBC/WBC certified.
Biochar Trader	A company that trades bulk biochar or bulk biochar-based products or that repackages biochar or biochar-based products and/or uses new labels. EBC/WBC certification as a Biochar Trader is required only when the traded products carry the EBC/WBC-certified label.
C-sink	Non-fossil-derived carbon that is verifiably stored for more than one year (temporary C-sink), preferably for more than 1000 years (geological C-sink)
C-sink matrix	Organic and mineral materials to which biochar is mixed. The biochar to matrix ratio must be lower than 1:1 (v/v) to exclude that the biochar could burn unintendedly or be recovered for combustion or other uses. See matrix positive list on the Carbon Standards' website.
C-sink matrix provider	An entity that incorporates EBC/WBC-certified biochar into an eligible C-sink matrix without further physical or chemical processing of the biochar itself. A C-sink matrix provider is not required to hold EBC/WBC processor certification.
C-sink owner	Owner of a C-sink matrix, C-sink material, or, when applied to soil, owner of the climate effect of the C-sink.
C-sink potential	The pyrogenic carbon of a biochar that was not yet applied to a C-sink matrix. Its unit is t CO_2e.
C-sink trader	An endorsed company or organization that trades the climate effect of a C-sink.
C-sink unit	A C-sink unit is the registered amount of a geo-localized biochar C-sink of the same EBC/WBC certified quality. The minimum size of a C-sink unit is 1 t CO_2e.
C-Sink_H	Annual average amount of biochar carbon sequestered over a time horizon of H years. For each year, the stored biochar carbon is evaluated. These annual carbon values from year 1 through year H are summed and then divided by H years to obtain the metric C-Sink_H, expressed in tons of annual CO_2e (t aCO_2e) - e.g., C-Sink_100).
Certifier	The Certifier is a Carbon Standards' endorsed third party inspection and verification body (VVB).
Diffuse C-sink	Biochar that was mixed to a C-sink matrix preventing the oxidation of biochar and which, due to the nature of the matrix, will be applied in small quantities well-distributed in space and time.
dMRV provider	A company that is endorsed to monitor and digitally track biochar from the production site to the C-sink site, assessing all occurring

	emissions, potential carbon leakages, and verifying the compensation and offsetting of those emissions.
Emission portfolio	Registered list of all GHG emissions caused by a production facility or a company or the entire production and establishment of a C-sink.
Endorsing agent	The Carbon Standards AG is in the role of endorsing agent. Carbon Standards (1) endorses dMRV provider, (2) endorses tracking and monitoring tools and IT systems used by dMRV provider, (4) conducts trainings for the certifier, (5) endorses the certifier, (6) verifies the reporting by the dMRV provider and the certifier, (7) endorses laboratories.
Geological C-sink	Non-fossil carbon that was applied to soil, sediments, the oceans, or the lithosphere and presents a persistence of more than 1000 years.
Global Cooling	The climate impact of a carbon removal and its storage, measured in tons of annual CO_2e, over a specified period. An amount of global cooling can compensate an equivalent amount of global warming for the duration that the persistence of the cooling effect is demonstrable.
Global C-Sink Registry	The Global C-Sink Registry contains all relevant information about a C-sink to ensure the corresponding climate service and prevent double counting.
GPC-Fraction	Geologically persistent carbon pool: The portion of biochar carbon that is expected to persist for more than 1000 years and enters the geological carbon cycle.
Temporary C-sink	Non-fossil carbon that is stored and/or used for a verifiable time of at least one year and preferably for more than 35 years as suggested by the EU for the carbon removal policy. Temporary C-sinks are a function of time given in years. The carbon contained in the temporary C-sink is calculated for each registered year as annual carbon (aCO_2e). The total climate effect (TCE) of the temporary C-sink depends on the year of the initial carbon removal and its expected decomposition.
Total Climate Effect (TCE)	The time-integrated radiative forcing of a greenhouse gas emission or carbon dioxide removal over a specified time horizon, expressed in tCO_2e·yr. A positive TCE corresponds to net warming (emissions), a negative TCE to net cooling (removals); offsetting is achieved when the TCE of the compensating C-sink equals or exceeds the TCE of the emission over the same time frame.
Methane compensation	A temporary carbon sink that has the same or higher total climate effect (TCE) during 20 years as the absolute global warming effect of the methane emission over 100 years.
Negative Emission Technology (NET)	Negative Emission Technologies (NETs) are techniques that remove more carbon dioxide from the atmosphere than they emit, thereby reducing the atmospheric concentration of CO_2 to mitigate the effects of climate change.
Non-fossil carbon	Non-fossil carbon refers to carbon originating from the atmosphere, which includes CO_2 obtained from biomass, direct air-capture, and any biomass-derived material or substance. It excludes fossil carbon such

	as coal, lignite, peat and similar materials. It also excludes carbon in rocks, e.g. CO_2 from calcination.
Persistence	Persistence refers to the duration that a defined fraction of biochar is stable in the environment or in a matrix to which the biochar was applied and does not degrade or decay and emit GHG emissions. Sometimes also referred to as "durability".
SPC fraction	The semi persistent carbon (SPC) fraction of biochar is defined as the biochar-carbon fraction that is expected to decay within the first 1000 years after soil application.
Standard developer & holder	The Global Biochar C-Sink Standard was developed and is continuously updated by the Ithaka Institute. The Global Biochar C-Sink Standard is owned by Carbon Standards and can only be used under a licensing agreement. Carbon Standards is the standard owner managing the entire licensing and endorsement process of biochar producers, biochar processors and traders, dMRV providers, laboratories, the registry and C-sink traders.
Validation & Verification Body	Independent, internationally accredited organization endorsed by CSI that does validation and verification of the carbon dioxide removal procedures and C-sink values before the issuance of C-sink certificates.

Persistence Glossary (related mainly to chapter 3)

1000-year threshold
Carbon in soil that survived 1000 years is considered as having entered the geological carbon cycle. However, the distinction between the fast and geological carbon cycles is conceptual rather than absolute; the 1000-year threshold represents a policy-relevant boundary at which carbon storage is treated as geological, acknowledging that carbon-cycle processes operate along a continuum of timescales.

Aromatization, **aromatic ring condensation**, and **structural ordering of aromatic domains** describe complementary aspects of biochar carbon speciation that emerge concurrently with increasing pyrolysis severity, while differing in their sensitivity to specific process parameters and analytical proxies. The definitions of the four principal terms are outlined below.

Aromatization (aromaticity increase)
The conversion of non-aromatic carbon structures (aliphatic, oxygenated and other compounds) in biomass into aromatic carbon domains during pyrolysis. Increasing aromatization is typically reflected by decreasing molar H/Corg (and typically O/Corg) ratios. More aromatization results in purer aromatic carbon rings with lower hydrogen, oxygen, and other heteroatom content.

Aromatic ring condensation (extend of ring fusion)
The progressive fusion of aromatic rings into larger clusters (polycondensation) and the shift toward larger polycyclic aromatic structures composed of an increasing number of fused rings.

Higher aromatic ring condensation corresponds to larger polycyclic aromatic domains, lower molar H/C_{org} and is associated with reduced chemical and biological reactivity. Hydropyrolysis (HyPy) operationally isolates a carbon fraction dominated by highly condensed aromatic clusters (commonly comprising more than seven fused rings), thereby distinguishing it from less condensed aromatic structures. Random reflectance (Ro) increases with increasing aromatic ring condensation and reflects the growth and maturation of fused aromatic domains.

Fast Carbon Cycle

The part of the global carbon cycle involving the exchange of carbon among the atmosphere, biosphere, soils, and oceans through biological, chemical, and physical processes operating on timescales from years to centuries and extending up to millennial timescales. Carbon within the fast carbon cycle remains part of the climate-relevant surface Earth system and may return to the atmosphere on policy-relevant timescales.

Geological Carbon Cycle

Carbon storage and transfer through geological processes operating over millennial to geological timescales, including burial, sedimentation, mineralization, vulcanic activity, and tectonic recycling.

Pyrolysis severity

The combined thermal and chemical forcing of biomass during the pyrolysis process, determined by process parameters such as temperature, heating rate, residence time of gas and solid pyrolysis products, and gas pressure or atmosphere in the reactor. Pyrolysis severity governs the extent to which biochar carbon undergoes chemical and structural transformation. Applying the same pyrolysis intensity to two types of biomass can result in biochars with different reactivity. Not only different carbon structures of the feedstock, but also catalytic effects of mineral components affect biochar reactivity and its poly-condensed structure.

Structural ordering of aromatic domains

The increased ordering and maturation of aromatic carbon domains (fused aromatic clusters) with rising pyrolysis severity. Structural ordering includes greater alignment, stacking, and connectivity of polycondensed aromatic structures and enhanced π-electron delocalization. It reflects a transition from disordered aromatic clusters toward more ordered, graphitic-like arrangements and is captured by proxies such as random reflectance and solid-state electrical conductivity.

Introduction to Biochar C-Sink Certification

When the EBC certification of carbon sinks (C-sinks) was introduced in 2020, it represented a decisive step towards implementing climate change mitigation. While traditional carbon dioxide (CO_2) credits mostly certified the reduction of emissions compared to a reference scenario, the newly introduced certification of C-sinks guaranteed storage of carbon in the terrestrial and geological system that can be verified at any time and be traced back to the year of the initial carbon removal from the atmosphere.

Carbon sinks are the result of (1) an active removal of CO_2 from the atmosphere, (2) the transformation of the removed carbon into a storable form, and (3) its verifiable storage outside the atmosphere. In the case of biochar, the removal occurs through biomass growth (photosynthesis), transformation through pyrolysis, and storage via application, e.g., to soils or materials (C-sink matrix). Complete and batch-accurate tracking of each sequestered unit of biochar-carbon ensures the occurred removal of CO_2 from the atmosphere, quantifies the C-sink, and accounts for its persistence. All C-sinks must be registered in the Global C-Sink Registry to allow monitoring, reporting, and verification (MRV) and thus create the transparency and trust needed in the new carbon economy.

Likewise, all greenhouse gas (GHG) emissions that occurred due to the biomass production (carbon removal) and all other activities necessary to establish and maintain the C-sink have to be assessed. For biochar, this includes all emissions of biomass provision, storage, transport, transformation, and biochar application. These emissions must be registered in an emission portfolio in the Global C-Sink Registry. All those emissions caused by the C-sink production must be compensated before the C-sink can be validated in the Global C-Sink Registry and, therefore, used to compensate GHG emissions.

The Global Biochar C-Sink certifies the amount of carbon that is effectively and measurably stored in the form of biochar and thus prevented from returning to the atmosphere but does not issue CO_2 certificates for the avoidance of emissions.

As of 2023 and still 2026, biochar from pyrogenic carbon capture and storage (PyCCS, cf. Schmidt 2019) was the most mature and in terms of delivered C-sinks the most important negative emission technology (NET). However, the portfolio of negative emission technologies (NETs) is steadily growing. Reforestation with single tree tracking, biomass materials, enhanced rock weathering, and marine biomass deposition are equally scaling. Certification standards for the different types of C-sinks allow interlinkages between the standards and follow overarching principles of carbon accounting and registration.

1.1 Global Biochar Carbon Sinks

Plant biomass consists of approximately 50% carbon in its dry matter, which was removed during the plant's lifecycle from the atmosphere in the form of CO_2. Using the energy from sunlight, the plant converts CO_2 into organic molecules such as glucose, cellulose, or lignin.

When plant biomass is burnt or decomposed, the assimilated carbon is released again in the form of CO_2. However, if the plant biomass is pyrolyzed, about half of the plant carbon is transformed into a mixture of predominantly very persistent carbon compounds that form a solid material known as biochar. While in the environment, practically all carbon compounds are subject to degradation; for most components of biochar, this process is extremely slow and difficult to measure over spans of thousands of years. Provided that the biochar is not burned, the large majority of biochar carbon remains as a C-sink in the terrestrial and geological system, with persistence depending on the degree of aromatic condensation of the biochar and the environmental conditions of the C-sink matrix, as detailed in Chapter 3.

If biochar with an H/C_org ratio ≤ 0.40 is applied to soil, a major part of its carbon is considered geologically persistent carbon (GPC) and will constitute a carbon sink for more than thousand years (Camps-Arbestain et al., 2015; Howell et al., 2022; Sanei et al., 2025; Schmidt et al., 2025a). A minor though relevant part of the biochar carbon is less persistent and may be degraded within decades to centuries with a minimum half-life of 50 years (MRT of 83 years). The biochar carbon that may be decomposed within the first 1000 years after application to soil is called semi-persistent carbon (SPC) and constitutes a temporary C-sink. For biochars presenting an H/Corg ratio ≤ 0.40, the GPC fraction is conservatively set by this standard at 75% and the SPC fraction at 25% (lower persistence class). If, in addition, the biochar presents a mean random reflectance of Ro $\geq$ 3.8% and/or a fraction resisting hydopyrolysis of BC_HyPy $\geq$ 90%, the upper persistence class is reached, and the GPC fraction is set to 90% and the SPC fraction to 10%. Biochars with an H/C_org ratio > 0.40 are considered entirely semi-persistent (100% SPC). The analytical methods and persistence classes are described in detail in Chapter 3 and will be further refined in the next standard update (2026/27).

If biochar is used as a functional additive in materials such as composites and plastics (c.f., matrix positive list), it is assumed that the entire carbon content of the biochar persists and remains a C-sink for as long as the material itself exists. Only when the biochar-containing material is disposed of, destroyed, or decomposed can the sequestered carbon be released back into the atmosphere, causing the C-sink to lose its value and to be removed from the Global C-Sink Registry.

Construction materials using cement, lime, clay, gypsum, or geopolymers as binders are considered a permanent matrix for biochar C-sinks. Once disposed of to a landfill, the same persistence curves apply as for soil application, starting with the year of soil application.

1.2 Global C-Sink Registry

The Global C-Sink Registry (www.global-c-registry.org/) is a digital database for temporary and permanent carbon sinks. All biochar C-sinks certified under the present standard are registered in the Global C-Sink Registry, which is owned and run by Carbon Standards. The registry contains all relevant information to evaluate certified carbon sinks and to trade their climate cooling effects. The amount and location of biochar application, the biochar quality, the persistence of the C-sink, the year of the original carbon removal, and the owner of the C-sink are the most important information contained in the registry. Moreover, all GHG emissions caused by establishing a C-sink are registered in the emission portfolio and must be offset in order to use the C-sink for emission compensation or offsets. CO_2 and N_2O emissions must be offset with geologically persistent carbon (GPC). CH_4 emissions must be offset with temporary C-sinks. The offset value is calculated based on the total climate effect (TCE) that the temporary C-sink delivers within a period of 5 to 20 years. Any carbon register should allow the conversion of every C-sink and every GHG emission into its TCE to correctly match C-sinks and GHG emissions for annual compensation of climate effects.

1.3 Executive Summary: Global Biochar C-Sink Certification and Registration

To certify the carbon sink and its sustainable establishment, to calculate the total climate effect (TCE) of the carbon sink, and to assess all emissions that occurred during the carbon sink establishment, the following parameters must be assessed, controlled, and registered:

- The year of the initial biomass CO_2 removal is assessed so that the Total Climate Effect of the C-sink can be calculated as a function of time.
- All greenhouse gases, with the exception of non-fossil CO_2 emissions, released during the cultivation and handling of the biomass, the pyrolysis process, packaging, further product transformation, transport, and application to the C-sink or C-sink matrix are tracked and registered in an emission portfolio (c.f., Chapter 4).
- All emissions in the emission portfolio must be offset by retiring a corresponding part of a C-sink in the Global C-Sink Registry.
- The C-sink efficiency of the transformation of biomass into pyrolytic carbon is assessed and must be declared. It is controlled that the biochar C-sink does not replace a more carbon-efficient baseline scenario. The pyrolytic use of biomass must be additional (c.f., Chapter 8.1).
- The energy efficiency of the entire process of transforming biomass carbon into pyrolytic carbon sinks, materials, and energy must be higher than 60% (c.f., Chapter 8.2)
- The emission of fossil carbon, i.e. the use of fossil fuels and fossil-fuel-derived electricity within the entire process from biomass production to biochar packaging at the pyrolysis facility must be reduced to less than 100 kg CO_2e per ton of biochar until 2030 and to less 20 kg CO_2e per ton of biochar until 2035 (c.f., Chapter 8.2).
- Only biochar certified under the European Biochar Certificate (EBC) or the World Biochar Certificate (WBC) is entitled to Global Biochar C-Sink certification. The EBC/WBC certification guarantees the sustainability of the biochar production and use.
- The EBC/WBC certificates provide the analytical values needed to calculate the size and persistence of the biochar C-sink. Analyses that go beyond the EBC basic package, such as random reflectance and hydropyrolysis, will only be accepted if they were requested as part of the EBC/WBC batch analysis. Separate sampling and analysis cannot be accepted.

- The C-sink matrix and, when indicated in the matrix positive list, the GPS location of the final biochar application site is recorded.
- The establishment of C-sinks can only be certified when the biochar is used according to its EBC or WBC certification class. To give two examples, only biochar that is at least certified as EBC-Agro or WBC-Agro can be used to establish a C-sink in agricultural soil. WBC-Material and EBC-BasicMaterial must not be used to establish a C-sink in a soil matrix.
- If the biochar is applied to soil, the registered landowner or tenant must agree that his land acts as an entry point for the biochar carbon to become a geological C-sink (chapter 10.1).
- If the persistence of the biochar C-sink does not follow an acknowledged decay function (c.f., Chapter 2.4, Chapter 0), the monitoring method and controlling period of the C-sink are fixed by the standard depending on the C-sink matrix.
- The verified C-sinks are registered in the Global C-Sink Registry run by Carbon Standards.

The necessary inspections at the production site must be carried out by a verification and validation body (VVB) endorsed by Carbon Standards. The relevant inspection requirements and calculation templates for certifying biochar carbon sinks are detailed in the following pages of the Global Biochar C-Sink Standard.

2. Biochar Use and C-Sinks

2.1 Calculation of Biochar C-Sinks

To account for the carbon stored in a biochar C-sink, the organic carbon (C_{org}) content of the biochar must be determined according to the EBC or WBC standard. It is indicated as a mass proportion (in %) based on the biochar's dry weight. The mass of a biochar C-sink at the time of application (C-Sink_0) is thus:

$$\text{C-Sink\_0} = \text{Corg}_{\text{biochar}} * \text{dry\_mass}_{\text{applied biochar}}$$

Equation 1: Amount of carbon stored in a biochar C-sink just after applying. The unit of C-Sink_0 is tons of carbon.

However, every biochar C-sink underlies a time-dependent evolution, and the C-sink is a measure of the mass of carbon that is physically present in the C-sink matrix at any given moment in time since the establishment of the C-sink. The size of a biochar C-sink is, thus, a function of the type of biochar determining its specific persistence in a specific C-sink matrix and the time since the application to the C-sink matrix.

$$C_{remain}\text{ (years)} = \text{C-Sink\_0} * \text{specific persistence (years)}$$

Equation 2: Size of C-sink at a defined time in years after the application. The specific persistence is nondimensional and depends on the biochar and the type of C-Sink matrix. The unit of C_{remain} *(years) is tons of carbon.*

To assess the time-dependent climate effect of a biochar C-sink over a given number of years, the carbon that is stored on average during this period is calculated using the following equation:

$$\text{C-Sink\_H} = \frac{\sum_{n=1}^{years} C_{remain}(n)}{n}$$

Equation 3. Average annual biochar C-sink over a period of X years. The variable for the time horizon H *represents the number of years since biochar application, ranging from a minimum of one year up to 1,000 years, which is defined as the temporal limit at which soil-applied biochar carbon is considered part of the geological carbon cycle. The sum of the annual amounts of biochar carbon remaining in the C-sink (*C_{remain}*) is divided by the number of years since establishment of the C-sink.* C-Sink_H *is expressed in tonnes of annualized* CO_2 *equivalents (t* aCO_2e*), as detailed in the text.*

While some labile fractions of the biochar decompose more quickly during the first 50 to 100 years, the persistent fractions are stable over geological time spans of more than a thousand years. The SPC fraction of biochar is defined as the fraction that may degrade over 1000 years in soil, while the GPC fraction is the fraction that persists beyond 1000 years and enters the geological carbon cycle. Biochar C-sinks present the highest sequestered carbon in the first years, which decreases more quickly initially and then more slowly after the first decade. The SPC degradation over 1000 years is modeled as an exponential function. To specify the total climate effect (TCE) of biochar-based C-sinks, the average mass of a biochar C-sink over X years (e.g., C-Sink_35, C-Sink_50, C-Sink_100, or C-Sink_200) can be calculated. This average is also referred to as the average annual biochar C-sink expressed in t aCO_2e (tons of annual CO_2e). For soil-applied biochar, the average slightly underestimates the amount of sequestered carbon and thus the climate effect in the first few years and slightly overestimates it in later years. Potential uses of average annual biochar C-sinks are discussed in Chapter 3 below. Calculation examples are presented in Table 1.

As strong climate action is urgently needed in the near future to limit global warming, the average annual biochar C-sink becomes an important, marketable asset for financing biochar C-sink projects. Since 1,000 years is generally defined as the time limit beyond which soil carbon is considered part of the geological carbon cycle, the average annual biochar C-sink is calculated only over the first 1,000 years. The fraction of biochar carbon remaining beyond this period is expressed as C-Sink_1000+ and represents carbon with no defined time limit; therefore, no meaningful average annual biochar C-sink can be calculated for this fraction.

As long as biochar materials are not applied to soil or another long-lasting matrix, total or partial losses of biochar-carbon are possible. Fire could destroy biochar, or a customer could buy it for co-firing in a biomass power plant or use it as a reducing agent for steel production. Therefore, biochar must not only be tracked from the production site to the final C-sink site, but the final C-sink site must be monitored for as long as the biochar or biochar-material is not yet applied to soil, concrete, or asphalt. Exceptions to the above rule apply for diffuse C-sinks where the biochar is incorporated into an eligible matrix at a volumetric ratio of less than 1:1 (v/v). Such incorporation effectively prevents unintended combustion or recovery of the biochar for applications that could lead to carbon release. For certain matrices with multiple potential end uses (e.g., animal feed or plastic and textile additives), additional documentation must be provided to demonstrate that the matrix-embedded biochar will remain within a permissible C-sink pathway.

As long as there is a risk that the stored carbon may be released into the atmosphere, the biochar carbon must be considered a temporary C-sink. Contrary to geological C-sinks, temporary C-sinks have to be either (1) monitored and controlled regularly to guarantee their persistence or (2) a mathematical model, depending on the natural and social conditions, must reliably calculate the probability of persistence over defined time horizons. Certificates for temporary C-Sinks should not be used for CO_2 offsets.

When biochar is stored for more than one year under controlled conditions (i.e., not exposed to rain and wind) before being applied to a C-sink matrix, it can be certified as a temporary C-sink for the controlled storage time.

2.2 Geological C-Sink (biochar applied to soil)

When biochar is mixed irrevocably into an non-inflammable C-sink matrix that eventually is applied to soil (c.f., Chapter 0), the non-SPC fraction of biochar becomes geologically persistent carbon (GPC). When mixed with animal feed, manure, compost, liquid fertilizer, or anaerobic digestate, the risk that a significant portion of it may burn is essentially eliminated except for countries where dried manure is used for cooking. When biochar eventually reaches the soil after it was used, e.g., as livestock bedding or as part of similar organic substrates for agriculture, or when it becomes an intrinsic component of similar mineral materials, the terrestrial C-sink can be characterized with mathematically defined degradation rates, reflecting the content of GPC/SPC, reaching far into the future (i.e., > 1000 years) which makes it entering the geological carbon cycle and, thus, a geological C-sink.

Biochar with an H to C_{org} ratio ≤ 0.40 that is applied to soil enters the slow (geological) carbon cycle, passing the pedosphere to the lithosphere (Schmidt and Hagemann, 2024). Soil application can thus be described as the beginning of a transition into geology. As most of such biochar consists of inertinite comparable to fossil coal (Sanei et al., 2023), soil-applied biochar will eventually (in the 10’000+ years perspective) become the future fossil carbon and replenish, thus, the geological carbon pool.

Biochar-containing building materials such as cement-, lime-, or geopolymer-based concrete, clay, or gypsum are usually recycled into aggregates or deposited in land or road fills at the end of the product life. If reused as aggregate, the biochar is protected from decomposing by the new matrix. When deposed in land- or other soil-located fills, the biochar becomes a geological C-sink. Eventually, biochar-containing building materials will enter the soil and, thus, become a geological C-sink.

The geological C-sink is registered with its persistence curve reaching over more than 1000 years.

2.3 Temporary C-Sink (biochar used in materials)

If biochar is used as an additive in materials such as asphalt, plastics, textiles, and composite materials, it can be assumed that the entire carbon content of the biochar persists and remains a C-sink for as long as the material itself persists. Only when the biochar-containing material is dismantled, recycled, or (waste) incinerated could the sequestered carbon be released back into the atmosphere, causing the C-sink to lose its value. It must by then be removed from the C-sink registry.

Matrixes such as plastics, textiles, paper, or composites cannot fundamentally prevent the oxidation of biochar. The likely end-of-life scenario of such materials is waste incineration, although the deposition in landfills is still common practice in many countries.

Using biochar in materials is often recommended to optimize material properties or replace other materials made from or under the use of fossil fuels. For as long as these biochar materials are in use, the carbon in the biochar remains stored outside the atmosphere and is eligible for climate cooling services.

For most consumer products such as water pipes, skis, or car parts, tracking all possible use cases is not feasible. However, as they are produced and marketed in large quantities, statistics for specific products can determine an average lifetime. With a statistically validated lifetime before it may end up in waste incineration, the biochar carbon can be certified as a temporary C-sink for the defined product lifetime.

If large amounts of biochar are used in infrastructure (e.g., in asphalt), the location should be registered and the C-Sink certified under the Global Construction C-Sink Standard.

Thus, temporary material C-sinks are registered once embedded into a C-sink matrix with their statistically validated lifetime or their control period. If the control at the end of the defined controlling period confirms the continued presence of the C-sink, the registry entry of the temporary C-sink is prolonged until the end of the next controlling period. The duration of the new controlling period is updated at the end of each controlling period.

The value of temporary C-sinks is given as the annual average mass of carbon in carbon dioxide equivalents (t aCO_2) over the certified period in years, e.g., C-Sink_35, C-Sink_50, or C-Sink_100.

2.4 Temporary Storage of Biochar

Biochar can be stored to preserve it for later years when, e.g., demand and prices increase. For as long as the biochar is stored under controlled conditions and with regular verification, such as in containers, below ground protected from water and biologically active matrices, and in ancient salt or coal mines, it can be considered a temporary C-sink during the controlled storage time. The control is usually assured remotely with continuous temperature and/or CO_2 concentration measurements (for more details see Chapter 12.6).

A temporary storage of biochar is defined by the fact that the biochar can be recovered as such and used later in various industrial ways of the circular carbon economy. When biochar is mixed into a C-sink matrix such as soil or ash, the largest part of the biochar cannot be recovered to be used as unmixed material, and thus the C-sink is not considered a storage.

The registered amount of carbon in temporary carbon storage must be updated annually. As the biochar in temporary storage can be used at any time, it is not permissible to calculate an average C-Sink value for the carbon stored beyond the horizon of 1 year.

The stored carbon must not be used to offset emissions caused by the biochar and C-sink production.

2.5 Geological Storage of Biochar

If biochar is applied

- deep below the soil in geological horizons,
- where no soil organic matter can be detected,
- where no biological activity is sustained, e.g., in abandoned mining sites,
- where the biochar is protected from air and water and
- where it cannot be recovered because of a sealed cover or because of its embedding in a C-sink matrix (e.g., mixing to ash or sediments),

the storage can be considered a geological carbon storage with no decomposition for > 1000 years. A security leakage margin of 5% must be applied.

For geological storages above 10,000 m3, continuous monitoring of temperature and gas evolution must be set up.

3. Persistence of Soil Applied Biochar

3.1 The structure of biochar

The principal structure of biochar consists predominantly of aromatic rings, which are structural units composed of six carbon atoms. These rings are fused into clusters, such that adjacent rings share carbon atoms along fused ring edges. Clusters of fused aromatic rings vary in size, complexity, and degree of structural organization. The biological and chemical stability of biochar increases with increasing aromaticity (i.e. the share of organic carbon bound in aromatic ring structures), increasing aromatic ring condensation (i.e. the size of fused aromatic clusters), and increasing structural ordering of aromatic domains (i.e. the three-dimensional organization and connectivity of aromatic clusters) - see Persistence Glossary following the main Glossary.

While no biochar carbon fraction can be regarded as completely inert, increasing aromatic condensation and ordering substantially reduces the probability of biological or chemical degradation (Schmidt et al., 2025a). Biochar carbon that is dominated by highly condensed aromatic structures exhibits a markedly increased likelihood of surviving for more than 1000 years after application to soil, as supported by observations of ancient charcoal and pyrogenic carbon persisting over millennial timescales in soils and sediments (Howell et al., 2022). Persistence beyond this timescale is commonly interpreted as a transition from the fast carbon cycle into the (slow) geological carbon cycle (c.f. Glossary A1.5) (Archer, 2005; Falkowski et al., 2000; Schmidt and Noack, 2000). Biochar carbon that reaches millennial persistence can therefore be considered a geological carbon sink, acknowledging that this classification reflects a probabilistic assessment of long-term stability rather than absolute permanence (see Chapter 2.2 of the Global Biochar C-Sink Standard).

Geologically Persistent Carbon (GPC) replaces PAC terminology

In Version 3 of the Global Biochar C-Sink Standard, two carbon pools were defined and referred to as persistent aromatic carbon (PAC) and semi-persistent carbon (SPC). The sizes of these pools cannot be determined from biochar analysis alone and are therefore allocated using a probabilistic evaluation approach. To avoid misunderstandings arising from the chemical-analytic connotation of the term “aromatic”, the present Version 3.3 of the Standard replace PAC with the term geologically persistent carbon (GPC). It denotes the portion of biochar carbon that persists beyond 1000 years and thus enters the geological carbon cycle. The SPC terminology and the degradation function describing the modelled decay of this fraction over a 1000-year time horizon remain unchanged.

3.2 The probabilistic approach

The Global Biochar C-Sink Standard distinguishes between two conceptual carbon-sink pools based on persistence probabilities following biochar application to soil. The geological persistent carbon (GPC) pool denotes the portion of biochar carbon that persists beyond 1000 years after soil application and thus enters the geological carbon cycle. It is defined by its fate to survive the biosphere (i.e., to remain stable in the terrestrial system beyond the 1000-year threshold). The semi-persistent carbon (SPC) denotes the remaining portion that provides temporary carbon storage and returns to the rapid carbon cycle within the first 1000 years. These pools are defined by their fate over a 1000-year horizon. However, their relative sizes cannot be determined from analytical characterization alone. Long-term biochar degradation and stabilization in soil depend on complex environmental conditions such as soil mineralogy, drainage, biological activity, and climatic conditions that cannot be quantified with certainty over millennial timescales. The partitioning of biochar carbon between GPC and SPC is therefore estimated probabilistically using measurable structural proxies.

Aging of biochar in soil is not only characterized by slow biological and chemical degradation processes but also by physical and chemical stabilization mechanisms (Lehmann et al., 2024). Biochar persistence is therefore determined not only by its condensed polyaromatic structure but also by environmental factors such as the soil type and structure, its mineral content, and biological activity, temperature, rain events, pollution, slope and exposition as well as vegetation cover and land management practices[1]. While all these parameters influence the probability of persistence, the condensed poly-aromatic structure of biochar is resistant to nearly everything that may happen. Moreover, with increasing residence time in soil, more biochar carbon becomes physically and chemically protected within soil particles and complexation increases. Mineral-associated stabilization may allow pyrogenic carbon to be preserved over very long timescales, even when its molecular structure is less aromatic or partly degraded (Czimczik and Masiello, 2007; Sorrenti et al., 2016).

While any fraction of biochar carbon may become physico-chemically protected in soil, the probability for a given fraction of biochar-carbon to persist for more than 1000 years increases with increasing aromatic ring condensation and structural ordering. The portion of biochar that persists for 1000 years (GPC) and the portion that experiences degradation (SPC) consist both of a continuum of aliphatic and mostly aromatic structures with varying degrees of condensation. However, the GPC pool will contain significantly more poly-condensed structures than the SPC pool with more aliphatic and smaller aromatic structures. GPC and SPC are not defined by chemically distinct or sharply separable fractions, but they are probabilistic pools reflecting different likelihoods of long-term persistence.

The degradation of SPC can partly be assessed, e.g., by incubation of biochar in soil or controlled lab environments exposed to microbial communities. Reasonable incubation times of 1-10 years have been achieved to provide useful information to this end (Azzi et al., 2024). However, within such time frames, only the most labile carbon compounds can be degraded. The persistence of GPC must, therefore, be derived from observations of the global pyrogenic carbon cycle (see Appendix

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[1] *It has been suggested that biochar degrades faster at higher soil temperatures in the first 100 years after soil application* (Woolf et al., 2021). *However, this is based mainly on laboratory studies, in which the stabilizing mechanisms can hardly come into effect.* Data are simply not sufficient to quantify the temperature effect globally.

1 in (Schmidt et al., 2022)) or from thermodynamic and kinetic conclusions for the chemical and microbial degradation of the polycyclic molecules (Sanei et al., 2023).

The distinction of these two defined carbon pools changes the key question from "how stable is biochar" to "what is the size of the GPC fraction of a given biochar?" and thus, what portion of a biochar can be considered as geological C-sink once applied to soil. While the predicted size of the GPC and SPC fractions is a function of the severity of the pyrolysis conditions (i.e., mainly temperature, but also residence time and pressure) as well as feedstock composition (Bowring et al., 2020, 2022; Zimmerman and Gao, 2013), the actual size that would be found after 1000 years will also have depended on soil and climatic conditions. The proportion of GPC and SPC is related but not determined by the H/C_{org} ratio and the electric conductivity of the solid biochar. To estimate the relative sizes of the GPC and SPC pools for a given biochar, analytical proxies based on measurable structural properties are required. So far, the biochar fraction resisting hydropyrolysis ((Hagemann et al., 2025; McBeath et al., 2015a) and random reflectance (Sanei et al., 2025) have proven to be effective proxies.

The analytical proxies used to estimate the relative sizes of the GPC and SPC pools are described in the following Section 3.3. Readers primarily interested in the operative persistence classes for C-sink certification may continue directly with Section 3.4.

3.3 Analytical proxies for biochar persistence

The degree of aromatic condensation represents an average structural property of a biochar sample that integrates a wide range of molecular configurations. It cannot be measured directly as a single physical parameter but can be approximated using several analytical proxies that correlate with the extent of aromatic ring condensation.

Historically, the molar hydrogen-to-organic-carbon ratio (H/C_{org}) has been the most widely used proxy to characterize the degree of aromatic condensation in biochar and to infer its relative persistence (Zimmerman and Gao, 2013). During pyrolysis, hydrogen is preferentially lost as volatile compounds, while carbon increasingly forms aromatic and polycondensed structures. As a result, decreasing H/Corg ratios generally indicate increasing aromaticity (Wiedemeier et al., 2015). This relationship has been demonstrated across a wide range of feedstocks and pyrolysis conditions and has therefore been adopted as a practical, cost-effective proxy for biochar stability (Budai et al., 2016; Woolf et al., 2021).

A key advantage of H/Corg is its empirical linkage to biochar degradation observed in pot and field experiments. Most long-term incubation, pot, and field trials that quantify biochar-derived CO_2 emissions have relied on elemental analysis as part of biochar characterization, making H/Corg the only proxy for which a substantial empirical basis exists across diverse soils, climates, and biochar types. Recent harmonized analyses and re-evaluations of biochar decomposition datasets confirm that H/Corg remains one of the most robust predictors of relative biochar persistence when evaluated against long-term mineralization data (Lehmann et al., 2024; Woolf et al., 2021). However, the analysis of the H/C ratio and its correlation to other biochar parameters have some limitations (Azzi et al., 2024; Lebrun Thauront et al., 2024).

H/Corg represents an average bulk property of a biochar sample and does not resolve the internal heterogeneity of aromatic structures. In particular, it cannot sufficiently account for the influence of mineral bound H on this ratio (Hagemann et al., 2025; Sanei et al., 2025). High-ash biochars may exhibit elevated H/Corg ratios despite containing highly aromatic and polycondensed carbon structures, due to mineral-bound hydrogen and catalytic interactions during pyrolysis that alter hydrogen retention without proportionally reducing aromatic condensation (Buss et al., 2019; Grafmüller et al., 2022; Lebrun Thauront et al., 2024). However, higher ash content and specifically the content of amorphous silica, may also inhibit the formation of polycondensated structures (McBeath et al., 2015b). As a consequence, H/Corg may both under- and overestimate the persistence potential of ash-rich biochars and does not reliably distinguish between different architectures of condensed aromatic clusters that may differ substantially in long-term stability.

Therefore, while H/Corg provides a conservative and empirically grounded approximation of biochar persistence, its limitations motivate the use of complementary analytical proxies that more directly capture the abundance and structural organization of highly condensed aromatic carbon fractions.

Hydropyrolysis (HyPy) has been developed as an analytical method to isolate aromatic carbon fractions with a higher degree of ring condensation in biochar by selectively removing labile and less condensed carbon compounds under high-pressure hydrogen at high temperatures. The residual carbon fraction obtained by HyPy (BC_{HyPy}) consists of aromatic clusters with more than seven condensed rings and is therefore considered a reliable approximation of the more stable biochar carbon pool (Howell et al., 2022). The carbon fraction volatilized under these extremely harsh conditions is operationally defined as the reactive carbon fraction (C_{react}) and is characterized by a substantially lower probability of surviving for more than 1000 years after application to soil.

Solid-state electric conductivity (SEC) has recently been proposed as an additional proxy for aromatic condensation, reflecting the increasing connectivity and delocalization of π-electrons in polycondensed aromatic carbon structures. It shows strong correlations with H/Corg and BC_{HyPy} (Hagemann et al., 2025), at least for biochars produced from the same or very similar feedstock. Quantification of SEC is relatively simple and cost-efficient, can be conducted at the production site, and has the potential to complement other analytical proxies on a continuous basis (Hagemann et al., 2025). Due to the feedstock-dependency, SEC is not used as a standalone criterion for assigning biochars to persistence classes under this standard. Its role at present is limited to supporting quality control at the production site and complementing the primary proxies H/C_org, Ro, and BC_HyPy.

Random reflectance (Ro) provides a detailed and robust measure of the structural ordering and maturation of aromatic carbon domains at the microscale. The mean Ro value, which has been suggested for persistence-related evaluations (Petersen et al., 2023; Sanei et al., 2025), is derived from at least 500 individual point measurements across a biochar sample (Sanei et al., 2025)), thereby capturing its intrinsic heterogeneity. For biochar produced under constant pyrolysis conditions, the distribution of individual Ro measurements generally follows a Gaussian distribution, with the standard deviation reflecting the internal variability of aromatic condensation. Originally developed in coal petrology, Ro has been adapted for biochar analysis (Alami Sounni et al., 2026; Mastalerz et al., 2025; Sanei et al., 2025).

At each measuring point, higher reflectance values indicate a higher degree of aromatic ordering and polycondensation. Ro has been shown to correlate with pyrolysis severity, including temperature, pressure, and residence time, as well as with H/Corg ratios (with the above-discussed exceptions) and the relative abundance of more condensed aromatic carbon structures (Sanei et al., 2023, 2025). In addition, yet unpublished, datasets indicate strong correlations between Ro, SEC, and the fraction of biochar carbon resistant to hydropyrolysis, further supporting its relevance for persistence assessment.

Unlike bulk elemental proxies, Ro explicitly accounts for the coexistence of differently ordered aromatic domains within a single biochar sample, thereby providing insight into the internal distribution of more- and less-stable carbon structures. Importantly, high Ro-values do not necessarily imply chemical inertness or absolute persistence, but serve as a relative indicator of the likelihood that a given fraction of biochar carbon belongs to the more condensed end of the aromatic continuum and is more likely to resist biological degradation (ICCP, 1963; Schmidt et al., 2025a). In this sense, Ro supports a probabilistic interpretation of GPC and SPC pools for soil applied biochar and complements both H/Corg and HyPy by resolving structural heterogeneity that bulk and operational proxies cannot capture.

3.4 The SPC Pool

The semi-persistent carbon (SPC) fraction of biochar is defined as the portion of biochar carbon that does not persist for 1000 years after soil application. The remaining fraction after 1000 years is assigned to the geologically persistent carbon (GPC) pool. Accordingly, the SPC retention function is parameterised such that $f_{\mathrm{SPC}}(0) = 1$, the time to 50% remaining is ≈ 50 years, and $f_{\mathrm{SPC}}(1000) \approx 0$, i.e. the SPC pool is effectively exhausted over a millennium. Based on conservative fits to biochar decomposition datasets, the SPC retention is described by a two-exponential function (Schmidt et al., 2025):

$$f_{SPC}(t) = 0.1787\, e^{-0.5337t} + 0.8237\, e^{-0.00997t} \qquad (4)$$

Equation 4: Modelized SPC decay function where t is time in years after soil application.

The SPC fraction has a mean residence time of 83 years and constitutes a temporary carbon sink. The mean residence time (MRT) of 83 years and the half-life of 50 years for the SPC fraction are based on the most conservative meta-analytical estimate for biochar carbon degradation published to date (Schmidt et al., 2022). Other sources report significantly lower degradation rates depending on pyrolysis intensity and the experimental design (IPCC, 2019; Kuzyakov et al., 2014; J Lehmann et al., 2015; Zimmerman and Gao, 2013). Furthermore, 83 years corresponds to the MRT of bulk soil organic carbon (SOC) (Schmidt et al., 2011). As it is generally understood that

SOC is less persistent than biochar (Lehmann et al., 2015; Lehmann et al., 2020; Schmidt et al., 2011), the assumption of an MRT of 83 years for the SPC fraction is conservative.

Strictly speaking, the SPC pool must not be used for CO_2 offsetting, because the climate forcing of a CO_2 emission persists for millennia to geological timescales — far beyond the 1000-year time horizon over which the SPC pool is presumed to have decayed (Schmidt and Hagemann, 2026). Offsetting a CO_2 emission requires that the compensating C-sink delivers a negative total climate effect (TCE) for as long as the emitted CO_2 exerts radiative forcing, which effectively demands geological permanence and can therefore only be achieved with the GPC pool. However, in economic and regulatory terms, time-limited conventions for CO_2e compensation — such as 100, 200, or 500 years — may be adopted, provided that the temporary nature of the compensation is transparently communicated and that the distinction from geological offsetting is maintained. It is the prerogative of legislators, carbon market regulators, traders, and buyers to define such time conventions and to determine the appropriate valuation of temporary versus geological climate services. However, even if CO_2e offsetting is only permitted with the GPC pool, the SPC pool can be used for methane offsetting, temporary CO_2e offsetting, and the creation of C-sink portfolios. The annual SPC available for climate services is calculated as the average of the integral of the SPC function over the time horizon H. An SPC calculator is provided on the website of Carbon Standards. An example can be found in Table 1 below.

Table 1: Climate services of the SPC fraction provided in CINK_H. CINK_H is the annual average of carbon stored of over H years in t CO_2*e. To calculate the amount of carbon stored over H years, the integral of the SPC function from 0 to H years is used.*

Amount of SPC in ton of carbon	Amount of SPC in ton of CO2e	CINK_01	CINK_05	CINK_20	CINK_50	CINK_100	CINK_200
250	916.7	878.2	793.7	699.9	600.7	460.8	314.9
100	366.7	351.3	317.5	280.0	240.3	184.3	125.9
0.27	1	0.9581	0.8658	0.7635	0.6553	0.5027	0.3435

3.5 The Lower Persistence Classes of Biochar

EBC- and WBC-certified biochar that is applied to soil and presents an H/C_org ratio < 0.40 but does not meet the criteria for the upper persistence class (i.e., Ro $< 3.8\%$ and/or BC_HyPy $< 90\%$) is registered with a GPC fraction of 75% and an SPC fraction of 25% in the Global C-Sink Registry. The remaining carbon of such soil-applied biochar is calculated as a function of time with the following approximation using the SPC function:

$$C_{remain}\,(H) = M_{BC} * C_{BC} * (\%GPC + \%SPC *(0.1787 * e^{-0.5337 * H} + 0.8237 * e^{-0.00997 * H})) \qquad (5)$$

Equation 5: Modelized decay function of biochar calculating how much biochar carbon remains in a C-sink H-years after having been applied to soil. M_{BC} *= mass of biochar;* C_{BC} *= carbon content of biochar;*

C_remain = mass of biochar carbon remaining in the C-sink after the indicated number of years since soil application. %GPC is the proportion of biochar carbon assigned to the GPC pool, and %SPC is the proportion assigned to the SPC pool. For the lower persistence class, %GPC = 0.75 and %SPC = 0.25, for the higher persistence class, %GPC = 0.90 and %SPC = 0.10, while for biochars with H/Corg > 0,4, %GPC = 0 and %SPC = 1.0. The equation is valid for 0 to 1000 years since soil application.

Biochars with an H/C_org ratio > 0.40 that are applied to soil are registered with an SPC fraction of 100%, and no GPC fraction can be registered. For such biochars, Equation 4 applies with %GPC = 0 and %SPC = 1.00. While it is still likely that a relevant proportion of carbon in biochars with H/C_org > 0.40 will survive 1000 years and more when applied to soil, the present standard cannot establish with sufficient confidence the probability of how much carbon will persist. Carbon Standards has therefore chosen the prudent approach of certifying such biochar only as SPC.

3.6 The Upper Persistence Class of Biochar

The lower persistence classes defined in Section 3.5 groups all biochars with H/C_org ≤ 0.40 into a single category with 75% GPC. However, biochars at the upper end of aromatic condensation warrant differentiation. Over the past years, analytical methods additional to the EBC - most notably random reflectance (Ro) and hydropyrolysis (HyPy) - have generated a substantial and consistent body of data demonstrating higher discriminatory power for identifying biochars with very high degrees of aromatic condensation and structural ordering. These methods enable a more precise identification of biochars in which the reactive carbon fraction is exceptionally low and the probability of millennial-scale persistence is correspondingly high.

Analyses combining Ro, HyPy, and SEC reveal a non-linear transition in biochar structure at high degrees of aromatic ring condensation. Biochars exhibiting a Mean Ro higher than 3.8% show a marked and consistent shift across multiple independent indicators. Above this threshold of 3.8%, the content of biochar carbon resistant to hydropyrolysis (BC_{HyPy}) consistently exceeds 90% of the total carbon. At the same time, SEC increases by more than one order of magnitude, indicating that aromatic cluster connectivity has progressed to a level at which biochar transitions from an electrical insulator to a semi-conductive carbon (Grafmüller et al., 2026, submitted). These converging changes indicate that aromatic domains are no longer merely larger, but qualitatively more ordered and interconnected.

The transition observed around a Mean Ro value of 3.8% reflects a structural inflection point rather than a gradual progression. Beyond this point, further increases in pyrolysis severity lead to only minor changes in reactivity, while increased ordering and connectivity dominate material behavior. The Mean Ro threshold of 3.8% represents a conservative, empirically derived boundary at which biochar carbon shifts into a regime characterized by exceptionally low reactivity and a very high probability of millennial-scale persistence. This regime corresponds approximately to molar H/Corg ratios below 0.25 for woody feedstock, as independently observed in recent datasets (Hagemann et al., 2025; Sanei et al., 2025, 2024).

Based on the expanded analytical data, the present version of Global Biochar C-Sink Standard (i.e., version 3.3) introduces an upper persistence class to capture biochars at the higher end of aromatic condensation and structural ordering.

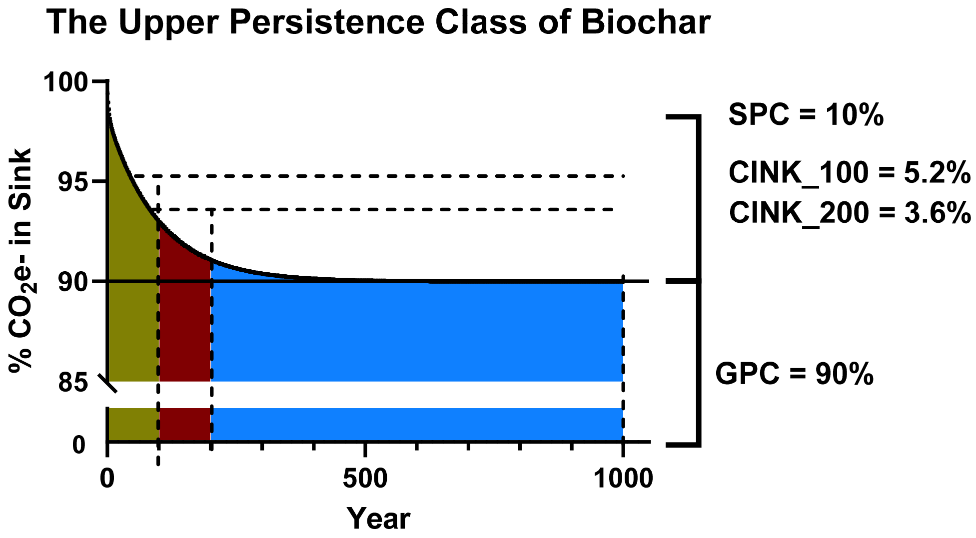

Figure 1. Schematic illustration of the partitioning of biochar carbon into geologically persistent carbon (GPC) and semi-persistent carbon (SPC) for biochars of the upper persistence class. GPC is conservatively set to 90% of total organic carbon and treated as a stable pool persisting beyond 1000 years, representing transfer into the geological carbon cycle. The remaining 10% is assigned to SPC and follows an exponential degradation function as defined for the SPC pools. CINK_100 and CINK_200 are the annual average SPC-sinks over 100 and 200 years, respectively.

Biochars are assigned to the new upper persistence class if they meet at least one of the following criteria:

(i) a mean random reflectance of Ro ≥ 3.8%, while no more than 3% of all measured points present Ro < 2% and data from ≥500 measured points shows a Gaussian distribution with a heterogeneity score ≤ 8.

(ii) a fraction of biochar carbon resistant to hydropyrolysis exceeding or equal to 90%.

For biochars assigned to this upper persistence class, 90% of total biochar carbon are assigned to the GPC pool and 10% to the SPC pool. The allocation corresponds to a conservative lower-bound probability of long-term persistence, since such biochars typically exhibit less than 10% reactive carbon. Accordingly, the probability that biochar carbon within this class persists for more than 1000 years after application to soil can be conservatively considered to be at least 90%.

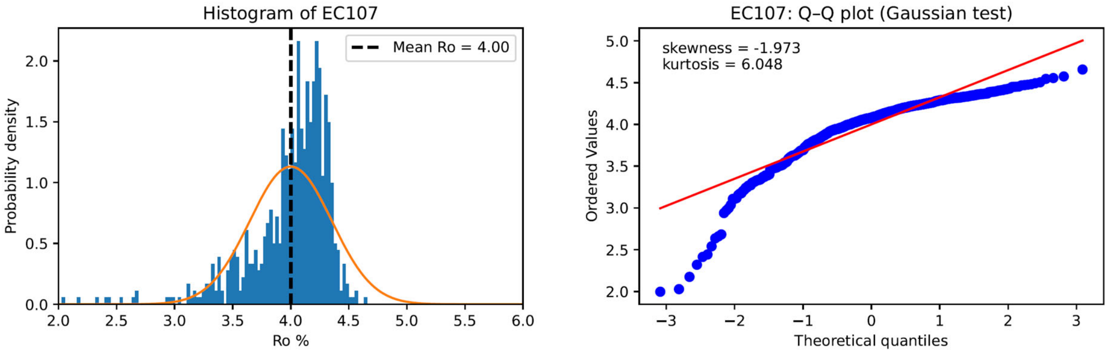

Figure 2: Example of a random reflectance (Ro) distribution for a biochar sample meeting the upper persistence class criteria. The sample (n = 687 measurements) presents a mean Ro of 4.00%, a molar H/C_org ratio of 0.17, and a heterogeneity score of 5.00. The histogram and cumulative distribution function illustrate the spread of individual Ro measurements around the mean. Less than 1% of measurements fall below the 2% Ro threshold. Detailed distributional diagnostics, including outlier treatment and normality assessment, are part of the standard data analysis executed by Carbon Standards to test the representativeness of the sample based on at least 500 Ro measurements provided by an CSI-endorsed laboratory.

Ro and HyPy are strongly related to aromatic condensation, but differ in analytical nature, availability, and operational constraints. Random reflectance resolves microscale heterogeneity and is particularly effective at detecting mixed biochars and unstable pyrolysis conditions, whereas hydropyrolysis isolates an operationally defined carbon fraction associated with higher ring condensation. When investigating biochar sets produced systematically under increasing pyrolysis severity from different feedstocks, both methods indicated the same structural transitions and showed consistent agreement with other persistence-relevant indicators such as H/Corg and SEC. Accepting either criterion, therefore, preserves scientific robustness while enabling practical implementation across different production and laboratory settings. The allocation of 90% of total carbon to the GPC pool is conservative regardless of whether classification is based on Ro or HyPy.

3.7 Practical Considerations and Implementation

For C-sink trading purposes, the average annual mass of the SPC pool stored for a given number of years (cf. Equation 4) can be displayed in the Global C-Sink Registry and is provided on the C-sink certificate. It can be used for methane compensation and temporary offsetting of global warming effects. Here, the annual average of the temporary C-sink (e.g., CINK_20) can be employed if the total climate effect of the emission and the climate cooling effect of the C-sink have a similar timing (e.g., 20 years or less for methane offsetting).

Currently, most C-sink traders use the mean annual C-sink over 100 years (CINK_100) or 200 years (CINK_200) to compensate for CO_2 emissions. However, the global warming effect of a CO_2 emission reaches far into thousands and millions of years. If the objective is full offsetting — i.e., annulling the total climate warming effect of the CO_2 emission once and for all — the C-sink must persist for as long as the emitted CO_2 exerts radiative forcing, which effectively requires geological permanence. Under this condition, CO_2 offsetting can only be achieved with the GPC pool of biochar carbon. However, offsetting the total climate effect (TCE) over a defined period of time using CINK_100 or CINK_200 derived from the SPC pool remains a legitimate climate service, provided it is transparently distinguished from geological offsetting (cf. Section 3.4)

The calculation of the average annual mass of stored carbon depends on the C-sink matrix. For soil-applied biochar, it depends on the persistence class as determined by Ro, BC_HyPy, and the H/C_org ratio (cf. Equation 4 and Table 1). For biochar used in concrete or asphalt, the SPC decay is considered to begin only after an initial period of 100 years during which the embedded biochar carbon is protected by the mineral matrix (cf. Chapters 12.3 and 12.4).

Table 2: Exemplary calculation of C-sink values for 100 t of biochar (dry matter) with a carbon content of 80% applied to soil, illustrating the three persistence classes. The total biochar carbon of 80 t corresponds to 293.3 t CO_2e. The first row represents a biochar meeting the upper persistence class (Ro $\geq$ 3.8%, GPC = 90%), the second row a biochar in the lower persistence class (H/C_org $\leq$ 0.40, Ro < 3.8%, GPC = 75%), and the third row a biochar assigned entirely to the SPC pool (H/C_org > 0.40, GPC = 0%). The GPC fraction is available for CO_2 offsetting (rightmost column). The SPC fraction is expressed as CINK_H values for selected time horizons (1, 5, 20, 100, 200, and 1000+ years), calculated as the annual average of carbon stored over H years using the integral of the SPC decay function (cf. Equation 3 in Section 3.4). All values are given in t CO_2e. An online SPC calculator is available on the Carbon Standards website.

Amount of biochar with 80% C applied to soil in t biochar	H/Corg	Ro	GPC in t CO2e	SPC in t CO2e	CINK_05 generated from SPC	CINK_20 generated from SPC	CINK_100 generated from SPC	CINK_200 generated from SPC	CINK_1000+ generated from GPC
100	0.15	3.90%	264	29.3	25.4	22.4	15.4	10.5	264
100	0.30	2.80%	220	73.3	63.5	56.0	38.5	26.3	220
100	0.60	1.80%	0	293.3	254.0	224.0	153.9	105.2	0

The current version of the standard (version 4.0) defines three persistence classes: the upper and lower persistence classes, with GPC fractions of 90% and 75% respectively, and a class for biochars with H/C_org > 0.40, which is assigned entirely to the SPC pool (0% GPC). This classification will be further refined in the next standard update. If an updated calculation method allows higher GPC proportions for a given biochar batch, existing register entries may be adjusted retrospectively under conditions to be specified at the time of the update.

4 Emission Portfolio and Compensation

The carbon expenditure of a biochar C-sink englobes all GHG emissions caused by biomass production, transport, preparation, pyrolysis, milling, packaging, transportation, mixing, and application to a C-sink matrix. It presents the complete carbon footprint of the biochar from the initial capture of atmospheric carbon till the application to the final C-sink site.

The emissions from biomass production to the packaging of the biochar and its storage at the factory gate are assessed with Carbon Standards' Biochar Tool, and the biochar producer must offset these emissions for every batch and every year of production.

The emissions occurring from the biochar factory gate to the final C-sink site have to be tracked by dMRV providers. Those post-factory-gate emissions are relatively small compared to the C-sink value of the biochar. They must be offset before the C-sink can be registered. It is commonly done by the C-sink owner, processor, or trader through retiring part of the biochar C-sink.

If biochar or biochar products are transported from the producer or processor to a next processor, a trader, or to the C-sink location, the receiving organization (e.g., the trader, the farmer, the construction company, etc.) is responsible for reporting and offsetting the transport emissions.

All production emissions are registered in the ***emission portfolio*** of the production companies for each biochar production batch. Moreover, each packaging unit has its own emission portfolio to ensure that all emissions occurring between the factory gate and the final C-sink are recorded and offset.

All fossil CO_2 emissions from biomass production to C-sink application must be offset by long-term carbon sinks before the registration of a biochar C-sink can be validated in the Global C-Sink Registry. The same must be done for N_2O emissions from biomass cultivation. The climate warming effect of CH_4 emissions can be offset by an equally sized cooling effect of a C-sink over a 20-year period, which must be validated in the Global C-Sink Registry.

4.1 Note on Terminology

In this standard, the time-integrated climate impact of greenhouse gas emissions and carbon sinks is expressed using the **Total Climate Effect (TCE)**, measured in t $CO_2e \cdot yr$ (i.e., ton-year). The TCE quantifies the cumulative warming or cooling that an emission or a carbon sink delivers over a defined time horizon H (in years). By convention, a positive TCE corresponds to net warming caused by emissions, whereas a negative TCE corresponds to net cooling achieved through carbon dioxide removals. The TCE is derived from the atmospheric CO_2 impulse–response function (IRF) as described in Schmidt and Hagemann (2026).

For a CO_2-equivalent pulse exchanged with the atmosphere at $t = 0$, the TCE over horizon H is given by:

$$\text{TCE(H)} = \text{M\_CO}_2\text{e} \cdot \text{IRF\_int(H)} \qquad (6)$$

where M_CO$_2$e is the CO$_2$-equivalent mass of greenhouse gases exchanged with the atmosphere (positive for emissions, negative for removals) and IRF_int(H) is the time integral of the impulse–response function over the horizon H.

While the TCE is a measure of the cumulative warming or cooling effect of an emission or a C-sink over the horizon H, the CINK_H metrics (for example CINK_20, CINK_100) quantify the average annualized CO$_2$-equivalent storage of a carbon sink over H years. CINK_H describes how much carbon is, on average per year, contained in a C-sink over the period H. In contrast to the TCE, CINK_H does not account for the decline in atmospheric CO$_2$ response described by the impulse-response function; it reflects only the average carbon stock in the sink, not the time-dependent radiative response.

4.2 Production Emissions Included in the Emission Portfolio

The emissions of fossil-carbon-derived CH_4, N_2O, and CO_2 caused by biochar production are recorded as follows:

a) Emissions from the provision of biomass (c.f. Chapter 5.3), which covers biomass production, processing, and transportation.

b) Emissions from the storage of the biomass (cf. Chapter 6)

c) Emissions from the pyrolysis process and other equipment at the production site (c.f., Chapter 7.1).

d) Emissions from postproduction and transportation to the C-sink site (c.f. Chap. 10).

e) A safety margin in the amount of 20 kg CO$_2$e per ton of biochar is added to account for all additional emissions not covered under the regular assessment (cf. Chap. e).

Emissions are recorded in the emission portfolio in tons of CO_2, tons of N_2O, and tons of CH_4. For methane offsetting, the global warming effect of methane over 100 years must be offset with the same climate cooling effect of a C-sink delivered during the first 20 years since the emission.

The emission factor is calculated by adding all the above-listed emissions as CO$_2$e. For N_2O the GWP100 of 298 t CO$_2$e t^{-1}, for biogenic methane the GWP100 of 27.0, and for fossil methane the GWP100 of 29.8 t CO$_2$e t^{-1} are used as conversion factors, respectively (IPCC, 2022; Smith et al., 2021). The emission factor is given as mass proportion based on the dry weight of the biochar (t CO$_2$e t^{-1}). It is calculated by dividing the total amount of carbon expenditures per batch by the dry weight of the total amount of biochar produced per batch.

4.3 Offsetting of Production Emissions

CO_2 must only be offset with geological C-sinks, such as the GPC pool of soil-applied biochar, that are registered in the Global C-Sink Registry.

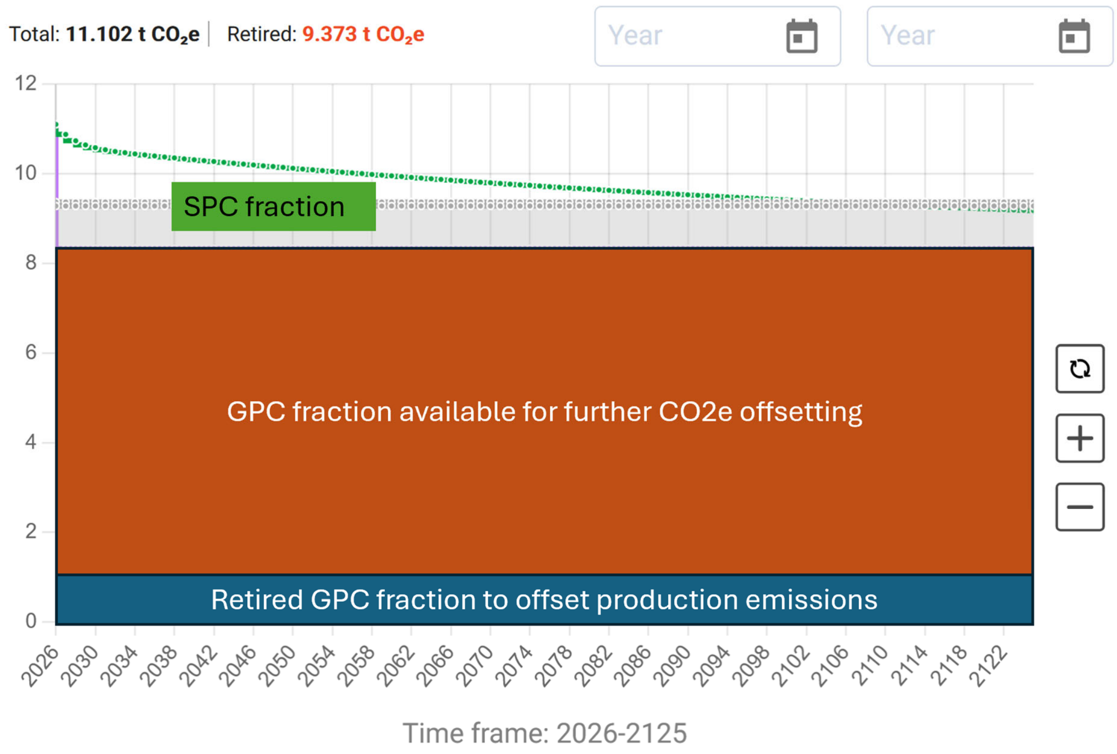

Figure 3: Exemplary figure for a global carbon registry entry. The green line shows the persistence of a biochar C-sink over the next 100 years (slow degradation of the SPC fraction). The blue and red frame show the GPC fraction of the biochar carbon sink. The blue area was already retired to offset the fossil CO_2 *emissions occurred during production. The red area is the part of the C-sink that can be used to generate CINK_1000+ to offset* CO_2e *emissions. The C-sink represented by the area below the green curve and above the red area is the temporary C-sink that can be used for methane offsetting or other temporary climate services.*

The global warming potential (GWP100) of methane (CH_4) emissions can be offset by an equally sized cooling effect (i.e., negative global warming). However, given that most of the warming caused by CH_4 emissions occurs in the first two decades, the offset of the GWP100 must be delivered during the first 20 years following the CH_4 emission (Schmidt & Hagemann, 2026). Further details are provided in Chapter 4.4

Nitrous oxide (N_2O) has a long residence time in the atmosphere and thus must be offset with geological C-sinks registered in the Global C-Sink Registry. For this purpose, emissions are converted into CO_2e using the GWP100 of 298 tons CO_2 per ton N_2O (Aamaas et al., 2016; Allen et al., 2016; IPCC, 2022; Myhre et al., 2013).

The emission offsets can be realized with the registered biochar C-sink whose production had caused the emission.

4.4 Methane Emissions and their Offsetting

Although the atmospheric concentration of methane is roughly 200 times lower than that of carbon dioxide (approximately 1.9 ppm compared to 420 ppm in 2025), methane currently accounts for 20% to 30% of the anthropogenic contribution to global warming, depending on whether the share is expressed in terms of instantaneous radiative forcing or cumulative temperature response.

Unlike CO_2, methane is chemically unstable and is continuously removed from the atmosphere by oxidation reactions with hydroxyl radicals (OH) and other reactive species, as well as by microbial and chemical processes in the soil–atmosphere interface. These degradation pathways lead to the formation of CO_2 and H_2O and involve several reactive intermediates such as ozone (O_3) and formaldehyde (HCHO). Part of the oxidation-derived H_2O is generated in the stratosphere, where it acts as a long-lived greenhouse gas and contributes further to radiative forcing.

Because the oxidation products — especially CO_2 and stratospheric H_2O — continue to exert a warming influence long after the original methane has decayed, the cumulative warming effect of a methane emission over 100 years is greater in absolute terms than over 20 years, even though its 100-year GWP ($\approx$ 27) is numerically smaller than its 20-year GWP ($\approx$ 81). The mean atmospheric lifetime of methane is approximately 12 years, corresponding to a half-life of about 8 to 9 years (IPCC, 2022, 2013; Myhre et al., 2013). The short residence time of methane has two major consequences for offsetting:

(1) There is no need to compensate for global warming caused by methane with geological C-sinks; temporary C-sinks can and should be used instead. Since the GPC fraction of C-sinks has a negative TCE of more than 1000 years, offsetting the short-term warming of methane with geological C-sinks is neither economically efficient nor physically necessary or adequate.

(2) Compensation must be carried out promptly after the emission. The decades up to 2050 are the decisive period for limiting anthropogenic global warming. Since methane emissions occurring today and in the upcoming decade have a particularly severe climate impact until 2050, the Global Biochar C-Sink Standard requires that the TCE of the methane emission over 100 years be fully offset by a C-sink delivering an equally sized negative TCE within the first 5 to 20 years following the emission. This reflects the comparatively short but intense impact of methane and is in line with recommendations from various organizations and scientists (Balcombe et al., 2018; Schmidt and Hagemann, 2026; Venmans et al., 2025)).

The global warming potential (GWP) was developed as a metric to compare the climate effects of different greenhouse gases over a specified time horizon. The 100-year time horizon (GWP_{100}) is most commonly used for this (Fuglestvedt et al., 2003). Other metrics have been proposed; however, despite various limitations, GWP_{100} is still the most widely used and accepted method and has been identified as particularly useful for guiding political decision-making (Moosmann and Herold, 2023).

The estimation of the GWP_{100} for methane has changed over successive IPCC Assessment Reports. In the early reports it was set to 21 in the First and Second Assessment Reports, increased to 23 in the Third, to 25 in the Fourth, and to 28 (or 34 when climate–carbon feedbacks are included) in the Fifth Assessment Report. In the Sixth Assessment Report (AR6), the generic methane GWP_{100} is given as 27.9, falling between biogenic methane, with a GWP_{100} of 27.0, and fossil methane, with a GWP_{100} of 29.8 (Allen et al., 2014; Forster et al., 2021; Smith et al., 2021). Until version 3.2, the present standard used a GWP_{100} of 25. With version 4.0, the standard adopts the GWP_{100} of 27.0 for biogenic methane and 29.8 for fossil methane, consistent with the IPCC AR6 values. To accommodate existing contractual commitments for methane offsetting, a transition period until 1 January 2027 is granted during which the former GWP_{100} of 25 may still be applied.

Using a GWP_{100} of 27.0 for biogenic methane, an emission of 1 t CH_4 has the same 100-year integrated global warming effect as 27.0 t CO_2. Because methane has an effective atmospheric half-life of roughly 10 years, more than 80% of a pulse emission is oxidised after 20 years. Most of methane's total climate effect (TCE) therefore occurs in the first 20 years following its emission. After 100 years, essentially all ($> 99.9\%$) of the emitted methane is degraded. However, the degradation products – especially tropospheric ozone and stratospheric water vapour, and in some metric definitions also the resulting CO_2 – exert a small but significant warming effect over 100 years, which adds to the direct effect of methane and is (partly) included in the GWP_{100} value. In the AR6 framework, if the emitted methane is of biogenic origin, as is the case in biochar production, the additional effect of the oxidation product CO_2 is not counted as a net contribution in the non-fossil GWP_{100} value.

The methane offsetting condition requires that the positive TCE of the methane emission over 100 years is balanced by an equally sized negative TCE delivered by a C-sink within a delivery horizon between 5 and a maximum of 20 years:

$$\text{TCE\_CH}_4(100) + \text{TCE\_sink(H\_del)} = 0, \text{ with } 5 \leq \text{H\_del} \leq 20 \quad (7)$$

The required amount of CO_2 removal depends on the type of C-sink used for offsetting. For a constant, leakage-free C-sink, offsetting 1 t of biogenic CH_4 requires approximately 94.6 t CO_2e stored over 20 years. When the semi-persistent carbon (SPC) fraction of soil-applied biochar is used, the required initial SPC removal increases to approximately 122 t CO_2e per t CH_4, because part of the initially removed carbon is lost during the 20 years due to the SPC decay (Schmidt and Hagemann, 2026).

The detailed mathematical derivation of methane offsetting using the impulse–response function (IRF) based TCE framework, including the application to constant sinks, diminishing sinks (such as the biochar SPC pool), and increasing sinks (such as tree growth), is provided in Schmidt and Hagemann (2026). The Methane Calculator, freely available on the website of Carbon Standards, implements this methodology and can be used to calculate the required amount of carbon dioxide removal needed to offset the TCE of a methane emission for any given C-sink type and delivery horizon.

4.5 Reduction of Fossil Carbon Emission

Given that global GHG emissions are successfully reduced by 2050 to less than 10% of the emissions recorded for the year 1990, negative emissions of at least 800 Gt CO_2e are still needed until the end of the century to limit global temperature rise to about 2 °C. The remaining 10% of GHG emissions will mainly comprise emissions from agriculture and waste decomposition but must not originate from fossil carbon sources. Consequently, C-sink producers must reduce their fossil carbon emissions, too. It is neither convincing nor acceptable in the long term if C-sink producers consume fossil carbon for the provision of machine fuel and electricity. Therefore, **certified biochar producers must present a plan outlining how to reduce fossil GHG emissions of biochar production as specified below to less than 100 kg CO_2e per ton of biochar-carbon in 2030 and to less than 20 kg CO_2e per ton of biochar-carbon in 2035** (for an example of such a plan, see Carbon Standards' website).

The following fossil carbon emissions must be included: biomass production, harvest, transport, preparation such as chipping or pelletizing, drying, pyrolysis, and packaging. Methane emissions from storing and pyrolysis should equally be avoided but are not included in the fossil carbon emission reduction plan because of their biogenic origin. Fossil carbon emissions from biochar transportation and external processing do not fall under the responsibility of the biochar producer and will be part of the control of biochar traders, biochar product manufacturers, and users.

$$\text{Biochar\_GHG\_balance (t CO2e / t BC)} = \frac{\text{Total emission until factory gate (t CO2e)} - \text{non fossil CH4 emissions (t CO2e)}}{\text{mass of biochar per batch (t DM)} * C_{\text{content}} \text{ of biochar}}$$

Equation 8: Calculation of the GHG balance of biochar production from feedstock production until biochar packaging at the biochar production facility in tons of emitted CO2e per ton of produced biochar. The unit of all emissions is CO_2e. Non-fossil emissions such as methane emissions from storage and pyrolysis are excluded.

The fossil emission reduction plan must be updated annually and include a short progress report. The plan can be managed online in the Global Biochar Tool or uploaded annually in a new version of the tool.

4.6 Pro Rata Calculation of GHG Footprint

It should be expected that not only the biochar production as such but the entire biomass processing facility (i.e., the project) with all resulting products (i.e., biochar, electricity, heat, hydrogen, pyrolysis oil, etc.) will be climate neutral.

However, in most industrial setups, biochar is only a secondary product of the pyrolysis or gasification process. It may, therefore, not be appropriate to attribute the entire carbon footprint of the production facility to biochar alone. Instead, the greenhouse gas (GHG) emissions may be distributed proportionally among the other pyrolysis products (c.f., ISO 14040) such as charcoal, hydrogen, pyrolysis oil, electricity or thermal energy. The GHG allocation between the various products is calculated on the energy base of the products (see Box 6).

To be eligible to use the pro-rata GHG calculation, the producer has to prove that the non-biochar products are regularly traded and generate substantial income or measurable add value. The income or added value for all non-biochar products must not be inferior to 30% of the income generated with biochar.

The input energy (E_{input}) is calculated by multiplying the analyzed lower heating value (LHV) of the biomass feedstock ($LHV_{feedstock}$) with the mass of the feedstock on a dry matter base ($m_{feedstock, dm}$). The output energy of the non-biochar products ($E_{nonBCoutput}$) is calculated by multiplying the LHV of the **marketable non-biochar solid** (e.g., charcoal)**, liquid, and gaseous products** with the respective mass of the products on a dry matter base and adding the produced, **measured electric energy** ($E_{electric}$) and **thermic energy** ($E_{thermic}$). A pyrolysis product is considered as marketed when it is sold to or used in processes not directly linked to the pyrolysis/gasification facility. For example, hydrogen is considered a marketable product when hydrogen is produced, stored in a tank, and sold to another company or used, e.g., in a methanol synthesis at the production site. If the hydrogen is combusted in the combustion chamber of the pyrolysis unit or in a directly linked generator for electricity production, the hydrogen is not considered a marketable product. The use of thermic energy to dry the pyrolysis feedstock is considered part of the biochar production and cannot be accounted for the pro-rata GHG allocation.

$$(1)\quad E_{input} = LHV_{feedstock} * m_{feedstock,\,dm}$$

$$(2)\quad E_{nonBCoutput} = LHV_{nonBCsolid} * m_{nonBCsolid,\,dm} + LHV_{liquid} * m_{liquid} + LHV_{gas} * m_{gas} + E_{electric} + E_{thermic}$$

$$(3)\quad E_{biochar} = LHV_{biochar} * m_{biochar\ (DM)}$$

Equation 9: Calculations of energy content based on the lower heating value (LHV) of the biochar, the pyrolysis oil, the pyrolysis gas, and the electric and thermic energy. Units of E are usually given in MJ and LHV in MJ per kg.

To calculate the GHG attribution of the biochar product, the total emissions assessed for the entire process from biomass production to biochar output are multiplied by the ratio of $E_{biochar}$ to the total E_{output} ($=E_{nonBCoutput} + E_{biochar}$).

$$\boxed{BC_{emission} = \text{Production emissions}\ \frac{E_{biochar}}{E_{nonBCoutput} + E_{biochar}}}$$

Equation 10: Calculation of the part of total emissions to be accounted for the biochar production on a pro rata base.

All emissions that occur between the biochar output from the pyrolysis unit to the eventual carbon sink must be attributed to the emission portfolio of the biochar.

Box 6: Pro-rata attribution of GHG emissions caused by the biochar facility.

Example for the pro-rata calculation for GHG attribution:

- **Input (feedstock):** Annual feedstock 4000 t of wood with a dry matter content of 65%, carbon content of 48%, and a lower heating value (LHV) of 4 kWh/kg (@ 80% DM) representing (3250 t (@80% DM) * 4 MWh/t =) 13,000 MWh.
- **Output:** The unit produces 260 t biochar (DM) per year with an LHV of 7.9 kWh/kg and a C-content of 85%, representing 2054 MWh; 3140 MWh electricity and 4800 MWh thermic energy for district heating, representing 7940 MWh nonBCoutput.
- **GHG attribution:** The biochar to total products ratio is (2054 MWh / (2054 MWh + 7940 MWh) =) 20.6%. Thus, 20.6% of carbon expenditure (excluding the margin of safety, chap. 4.7) are attributed to the biochar production. To set the biochar production climate neutral, 20.6% of all CO_2 (incl. the margin of safety) and N_2O production emissions must be offset with long-term C-sinks, and 20.6% of CH_4 emissions compensated with temporary C-Sinks (C-Sink_20). GHG emissions occurring from the packaging station to the factory gate and then to the final C-sink are entirely attributed to the biochar.

We hope that latest by 2035, regulations will require all bioenergy and biomaterial productions to become climate neutral.

4.7 Margin of Safety

In the calculation of carbon footprints of an organization, the emissions accounted for are usually divided into Scope 1 (direct emissions at the production site, in this case, combustion of pyrolysis gas, methane emissions during biomass storage, combustion of natural gas for preheating the reactors), Scope 2 (indirect emissions from externally purchased energy, in this case mainly electricity) and Scope 3 (further indirect emissions, in this case, e.g., production emission of the pyrolysis plant, electricity for external server maintenance, emissions of purchased biomasses, fertilizers, transport of biomass).

For the Global Biochar C-Sink, the emissions from Scope 1 and 2 of each involved and registered organization (producers and processors) are fully recorded. If the conditions for the pro-rata approach (chapter 4.5) are met, the emissions are allocated to the biochar and other products.

For Scope 3 emissions of involved organizations, only the emissions from biomass production and its transport are directly quantified.

Other indirect emissions from Scope 3 are not recorded individually due to their comparatively low volume but are instead included in the calculation with a flat margin of safety to account for the whole value chain. This includes, for example, the emissions caused by:

- Production and disposal of polypropylene bags,
- Electricity for the operation and cooling of the company's external computer servers,
- Potential methane emissions during the first month of storage of the biomass,
- Fuel consumption by employees for commuting to work and for business trips,
- Marketing and management activities including trade shows and conference attendance,
- Operation of chainsaws or harvesters for felling and peeling trees and for digging up roots,
- Emissions from machine fuels during cultivation of agricultural land and plant protection measures,
- Production, maintenance, repair, and disposal of pyrolysis equipment, transport vehicles, warehouses, and other machinery.
- The margin further accounts for unavoidable imprecisions in sampling, packaging, volume and dry mater analysis, etc.

There are many small, indirect scope 3 emissions that need to be included when creating a perfect carbon footprint. Compared to the total amount of CO_2e from Scope 1 & 2 as well as from biomass provision within Scope 3, and to the vast amount of carbon accumulated in biomasses, the remaining indirect emissions in Scope 3 play only a minor role. To account for all these GHG emissions that are not directly quantified, a flat margin of safety is defined. The margin of safety generally amounts to 20 kg CO_2e per ton of biochar (dry matter) which corresponds to roughly 0.7 % of the biochar carbon. The margin of safety is applied per ton of biochar at the factory gate of the producer and is, thus, not affected by pro-rata accounting. This is an industry-standard margin for the inherent uncertainty of the overall process that allows Carbon Standards to keep the certification process lean and efficient without misappropriating emissions.

If a company produces like in the example above 260 tons of biochar with a C-content of 85%, the GHG margin would be (260 t biochar * 0.02 t CO2e t biochar^{-1}=) 5.2 t CO_2e. Thus, if the biomass provision causes, e.g., 92 kg CO_2e / t biochar and the pyrolysis process 110 kg CO_2e / t biochar), the total GHG emissions would be (92 kg CO_2e for biomass + 110 kg CO_2e for pyrolysis + 20 kg CO_2e for the margin =) 222 kg CO_2e per ton of biochar. The margin would thus be (20 kg / (92 kg +110 kg) =) 10%. This margin of safety covers the indirect emissions not quantified in the system and unavoidable imprecisions in measuring and analyzing the produced biochar.

The size of the margin will be verified and, if necessary, adapted at least every second year according to the evolution of global GHG emissions and the average footprint of scope 3 emissions.

5 Biomass Feedstock for Biochar C-Sink Production

The overarching goal of the C-sink certification is to increase the total amount of carbon stored in the terrestrial system and thus reduce the concentration of greenhouse gases in the atmosphere. When certifying C-sinks, it must be ensured that the establishment of the certified C-sink does not reduce the total terrestrial carbon sink. The C-sink must be additional to the total terrestrial carbon sink compared to the moment of CO_2 removal.

The evaluation of a biochar C-sink does not start with the production of the biochar or the transport of the feedstock but precisely at the moment when the growing biomass removes CO_2 from the atmosphere. The climate effect of the carbon sinks is caused by the reduced atmospheric CO_2 concentration while preserving the removed carbon in the carbon sink avoids its re-emission.

The Global Biochar C-Sink certification verifies that the use of biomass does not deplete a long-term natural or otherwise registered carbon sink. It evaluates the climate neutrality of the feedstock production and provision along the criteria for the different feedstock types outlined in chapter 4.3 (*Approved biomass and carbon expenditures for their production*).

5.1 Carbon Neutrality of Biomass Feedstock

Feedstock to be used for biochar production must be carbon neutral under the following definition of feedstock carbon neutrality:

A feedstock material (biomass) for the generation of a C-sink is considered C-neutral if it is either the residue of a biomass processing operation or if the biomass removal did not, over the reference period, lead to the reduction of the total carbon stock of the system in which the biomass had been grown.

Only C-neutral biomass input materials are permitted for the production of biochar C-sinks. Biochar produced from biomass whose harvesting resulted in the destruction or depletion of a natural C-sink (e.g., clear-cutting of a forest) or has contributed to the disappearance of an existing sink (e.g., inappropriate agricultural practices on bog soil) does not render any positive climate service and must not be certified as C-sink.

Emissions resulting from biomass cultivation (i.e., fuel consumption for land preparation and harvest, fertilizer, irrigation, etc.) do not in themselves challenge feedstock carbon neutrality but are included as carbon expenditures. They are part of the emission portfolio and must be offset with registered long-term C-sinks.

Biomass cultivation for C-sink production may lead to activity shifts (e.g., from rice production to biomass feedstock) or market transformations (e.g., when biomass used as biochar feedstock can no longer be used in biomass power plants and is replaced by fossil fuels). It is the duty of the biochar producer to assess the risk of activity shifts and market transformation. The risk assessment must be submitted as part of the registration process, evaluated by Carbon Standards during the technical audit, and verified by the Certifier. A re-evaluation can be requested as a consequence of the annual inspection. The emissions resulting from activity shifts and market transformations in the C-sink activity must be incorporated into the emission portfolio and offset with registered long-term C-sinks.

5.2 Biomass Feedstock Additionality

Carbon from biomass shall be preserved as much and for as long as possible. Given the limited surface area of the planet on which plants can grow, natural carbon dioxide removal is limited, and the available biomass must be used responsibly. Biochar C-sinks must be additional to natural C-sinks that could or would have been realized with the same biomass feedstock in the absence of the biochar C-sink solution.

For example, a tree trunk that would normally have been transformed into construction wood or could, economically, be made into construction wood should not be pyrolyzed. Construction wood preserves the entire wood-carbon for as long as the wood is retained in the construction, thus creating a temporary C-sink. Pyrolyzing the same wood would only preserve 30-60% of the wood carbon in the biochar and result in the partial oxidation of the biomass to emitted carbon dioxide. However, if the trunk wood is used to create a C-sink material, the woody residues from processing the tree trunk into construction wood (bark, sawdust, offcuts) could be used as carbon-neutral feedstock for pyrolysis. Also, at the end of the lifecycle of the woody material, pyrolysis could preserve most of its carbon in long-term carbon sinks.

However, the decision about what is the most carbon-efficient use is often not clear. All biomasses can be used in multiple ways, and it is rarely evident which use scenario is more or less sustainable, economical, and carbon-preserving. Straw could be used for animal bedding (good economics, recycling to organic fertilizer replacing synthetic fertilizer, no carbon preservation, additional methane emissions), for biochar production (good economics, renewable energy, 50% of C-preservation), for straw bale housing (small market, 100% C-preservation). It would not make sense to give preference to or exclude one of these three scenarios due to additionality considerations.

If wood from a tree trunk is used to make wood chips for energy production by incineration, replacing fossil fuels, those wood chips could also be utilized in gasification, generating a similar amount of energy and producing some biochar as a byproduct. Carbon-preserving materials would be an even more C-efficient option compared to both scenarios. However, despite their clear climate benefits, when used for carbon-preserving purposes, wood materials are not favored by policymakers (c.f., LULUCF regulations) or the IPCC over bioenergy in today's context.

In light of the preceding factors, it is reasonable to consider that wood sourced from sustainable forest management and biomass residues collected in accordance with the guidelines outlined in chapter 5.1, should not be dismissed as potential biomass feedstock for biochar C-sink production on the ground of additionality considerations.

5.3 Approved Biomasses and Carbon Expenditures for their Production

Only biochar produced from carbon-neutral biomass is eligible for C-sink certification. Nevertheless, the provision of biomass for pyrolysis results in energy consumption and emissions that must be included in the carbon expenditure of biochar production. Depending on the type of biomass and the way it is produced, specific criteria for carbon expenditures apply.

Global Biochar C-Sink defines ten **general feedstock classes:**

(1) Biomass from annual cropping
(2) Biomass from pluriannual and perennial cropping including short rotation plantations
(3) Forest biomass
(4) Wood from landscape conservation, agro-forestry, forest gardens, field margins, and urban areas
(5) Wood processing waste and waste wood materials
(6) Organic residues from biomass processing
(7) Municipal waste and municipal waste digestate
(8) Manure and agricultural digestate
(9) Biosolids and biosolid digestate
(10) Other biogenic residues

The production of biomass usually causes emissions that need to be accounted for as carbon expenditures of the C-sink:

- If mineral nitrogen fertilization was used to produce the biomass, its carbon footprint, including soil borne N_2O emissions, must be accounted for according to the formula 100 kg N = 1 t CO_2e (Zhang et al., 2013).
- If pesticides were used, a flat value of 94 kg CO_2e per hectare (Audsley et al., 2009) is applied for their production-related emissions.
- The input of fuels for cultivation and harvest must also be added to the emission portfolio with a conversion factor of 3.2 ton CO_2e per ton or 2.7 t CO2e per m^3 diesel (Juhrich, 2016).

However, to keep the C-sink certification process lean and appropriate to the developmental stage of the nascent industry, the comparably low emissions for cultivation and harvest are included in the margin of safety (c.f., Chapter 4.7). Still, fertilization, pesticides, and transportation of the biomass from its origin to the pyrolysis plant need to be quantified and accounted for as carbon expenditures.

An overview about the accounting of carbon expenditures for the ten general feedstock classes is given in the following sub-chapters 5.3.1 to 5.3.10.

5.3.1 Biomass from annual cropping

If annual crops are grown on agricultural land, it can be assumed that after one year at the latest, the same amount of biomass will have grown again on the same area, which means that approximately the same amount of CO_2 will again be removed from the atmosphere. The harvested biomass can thus be considered C-neutral based on a one-year period (reference period for annuals) so that a C-sink can be created by producing biochar from cropping residues or the entire annual biomass production. Crop rotations may result in differences of annual CO_2 removals, though over the years those differences even out.

Today, material like straw, the stalks of tomatoes, potatoes, cabbages, and other plants, leaves, and pruning wood are considered agricultural residues. The inclusion of carbon (i.e., biomass) as a full-fledged product of agriculture would change this perception and the definition of agricultural residues. They would be considered an essential part of the agricultural (carbon) crop. The dry weight of any of these biomass types also contains 50 % carbon. Using pyrolysis, more than half of this carbon can be converted into long-term C-sinks instead of being lost as CO_2 in a relatively short period through decomposition or combustion, as is still common practice in most parts of the world. The use of biomass from companion plants and crop residues would become a key component of climate farming and critical to mitigating climate change. However, it is not recommended to completely remove all crop residues from the field and thus reduce the important ecological function of soil cover and organic matter recycling. Rather, the aim is to integrate biomass as an agricultural product into the field management plan while preserving its central ecological functions and replenishment of soil organic matter.

All biomass from annual cropping (i.e., the main crop, residues, companion plants) are considered to be C-neutral input material. The time of the CO_2-removal to be submitted to the Global C-Sink Registry is the year of harvest.

However, it must be ensured that the removal of harvest residues does not decrease soil organic carbon stocks (Whitman and Lehmann, 2015).

If biomass was deliberately grown to produce biochar, i.e., when it was the single or main product of this field, carbon expenditures for fertilization need to be accounted for. It must be included in the emission portfolio according to the formula 100 kg N = 1 t CO_2e (Zhang et al., 2013). If pesticides were used, a flat value of 94 kg CO_2e per hectare must be applied. All other cultivation-related related GHG emissions are included in the margin of safety (cf. chapter 6). If the main crop is used for food, animal feed, or biomaterials, no carbon expenditures for the cultivation must be accounted for the C-sink made from its residues.

Box 2: Calculations of the carbon footprint for biomass production

Example for the calculation of the carbon expenditure for the provision of annual biomass

- On one hectare, 10 t biomass were produced using 50 kg N and 25 kg (30.1 l) diesel, which are processed into 3 t biochar (dry matter = DM) with a carbon content of 75%.
- The emissions amount to (0.05 t N * 10 t CO_2eq * t^{-1} N / 3 t biochar =) 0.167 t CO_2e per ton of biochar for fertilization and (3.2 kg CO_2eq * 25 kg diesel / 3 t biochar =) 0.03 t CO_2e per t of biochar for the diesel used.
- The carbon expenditures for N-fertilization must be included into the emission portfolio. The emissions for the tractor diesel consumption are included in the security margin (c.f., Chapter 4.6) that is part of the emission portfolio.

5.3.2 Biomass from pluriannual and permanent cropping, including short rotation plantations

If pluriannual or permanent crops are harvested annually to provide feedstock for biochar production, there is no difference compared to the accounting for biomass from annual crops (i.e., N-fertilizers are accounted annually, the time of CO_2 removal is the year of harvest).

If the biomass harvest is only every second, fifth, or twentieth year, the carbon expenditures for fertilizers and fuels must be accounted for the entire growing period. The time of CO_2 removal must be tracked for every single year of growth and entered accordingly into the Global C-Sink Registry to correctly calculate the total climate effect (TCE) effect of the resulting biochar carbon sink.

The cultivation of mixed and perennial crops, agroforestry and meadows, which, in addition to biomass production, may promote the build-up of soil organic matter, is preferable to the cultivation of monocultures for biomass production. In principle, biomass from crop residues and companion plants should be recognized as a full-fledged tradable agricultural product ("carbon harvest"). The Global Tree C-Sink certification (cf. chap. 5.3.4) may support and facilitate this process. Food and feed production should be synergistic with the production of additional biomass. This would increase farm productivity, enhance biodiversity, soil organic matter, and enable the removal of CO_2 from the atmosphere.

5.3.3 Forest biomass

Unlike agricultural land, a forest is characterized by a high stock of carbon in the above-ground and below-ground biomass. Thus, the living biomass of a forest is a C-sink itself that must be maintained and must not be compromised when biomass is sourced for biochar production.

If the climate neutrality of a forest is not ensured by the official LULUCF reports of the respective country or by regional legislation, proof can also be provided by *Program for the Endorsement of Forest Certification* (PEFC) or *Forest Stewardship Council* (FSC) certifications and the Global Tree C-sink certification (cf. chap. 5.4). Alternatively, the carbon balance of the forest could be verified by ISO16064-accredited assessment of CO_2 fluxes for the last 20 years. Otherwise, the forest wood is not accepted as biomass input for producing EBC- or WBC-certified biochar. Accordingly, no C-sink of biochar produced from that biomass can be certified.

If, during forest establishment, denser stands are planted and gradually thinned out as they grow, the wood removed in this way is considered a C-neutral input because this measure accelerates the growth of the remaining trees and increases the total accumulation of carbon.

Forest wood damaged by wind, fire, drought, or pests is considered a C-neutral input provided that a climate-change-adapted reforestation plan is submitted to Carbon Standard for approval.

The CO_2e expenditure for forest maintenance and timber harvesting is included in the overall balance via the safety margin for scope 3 emissions (c.f., Chapter 4.7).

It is assumed that no fertilization occurs in the forest; otherwise, the CO_2e expenditure for N-fertilization would have to be deducted from the C-sink potential.

Background reflections about forest biomass

Under the present standard, an area is considered a forest when presenting a canopy density of at least 50%. The forest area units should not exceed 100 ha for efficient control of sustainable forest growth. The total biomass of an existing commercial forest of max. 100 ha must not decrease when the harvested biomass is used for the development of C-sinks. Therefore, the loss of wood must be balanced by the growth of forest wood in the referenced area unit. Furthermore, only a maximum of 80% of the harvested biomass must be removed from the forest to maintain the nutrient cycle and forest biodiversity. The degree of canopy density within the 100 ha must not fall below 50% because of the timber harvest.

If, for example, the annual regrowth of a 100 ha spruce forest amounts to 650 t (dry matter = DM), only a maximum of 650 t DM per year should be felled, of which a maximum of 520 t DM (80%) should be removed from the forest for wood processing and wood use.

However, there is currently no comprehensive forest assessment of area units of 100 ha or less in most countries of the world. The reference area units are considerably larger than 10,000 ha, and the forest regrowth is extrapolated using regional average values.

If, for example, in regional forests such as the Black Forest in Germany or the Arlberg in Austria, the total forest's standing biomass is higher than in the preceding years, the withdrawn biomass is regarded as climate neutral according to the European Regulation [2018/841] (EU-Parliament, 2018). Ecologically, it is at least questionable that, e.g., a densifying mountain forest is allowed to compensate for clear-cutting in a more accessible valley. However, until the expected reform of the EU LULUCF regulation (EU-Parliament, 2018), **all wood from forests whose regrowth demonstrably exceeds the removal, independent of its size and structure, is recognized as C-neutral input for the Global Biochar C-Sink certification. The time of the regrowth is set as time of**

removal. If the regrowth of last year is harvested and pyrolyzed, the time of removal is set to the year of harvest. If the regrowth of several years is harvested, the time of removal must be distributed proportionally to the growth years and entered accordingly into the Global C-Sink Registry as described in the Global Tree C-Sink Standard.

We want to justify here the decision to adhere to European forest legislation and UNFCCC accounting rules despite their imperfections. While it is our intention to set all Global C-Sink Standards on scientifically reliable feet, starting with too idealistic restrictions may suffocate the development of the nascent pyrolysis and C-sink economy. If the EU nations promote bioenergy as climate-neutral and allow the regrowth of their forests to be counted as C-sinks in the National Declared Contributions (NDC), it is not up to the Global Biochar C-Sink to classify the same biomass as not climate-neutral. Nevertheless, it is our conviction that forests and forest wood should not be used for energy generation and when generating C-sinks, the process should be more efficient than simply pyrolyzing the extracted biomass for biochar only (Schmidt et al., 2018; Song et al., 2018). Instead, forest wood should first be used as a source for long-lived materials, whereas biochar can still be produced from residues, e.g., sawmills or debris.

5.3.4 Biomass from landscape conservation, agro-forestry, forest gardens, field margins, and urban areas

If trees or hedges on agricultural land are pruned or trimmed but not felled and thus grow back from their roots, the biomass is considered C-neutral. Biomass from nature conservation, landscape management, including disaster debris removal and roadside greenery, and urban areas, is also considered C-neutral.

Trees from forest gardens, orchard meadows, tree lines, and hedges for arable farming are often decades old. They have to be managed so that the amount of wood removed per unit area does not exceed the amount of the average annual regrowth. It should be monitored at the farm level (c.f., Chapter. 5.4).

If trees, hedges, reeds, and others have been newly planted on agricultural land for their ecosystem services and biomass production as co-benefit (e.g., landscape conservation, water management, buffer areas around ponds and streams, or agroforestry), the harvested biomass can be considered C-neutral at the time of harvest. However, it must be ensured that biomass production is maintained in the corresponding area either through new planting or rejuvenation.

For pruning and landscaping material, the time of CO_2 removal is assumed to be the year of cutting. Felled trees that are not used at least partly for material purposes but whose wood is entirely pyrolyzed, burnt or decomposed must be registered with their respective growth and thus CO_2 removal curve according to the Global Tree C-Sink Standard (link).

5.3.5 Wood processing residues and waste timber

Traceability of wood processing residues is often challenging, especially in larger sawmills, and it is, of course, better if the wood waste is used to build up C-sinks instead of being wasted. However, primary waste wood amounts to more than 50% of the harvested forest biomass and must, when used for C-sink and energy production, be considered a raw material and not a waste. Therefore, when using saw dust, bark, and lumber residues (primary wood waste) from a sawmill or directly from pre-processors in the forest or on the way to a sawmill, the wood must be certified as required under 5.3.3. The more primary waste wood gains prominence as a reliable economic asset, the more it influences secondary wood processors to encourage forestry managers to adopt climate-positive and sustainable management practices.

Secondary wood waste from recycled wood products (e.g., recycled construction and service wood such as lumber, pallets, furniture, etc.), often also referred to as waste timber, are considered C-neutral. The time of CO_2 removal is set to the year of pyrolysis.

5.3.6 Organic residues from the processing of food and other biomass

Pomace, nutshells, fruit stones, coffee grounds, and other organic residues from food processing are considered C-neutral input materials because the CO_2 footprint of food production is credited to the production of primary products (e.g., wine, olive, or any other kind of oil, fruit juice, coffee, etc.). Also, other industrial biomass processing residues such us paper sludge, bio fiber washing, fresh palm fruit bunches are considered C-neutral. The time of removal is set to the year of pyrolysis.

5.3.7 Municipal waste and municipal waste digestate

As municipal waste is pure waste, no emissions for its production must be accounted. Pyrolysis reduces emissions compared to incineration and also to landfill applications. Landfill-applied organic waste is, to a large extent, transformed into methane that is only partly recovered as landfill gas. Overall, the climate balance of soil or material applied biochar from municipal wastes is better than from landfills. Moreover, the contamination of soils at waste dumping sites is clearly reduced thanks to pyrolysis.

Municipal waste contains not only biogenic but also fossil carbon, such as plastic polymers, composites, textiles, etc. Only the proportion of biochar from the organic carbon fraction can be certified as C-sink and must be distinguished from fossil carbon.

To distinguish between organic and fossil carbon, the most reliable analytical method uses radiocarbon analysis (fossil carbon does not contain ^{14}C). As radiocarbon analysis is relatively expensive, and mixed waste is highly heterogeneous, biochar from mixed waste should be collected over a longer period (e.g., one month) before taking representative samples and determining the part of organically derived carbon in the well-mixed biochar made from mixed waste. The production, monitoring, homogenization, sampling, and analysis procedures are explained in detail in the *Municipal Waste Annex*. For organic waste, up to 5% of plastic contamination can be accepted without the need for further measures to subtract the fossil fraction. The fossil carbon content in the biochar is then covered by the safety margin.

5.3.8 Manure and agricultural digestate

Manure and manure digestate are secondary products of animal farming. The storage and application of animal manure and its digestate cause significant quantities of GHG emissions that can be reduced when manure or manure digestate is pyrolyzed (Rathnayake et al., 2023). The feed that animals transform into manure is made from biomass that has removed its carbon from the atmosphere. As animal growth and production is the operation's main objective, the feed production's carbon footprint is not accounted for in the manure. Manure and its digestate are thus considered as climate-neutral feedstock. Only transport emissions must be accounted for.

Biochar that is mixed with manure prior to manure pyrolysis or anaerobic digestion, or with digestate prior to its pyrolysis, must not be accounted for as a C-sink.

If biochar is used as animal feed, additional documentation must be provided to demonstrate that the resulting manure is ultimately destined for a soil-based application and that pyrolytic treatment can be excluded. Animal feed may contain biochar already registered as a diffuse C-sink (see Chapter 12.2). In such cases, the resulting manure must not be registered as C-sink.

The time of CO_2 removal is set to the year of pyrolysis.

5.3.9 Biosolids and biosolid digestate

Regarding the C-sink accounting, biosolids and their digestate are similar to manure. As food is the main original input material for biosolid production and food is mostly made from annual crops, the feedstock is considered carbon neutral. Non-organic polymers used in wastewater treatment (flocculation additives) and some industrial waste liquids containing fossil carbon-derived molecules may enter the sludge. For biosolids from municipal wastewater treatment plants, these aspects are largely covered by the margin of safety. Industrial wastewater treatment plants must document the origin of the carbon. The eligibility of industrial wastewater sludge as feedstock for C-sink certification can only be decided individually during the technical audit.

Overall, biosolids are considered as a climate-neutral feedstock for biochar production, and the time of CO_2 removal is set to the year of pyrolysis.

5.3.10 Other biogenic residues

Carbon neutrality can generally be assumed for all other biomass on the EBC and WBC positive list. However, depending on the feedstock used, this must be considered individually during the certification procedure. The time of removal would generally be the year of pyrolysis, though this is verified during the certification procedure.

New feedstock categories will be added for C-sink certification as required or requested.

5.4 Monitoring Perennial Biomass Production Systems

Until general monitoring of growth, storage, and use of biomass carbon is established on a broad scale, this standard relies on self-declaration by biomass producers regarding carbon neutrality, with the exception of forest wood (chap. 5.3.3), unless there is an urgent suspicion of carbon overexploitation. We encourage forestry biomass producers to become certified under the Global Tree C-Sink Standard, which generates remuneration opportunities for C storage in living biomass and guarantees the carbon neutrality of the biomass produced.

6 Storage of biomass feedstock

If moist biomasses are stored for too long in too large piles, uncontrolled self-heating occurs. In this process, the biomass is microbially degraded, similar to composting, which results in the loss of carbon as CO_2. Depending on the biomass and storage conditions, emissions of CH_4 and N_2O may also occur.

Biomass power plants often use the self-heating of wood chips to dry them. A review of 14 scientific studies on the decomposition of woodchips during storage has shown that depending on storage conditions, wood species, and wood moisture, between 0.6 to 4.3% of biomass carbon is degraded per month (Whittaker et al., 2016). For wood chip piles larger than 1 m^3, biodegradation of the wood leads to oxygen consumption inside the pile, eventually leading to anaerobic degradation and methane emissions. How high the actual methane emissions are depends on factors such as temperature, humidity, pile volume, type and age of the wood, and its C to N ratio. Measurements have shown that up to 20% of the gaseous carbon produced during storage inside the pile is transformed into methane (Pier and Kelly, 1997). However, Jaeckel et al. (2005) found that methanotrophic microorganisms in the heap's better-aerated near-surface layers degrade between 46% and 98% of the methane produced in the core before it can escape as an emission to the atmosphere. In summary, scientific studies of actual methane emissions from wood chip storage are sparsely available and often incomplete, so generalizations regarding storage emissions must be made cautiously (Ferrero et al., 2011).

However, storage emissions can be effectively avoided. Although this involves additional effort and possibly also costs, the avoidance of emission losses has the beneficial side effect of losing less of the biomass's energy content. The following measures are generally recommended for biomass storage and, if implemented correctly, would avoid any storage emissions to be added to the emission portfolio of the batch and production unit.

- Wood and other biomass should be chipped only a few days and at a maximum of four weeks before pyrolysis. Log storage is considered unproblematic regarding methane emissions; coarse wood (thinner logs, branches, cuttings, etc.) should be stored as airy as possible and not mixed with green waste.
- If just-in-time chipping is not possible, the wood chips or biomass should be dried as soon as possible, e.g., with the excess heat from pyrolysis and stored dry with a maximum of 20% residual moisture. If the biomass is sufficiently dry, biodegradation does not take place or is slowed down considerably.
- Pelleting of biomasses and dry storage of pellets avoids rapid biomass decomposition.
- Alternatively, the wood chips or the biomasses can be stored in small, well-ventilated containers such as lattice boxes (max. 2 m^3). Due to sufficient ventilation, anaerobic degradation and, thus, methane emissions can be prevented.
- Other practical methods, such as sieving the fine particles, will certainly also prove efficient.

If none of these recommendations can be implemented, it must be assumed that substantial methane emissions occur, that they are not covered by the margin of safety, and therefore must be calculated as follows:

For the storage of moist wood chips and sawdust, we assume that 2.5% of the biomass carbon is degraded per month, of which 20% is transformed into methane. 75% of this methane gets microbially degraded in the storage pile and is not released into the atmosphere. We thus calculate for moist storage of woody biomass that (2.5% * 20% * 25%=) 0.13% of the biomass C is emitted as methane-C per month.

For storing moist, non-woody biomasses such as straw, crop residues, pomace, etc., but also for wood waste with a high content of green plant material, data on methane emissions during uncontrolled composting are applied. According to the IPCC methodology, 10 g of CH_4 emissions are generated per kilogram of biomass (DM) during complete composting (Pipatti et al., 2006). This corresponds to about 1.5% of the carbon contained in the biomass. Assuming that a conventional windrow composting process takes an average of 6 months (Pier and Kelly, 1997), the composting storage results in an emission rate for methane-C of (1.5% / 6 =) 0.25% per month.

For the storage of wood chips and sawdust with more than 20% moisture for more than one month, CH_4 emissions of 0.13% of the original C-content are imputed per month. For all other biomasses with more than 20% moisture and storage time of more than one month, 0.25% of the original biomass C-content are accounted for CH_4 emissions per month. One kilogram of methane-C equals (1 kg / 12.011 kg $kmol^{-1}$ * 16.04 kg $kmol^{-1}$ =) 1.335 kg methane. Methane emissions that may already occur during the first month of biomass storage are sufficiently covered by the general margin of safety (c.f., Chap. 4.7).

$$\begin{aligned} CH_4\_wood\_storage = \; & \text{Mass of feedstock (DM)} * \text{C\_content of feedstock} * \\ & (\text{\#months of storage} - 1 \text{ month}) * 0.13\,\% * 16 \text{ kg mol}^{-1} / 12 \text{ kg mol}^{-1} \end{aligned}$$

Equation 9: Calculation of CH_4 emissions during the storage of moist woody biomass (> 25% water content) if storage exceeds 1 month.

$$\begin{aligned} CH_4\_non\text{-}wood\_storage = \; & \text{Mass of feedstock (DM)} * \text{C\_content of feedstock} * \\ & (\text{\#months of storage} - 1 \text{ month}) * 0.25\,\% * 16 \text{ kg mol}^{-1} / 12 \text{ kg mol}^{-1} \end{aligned}$$

Equation 10: Calculation of CH_4 emissions during the storage of moist non-woody biomass (> 25% water content) if storage exceeds 1 month.

For example, if wood chips that are used as feedstock for pyrolysis have a water content above 25% and are stored in a large pile for an average of two and a half months prior to pyrolytic processing, a C loss of ((2.5-1) months * 0.13% =) 0.195% of the total C of the pyrolyzed biomass is assumed. For an annual processing of 4000t (DM) of wood chips with a C-content of 48%, the methane emissions to be estimated for 2.5-month storage without preceded drying would correspond to (4000 t * 48% * 0.195% =) 3.74 t CH_4-C, which equals (3.75 t CH_4-C * 16 kg mol^{-1} /

12 kg mol^{-1} =) 5.0 t CH_4. The calculation is carried out using the values given above and rounded to 0.1 t.

If 4000 t (DM) of grape marc with a C-content of 48% were processed, the methane emissions to be estimated for 2.5 months of storage without prior drying would correspond to (4000 t * 48% C * 0.25% CH_4 * 1.5 months =) 7.2 t CH_4-C and (7.2 t CH_4-C * 16 kg mol^{-1} / 12 kg mol^{-1} =) 9.6 t CH_4.

For the storage period, not only the storage on the premises of the pyrolysis plant is considered, but the entire storage period of the biomass, whether at the harvest site or the site of any biomass processor or trader. For example, for the processing of pomace, the storage start time is considered to be the emptying of the wine press. For wood chips, the moment of chipping applies. During control, the logistics of biomass processing and its transport must be fully traceable.

During the on-site control visit, the core temperature of the biomass has to be measured for all sites where biomass is stored for more than one month. In case of temperatures of more than 5°C above ambient temperature, which cannot be plausibly explained, e.g., by diurnal fluctuations, the above formula is applied to calculate the accruing GHG emissions. The EBC and WBC certification monitoring may also specify an in-house temperature monitoring of the stored biomasses (e.g., daily measurement of the core temperature of one or more biomass storage facilities).

7 The Biochar Production Facility

7.1 Energy and Fuel Consumption for Transportation, Preparation of the biomass, the Pyrolysis Process and Post-Treatment of the Biochar

Biochar production usually produces an energy surplus. Still, some external energy is usually required to operate pyrolysis facilities. For example, electrical power is necessary for control systems as well as for conveying biomass and biochar. Depending on the type of pyrolyzer, (fossil) fuel gas or electricity is also required for preheating the reactors and/or burning chambers. Certain plant types produce pyrolysis oil and pyrolysis gas in addition to biochar but use electrical energy to heat the biomass. Consequently, to calculate the pyrolysis plant's carbon footprint, each plant must be equipped with meters for electricity and if applicable for natural gas and fuel.

The energy and fuel-related carbon expenditure for the entire process chain, from the provision of biomass to the packaging of the biochar, is calculated in CO_2e and included in the emission portfolio of the batch and the respective production unit (i.e., the pyrolysis unit that is used to produce the batch). This concerns in particular:

(1) Transportation of the biomass to the pyrolysis plant.

(2) Chipping, homogenization, pelletizing, and drying of the biomass.

(3) GHG emissions of the pyrolysis plant (i.e., electricity, heat, and fuel consumption).

(4) Post-pyrolysis treatment of the biochar (e.g., drying, mixing, liquid loading, grinding, pelletizing, etc.) and other products (e.g., purification of H_2, CO_2, and/or other gases, refining of pyrolysis oil, etc.).

(5) Transport of the biochar to the collection depot (factory gate).

Emissions due to post-pyrolytic treatment of non-biochar products need to be considered to allow accurate pro-rata calculation of carbon expenditures, even though these products are not certified under the present standard. Accounting for electricity and fuel consumption for all these individual steps is necessary for the certification. The conversion of electricity consumption into CO_2e is based on the specific information provided by the contractual energy provider or the average CO_2e value of the regional electricity mix used. If renewable energy is used, the CO_2e footprint can be close to zero. However, some greenhouse gas emissions occur also for solar, wind, biomass, and hydropower and must thus be declared and included in the emission portfolio. In the case that the energy provider cannot provide a reliable footprint assessment, average literature values will be used by the certifier (IPCC, 2022; Kadiyala et al., 2016; Nugent and Sovacool, 2014). If the pyrolysis plant itself generates at least as much electricity on an annual average as is consumed in the production facility and the entire production facility offsets its emission with biochar C-sinks, a CO_2e of zero may be assumed for electricity consumption.

The amount of fuel used to heat the pyrolysis reactors are to be reported per batch (invoices for purchasing fossil fuels) and are converted to CO_2e by fuel type (usually 65 t CO_2e per TJ (Juhrich, 2016))

For the consumption of diesel or benzine fuel for transportation, chipping, drying, etc., the conversion factor of 2.7 kg CO_2eq per liter of diesel fuel is applied (Juhrich, 2016).

7.2 Energy Surpluses

If the energy balance of a biochar production facility is positive, i.e., measurably more electrical and/or thermal energy is produced than consumed, the positive energy balance can be credited as an emissions reduction with the appropriate agencies, but not within the Global C-Sink. The positive energy balance can neither increase the C-sink nor offset emissions from biomass supply.

If all GHG emissions from biochar production are offset and compensated for, including the CO2 footprint of the production of the other pyrolysis products (e.g., electricity, hydrogen, pyrolysis oil, etc.), those secondary pyrolysis products can be certified as carbon neutral under the present standard. However, if the pro rata approach (chapter 4.6) is employed, carbon neutrality of the non-biochar pyrolysis products cannot be certified.

7.3 Methane Emissions during the Pyrolysis Process

During pyrolysis, the pyrolysis gases are usually oxidized in a suitably designed combustion chamber. Usually, the gaseous combustion products pass a filtration step and are then emitted mostly as CO_2. If the pyrolysis process is well-adjusted and the combustion chamber correctly designed, non-CO_2 GHGs and other pollutants can be kept at very low levels in the exhaust. However, CH_4, NOx, CO, and particulate matter (PM) are, as in all combustion processes, never completely absent and must be controlled. Concerning the net climate impact, methane emission is particularly important to measure. CO, NOx, SOx, and PM are also harmful to the environment, but according to the IPCC, they do not have a clear greenhouse gas effect (IPCC, 2013) and are therefore not accounted for the emission portfolio, while CH_4 is included.

As detailed in Chapter 4.4, for the conversion of the total climate effect of methane, the GWP100 is accounted for with a factor of 27, but it must be compensated within the first 20 years after the emission. Due to the high GWP100 of methane and the short compensation period, even very small methane emissions during the pyrolysis process have a major impact on the carbon footprint of biochar production. In pyrolysis plants without controlled combustion of the pyrolysis gases (e.g., Kon-Tiki or traditional charcoal kilns), the global warming effect of methane emissions can even exceed the climate-positive effect of biochar for the first 20 years.

Measuring methane emissions below 5 ppm is technically complex. Continuous measurement over an entire production year is not possible with currently available technology. Therefore, either at least two CH_4-emission tests per pyrolysis unit with the same feedstock representing the typical operation of the unit are required, or the pyrolysis unit must have a type certification according to EBC or WBC.

For CH_4 emission tests, a detailed measurement strategy with precise details of the measurement technology, measurement intervals, and measurement accuracy must be submitted in advance to

Carbon Standards for review. Once the procedures are accepted, the methane emissions factor of the pyrolysis unit is calculated as the mean of the two measurements plus one standard deviation as the margin of security.

Box 4: Calculation of pyrolytic carbon expenditures.

Example for the calculation of the carbon expenditure of pyrolysis (continued)

- With an annual production of 500 t of biochar (DM) having a carbon content of 75.0%**, 50,000 kWh of electricity** is used to operate the pyrolysis plant (measured with a dedicated electricity meter at the pyrolysis unit). The local electricity mix emits 450 g CO_2eq per kWh. Thus, the carbon expenditure for electricity consumption is 50,000 kWh * 0.45 kg CO_2e $(kWh)^{-1}$ = 22.5 t CO_2e per year.
- Emission measurement of pyrolysis exhaust gases resulted in a **methane content of 10 ppm** (6.6 mg CH_4 m^{-3}) in the exhaust gas for 7000 operating hours per year at a gas volume flow of 1500 m^3 per hour. This results in methane emissions per annual batch of (1500 m^3/h * 7000 h * 6,6 mg CH_4 m^{-3} =) 69,3 kg CH_4.
- To preheat the pyrolysis reactors**, 5 t of liquefied petroleum gas (LPG;** 3 t CO_2e t^{-1}) are consumed per year. This results in a carbon expenditure of 15 t CO_2e per year.
- The above results in an emission portfolio entry of 22.5 t CO_2e electricity + 15 t CO_2e LPG + 69.3 kg CH_4 pyrolysis emissions per batch.

For the EBC and WBC pyrolysis type certification, at least three installations of the same type from the same manufacturer must be in commercial operation at different sites. For each of these three plants, at least two independent, state-accredited emission measurements including CH_4 or C_xH_x must be available. From these measurements, a statistical mean value with standard deviation is calculated. The average methane emission of this type of plant is then set to be the mean value plus one standard deviation. If an emission measurement for methane or C_xH_x is below the measuring accuracy of the instruments, the limit of quantification (LOQ) is used. The assessed methane emissions are thus higher than the calculated average and provide a sufficiently high safety margin to cover any potential emission peaks, e.g., during start-up and shutdown of operation. The measured values for methane emissions are given in ppm of the flue gas (i.e., combusted pyrolysis gas) and converted into g CH_4 per ton of biochar via the flue gas flow per mass unit of biomass input or biochar output. This resulting value is then registered as the methane emission factor for all pyrolysis units of the same type, utilizing a consistent standard feedstock.

8 Carbon and Energy Use Efficiency

Biomass is a valuable resource that must be utilized responsibly. In the Global Biochar C-Sink, this is assessed using the carbon and energy use efficiency. While there is minimum limit value for the energy use efficiency that all certified pyrolysis units must comply with, the carbon use efficiency is only indicative value registered in the Global Biochar Tool.

8.1 Carbon Efficiency of Pyrolysis Operations

Carbon efficiency refers to the ratio of carbon transformed into a storable form (i.e., amount of carbon in a batch of biochar) to the input of carbon (i.e., amount of carbon in the biomass used to produce the biochar). To reach at least 15 Gt CO_2e of global long-term carbon sink establishment per year, the carbon efficiency of biomass-based negative emission technologies must be increased. Plants are highly efficient in concentrating atmospheric carbon into dense carbon molecules. The removed carbon is preserved and acts as a C-sink for as long as a plant lives. Every transformation step of biomass leads to carbon losses, i.e., emissions of (biogenic) CO_2. The harvest induces the decomposition of roots and harvest residues, GHG emissions occur during the manufacturing of food, feed, and biomaterials, and, finally, waste management, where composting, anaerobic digestion, waste incineration, or landfills also result in biomass decomposition in one way or the other. Typically, the carbon balance is zero as all carbon that is emitted from biomass use was initially removed by plants from the atmosphere. However, considering that plants provide a natural carbon service (removing carbon from the atmosphere), humanity could use this carbon pump to tweak the biomass-use systems to remove as much carbon as possible from the atmosphere. The area on earth where plants can grow is limited. Even the ocean area that we can use wisely to grow brown algae or other biomasses is limited. Using finite resources makes mankind responsible for using them wisely and efficiently.

Compared to composting, mulching, incineration, or waste dumping, pyrolysis significantly increases carbon efficiency. However, when using primary biomass such as wood, pyrolysis is less C-efficient than its material use in buildings, infrastructure, furniture, composites, or textiles. Also, storage of compressed, dry biomass in controlled geological storage, such as salt domes or oil wells, could be more C-efficient, preserving close to 100 % of the biomass carbon for extended, though not geological, periods of time.

Depending on production parameters and feedstock, pyrolysis preserves about 30 to 60% of the biomass carbon in the biochar. When pyrolysis oil can also be sequestered, C-efficiencies of around 80% can be reached (Schmidt et al., 2018); with CO_2-CCS of the combusted pyrolysis gas, even higher C-efficiencies are possible.

If, in a pyrolysis process, only the biochar-C is preserved, the carbon efficiency is too low to aspire for large-scale negative emissions (Werner et al., 2018). For developing pyrolysis technology in the next decade, this might still be acceptable, but as long as biomass carbon is the principal source for carbon sinks, no carbon must be squandered.

The carbon efficiency of a pyrolysis facility is a measure of the part of biomass-carbon that is preserved by a technical transformation process as a potential C-sink. It is assessed at the factory gate of the pyrolysis facility independent of the further storage and use of the carbon products.

At the current stage of pyrolysis and other CDR technology development, imposing specific thresholds for C-sink efficiency would be overly restrictive. This is further emphasized by the increasing role that pyrolysis energy plays in providing process heat for industry and district heating while reducing reliance on fossil fuels. However, it is essential to have a clear objective of transforming a growing proportion of biomass carbon into carbon sinks. This also may comprise temporary C-sinks in rather short-lived products, e.g., from pyrolysis oil; and replacing crude oil products in everyday lives is also part of climate change mitigation. To achieve this, C-sink efficiency must be evaluated and used as a benchmark for progress. The carbon efficiency is not disclosed on the carbon sink certificate.

The C-sink efficiency of a biochar batch is calculated by dividing the total sequestrable pyrogenic carbon (biochar, pyrolysis oil, purified CO_2, and derived products) by the total biomass carbon used as feedstock for the entire batch. Only biochar, pyrolysis oil, and CO_2 that is or will be registered as C-sink are included. Biochar that is or will be sold as charcoal for barbecue, for the metal industry or other applications where the carbon is oxidized and reemitted to the atmosphere must not be included. The value is given as a percentage of initial biomass carbon.

To estimate the carbon efficiency, the pyrolysis company is requested to declare for what markets their products are intended. The carbon efficiency is calculated at the factory gate.

8.2 Energy Use Efficiency of Pyrolysis

The limited availability of biomass necessitates its efficient utilization. To address this, the standard incorporates two complementary strategies. While the C-sink efficiency discussed in the previous chapter is introduced for transparency purposes (customer information), there is a threshold value for energy efficiency that must be met in the production of each biochar batch for Global Biochar C-Sink certification.

The energy use efficiency provides the rate of how much of the energy contained in the biomass feedstock was transformed into usable energy and other beneficial products with a market value. The energy use efficiency does not express how beneficial and meaningful the different products are but provides a measure of how energy efficient the biomass carbon is used within the process. This may include the following uses on top of biochar production:

- Thermal and electric energy production to replace fossil fuel-derived energy, it avoids GHG emissions. Thermal energy can be used, e.g., in district heating or industrial processes.
- Thermal energy from combusting pyrolysis gas can be used to dry biomass feedstock for the pyrolysis plant itself, which would be accepted as a meaningful energy use.

- Charcoal is used for metallurgy to replace fossil carbon and thus reduces GHG indirectly. If it is used for barbecue or for other applications where it is oxidized and the carbon is reemitted as GHG to the atmosphere, it can still be seen as financially reasonable and climate-neutral carbon use.
- Pyrolysis oil can be used for the chemical industry or as fuel. Its carbon will, thus, be oxidized and returned as CO_2 back to the atmosphere within a relatively short time. Still, it will not cause more emissions than the biomass had removed from the atmosphere during its growth.
- Pyrolysis gas contains hydrogen and methane, that can be extracted.
- CO_2 can be extracted in pure form from the combustion of pyrolysis gas and pyrolysis oil for further use (i.e., carbon capture and use – CCU) or storage.

Therefore, if the non-biochar fraction of the pyrolysis products is used for energy production or as raw material for chemical or other industries, the biomass-carbon is considered as having been used meaningfully.

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The energy use efficiency is calculated as follows (in kWh):

- The energy content of the feedstock is quantified as the lower heating value (LHV). If the feedstock is clearly defined, the LHV can be taken from the literature. Mixed and not clearly defined biomass and feedstock known for its high energy content variability (e.g., sieving residues from composting) must be analyzed in a laboratory endorsed by Carbon Standards. A list of endorsed laboratories is available on the Carbon Standard webpage.
- The energy content of the biomass processed for production of the batch is calculated by multiplying dry mass and lower heating value providing the parameter $E_{feedstock}$.
- The energy needed to produce the batch is quantified according to Chapter 4.2 ($E_{Expenditures}$)
- The energy content of the solid pyrolysis products (biochar, charcoal) is quantified as the LHV and multiplied by the total dry mass of biochar produced (E_{solid}). The LHV of the biochar and charcoal must be analyzed from the EBC/WBC certification sample.
- If pyro-oil is separated for storage or use, its LHV is quantified and multiplied by the total amount of pyro-oil co-produced with the biochar batch ($E_{pyrooil}$). The LHV of the pyro-oil must be analyzed in a laboratory endorsed by Carbon Standards. If different fractions of the pyro-oil are produced, the LHV of each fraction has to be analyzed.
- If thermal energy is used for drying biomass, 810 kWh per ton of evaporated water (2.44 kJ per gram of water + 20% margin) can be accounted for. The amount of evaporated water can be calculated based on the mass and moisture content of the biomass received and the achieved moisture content (e.g., 15% as required by most pyrolysis units) (E_{drying}).
- If thermal energy is supplied to district heating or industry, the actual amount used must be metered ($E_{thermal}$)
- If the pyrolysis gas is used to produce hydrogen, methanol, or other marketable fuels or chemicals, their energy content is to be provided as $E_{fuel\_products}$. If CO_2 is separated after oxidation of the pyro-gas, this can be accounted for with a maximum of 1000 kWh t^{-1} CO_2 which provides the parameter (E_{CO2pur}) (Zheng et al., 2023).

The total amount of used electrical and thermic energy, and the heating value of the marketed pyrolysis products is divided by the sum of the energy content of the biomass feedstock and the external energy used to produce the entire batch. The value is given as a percentage.

$$E_{eff} = \frac{E_{solid} + E_{pyrooil} + E_{fuelproducts} + E_{thermal} + E_{drying} + E_{electric} + E_{co2pur}}{E_{feedstock} + E_{expenditures}}$$

Equation 11: Calculation of the energy efficiency (E_{eff}) using the energy content of the biochar (E_{solid}), the pyrolysis oil ($E_{pyrooil}$), the fuels produced by the pyrolysis proces ($E_{fuelproducts}$), the produced thermal energy ($E_{thermal}$), the energy used for feedstock drying (E_{drying}), the electricity produced ($E_{electric}$), the energy value of separated CO2 from the flue gas (E_{CO2pur}), the lower heating value of the feedstock ($E_{feedstock}$), and the energy expenditures for the entire pyrolysis facility ($E_{expenditures}$).

In most cases of today's pyrolysis facilities, the calculation looks a lot simpler:

$$E_{eff} = \frac{E_{solid} + E_{thermal} + E_{drying} + E_{electric}}{E_{feedstock} + E_{expenditures}}$$

Equation 12: Simplified calculation of the energy efficiency to be used for most biochar production facilities.

For every batch of a certified pyrolysis unit, at least 60% of the sum of the energy contained in the biomass and all energy expenditures of the process must be used.

Box 5: Exemplary calculation of the energy use efficiency

Example for the calculation of the energy use efficiency of a wood gasification plant for one annual batch:

- **Input (feedstock):** Annual feedstock 4000 t of wood with a dry matter content of 65%, a carbon content of 48%, and a lower heating value (LHV) of 4 kWh/kg (@ 80% DM) representing (3250 t (@80% DM) * 4 MWh/t =) 13,000 MWh.
- **External energy input (consumption):** Electricity consumption of the facility during the batch 375 MWh, 3 t LPG starter gas with 13 kWh/kg, 13 t diesel for feedstock preparation and transport with 11.8 kWh/kg representing (375 MWh + 3 t * 13 MWh/t + 13 t * 11.8 MWh/t =) 567.4 MWh
- **Output:** The unit produces per year 260 t biochar with LHV of 7.9 kWh/kg representing 2054 MWh, 5000 MWh of used heat, 2340 MWh electricity, and uses 800 MWh of the heat for feedstock drying representing (2054 MWh biochar + 5000 MWh used heat + 800 MWh drying + 2340 MWh electric =) 10,194 MWh.
- **Energy efficiency of batch**: 10,194 MWh / (13,000 MWh + 567.4 MWh) = 75.1%.

The 75,1 % energy efficiency is higher than the threshold of 60%, the facility can be certified.

9 Labeling of Biochar Properties for C-Sink Certification

9.1 EBC/WBC Labeling

If a pyrolysis plant is certified according to the EBC or WBC standard, the following information must be provided on each packaging and on delivery bills:

1. EBC or WBC certification is a prerequisite to Global Biochar C-Sink certification, so the QR code of the respective EBC or WBC batch must be printed on the delivery note and attached to each packaging unit. This QR code refers to the Global Biochar Tool, which documents the corresponding biochar batch's analytical data and production conditions.
2. Since the C-sink potential refers to water-free biochar, the dry weight of the biochar must be indicated for each packaging unit. The dry weight is the mass of the dry substance and is stated in tons or kilograms, rounded to 1% of the total weight. If the analysis of the dry weight results, for example, in 455.57 kg of 1000 kg fresh weight, the dry weight is rounded to 1% of the 1000 kg, i.e. to 10 kg. The dry weight would, therefore, be 460 kg.

The specifications for the labeling of products can be found in the Design Manual of Carbon Standards.

This QR code must also serve the dMRV system to track the biochar from the factory gate to its final use. The EBC/WBC and the Global Biochar C-Sink use the same QR code generated by the Global Biochar Tool. Alternatively, the dMRV provider may use its own QR code but must link then from the QR code landing page to the batch information provided by the Global Biochar Tool.

9.2 Dry Matter Content of Biochar: on-site measurement

The size of a C-sink is defined by its mass and carbon content. Mass here refers to dry mass, and it is a true challenge to measure it regularly onsite. The dry matter content of biochar cannot be measured directly but must be calculated from the fresh weight and the measured water content.

The water content of biochar can be subject to considerable fluctuations at the time of sale or even directly at the discharge of the pyrolysis plant. Reasons for this can be a fluctuating intensity of the quenching at the discharge, the absorption of air humidity, or air drying. Therefore, it is impossible to determine the C-sink using the dry matter content analyzed once per batch during the annual EBC/WBC-accredited laboratory analysis.

Also, the bulk density, which is needed to calculate mass from a given volume, can vary significantly within a batch, mainly due to variations in the particle size distribution of the pyrolyzed biomasses and abrasion during the transfer and transport of the biochar. Thus, a volumetric determination of the dry weight of the produced biochar is also not appropriate.

Therefore, the reliable and regular determination of the dry matter (DM) content is a prerequisite to indicate the dry weight and, thus, the C-sink potential of a packaging unit of biochar. This is a considerable effort for biochar producers, which is, however, unavoidable to maintain verifiability and, thus, confidence in the Global Biochar C-Sink Standard.

For each sub-quantity of max. 10 m³ of biochar, at least 20 individual sub-samples must be taken using a sampling stick. Combining a minimum of 20 sub-samples must yield at least a total sample volume of 10 liters of biochar. The individual sub-samples can be taken either from a collected pile or container of max. 10 m³ of biochar or from each of several big bags presenting a total amount of max. 10 m³. The combined sample is weighed using a scale with a precision of at least 1 gram. The biochar is then dried at 110 °C for at least 16 hours and weighed again. Weighing must be done immediately (max. 1 minute) after removal from the 110 °C drying oven. Otherwise, moisture may condense on the biochar and falsify the result. This method simplifies the usual DIN 51718 and ISO 589, which may also be followed.

Alternatively, CSI-endorsed moisture analyzers working on the thermogravimetric / loss on drying (LOD) principle like the PCE MA 110TS may be used to determine the dry matter content more rapidly. Here, the stop criteria selected on the device for reading the moisture content must be set to a maximum variation of 20 mg within 60 seconds. See annex X for a detailed description of the procedure.

The resulting moisture and dry matter values are recorded and used for the calculation.

$$\text{DM [\%]} = \frac{net\ weight\ after\ drying}{net\ weight\ before\ drying}$$

Equation 13: The dry matter content (DM) is calculated by dividing the net weight after drying by the net weight before drying.

If, for example, big bags (i.e., super sacks) of 1.3 m³ are used for storing biochar, a maximum of seven big bags may be combined for one representative sample. At least three sub-samples from each of the seven big bags must be taken with a standard sampling drill stick. All 7x3 subsamples are then combined and weighed as described above, dried, and weighed again. If the 10-liter sample weighs 3.057 kg before drying and 2.139 kg after drying, the dry matter content is (2.139 kg / 3.057 kg =) 69.970%. This value is rounded to full percentages for further calculations (here: 70%). The DM content determined in this way must then be multiplied by each big bag's individually determined (fresh) weight (see example in Table 1). This results in each big bag's respective dry weight, with which each big bag must then be labeled. For instance, if a big bag weighs 200 kg (fresh weight, net weight) and has a determined DM content of 70%, the dry weight is (200 kg * 70% =) 140 kg. It is rounded to whole kilograms.

For the described DM determination via drying of a representative sample, a relatively large drying oven and correspondingly accurate scales are required. Still, the effort for 10 m³ or seven big bags is manageable. Weighing of the big bags should be done on the same day as the sampling.

Deviations from the procedure described here can be regulated during the technical EBC/WBC audit, if, e.g., the dry weight is determined via a deviating method. If a producer can prove that the dry matter content does not change by more than ±2% over extended periods and production quantities, larger intervals between measurements can be authorized. If biochar with a particle size of more than 30 mm is produced, the subsamples' volume must be increased accordingly.

Table 2: Example of calculation of dry weight of a series of seven big bags.

Serial number of big bag	Volume	Weighed weight	Dry matter content	Dry weight
Big bag 2020-490	1,3 m3	195 kg	70%	137 kg
Big bag 2020-491		200 kg		140 kg
Big bag 2020-492		200 kg		140 kg
Big bag 2020-493		210 kg		147 kg
Big bag 2020-494		195 kg		137 kg
Big bag 2020-495		200 kg		140 kg
Big bag 2020-496		200 kg		140 kg

10 Post-Production dMRV: transport, processing, and tracking of biochar

10.1 Biochar dMRV System

From the moment a packaging unit filled with biochar (e.g., a big bag = super sack or a container) leaves the EBC or WBC certified factory site, many things can happen that may reduce or eliminate the potential C-sink of the traded biochar. The biochar may be burned, for example, as charcoal, processed into activated carbon, or used as a reducing agent in steel production, a significant amount of carbon would be lost to the atmosphere. Also, fossil fuels may be burned for the transport of biochar, and/or electricity may be consumed during pelleting or any other post-pyrolytic treatment. All resulting emissions must be compensated for.

Thus, biochar must be tracked by a digital Monitoring, Reporting and Verification (dMRV) system. The dMRV systems track the transport of each packaging unit from the factory gate to the C-sink or the C-Sink Matrix and assess the related emissions. These emission data are either added to the emission portfolio of the respective biochar batch and must be offset by the biochar producer or become part of the emission portfolio of the processor, trader, matrix-provider, or C-sink owner who are then responsible for offsetting them.

The dMRV system is usually provided by an external MRV system provider. External MRV systems and tools must be endorsed by Carbon Standards annually.

For as long as the packaging unit is stored closed on the factory premises and is protected from wind, rain, gases, and unauthorized diminution of stock, the C-sink potential remains unchanged. If the biochar is stored for more than one year, it can be registered as a temporary C-sink for the time of storage (cf., Chapter 12.6).

Once the biochar leaves the producers' premises, further emissions must be tracked. For this purpose, every packaging unit must be labeled with a scannable identification code (i.e., usually a QR code, cf. Carbon Standards design manual). The label accompanies the product on all transports and must provide the following information:

- Batch ID
- Link the EBC/WBC biochar analyses
- Date of production
- Year of CO_2 removal
- Owner of C-sink material
- Point of departure (GPS) for biochar transports
- Amount of biochar in dry matter tons.
- Biochar C-content
- Link to the emission portfolio

It is not necessary that all this information are accessible to the buyer of the biochar or biochar product, but the dMRV provider must make it accessible to the VVB and to Carbon Standards.

The tracking tool accompanies the cargo on its way. At the destination where the packaging unit is discharged, the packaging unit must be scanned and the new location registered to calculate the traveling distance and the CO_2e footprint of the transportation means. If the product changes ownership, it must be technically transferred to the new product owner. The new product owner confirms the transfer request online, and with this step, the seller and the buyer confirm the transfer of ownership.

When the biochar or biochar product is applied to soil, the landowner or tenant must agree explicitly to provide the soil plot as the entry point of the biochar carbon to geological storage (i.e., to the lithosphere and thus the slow carbon cycle). The landowner or tenant agreement can, e.g., be part of the general terms and conditions or the invoice for the purchased biochar product. The landowner does not necessarily become the C-sink owner as the biochar carbon will enter the commons (migrate from private property) once applied to soil.

When substantial amounts of biochar are integrated into materials to become a temporary C-sink (e.g., a building made of biochar-containing concrete), the material owner (e.g., the building owner) must be registered as C-sink owner and becomes the responsible entity for the maintenance of the temporary C-sink.

If the certified biochar is mixed into a C-sink matrix (cf. matrix positive list), the matrix incorporation can constitute the end of tracking, as the matrix guarantees that the biochar carbon cannot be lost through oxidation to the atmosphere. In such cases, registration of the geographic location of the physical C-sink is not required.

To ensure that the MRV system works without leakage and that only high-quality, verifiable C-sinks are sold as a climate service, Carbon Standards endorses the external MRV software tools. Endorsed dMRV providers may use their own dMRV Tool to track biochar along the supply chain on behalf of the C-sink owner.

10.2 Biochar Processor

If the biochar is delivered to a processing company that makes new biochar-based products and intends to use or trade these products under the EBC or WBC certificate, the processing company must be certified as a Biochar Processor under the EBC or WBC standard. Entities that only incorporate biochar into a matrix without further physical or chemical processing may alternatively qualify as C-sink matrix providers under Section 10.4, which does not require certification of the matrix provider nor processor.

All processing steps must be recorded with their CO_2e footprint. The annual EBC/WBC audit controls that the processing company supplies the data into the MRV system regularly for each batch that was handled. Once the products are repackaged, they must be registered as new product and C-sink unit providing the following information:

- Product processor
- Biochar production batch ID and/or QR code to access EBC/WBC biochar analysis.
- Date of biochar production

- Year of CO_2 removal
- Owner of C-sink material
- Point of new departure (GPS)
- Biochar C-content of product
- C-sink matrix, if mixed to one
- Emission that occurred during processing
- Link to the emission portfolio of the C-sink unit and/or company

Biochar that is incorporated into a C-sink matrix eligible for diffuse C-sinks (marked as *Diffuse C-Sink Authorized* in the matrix positive list of the Global Biochar C-Sink Standard) may be registered as a diffuse C-sink. This must be made visible by printing the Carbon Standards registered seal *Registered C-Sink* and a QR code linking to detailed information on the C-sink registration and its use. Additional specifications and formatting requirements are provided in the Carbon Standards Design Manual.

10.3 Biochar Trader

Biochar traders who trade bulk biochar must be registered as traders at Carbon Standards. Biochar traders that only sell packaged biochar, biochar containing products, and diffuse C-sinks do not need to register.

Biochar traders who do not repack the packaging units only need to scan the ID and add the storage location and date of arrival to the registered data. Once it leaves the premises again, the date of departure must be registered.

If the biochar is repackaged, the new packaging units must be registered and linked to the former registered packaging unit and all material and transportation data.

10.4 C-Sink Matrix Provider

A C-Sink Matrix Provider is an entity that incorporates EBC- or WBC-certified biochar into an eligible C-sink matrix or product without further physical or chemical processing of the biochar itself. Incorporation includes mixing, blending, or embedding biochar into a matrix as received from the biochar producer or trader. If the entity performs any physical processing of the biochar prior to incorporation — such as milling, pelletizing, or thermal post-treatment — it is considered a Biochar Processor and must be certified accordingly under Section 10.2. Likewise, a C-Sink Matrix Provider may not use the EBC or WBC logo on its products; if product-level certification is desired, Biochar Processor certification must be obtained.

C-Sink Matrix Providers must deliver the following data to their contracting entity (i.e., the upstream supplier, dMRV provider, or C-sink owner managing the C-sink registration):

- Acknowledgment of receipt of each packaging unit of biochar, e.g., by scanning the QR code on the packaging unit.
- Declaration of the amount of product produced and the biochar content (in mass percent) incorporated into the matrix.

Further specifications on the required documentation and evidence for specific matrices are provided in the C-sink matrix positive list published on the Carbon Standards website.

C-Sink Matrix Providers are not required to register with Carbon Standards AG. However, if they wish to become the C-sink owner and publicly communicate their role in the C-sink programme, they may optionally register as C-Sink Processors under Section 10.2.

If the C-Sink Matrix Provider is not registered with Carbon Standards, the following conditions must be confirmed with the contracting entity:

1. The C-Sink Matrix Provider consents to the sharing of the above data with the Validation and Verification Body (VVB) and Carbon Standards for the purposes of verification and registry management.
2. The C-Sink Matrix Provider confirms that it does not claim, use, or resell the C-sink value of the incorporated biochar.
3. The C-Sink Matrix Provider acknowledges that the C-sink value of the biochar incorporated into its products is registered and managed within a C-sink programme by the upstream contracting entity.
4. The C-Sink Matrix Provider accepts that, in justified cases, the VVB acting within the C-sink programme may audit the matrix provider's records relating to biochar receipt and incorporation.

Emissions arising from the incorporation of biochar into the matrix by the C-Sink Matrix Provider are not subject to separate emission tracking, as such activities are considered part of the provider's regular production process and do not generate additional emissions attributable to the C-sink establishment. Transport emissions from the C-Sink Matrix Provider to the C-sink site or to a subsequent processor or trader are attributed to the receiving entity unless already covered by a flat-rate transport emission factor agreed with the upstream supplier.

11 Geo-Localized and Diffuse C-Sinks

11.1 Geo-Localization of C-Sinks

The geo-localization of biochar C-sinks must be registered for all C-sinks containing more than 1 $tCO2_e$.

When biochar is applied to soil, the carbon sink must be registered with at least one GPS point situated within the land where the biochar is applied. The landowner or tenant must grant the right of passage to geology for the applied biochar carbon that thus returns to the slow carbon cycle (Schmidt and Hagemann, 2024). The landowner does not become the carbon sink owner by simply owning the soil but only by producing or purchasing the biochar, including its C-sink value. Biochar can be traded with or without its C-sink value.

Once the biochar carbon is applied to the soil, the property rights of the carbon expire and are transferred to the commons. Also, the farmer cannot be made legally responsible for preserving and maintaining the C-sink. The farmer or landowner may claim a unique financial compensation for granting the right of passage to geology but not for providing stewardship to the land where the biochar was applied. The activities of carbon removal, pyrolytic transformation, and eventual application to soil are climate services to be remunerated as climate action independently from private or communal land property. The eventual C-sink will eventually transfer far below and away from the initial soil in the lithosphere, waterways, and sediments, where no private property rights are granted.

The case is diametrically different for temporary C-sinks. Here, the biochar-carbon is part of a material matrix that is owned by a legal entity, and the C-sink cannot be dissociated from the imbedding material such as thermoplastics, textiles, carbon fiber composites, asphalt, or concrete. Here, the owner of the material is also the owner of the C-sink and must be registered. When biochar finds application in large materials such as constructions for residential, infrastructural, or road-related purposes, registration of the geolocation is required.

Recording the ownership and location of temporary C-sinks is essential for subsequent monitoring of their fate and maintenance.

11.2. Diffuse C-Sinks

If the biochar is incorporated into a C-sink matrix authorized for diffuse C-sinks (designated as *Diffuse C-Sink Authorized* in the C-sink matrix positive list for Biochar C-Sinks), it may be registered as a diffuse C-sink.

The C-sink matrix positive list (see Carbon Standards' website) classifies and specifies all permissible C-sink materials and applications that may be used to establish diffuse C-sinks.

Diffuse C-sinks are restricted to matrices in which the final C-sinks are highly spatially distributed. For example, when approximately 0.5 % biochar is incorporated into slurry and applied at 40 m^3 per hectare per year, this corresponds to about 0.2 tonnes of biochar per hectare annually. Adequate knowledge of the matrix's properties must be available to allow reliable modelling of the degradation behaviour of the applied biochar's SPC fraction.

A distinction is made between biochar-containing products that will eventually be applied to soil (e.g., compost, liquid fertilizers, manure additives, potting soil, feed) and industrial or consumer materials where waste treatment or disposal is the expected end-of-life scenario. If biochar was mixed at a volume ratio of at least 1 to 1 with compost, manure, feed, liquid fertilizer, rock powder, clay, lime, or ash, the spontaneous combustion or decomposition of the biochar and, thus, the loss of carbon can be practically excluded. Given the biochar-containing product is labeled and marketed as a soil amendment, feed product, potting soil, or manure additive, an eventual soil application can be expected, and the resulting C-sink may be registered as a geological C-sink. For certain matrices, additional documentation must be provided to demonstrate that the biochar–matrix will ultimately be applied to soil.

Biochar products not intended for soil application may have shorter or longer lifetimes but will eventually end up in waste incineration or recycling processes, releasing carbon as a greenhouse gas back into the atmosphere. For those products, either a control period (to check if the carbon product is still in use) or the average lifetime of the product is applied to define the lifetime of the C-sink.

It can be expected that CO_2 capture from waste incineration plants will become obligatory until 2050 and that the biochar-carbon of those industrial or consumer materials will never be released back into the atmosphere. However, as long as CO_2 capture from incineration and thermal waste treatment are not yet state-of-the-art, only the average lifecycle of the C-sink products can be registered.

When biochar is distributed in small amounts over a large number of serial products (e.g., several grams of biochar in a million pairs of skies), the registration of the temporary C-sink lies with the producer using the average lifetime of the products, and no C-sink location is required. In those specific instances where marginal quantities of biochar are applied or utilized in products, the registration of **diffuse carbon sinks** is permitted.

Diffuse C-sinks may present a risk of double counting if, e.g., the biochar-based product (e.g., a 30-l biochar-compost bag or the 25 kg bag of biochar clay plaster) was certified as a diffuse C-sink by the processor while the client thinks to compensate for some of its own global warming effects when using the biochar product in a garden or for the renovation of a house. To avoid such misunderstandings, diffuse C-sinks that are already registered as such must be labeled as a C-sink product, informing the buyer that the C-sink of the product is already registered and cannot be claimed for other emission compensations. This reference must at least be made by printing the following Carbon Standards registered seal: "Registered C-Sink" and a QR-Code with the web link to more detailed information about the C-sink registration and use. Further details can be found in Carbon Standard's Design Manual.

If a biochar-based product is used in a garden as a diffuse C-sink and the gardener applies for soil organic carbon certification ("humus certificates"), double accounting could theoretically occur because the usual measurements used to quantify soil carbon will account for biochar as soil organic carbon. However, as diffuse C-sinks, by definition, represent well-distributed quantities in spatial terms, the amount of biochar present at any single location is minimal. Such small amounts are hardly measurable using common methods for measuring soil carbon; therefore, the risk of double certification can be considered nonexistent (Rathnayake et al., 2023a). Moreover, as Rathnayake et al. (2023) recommended, certification of soil organic carbon (SOC) requires declaring any biochar application and deducing it from certified SOC.

12 Approved Biochar Uses for C-sinks

Biochar that is mixed into a C-sink matrix listed in the C-sink matrix positive list (c.f., Carbon Standards' website), can be registered a C-sink, given the conditions marked in the C-sink matrix positive list are met. The following subchapters provide a complementary orientation for general categories of biochar C-sinks.

When biochar or biochar-based products arrive at the site where the C-sink will be established (e.g., a farm, a construction site, a composite factory), the GPS coordinates of the location and date of arrival must be registered in the MRV tool. Any further onsite transformation, such as mixing to a C-sink matrix such as compost, animal feed, or concrete must be documented. When the biochar or biochar-based product is applied to a defined field or site, a GPS point situated within the field or plot of application must be registered. A photo showing bulk applications with date and geolocation should be uploaded to the MRV system. Further documentation may be required depending on the site and application type, as further detailed in the following subchapters.

12.1 Soil Application

Mixing with soil or another eligible C-sink matrix (c.f., matrix positive list) at a portion of at least 50:50 (vol/vol) must be guaranteed, which is fulfilled in most cases of agricultural biochar application. Biochar depositions at a lesser mixing proportion are considered temporary biochar storages (c.f., Chapters 2.4 & 12.6)

12.2 Application in Animal Farming

If the biochar is first applied as feed, bedding, or manure additive, it becomes blended with a C-sink matrix and is therefore eligible as a C-sink. Registration as a diffuse C-sink is possible if documentation is provided demonstrating that the complete manure will ultimately be applied to soil.

Particular attention must be paid to horse and poultry feed, as manure from these animals is often used for energetic purposes, which must be excluded. Pet feed products are generally excluded, as pet excreta are typically disposed of via waste treatment systems rather than soil application.

If biochar-containing animal manure or compost is applied or incorporated on the producing farm, or transferred for use on another farm, the entire farm area may be designated as the C-sink location. Tracking to the specific field sites is recommended to improve traceability and verification.

12.3 Concrete Construction Materials

Biochar incorporated into cement-, lime-, clay-, or geopolymer-based construction materials is considered a carbon sink.

Structures like the Roman Colosseum, the Egyptian pyramids, and the old city of Fulda show that buildings may last longer than empires and constitutions. However, the average life cycle of reinforced cement-based concrete constructions is specified by various standards and publications, such as LEED v4.1 and Minergy/SNBS, to be approximately 60 years (20 years for logistic and production structures). These relatively short life cycles are primarily due to steel corrosion and urban planning. While extending the lifetime of these materials is both possible and desirable, given the current state of the global building industry, an average lifespan of 60 years for buildings and urban infrastructures and 20 years for logistics and production facilities is representative.

During the building's existence, the concrete matrix protects the biochar, e.g., from water, air, and chemicals, so it does not mineralize, and no carbon is released to the atmosphere. No biochar carbon is lost when incorporated into the construction material for as long as the building exists, and the biochar carbon contained in the construction material can be registered with 100% carbon persistence. This holds true regardless of the binder used in the construction material, whether cement, lime, clay, or geopolymers.

While the preservation of biochar carbon during a building's lifetime is undisputed, the end-of-life scenario becomes crucial for certifying it as a permanent carbon sink. Different scenarios must be considered at this stage:

1) **Landfill**: Demolished building materials are often deposited in dedicated construction and demolition (C&D) landfills and are, thus, indirectly applied to the soil. However, demolished concrete placed in C&D landfills is a persistent, mineral material. In the buried, intermittently moist, and relatively low-CO_2 conditions typical of such landfills, concrete fragments (centimeters to decimeters in size) undergo only very slow surface carbonation and limited leaching. Bulk disintegration does not occur on any human-planning horizon (decades to centuries). Consequently, biochar embedded within these fragments is largely shielded from microbial and chemical attack until progressive fragmentation or rare exposure events reach it. While concrete-embedded biochar carbon will eventually, on geological timescales, be exposed to environmental conditions, the diminution and dissolution of concrete debris - which is essentially the same as rock weathering - do not occur in a landfill within any meaningful human timeframe. This interpretation aligns with well-established knowledge of concrete durability and carbonation kinetics, as well as with landfill studies that focus on leachate composition rather than concrete mass loss (Aneja et al., 2022; Chen et al., 2022; You et al., 2022). If a construction is demolished and applied to a C&D landfill, the biochar contained in the concrete matrix is considered persistent for at least 100 years without any accountable carbon losses to the atmosphere (C-Sink_100 = 100%).

2) **Conventional concrete recycling**: Demolished concrete is increasingly recycled into new construction materials or fillers. To achieve this, the rubble must be crushed. During the crushing process, the biochar remains embedded within the resulting pebbles. Depending on the size and quality of the crushed materials, these pebbles are used as filler (e.g., in road construction) or as aggregate for new concrete and other construction materials. Both scenarios differ slightly in long-term carbon persistence, though only on very long timescales.

   2.1 When used as filler for roadbeds, retaining walls, or landscaping gravel where no binder is applied, the biochar carbon remains protected within the crushed concrete matrix for decades to centuries. The scenario is comparable to the C&D landfill case, except that debris has been crushed into smaller pieces. Nevertheless, the pebbles are still large enough to prevent rapid geological weathering (Aneja et al., 2022; Chen et al., 2022; You et al., 2022), and the embedded biochar can be considered persistent for at least 100 years (C-Sink_100 = 100%).

   2.2 When used as aggregate for new construction materials - i.e., when the aggregate is mixed with a new binder - a new life cycle as a building material begins, typical with an average service lifetime of 60 years and no decomposition of the embedded biochar carbon. This cycle of reuse in building materials can be repeated many times before ultimately reaching an end-of-life stage as filler (scenario 2.1) or as landfill material (scenario 1) (C-Sink_100 = 100%).

3) **Thermo-oxidative cement recycling:** A new process developed at laboratory scale aims to recycle cement from concrete materials and reuse it as a cement binder. To do this, the concrete is ground very finely and sieved to separate the used binder (fine material) and aggregates (oversized particles). The sieved oversize can be reused as aggregate, which is particularly important as sand is a non-renewable, limited resource (Wang et al., 2021). The fines, i.e., hydrated and aged cement, can then be reactivated by thermal treatment at 600 to 1400 °C under an oxidative environment (Bogas et al., 2022, 2021; Carriço et al., 2020; Dunant et al., 2024; Mostazid and Sakai, 2023). It can be assumed that biochar would predominantly end up with the fines and thus would be oxidized during the thermal treatment.

While this procedure is theoretically possible, thermo-oxidative cement recycling is unlikely to be implemented at scale and thus not become an end-of-life scenario for biochar-amended concrete. Lab experiments demonstrated that the reactivation of recycled cement may require less energy than conventional cement production from limestone (Real et al., 2022). However, recycled cement past present significant lower purity and homogeneity and thus quality than limestone (Bogas et al., 2022) that is abundantly available in the earth's crust, is inexpensive and its use and quality assurance is well established. Cement-based concrete captures significant amounts of atmospheric CO_2 during aging, transforming it into highly stable carbonates. When concrete or recycled cement paste is deposited in non-acidic landfills, these carbonates form a very stable, long-term carbon sink. Aged concrete contains more than 20 kg CO_2e per m^3 in the form of carbonates formed with CO_2 captured from the atmosphere and/or industrial sources (Monkman and MacDonald, 2017; Pae et al., 2024; Zhao et al., 2024), which may even have been certified as a carbon sink (Puro Earth, 2022). If biochar were added as a cement additive or sand replacement, the carbon content could exceed 10% (m/m).

If the cement paste were thermo-oxidatively recycled, the captured and concrete-sequestered carbon would be released as CO_2. Given that by 2050, all industrial emissions must be equipped with CCS, the additional cost of recycling cement paste would make it comparatively more expensive than sequestering the cement paste in a soil matrix and producing new cement from limestone with CCS already in place. Maintaining the carbon sink in the long term by sequestering hydrated and aged cement without thermal treatment is the most sustainable and economical recycling option.

Dunant et al. (2024) investigated combining steel and cement recycling by using recycled cement paste as flux in the melting of waste steel. Although this approach appears promising, many questions remain regarding the industrial scale-up with highly heterogeneous cement pastes. While steel melting does not cause major CO_2 emissions if conducted in electric furnaces, the thermo-oxidative treatment of carbonate and biochar-containing cement pastes would release significant amounts of CO_2. This would necessitate CCS, further increasing recycling costs.

If human civilization succeeds in limiting climate change, which is the primary goal of establishing the carbon sink economy, it is clear and unavoidable that by 2085—sixty years from now and the average life cycle of concrete buildings—no industrial CO_2 emissions will enter the atmosphere but will instead be recycled for carbon materials or sequestered geologically. Given that CCS of emissions from industrial processes will become legally mandatory in the coming decades, conventional limestone-based cement companies will not only produce cement but also purified CO_2 for the carbon cycling economy (Schmidt and Hagemann, 2024). Cement production will become carbon neutral by then.

As landfill application of waste cement paste is accepted as carbon sequestration (for both carbonate and biochar carbon contained in the paste), recycling the heterogeneous paste with mandatory CCS would clearly be at an economic, energetic, and environmental disadvantage compared to its carbon-sequestering landfill application and fresh cement production with CCS.

It can thus be concluded that thermo-oxidative cement recycling is highly unlikely to develop due to both economic and physical considerations. According to the EU definition of permanent carbon removal as *any practice or process that, **under normal circumstances and using appropriate management practices**, captures and stores atmospheric or biogenic carbon for several centuries* (Eur-Lex, 2024). Under normal circumstances, thermo-oxidative cement recycling can be excluded as an end-of-life scenario for biochar-containing concrete materials. However, the evolution of the recycling technology will be closely observed, and if the recycling technology develops unexpectedly into a scaling solution, the present standard will adapt in due time.

Biochar applied in construction materials, such as buildings, urban constructions, and infrastructure, is typically pre-mixed at a processor's site. In most cases, these pre-mixed materials are transported as bulk material, measured by weight or volume, rather than in packaging units. Appropriate tracking of the materials to the construction site, and thus to the carbon sink site, is recommended. However, it is only obligatory when certified under the Global Construction C-Sink Standard.

To avoid exposing biochar particles during shredding of construction debris, and to ensure they remain sufficiently protected by the mineral matrix, biochar used in construction materials should be milled to a particle size below 1 mm.

To register the concrete-embedded biochar C-sink, the GPC fraction of the biochar is registered as persistent for > 1000 years. The SPC fraction of the biochar is registered without decay for the first 100 years since its first use in a concrete matrix. Starting at year 101, the concrete embedded biochar is conservatively considered as applied to soil independent of the recycling or landfill deposition scenario (c.f., figure 3), and the SPC decay function applies (c.f., equation 4).

Accordingly, the persistence of concrete-embedded biochar carbon is:
C-Sink_100 = 100%
C-Sink_1000+ = 75.0% or 90%, respectively, depending on the persistence class

A concrete embedded biochar C-Sink of 1000 t CO_2e can, thus, be classified as a C-Sink_100 of 1000 t CO2e. However, it could also be divided into a C-Sink_1000+ of 750 t CO_2e or 900 t CO_2e (i.e., the GPC fraction) and a C-Sink_100 of 250 t or 100 t CO_2e, respectively, (i.e., the SPC fraction over 100 years). The C-Sink_1000+ can be used to offset emissions from C-sink generation.

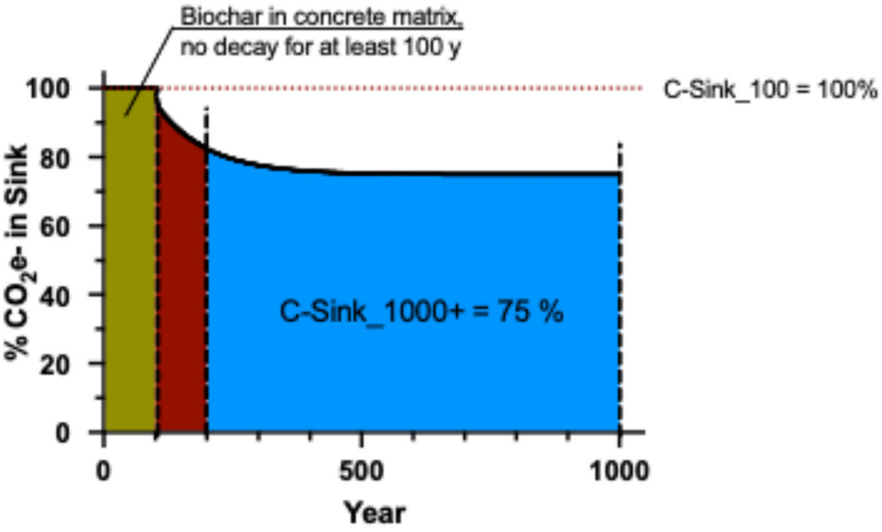

Figure 4: C-sink curve of concrete embedded biochar with an H/Corg ratio ≤ 0.4 and Ro < 3.8%. The GPC fraction is registered with a persistence of > 1000 years. The SPC fraction is 25% and registered without decay for 100 years. After 100 years, the concrete embedded biochar is conservatively considered as if applied to soil independent of the recycling or landfill deposition scenario*. The C-Sink_100 of this construction C-Sink is 100% and the C_Sink_1000+ is 75.0%.*

The packaging/delivery note of certified biochar-containing construction materials must clearly state that the biochar carbon contained in the concrete material has already been registered as C-sink and must not be registered again as part of a construction or any other use. If the biochar C-Sink is intended to be registered and certified under the Construction C-Sink Standard, it must be tracked to the construction site and registered as part of the construction itself.

To summarize:

When biochar is incorporated into mineral-bound construction materials (cement-, lime-, clay-, or geopolymer-based), the GPC fraction is registered as a geological C-sink (CINK_1000+). The mineral matrix fully protects the SPC fraction from degradation for the lifetime of the construction. Once the construction debris is shredded and disposed of in a soil matrix, the particle-size restriction (i.e., < 1 mm) prevents rapid exposure of biochar particles to biological processes. This bridges the period between demolition and the 100-year mark, ensuring that no accountable SPC decay occurs within the first 100 years; the CINK_100 is therefore 100%. From year 101 onward, the concrete-embedded SPC fraction is conservatively treated as if applied to soil, and the modelled SPC decay function applies.

12.4 Asphalt

The use of biochar in asphalt represents another promising pathway for long-term carbon storage within the built environment. Asphalt, or bituminous mixtures, are widely used in road construction, parking areas, and roofing applications, making them one of the most extensive material stocks in modern infrastructure. Incorporating biochar into asphalt can enhance bitumen adsorption and improve rheological performance, potentially increasing resistance to rutting and fatigue cracking (Zhou et al., 2024). Biochar can be introduced into asphalt either as a partial replacement for mineral fillers (e.g., limestone dust), as an additive to modify bitumen, or as a fine component blended into recycled asphalt mixtures.

When applied to asphalt, biochar’s carbon is effectively encapsulated within the bitumen matrix – a hydrophobic and oxygen-limited environment – greatly slowing down any oxidative or microbial degradation. From a carbon persistence perspective, asphalt pavements have service lifetimes of several decades. After their use phase, reclaimed asphalt pavement (RAP) is recycled into new mixtures or used in unbound and civil-engineering layers, with almost no landfilling. As a result, biochar carbon embedded in asphalt can remain stable through multiple recycling cycles before eventually fragmenting or entering the soil as fine mineral–organic particles. The overall persistence of biochar in asphalt is therefore comparable to that in mineral-bound construction materials, with the bituminous binder providing an additional hydrophobic barrier against oxidation and leaching.

12.4.1 Recycling and Carbon Persistence in Hot vs. Cold Asphalt

Asphalt pavements are routinely recycled, and the recycling pathway depends strongly on the type of bituminous mix used. Two main systems are distinguished: hot-mix asphalt (HMA) and cold-mix asphalt (CMA). Both can incorporate biochar, yet their recycling behaviour – and thus the long-term carbon persistence of the embedded biochar – differ.

Hot-mix asphalt (HMA) is produced at elevated temperatures (typically 140–180 °C), ensuring that the bitumen binder fully coats the mineral aggregates. During recycling, reclaimed asphalt pavement (RAP) is reheated and blended with fresh binder and aggregates. The heating process softens and reactivates the aged bitumen, enabling it to integrate into the new mixture. As HMA production temperatures are far below the pyrolysis temperatures used for biochar production, the bitumen-embedded biochar remains thermally stable and is preserved through all HMA recycling cycles. Each reuse extends the effective residence time of biochar carbon within a bituminous environment that is hydrophobic and low in oxygen, thereby preventing oxidation or microbial degradation. Consequently, biochar incorporated into HMA can be considered persistent for at least a century through successive cycles of reuse.

Cold-mix asphalt (CMA) is produced and applied at or near ambient temperature using bitumen emulsions or foamed bitumen. Recent formulations and additives demonstrate that similar mechanical strength and binder cohesion compared to HMA can be achieved (Meena et al., 2024). When cold-mix pavements or layers reach the end of their service life, they are typically reused as unbound or partially bound base material rather than being reheated and reincorporated into new asphalt. The bitumen in these materials is not reactivated, and the matrix gradually breaks down under environmental exposure. While the embedded biochar remains protected within the residual bituminous coating for several decades, it will ultimately be exposed to moisture and oxidation. Carbon persistence is therefore lower than in hot-mix systems, though this difference would only become relevant over infrastructure lifetimes exceeding 100 years.

12.4.2 End-of-Life - Fate of Asphalt

Aged asphalt that cannot be reprocessed is crushed and reused as unbound aggregate in road sub-bases, embankments, or other earthworks. Here, the asphalt behaves as a granular mineral material. While mechanical fragmentation may increase over time, the embedded biochar remains largely protected within the residual bituminous coating. This represents a stable carbon storage form, with no degradation for several decades to centuries, depending on exposure to moisture, oxygen, and physical disturbance.

When asphalt materials can no longer be reused, they are treated as construction and demolition (C&D) waste and landfilled, often alongside concrete, bricks, and other inert C&D materials. In this environment, the asphalt pieces are buried under low-oxygen, low-moisture conditions. The bituminous binder, being hydrocarbon-based, remains largely inert, and oxidation processes slow dramatically. Consequently, any biochar encapsulated within the asphalt remains protected within both the bitumen and the surrounding mineral aggregate – very similar to the persistence of biochar in concrete or other mineral matrices. Over geological timescales, gradual fragmentation and mineral weathering will expose small portions to air and moisture, but decomposition within a landfill does not occur on any human-planning horizon.

Incineration or energy recovery from asphalt waste is rarely practiced - practically zero in most countries, with some EU countries reaching up to 1%. The high mineral content and low net calorific value make combustion inefficient and technically challenging. Where it does occur (e.g., for contaminated asphalt removed from industrial sites), most biochar and bitumen carbon would be oxidized and released as CO_2. This is considered the only true carbon loss pathway in the asphalt life cycle.

To avoid exposing biochar particles during recycling processes and to ensure they remain sufficiently protected by the mineral matrix, biochar used in asphalt should be milled to a particle size below 1 mm.

To account for this rare but non-zero possibility of incineration or pyrolysis of contaminated asphalt, a 5% leakage margin must be deduced before registration of the asphalt-embedded biochar.

Accordingly, the persistence of asphalt-embedded biochar carbon is:
C-Sink_100 = 95 %
C-Sink_1000+ = 71.3 % (= 75% * 95%) for the lower persistence class and
= 85.5 % (= 90% * 95%) for the upper persistence class

Biochar applied in asphalt is typically pre-mixed at a processor's site. In most cases, these pre-mixed materials are transported as bulk material, measured by weight or volume, rather than in packaging units. Appropriate tracking of the materials to the construction site, and thus to the carbon sink site, is recommended. However, it is only obligatory when certified under the Global Construction C-Sink Standard.

12.5 Application in Composite Materials

Biochar can be used as an additive or filler to a multitude of composites, thermoplastics, textiles, organic or mineral fibers, paper, filters, metal, electronic, and other materials. Most of these materials are of small size, have a relatively short lifetime of a few years, but exist in thousands to millions if not billion replicates. It is impossible to register each individual product (e.g., the handle of a hammer, the housing of a watch, a T-shirt, or a sewage pipe).

To register the carbon of such products, the average lifetime of the product must be assessed. A monitoring plan to verify and, where necessary, correct the average product lifetime must be submitted to Carbon Standards. Depending on the size of production, the monthly (> 1000 t CO_2e per month), quarterly (> 1000 t CO_2e per quarter) or annual (≤ 1000 t CO2e per quarter) production of one product type at one production site must be registered as a C-sink unit in the Global C-Sink Registry. Annual global cooling services can be traded for periods given by the average lifetime of the product.

The application of biochar in asphalt roads must be tracked and registered with the road location.

12.6 Temporary Biochar Storage

It is possible to store carbon temporally in geological sites such as salt domes, crude oil wells, coal mines, or even in silos. For as long as the biochar is stored under controlled conditions and with regular verification, protected from water and from biologically active matrices, it can be considered a temporary C-sink during the controlled storage time. The control is usually assured remotely with continuous measurements of temperature, humidity, and CO_2 concentration. The monitoring plan must be approved by Carbon Standards.

The biochar carbon can be registered as total stored carbon, and the amount of stored carbon must be updated annually in the Global C-Sink Registry. Annual climate services of stored carbon can be traded only one year in advance. This means that the total climate effect of a temporary C-sink may only compensate for the global warming effect of past emissions for the coming year.

12.7 Other Forms of C-Sink Establishments

Carbon Standards may approve other application and storage methods not mentioned or covered in the C-sink matrix positive list. A request for approval, including a detailed description of the new method, must be submitted to Carbon Standards.

13 Registration of the C-Sink

The Global Biochar C-Sink certification is the prerequisite for generating marketable C-sink certificates. However, before the climate effect of C-sinks can be traded and used to achieve climate change mitigation targets of individuals, companies, organizations, regions, or nations, they must be registered in the Global C-Sink Registry.

The following information are registered for biochar carbon sinks:

1. C-sink owner (owner of the material that contains the biochar, or producer of biochar containing products).
2. A GPS point of the land or area where the C-sink was established.
3. For soil application: Consent of the landowner or tenant to accept the biochar application to his soil (usually part of the purchase contract).
4. Date of C-sink establishment.
5. Year of CO_2-removal (date of carbon uptake of biomass that was pyrolyzed).
6. EBC/WBC batch number.
7. Biochar analysis - can be linked with the Carbon Standard Biochar Tool
8. Type of C-sink (geo-localized or diffuse).
9. C-sink matrix.
10. Amount of biochar in dry tons.
11. Amount of carbon in CO_2e.
12. Persistence curve of C-sink (depending on C-sink matrix).
13. Controlling period (depending on C-sink matrix).
14. C-sink project documentation
15. Report of the verification and validation body
16. Confirmation of the compensation of the emission portfolio of the biochar

This information is collected by the biochar producer, processor, trader, C-sink owner, and/or dMRV provider at the various stages of the biochar and C-sink life cycle using dMRV. The C-sink owner must ensure the completeness and correctness of the data, which is controlled by the verification and validation body.

The C-sink project documentation contains different documents. Project Design Document (PDD), Monitoring report, Validation report and Verification report will be published in the Global C-Sink Registry together with the C-sinks.

The right to use the "registered C-Sink" seal, owned by the Global Carbon Register Foundation, is acquired by registration of the corresponding C-sink in the Global C-Sink Registry. All logos can be downloaded from the Carbon Standards website (www.carbon-standards.com).

registered
C-SINK

Manufacturers of EBC/WBC certified biochar are advised to sell the registered C-sink effects only through Carbon Standards' endorsed C-sink traders. This is the only way to guarantee that exactly the amount of carbon actually removed from the atmosphere in the form of CO_2 and the respective global warming effects are certified and sold.

Biochar producers may equally become endorsed as C-Sink Traders and thus sell C-sink effects (global cooling services or CO_2e offsets) to third parties or offset their own emissions.

For more detailed information, please refer to the Global Carbon Register Foundation (www.global-c-registry.org). Carbon Standards collaborates with the Global Carbon Register Foundation. Carbon Standards' C-sink tools provide direct data exchange with the Global C-Sink Registry and support its methodology. However, Carbon Standards and its standards are free to collaborate also with other registries given they provide the same data security and science-based calculations of annual cooling and warming effects.

14 Quoted Literature

Aamaas, B., Berntsen, T.K., Fuglestvedt, J.S., Shine, K.P., Bellouin, N., 2016. Regional emission metrics for short-lived climate forcers from multiple models. Atmos. Chem. Phys. 16, 7451–7468. https://doi.org/10.5194/ACP-16-7451-2016

Alami Sounni, K., Camps-Arbestain, M., Kaal, J., Tighe, C.J., Titirici, M.M., Siavalas, G., 2026. Assessment and integration of different methodologies for the characterisation of carbon aromaticity and structure in biochar. Int. J. Coal Geol. 313, 104925. https://doi.org/10.1016/J.COAL.2025.104925

Allen, M., Barros, V., Broome, J., Cramer, W., Christ, R., Church, J., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N., Edenhofer, O., Elgizouli, I., Field, C., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, L., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Jimenez Cisneros, B., Kattsov, V., Lee, H., Mach, K., Marotzke, J., Mastrandrea, M., Meyer, L., Minx, J., Mulugetta, Y., O'Brien, K., Oppenheimer, M., Pachauri, R., Pereira, J., Pichs-Madruga, R., Plattner, G.-K., Pörtner, H.-O., Power, S., Preston, B., Ravindranath, N., Reisinger, A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T., Tschakert, P., van Vuuren, D., van Ypersele, J.-P., Blanco, G., Eby, M., Edmonds, J., Fleurbaey, M., Gerlagh, R., Kartha, S., Kunreuther, H., Rogelj, J., Schaeffer, M., Sedláček, J., Sims, R., Ürge-Vorsatz, D., Victor, D., Yohe, G., 2014. IPCC fifth assessment synthesis report - Climate Change 2014 synthesis report.

Allen, M., Fuglestvedt, J., Shine, K., et al., 2016. New use of global warming potentials to compare cumulative and short-lived climate pollutants. Nature Clim Change 6, 773–776.

Aneja, A., Sharma, R.L., Singh, H., 2022. Mechanical and durability properties of biochar concrete. Mater. Today Proc. 65, 3724–3730. https://doi.org/10.1016/J.MATPR.2022.06.371

Archer, D., 2005. Fate of fossil fuel CO2 in geologic time. J. Geophys. Res. Oceans 110, 1–6. https://doi.org/10.1029/2004JC002625;WGROUP:STRING:PUBLICATION

Audsley, E., Stacey, K., Parsons, D.J., Williams, A.G., 2009. Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use.

Azzi, E.S., Li, H., Cederlund, H., Karltun, E., Sundberg, C., 2024. Modelling biochar long-term carbon storage in soil with harmonized analysis of decomposition data. Geoderma 441, 116761. https://doi.org/10.1016/J.GEODERMA.2023.116761

Balcombe, P., Speirs, J.F., Brandon, N.P., Hawkes, A.D., 2018. Methane emissions: choosing the right climate metric and time horizon. Environ. Sci. Process. Impacts 20, 1323–1339. https://doi.org/10.1039/C8EM00414E

Bogas, J.A., Carriço, A., Real, S., 2022. Thermoactivated Recycled Cement. London.

Bogas, J.A., Carriço, A., Real, S., Bogas, J.A., Carriço, A., Real, S., 2021. Thermoactivated Recycled Cement. Sustainability of Concrete With Synthetic and Recycled Aggregates. https://doi.org/10.5772/INTECHOPEN.98488

Bowring, S., Jones, M., Ciais, P., Guenet, B., Abiven, S., 2020. Fire as carbon sink? The global biome-dependent wildfire carbon balance. https://doi.org/10.21203/RS.3.RS-127629/V1

Bowring, S.P.K., Jones, M.W., Ciais, P., Guenet, B., Abiven, S., 2022. Pyrogenic carbon decomposition critical to resolving fire's role in the Earth system. Nature Geoscience 2022 15:2 15, 135–142. https://doi.org/10.1038/S41561-021-00892-0

Budai, A., Rasse, D.P., Lagomarsino, A., Lerch, T.Z., Paruch, L., 2016. Biochar persistence, priming and microbial responses to pyrolysis temperature series. Biol. Fertil. Soils 52, 749–761. https://doi.org/10.1007/S00374-016-1116-6/FIGURES/5

Buss, W., Jansson, S., Mašek, O., 2019. Unexplored potential of novel biochar-ash composites for use as organo-mineral fertilizers. J. Clean. Prod. 208, 960–967. https://doi.org/10.1016/J.JCLEPRO.2018.10.189

Camps-Arbestain, M., Amonette, J.E., Singh, B., Wang, T., Schmidt, H.-P., 2015. A biochar classification system and associated test methods, in: Lehmann, J., Joseph, S. (Eds.), Biochar for Environmental Management. Routledge, London, pp. 165–194.

Carriço, A., Bogas, J.A., Guedes, M., 2020. Thermoactivated cementitious materials – A review. Constr. Build. Mater. 250, 118873. https://doi.org/10.1016/J.CONBUILDMAT.2020.118873

Chen, Zhikun, Feng, Q., Yue, R., Chen, Zhi, Moselhi, O., Soliman, A., Hammad, A., An, C., 2022. Construction, renovation, and demolition waste in landfill: a review of waste characteristics, environmental impacts, and mitigation measures. Environmental Science and Pollution Research 29, 46509–46526. https://doi.org/10.1007/S11356-022-20479-5/METRICS

Czimczik, C.I., Masiello, C.A., 2007. Controls on black carbon storage in soils. Global Biogeochem. Cycles 21. https://doi.org/10.1029/2006GB002798

Dunant, C.F., Joseph, S., Prajapati, R., Allwood, J.M., 2024. Electric recycling of Portland cement at scale. Nature 2024 629:8014 629, 1055–1061. https://doi.org/10.1038/s41586-024-07338-8

Eur-Lex, 2024. EUR-Lex - 52022PC0672 - EN - EUR-Lex [WWW Document]. URL https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0672 (accessed 6.30.24).

Falkowski, P., Scholes, R.J., Boyle, E., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Hogberg, P., Linder, S., Mackenzie, F.T., Moore, B., Pedersen, T., Rosental, Y., Seitzinger, S., Smetacek, V., Steffen, W., 2000. The global carbon cycle: A test of our knowledge of earth as a system. Science (1979). 290, 291–296. https://doi.org/10.1126/SCIENCE.290.5490.291;WEBSITE:WEBSITE:AAAS-SITE;JOURNAL:JOURNAL:SCIENCE;WGROUP:STRING:PUBLICATION

Ferrero, F., Malow, M., Noll, M., 2011. Temperature and gas evolution during large scale outside storage of wood chips. European Journal of Wood and Wood Products 69, 587–595. https://doi.org/10.1007/s00107-010-0512-0

Forster, P., Alterskjaer, K., Smith, C., Colman, R., Damon Matthews, H., Ramaswamy, V., Storelvmo, T., Armour, K., Collins, W., Dufresne, J., Frame, D., Lunt, D., Mauritsen, T., Watanabe, M., Wild, M., Zhang, H., Pirani, A., Connors, S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J., Maycock, T., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B., 2021. SPM 923 7 Coordinating Lead Authors: Contributing Authors: Review Editors: Chapter Scientists: The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity 923–1054. https://doi.org/10.1017/9781009157896.009

Fuglestvedt, J.S., Berntsen, T.K., Godal, O., Sausen, R., Shine, K.P., Skodvin, T., 2003. Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. Clim. Change 58, 267–331. https://doi.org/10.1023/A:1023905326842

Grafmüller, J., Böhm, A., Zhuang, Y., Spahr, S., Müller, P., Otto, T.N., Bucheli, T.D., Leifeld, J., Giger, R., Tobler, M., Schmidt, H.P., Dahmen, N., Hagemann, N., 2022. Wood Ash as an Additive in Biomass Pyrolysis: Effects on Biochar Yield, Properties, and Agricultural Performance. ACS Sustain. Chem. Eng. 10, 2720–2729. https://doi.org/10.1021/ACSSUSCHEMENG.1C07694/ASSET/IMAGES/LARGE/SC1C07694_M003.JPEG

Hagemann, N., Schmidt, H.P., Bucheli, T.D., Grafmüller, J., Vosswinkel, S., Herdegen, V., Meredith, W., Uguna, C.N., Snape, C.E., 2025. Proxies for use in biochar decay models: Hydropyrolysis, electric conductivity, and H/Corg molar ratio. PLoS One 20, e0330206. https://doi.org/10.1371/JOURNAL.PONE.0330206

Howell, A., Helmkamp, S., Belmont, E., 2022. Stable polycyclic aromatic carbon (SPAC) formation in wildfire chars and engineered biochars. Science of The Total Environment 849, 157610. https://doi.org/10.1016/J.SCITOTENV.2022.157610

ICCP, 1963. International handbook of coal petrography. International handbook of coal petrography 1–232.

IPCC, 2022. IPCC sixth assessment report (AR6) - Working group III contribution, UNEP.

IPCC, 2019. Method for estimating the change in mineral soil organic carbon stocks from biochar amendments: basis for future methodological development, in: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, p. Ap4.1.

IPCC, 2013. Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge. ed. Cambridge.

Jaeckel, U., Thummes, K., Kaempfer, P., 2005. Thermophilic methane production and oxidation in compost. FEMS Microbiol. Ecol. 52, 175–184. https://doi.org/10.1016/j.femsec.2004.11.003

Jeltsch-Thömmes, A., Joos, F., 2019. The response to pulse-like perturbations in atmospheric carbon and carbon isotopes. Climate of the Past 1–36.

Juhrich, K., 2016. CO2-Emissionsfaktoren für fossile Brennstoffe. Berlin.

Kadiyala, A., Kommalapati, R., Huque, Z., 2016. Evaluation of the Life Cycle Greenhouse Gas Emissions from Hydroelectricity Generation Systems. Sustainability 2016, Vol. 8, Page 539 8, 539. https://doi.org/10.3390/SU8060539

Kuzyakov, Y., Bogomolova, I., Glaser, B., 2014. Biochar stability in soil: Decomposition during eight years and transformation as assessed by compound-specific 14C analysis. Soil Biol. Biochem. 70, 229–236. https://doi.org/10.1016/j.soilbio.2013.12.021

Lebrun Thauront, J., Soja, G., Schmidt, H.P., Abiven, S., 2024. A critical re-analysis of biochar properties prediction from production parameters and elemental analysis. GCB Bioenergy 16, e13170. https://doi.org/10.1111/GCBB.13170

Lehmann, J., Abiven, S., Azzi, E., Fang, Y., Singh, B.P., Sohi, S., Sundberg, C., Woolf, D., Zimmerman, A.R., 2024. Persistence of biochar: Mechanisms, measurements, predictions. Biochar for Environmental Management: Science, Technology and Implementation 277–311. https://doi.org/10.4324/9781003297673-11/PERSISTENCE-BIOCHAR-JOHANNES-LEHMANN-SAMUEL-ABIVEN-ELIAS-AZZI-YUNYING-FANG-BHUPINDER-PAL-SINGH-SARAN-SOHI-CECILIA-SUNDBERG-DOMINIC-WOOLF-ANDREW-ZIMMERMAN

Lehmann, J, Abiven, S., Kleber, M., Pan, G., Singh, B.P., Sohi, S.P., Zimmerman, A.R., 2015. Persistence of biochar in soil, in: Lehmann, Johannes, Joseph, S.D. (Eds.), Biochar for Environmental Management. Routledge, London, pp. 235–299.

Lehmann, Johannes, Abiven, S., Kleber, M., Pan, G., Singh, B.P., Sohi, S.P., Zimmerman, A.R., 2015. Persistence of biochar in soil, in: Lehmann, J., Joseph, S.D. (Eds.), Biochar for Environmental Management. New York, pp. 235–282.

Lehmann, J., Hansel, C.M., Kaiser, C., Kleber, M., Maher, K., Manzoni, S., Nunan, N., Reichstein, M., Schimel, J.P., Torn, M.S., Wieder, W.R., Kögel-Knabner, I., 2020. Persistence of soil organic carbon caused by functional complexity. Nat. Geosci. 13, 529–534. https://doi.org/10.1038/s41561-020-0612-3

Mastalerz, M., Drobniak, A., Liu, B., Sauer, P.E., 2025. Reflectance as an indicator of biochar permanence. Int. J. Coal Geol. 306, 104809. https://doi.org/10.1016/J.COAL.2025.104809

McBeath, A. V., Wurster, C.M., Bird, M.I., 2015a. Influence of feedstock properties and pyrolysis conditions on biochar carbon stability as determined by hydrogen pyrolysis. Biomass Bioenergy 73, 155–173. https://doi.org/10.1016/J.BIOMBIOE.2014.12.022

McBeath, A. V., Wurster, C.M., Bird, M.I., 2015b. Influence of feedstock properties and pyrolysis conditions on biochar carbon stability as determined by hydrogen pyrolysis. Biomass Bioenergy 73, 155–173. https://doi.org/10.1016/J.BIOMBIOE.2014.12.022

Meena, P., Naga, G.R.R., Kumar, P., Monu, K., 2024. Effect of Mechanical Properties of Cold Mix Asphalt Mixture Containing Different Proportion of Fillers. International Journal of Pavement Research and Technology 17, 982–998. https://doi.org/10.1007/S42947-023-00281-3/METRICS

Monkman, S., MacDonald, M., 2017. On carbon dioxide utilization as a means to improve the sustainability of ready-mixed concrete. J. Clean. Prod. 167, 365–375. https://doi.org/10.1016/J.JCLEPRO.2017.08.194

Mostazid, M.I., Sakai, Y., 2023. Thermal treatment of recycled compacted concrete: Effects on physical properties and hydration characteristics. Journal of Building Engineering 78, 107707. https://doi.org/10.1016/J.JOBE.2023.107707

Myhre, G.D., Shindell, F.M., Breon, W., Collins, J., Fuglestvedt, J., et al., 2013. Anthropogenic and Natural Radiative Forcing, in: Stocker, T., Qin, D., Platner, M., et al. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, New York, p. 712.

Nugent, D., Sovacool, B.K., 2014. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. Energy Policy 65, 229–244. https://doi.org/10.1016/J.ENPOL.2013.10.048

Pae, J., Kim, W.K., Moon, J., 2024. Mineral carbonation performance of wollastonite-blended cementitious composites through in-situ CO2 mixing. Constr. Build. Mater. 438. https://doi.org/10.1016/j.conbuildmat.2024.137160

Petersen, H.I., Lassen, L., Rudra, A., Nguyen, L.X., Do, P.T.M., Sanei, H., 2023. Carbon stability and morphotype composition of biochars from feedstocks in the Mekong Delta, Vietnam. Int. J. Coal Geol. 271, 104233. https://doi.org/10.1016/J.COAL.2023.104233

Pier, P.A., Kelly, J.M., 1997. Measured and estimated methane and carbon dioxide emissions from sawdust waste in the Tennessee Valley under alternative management strategies. Bioresour. Technol. 61, 213–220. https://doi.org/10.1016/S0960-8524(97)00064-3

Pipatti, R., Silva Alves, J., et al., 2006. Biological treatment of solid waste, in: IPCC Guidelines for National Greenhouse Gas Inventory.

Puro Earth, 2022. Carbonated Materials Methodology for CO 2 Removal [WWW Document]. URL https://7518557.fs1.hubspotusercontentna1.net/hubfs/7518557/Supplier%20Documents/Puro.earth%20Carbonated%20Materials%20Methodology.pdf (accessed 6.30.24).

Rathnayake, D., Schmidt, H.P., Leifeld, J., Mayer, J., Epper, C.A., Bucheli, T.D., Hagemann, N., 2023. Biochar from animal manure: A critical assessment on technical feasibility, economic viability, and ecological impact. GCB Bioenergy 00, 1–27. https://doi.org/10.1111/GCBB.13082

Real, S., Sousa, V., Meireles, I., Bogas, J.A., Carriço, A., 2022. Life Cycle Assessment of Thermoactivated Recycled Cement Production. Materials 2022, Vol. 15, Page 6766 15, 6766. https://doi.org/10.3390/MA15196766

Sanei, H., Rudra, A., Przyswitt, Z.M.M., Kousted, S., Sindlev, M.B., Zheng, X., Nielsen, S.B., Petersen, H.I., 2024. Assessing biochar's permanence: An inertinite benchmark. Int. J. Coal Geol. 281, 104409. https://doi.org/10.1016/J.COAL.2023.104409

Sanei, H., Rudra, A., Przyswitt, Z.M.M., Kousted, S., Sindlev, M.B., Zheng, X., Nielsen, S.B., Petersen, H.I., 2023. Assessing biochar's permanence: An inertinite benchmark. Int. J. Coal Geol. 104409. https://doi.org/10.1016/J.COAL.2023.104409

Sanei, H., Wojtaszek-Kalaitzidi, M., Schovsbo, N.H., Stenshøj, R., Zhou, Z., Schmidt, H.-P., Hagemann, N., Chiaramonti, D., Kiaitsis, T., Rudra, A., Lehner, A.J., Brown, R.W., Gill, S., Dorr, E., Kalaitzidis, S., Goodarzi, F., Petersen, H.I., 2025. Quantifying inertinite carbon in biochar. Int. J. Coal Geol. 310, 104886. https://doi.org/10.1016/J.COAL.2025.104886

Schmidt, H., Abiven, S., Cowie, A., Glaser, B., Joseph, S., Kammann, C., Lehmann, J., Leifeld, J., Pan, G., Rasse, D., Rumpel, C., Woolf, D., Zimmerman, A.R., Hagemann, N., 2025a. Biochar Permanence—A Policy Commentary. GCB Bioenergy 17, e70092. https://doi.org/10.1111/GCBB.70092;PAGE:STRING:ARTICLE/CHAPTER

Schmidt, H., Abiven, S., Hagemann, N., Meyer zu Drewer, J., 2022. Permanence of soil applied biochar. The Biochar Journal 1, 69–74.

Schmidt, H., Hagemann, N., 2026. Methane Emissions Offsetting with Temporary Carbon Sinks. Global Change Biology & Bioenergy.

Schmidt, H., Hagemann, N., 2024. Fossil C - The Legacy Bloodline. The Biochar Journal 1, 81–85.

Schmidt, H., Hagemann, N., Kammann, C.I., 2025b. Global Biochar C-Sink Standard 3.2 [WWW Document]. Carbon Standards. URL https://www.carbon-standards.com/en/home (accessed 6.9.24).

Schmidt, H.P., Anca, A., Nikolas, C., Werner, C., Gerten, D., Lucht, W., Kammann, C., 2018. Pyrogenic carbon capture and storage 1–19. https://doi.org/10.1111/gcbb.12553

Schmidt, H.P., Hagemann, N., 2024. Planetary Carbon Recycling - Global Cooling with Temporary C-Sinks. the Biochar Journal 16, 75–80.

Schmidt, M.W.I., Noack, A.G., 2000. Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. Global Biogeochem. Cycles 14, 777–793. https://doi.org/10.1029/1999GB001208

Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S., Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. Nature 478, 49–56. https://doi.org/10.1038/nature10386

Smith, C., Gasser, T., Nicholls, Z., Armour, K., Collins, W., Forster, P., Meinshausen, M., Watanabe, M., Pirani, A., Connors, S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J., Maycock, T., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B., 2021. The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity Supplementary Material Lead Authors: Contributing Authors.

Song, J., Chen, C., Zhu, S., Zhu, M., Dai, J., Ray, U., Li, Yiju, Kuang, Y., Li, Yongfeng, Quispe, N., Yao, Y., Gong, A., Leiste, U.H., Bruck, H.A., Zhu, J.Y., Vellore, A., Li, H., Minus, M.L., Jia, Z., Martini, A., Li, T., Hu, L., 2018. Processing bulk natural wood into a high-performance structural material. Nature 554, 224–228. https://doi.org/10.1038/nature25476

Song, X.-P., Hansen, M.C., Stehman, S. V, Potapov, P. V, Tyukavina, A., Vermote, E.F., Townshend, J.R., 2018. Global land change from 1982 to 2016. Nature. https://doi.org/10.1038/s41586-018-0411-9

Sorrenti, G., Masiello, C.A., Dugan, B., Toselli, M., 2016. Biochar physico-chemical properties as affected by environmental exposure. Science of the Total Environment 563–564, 237–246. https://doi.org/10.1016/j.scitotenv.2016.03.245

Venmans, F., Rickels, W., Groom, B., 2025. Temporary carbon dioxide removals to offset methane emissions. Nature Climate Change 2025 1–6. https://doi.org/10.1038/s41558-025-02487-8

Wang, B., Yan, L., Fu, Q., Kasal, B., 2021. A Comprehensive Review on Recycled Aggregate and Recycled Aggregate Concrete. Resour. Conserv. Recycl. 171, 105565. https://doi.org/10.1016/J.RESCONREC.2021.105565

Werner, C., Schmidt, H.-P., Gerten, D., Lucht, W., Kammann, C., 2018. Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5 °c. Environmental Research Letters 13. https://doi.org/10.1088/1748-9326/aabb0e

Whitman, T., Lehmann, J., 2015. A dual-isotope approach to allow conclusive partitioning between three sources. Nat. Commun. 6, 8708. https://doi.org/10.1038/ncomms9708

Whittaker, C., Macalpine, W., Yates, N.E., Shield, I., 2016. Dry Matter Losses and Methane Emissions During Wood Chip Storage: the Impact on Full Life Cycle Greenhouse Gas Savings of Short Rotation Coppice Willow for Heat. Bioenergy Res. 9, 820–835. https://doi.org/10.1007/s12155-016-9728-0

Wiedemeier, D.B., Abiven, S., Hockaday, W.C., Keiluweit, M., Kleber, M., Masiello, C.A., McBeath, A. V., Nico, P.S., Pyle, L.A., Schneider, M.P.W., Smernik, R.J., Wiesenberg, G.L.B., Schmidt, M.W.I., 2015. Aromaticity and degree of aromatic condensation of char. Org. Geochem. 78. https://doi.org/10.1016/j.orggeochem.2014.10.002

Woolf, D., Lehmann, J., Ogle, S., Kishimoto-Mo, A.W., McConkey, B., Baldock, J., 2021. Greenhouse Gas Inventory Model for Biochar Additions to Soil. Environ. Sci. Technol. 55, 14795–14805. https://doi.org/10.1021/ACS.EST.1C02425

You, X., Hu, X., He, P., Liu, J., Shi, C., 2022. A review on the modelling of carbonation of hardened and fresh cement-based materials. Cem. Concr. Compos. 125, 104315. https://doi.org/10.1016/J.CEMCONCOMP.2021.104315

Zhang, W.-F., Dou, Z.-X., He, P., Ju, X.-T., Powlson, D., Chadwick, D., Norse, D., Lu, Y.-L., Zhang, Y., Wu, L., Chen, X.-P., Cassman, K.G., Zhang, F.-S., 2013. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. Proc. Natl. Acad. Sci. U. S. A. 110, 8375–8380. https://doi.org/10.1073/pnas.1210447110

Zhao, Y., Cui, K., He, J., Zheng, Y., Shen, P., Poon, C.S., Peng, G., Guo, R., Xia, D., 2024. An innovative strategy for maximizing CO2 reduction in concrete through preparing carbon sequestration precursors by accelerated carbonation. Cem. Concr. Compos. 152. https://doi.org/10.1016/j.cemconcomp.2024.105618

Zheng, Y., Gao, L., He, S., 2023. Analysis of the mechanism of energy consumption for CO2 capture in a power system. Energy 262. https://doi.org/10.1016/j.energy.2022.125103

Zhou, Xinxing, Zhang, Z., Wang, H., Chen, M., Wu, S., Xu, S., Zhou, Xinglin, Ran, M., Li, L., Lu, G., Ma, Z., 2024. Review on the properties and mechanisms of asphalt modified with bio-oil and biochar. Journal of Road Engineering 4, 421–432. https://doi.org/10.1016/J.JRENG.2024.06.001

Zimmerman, A.R., Gao, B., 2013. The Stability of Biochar in the Environment, in: Ladygina, N., Rineau, F. (Eds.), Biochar and Soil Biota. Boca Raton, pp. 1–40.