Title: A Modular BECCS Process Chain Framework from Biomass to Carbon Removal

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Abstract

Bioenergy with Carbon Capture and Storage (BECCS) is widely discussed as a key pathway for achieving net-negative greenhouse gas emissions. However, the complexity and context-specific nature of BECCS systems continue to delay their deployment. This paper introduces a modular process chain that decomposes BECCS into transparent modules—from feasibility evaluation through to CO_2 storage. Developed within the German research initiative "CDR-Atlas", the framework integrates technical and ecological aspects of BECCS deployment, including feedstock differentiation, land management, biomass treatment, conversion technologies, and CO_2 logistics, while indicating where governance, MRV, and societal considerations become relevant. Each module is informed by peer-reviewed literature, supporting traceability and scientific robustness. Drawing from literature and stakeholder engagement, the process chain supports planning, communication, and systemic transparency. Its modular character allows adaptation across geographies, project scales, and policy environments. We propose this framework as a complementary tool to modeling approaches, supporting transparent system analysis, identifying implementation bottlenecks, and improving the traceability of BECCS deployment pathways.

1. Introduction

Achieving net-zero and net-negative emissions targets requires not only rapid emission reductions but also the deployment of scalable carbon dioxide removal (CDR) technologies.

Such approaches must ensure durable storage of CO_2 while operating within regulatory and monitoring frameworks. Among these, Bioenergy with Carbon Capture and Storage (BECCS) is one of the most widely discussed carbon dioxide removal options in mitigation scenarios and carbon removal assessments (Smith et al., 2016; Fuss et al., 2018; IPCC, 2022). BECCS combines biomass-based energy conversion with CO_2 capture and long-term geological storage, thereby offering the potential for durable removals (Fuss et al., 2018).

The feasibility of BECCS depends on multiple interlinked factors, including biomass availability, land use and cultivation practices, pre-treatment logistics, conversion efficiency, and the development of CO_2 transport and storage. Societal perceptions related to land competition, infrastructure siting, and distributional impacts influence project development and siting conditions. While existing studies have modeled BECCS in global scenarios or assessed individual steps such as feedstock supply, conversion technologies, carbon capture, or governance, few efforts have provided a transparent, systematically structured framework that reflects the full deployment logic of BECCS across the operational chain (Slade et al., 2014; Torvanger, 2019).

This paper addresses this gap by presenting a modular BECCS process chain that structures the operational sequence from biomass sourcing and preparation through conversion and CO_2 capture to transport and storage. The framework was developed within the CDR-Atlas initiative in Germany to support planning, stakeholder dialogue, and systematic assessment across disciplines. It integrates peer-reviewed literature, existing BECCS assessments, and workshop-based engagement with domain experts from natural sciences and engineering, while governance and monitoring, reporting, and verification (MRV) are treated as relevant boundary conditions rather than as fully developed assessment frameworks.

By introducing modular entry points and decision nodes, the framework provides a structured analytical framework that can be applied across geographies, project scales, and policy contexts. Rather than prescribing fixed pathways, it enables transparent exploration of feasibility conditions, trade-offs, and risks associated with different BECCS configurations.

2. Methods

2.1 Modular Framing and System Rationale

The methodological core of this study lies in the development of a modular process chain that represents the full operational structure of BECCS. The modularity is not merely a visual convenience but serves to organize the system into discrete yet interlinked stages, allowing dependencies between feedstock choice, pre-treatment, conversion technologies, CO_2 capture, transport, storage, and governance-relevant decision points to be traced transparently. Segmenting BECCS into discrete but interlinked modules enables the tracing of interdependencies, such as how the choice of feedstock affects available conversion technologies and CO_2 transport infrastructure. Each module represents one major stage in the process chain — from integrated method and biomass selection to CO_2 storage and includes key operational sub-steps, MRV entry points, and decision nodes. This framing supports interdisciplinary understanding and iterative refinement, particularly in participatory planning settings or at early project stages where comprehensive system overviews are critical. Feedback loops and decision nodes across technological, ecological, social, and governance domains are explicitly incorporated to capture interactions between key technical and system-level components. While governance and MRV aspects are addressed as cross-cutting elements throughout the framework, their detailed methodological implementation is not the primary focus of this process-chain description. Instead, MRV considerations are integrated conceptually across modules, while more detailed monitoring and verification frameworks are discussed in the dedicated MRV section (Section 3.9) of this paper.

2.2 Literature Synthesis and Thematic Structure

The framework builds upon a structured synthesis of peer-reviewed publications, technical reports, and institutional assessments, including IPCC reports (IPCC, 2022; IPCC, 2023), complemented by sources addressing monitoring and governance aspects where applicable. Sources were selected based on their relevance to core BECCS process components and alignment with established system boundaries. This informed the identification and structuring of key process elements across the BECCS chain. Some elements were derived from recurring themes in review papers; others were selected based on their repeated inclusion across policy reports, sectoral assessments, and techno-economic analyses.

2.3 Stakeholder Integration and Expert Dialogue

To refine the process structure and align it with practical implementation considerations, three iterative meetings were held with domain experts, complemented by two additional consultations on MRV and on governance. These exchanges addressed recurring issues such as the alignment of feedstocks with conversion methods, pre-treatment dependencies, and the positioning of MRV-relevant stages within the process chain, which were iteratively refined and incorporated. The consultations also highlighted the need for a structure that supports both top-down strategy development and bottom-up implementation planning. The framework is primarily informed by peer-reviewed literature, complemented by structured expert input and iterative conceptual refinement.

2.4 Visual Implementation Principles

Initial drafts were created using Miro, a collaborative whiteboard platform, allowing shared development of logic and layout. The final version was implemented using scalable vector graphics (SVG) within the CDR-Atlas web framework to support interactive layers, modular data linking, and integration with on-click information boxes for each feedstock and process module. Flow logic was tested with expert and non-expert users to ensure usability across disciplines. Particular attention was given to intuitive flow, clear categorization, and intermodular coherence.

2.5 Scope and Limitations

The process chain does not aim to simulate dynamic behavior, quantify costs, or provide region-specific LCA or techno-economic results. Instead, it complements techno-economic modeling and GIS-based scenario planning by providing a structural and communicative interface. The framework is best used in early-stage planning, cross-sectoral coordination, and education. Some components are informed by expert input and inductive structuring based on existing knowledge rather than formal systems modeling. These include, for instance, the schematic placement of governance and MRV elements or distinctions in land preparation and cultivation types that reflect practical implementation needs rather than standardized methodological frameworks.

2.6 Terminology and Process Definitions

To ensure clarity for an interdisciplinary readership, this study defines key concepts relevant to the BECCS process chain. Bioenergy with carbon capture and storage (BECCS) refers to the integration of biomass conversion into energy carriers with CO_2 capture and geological storage, resulting in net removal of atmospheric CO_2. Monitoring, reporting, and verification

(MRV) denotes the systematic measurement, documentation, and independent validation of CO_2 removals across the process chain and is essential for transparency, accountability, and storage integrity (IPCC, 2022).

Feedstocks are grouped into four main categories: agricultural biomass, forest biomass, waste biomass, and microalgae and aquatic biomass. Agricultural biomass is further subdivided into sugar-rich, starch-rich, and herbaceous feedstocks, with wetland biomass treated as a specific subcategory of herbaceous biomass due to its distinct ecological and management characteristics (Cherubini, 2010b; Fajardy and Mac Dowell, 2017). This classification reflects shared cultivation origins alongside differences in handling, processing requirements, and conversion suitability.

These categories form the basis for the integrated method and biomass selection step, providing the structural linkage to subsequent modules such as pre-treatment, conversion, product upgrading, and CO_2 transport and storage. Detailed descriptions of conversion technologies, pre-treatment options, and methodological assumptions are provided in Appendix 1.

3. Results

Overview

The BECCS system is structured into eight modules that together form a complete process chain (Figure 1). Each module represents one major step in the BECCS pathway. While a module marks a large unit in the chain, it often contains several smaller operational steps. This structure provides a transparent representation of system components and their interrelations. The process chain represents a conceptual system framework rather than a detailed engineering design. Individual steps may vary depending on feedstock properties, technological configuration, and site-specific conditions.

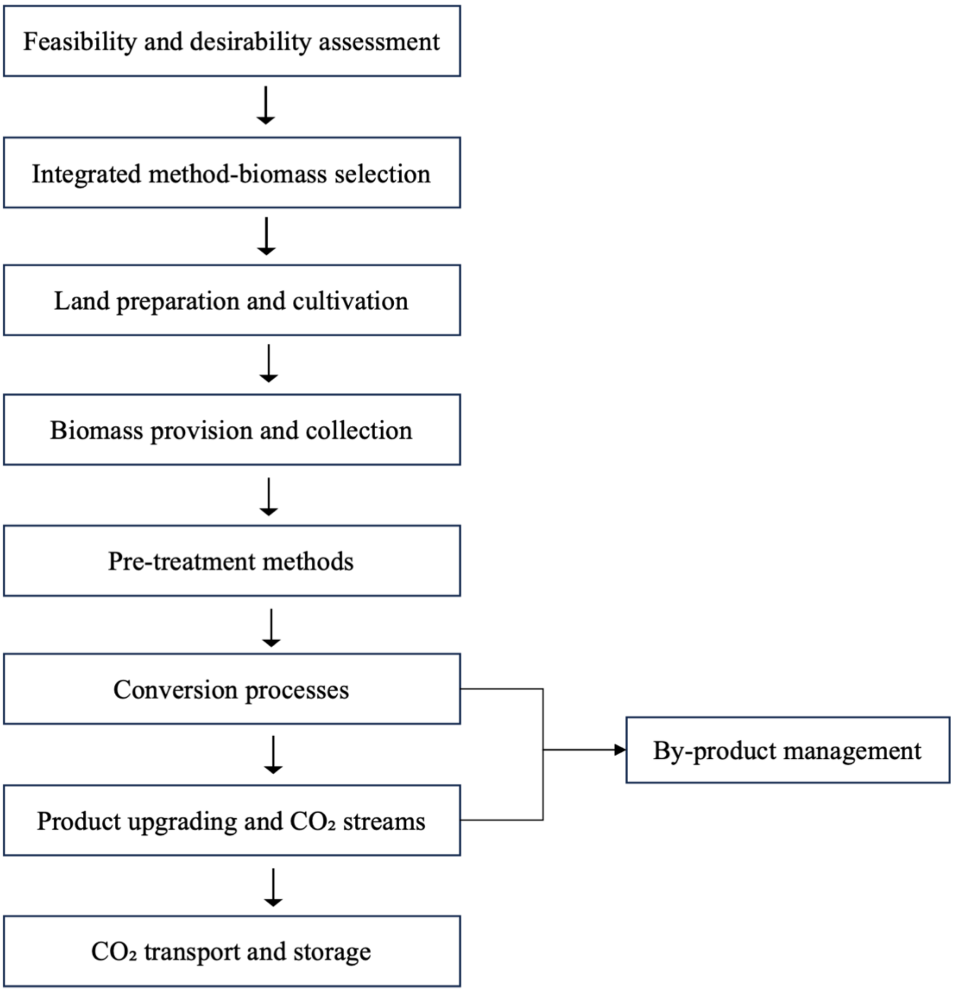

Figure 1. Schematic overview of the modular BECCS process chain. The figure presents eight main modules, ranging from feasibility and desirability assessment through integrated method and biomass selection, land preparation and cultivation, biomass provision and collection, pre-treatment processes, conversion processes, product upgrading and CO_2 streams, to CO_2 transport and storage. By-product management is represented as a side stream associated with the conversion and upgrading stages. Cross-cutting elements, such as MRV and societal dimensions, are conceptualized as integral components across all modules. Each box represents a major process stage comprising multiple operational sub-steps, which are detailed in subsequent figures and sections.

The first two modules represent entry points: the Feasibility Assessment examines whether a BECCS project is technically, logistically, and economically feasible in a given location. This distinction follows the feasibility/desirability framework proposed by Tank et al. (2025). Both gates must be passed before moving on.

Next comes the *Integrated Method and Biomass Selection module*, which links the choice of conversion method with suitable biomass types. This step includes the main technological pathways—combustion, thermochemical conversion, fermentation, and anaerobic digestion—and aligns them with compatible feedstock categories, including agricultural biomass, forest biomass, waste biomass, and microalgae and aquatic biomass. Wetland biomass is treated as a specific subcategory of herbaceous biomass within the agricultural group.

Recent literature indicates that waste biomass (e.g., industrial, municipal, or post-consumer materials of biological origin) is frequently treated as a distinct feedstock category in bioenergy and BECCS-related studies (Lee et al., 2019; Thrän et al., 2025).

The field-level steps *Land Preparation* and *Cultivation* describe how the chosen biomass can be grown and collected under local conditions. *Biomass Provision and Collection* covers harvesting, transport, and, if needed, short-term storage.

The next step, represented by the Pre-treatment Processes module, prepares biomass for subsequent conversion by modifying its physical, chemical, or biological properties. Typical pre-treatment approaches include size reduction, drying, torrefaction, hydrolysis, or other physicochemical treatments that improve feedstock handling, stability, and conversion efficiency depending on feedstock characteristics and the selected conversion pathway (Mata-Alvarez et al., 2014).

The Processes for Conversion module forms the technological core of BECCS and encompasses major biochemical and thermochemical pathways such as fermentation, combustion, gasification, pyrolysis, and anaerobic digestion. These processes convert biomass into solid, liquid, or gaseous energy carriers, including solid bioenergy products, liquid biofuels, and biogas, which can subsequently be used to generate heat, electricity, or transport fuels (IPCC, 2022).

In addition to energy carriers, biomass conversion generates CO_2-containing process streams. Depending on the conversion pathway, CO_2 may be separated during fuel upgrading processes such as biogas upgrading or bioethanol purification, or captured during energy conversion processes such as combustion or gasification. The separated CO_2 can then be directed to capture systems and subsequently transported and stored in geological formations (Fajardy and Mac Dowell, 2017; IPCC, 2022).

Product upgrading refers to processing steps that improve the quality of energy carriers produced during biomass conversion (e.g., biofuels, biogas, or syngas), while CO_2-rich gas streams generated during upgrading or energy conversion are separated and directed toward capture, transport, and geological storage.

Depending on the selected conversion pathway, additional material streams may arise, including biochar from pyrolysis, digestate from anaerobic digestion, or ash residues from combustion processes. These materials require appropriate by-product management and may be reused, treated, or disposed of depending on their composition, stability, contaminant content, and regulatory context (Lehmann and Joseph, 2015; Mata-Alvarez et al., 2014; IPCC, 2022).

3.1. Feasibility and desirability assessment

Feasibility assessment evaluates whether BECCS can be implemented under given conditions (Figure 2). It evaluates whether local or regional conditions are suitable for implementing a BECCS system from a technical, logistical and economic perspective. This includes the availability of sustainable biomass feedstocks, the suitability of land without major conflicts with food production or biodiversity protection, and the accessibility of infrastructure for biomass conversion, CO_2 transport, and geological storage (Popp et al., 2017). Feasibility also includes the question of whether (MRV) systems can be integrated in a robust way over time. MRV systems are required to enable transparent accounting of negative emissions. Finally, the availability of financing and clear responsibilities for long-term CO_2 liability and storage stewardship are critical. If these conditions are not met, implementing BECCS in a given region may result in technical, regulatory, or environmental challenges—highlighting the importance of this first module (Tank et al., 2025; Baatz et al., 2025).

Desirability assessment complements this technical screening by asking: *Should BECCS work here?* It shifts the perspective toward societal and ethical dimensions. This module considers whether a BECCS project is supported or rejected by local communities, whether it aligns with broader climate strategies, and whether its benefits and burdens are fairly distributed. Societal acceptance is a critical enabler—or barrier—for any carbon removal effort, and depends on perceived risks, transparency, and procedural inclusion (Bellamy et al., 2017; Fridahl, 2017). Political alignment is equally important: projects that do not fit into national or regional decarbonization pathways may face resistance or regulatory delays (IPCC, 2023). Additionally, potential conflicts with land-use priorities—such as food production, tourism, or nature conservation—must be carefully considered (Popp et al., 2017). Early stakeholder involvement and attention to distributional effects are essential for legitimate BECCS deployment, particularly where projects may affect land use, infrastructure siting, or local communities (Bellamy et al., 2017; Fridahl, 2017; Morrow et al., 2020).

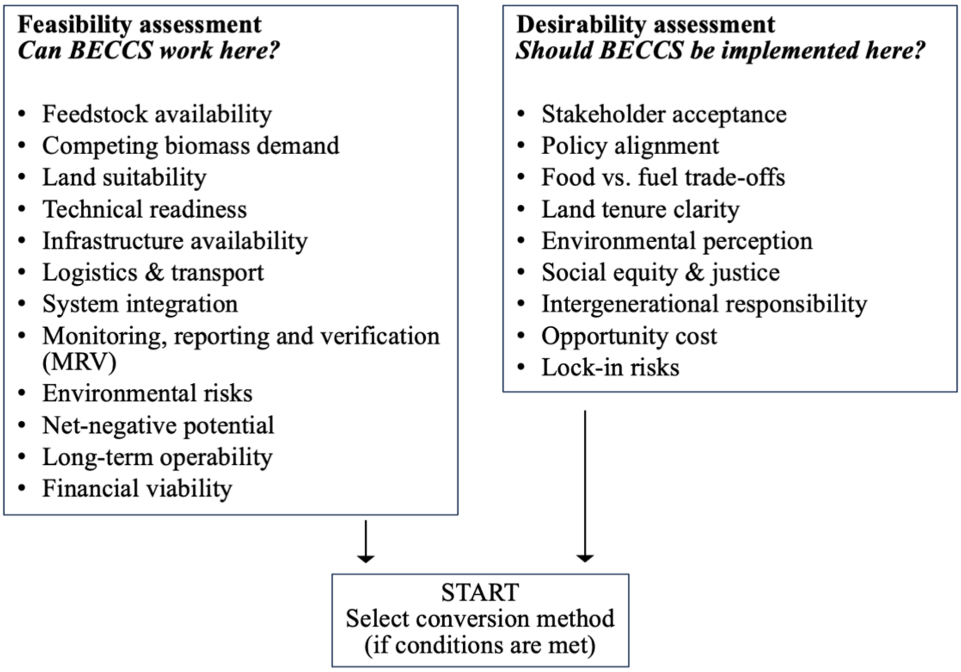

Figure 2. Feasibility and desirability assessments as entry gates to the BECCS process chain. The figure illustrates an initial screening step that evaluates key technical, ecological, and societal boundary conditions before further specification of feedstocks and conversion pathways. These assessments are not intended to represent a comprehensive decision framework but rather serve as early-stage entry gates that identify whether a BECCS pathway should be explored further. More detailed feedstock- and method-specific assessments are conducted in subsequent stages of the process chain.

Only if both feasibility and desirability conditions are fulfilled, the process can move forward to method selection. This logic defines an initial entry point that integrates technical, environmental, and societal aspects from the very beginning of any BECCS pathway.

3.2. Method Selection and Feedstock Categorization

Once the feasibility and desirability of a BECCS deployment have been evaluated for a given region, and both assessments yield positive outcomes, the process transitions into its first technical decision point: the Integrated Method and Biomass Selection module. This marks the entry into the engineering and operational dimension of BECCS planning, where suitable biomass types are aligned with compatible conversion methods in an integrated assessment. Because conversion methods differ significantly in terms of temperature regime, biochemical requirements, infrastructure needs, and carbon capture compatibility, their selection has downstream effects on every subsequent module of the chain. This relationship between feedstock characteristics and conversion pathways is summarized in Figure 3.

Conversion method	Forest biomass	Agricultural biomass	Waste biomass	Microalgae and aquatic
Combustion	✓	(✓)	✓	–
Gasification	✓	✓	✓	–
Pyrolysis	✓	✓	✓	(✓)
Anaerobic digestion	–	✓	✓	✓
Fermentation	–	✓	(✓)	(✓)

Figure 3. Integrated method and biomass selection. The table illustrates the linkages between major feedstock categories—forest, agricultural, waste, and microalgae and aquatic biomass—and the corresponding conversion methods in BECCS systems. The waste biomass category includes heterogeneous streams such as municipal solid waste, waste wood, organic residues, and processed fuels such as solid recovered fuels (SRF), whose compatibility with individual conversion methods depends on composition and pre-treatment. Symbols indicate compatibility: ✓ established; (✓) conditional; – not suitable.

The core conversion methods represented in this framework include fermentation, anaerobic digestion, and a collective category termed “Thermochemical Conversion Methods,” encompassing hydrothermal carbonization, combustion, gasification, and pyrolysis. These technologies are not interchangeable, and each has specific feedstock requirements as well as carbon capture implications. For instance, fermentation is predominantly suited for biomass that is rich in sugars or starch, as these compounds can be efficiently converted into ethanol or other biofuels. Feedstocks such as sugar beet, corn, food waste, and even microalgae like

Chlorella and Spirulina have been used in fermentation (Kheshgi and Prince, 2005). Anaerobic digestion, by contrast, operates under microbial processes and accepts a broader range of wet, biodegradable substrates, including herbaceous plants, municipal organic waste, wetland grasses, and algal residues (IPCC, 2022; Ogunleye et al., 2024). Waste-to-energy pathways extend beyond direct incineration and may include the combustion of municipal solid waste and waste wood, co-incineration of solid recovered fuels (SRF), and thermochemical conversion routes such as gasification and pyrolysis (ISO, 2021b).

Combustion systems—whether for direct electricity generation or combined heat and power generation—are technically mature but require dry material. Forest-derived biomass such as wood chips or sawmill residues are therefore well suited, while herbaceous biomass may only be suitable if sufficiently dried (Ogunleye et al., 2024). Further thermochemical conversion methods such as gasification and pyrolysis operate at elevated temperatures in low-oxygen environments and enable the production of syngas, bio-oil, and biochar. Gasification and pyrolysis are generally more suitable for dry or pre-treated forest and herbaceous biomass, including wetland-derived biomass after appropriate drying or conditioning. High-moisture feedstocks may instead require wet conversion routes or additional pre-treatment before thermochemical conversion.

However, the structural properties of herbaceous biomass can reduce conversion efficiency. Waste-to-energy pathways, particularly combustion and co-incineration of municipal solid waste and waste wood, are well-established and widely applied (Thrän et al., 2025; Milledge et al., 2019).

The feedstock–conversion linkages in this framework reflect both theoretical compatibility and practical experience from research projects and commercial-scale pilots. Forest biomass is commonly associated with combustion, gasification, and pyrolysis, whereas wet agricultural biomass—typically sugar-rich or starch-rich—is more closely linked to fermentation and anaerobic digestion. Herbaceous biomass, such as straw or hay, and wetland biomass, offer potentials for anaerobic digestion, gasification, or pyrolysis if sufficiently dried or pelletized. Residues from wood processing and waste wood are also typically converted in combustion or gasification, while wet biomass is used in fermentation or anaerobic digestion after separation and cleanup. Microalgae and aquatic biomass, though often associated with lower technology readiness levels in bioenergy processes, have demonstrated compatibility with fermentation and anaerobic digestion due to their high biochemical conversion yields (Lefvert and Grönkvist, 2024).

These interconnections are essential for interpreting BECCS as a modular and context-dependent system. Rather than a fixed sequence, it represents a network of process options where biomass characteristics, conversion technologies, and regional conditions jointly influence the configuration of each deployment.

3.3. Land Preparation, Cultivation, and Biomass Provision and Collection

3.3.1 Overview of Upstream Biomass Modules

Following the selection of a suitable conversion method and its corresponding feedstock category, the BECCS process chain proceeds through a sequence of upstream modules. These include a) *land preparation*, b) *feedstock cultivation*, and c) *biomass provision and collection*, the latter comprising three operational subphases: c1) *harvesting and collection*, c2) *transport* and c3) *temporary storage options*. After harvesting and transport, biomass feedstocks are often subject to temporary storage prior to conversion or pre-treatment, which serves to balance seasonal supply, control moisture, and preserve biomass quality. Together, these components describe the upstream stages of biomass provision within the BECCS process chain.

While these activities are extensively documented in agronomic, silvicultural, ecological, and industrial literature, this paper provides a structured description of their application to BECCS. Rather than reproducing detailed technical manuals, the following section outlines the key operational steps for the main feedstock types represented in the process chain. These include *sugar-rich biomass, starch-rich biomass, herbaceous biomass (including wetland biomass), forest biomass, waste biomass,* and *microalgae and other aquatic biomass*. For each of these feedstock types, the steps of land preparation, cultivation, harvesting and collection, and transport are described in the order in which they appear in the process chain (Figure 1).

The third subphase of biomass provision, *temporary storage options*, is treated collectively at the end of this module, as practices for short-term storage often depend more on downstream conversion needs and logistical integration than on biomass type alone.

Scientific references are provided throughout, and more comprehensive insights into the ecological, agronomic, and logistical nuances can be found in specialist publications (e.g., Cherubini, 2010a; Wichtmann et al., 2016; Milledge et al., 2019).

Although wetland biomass is often grouped under herbaceous or agricultural categories in conventional bioenergy classifications, it is treated here as a specific subcategory of herbaceous biomass due to its distinct hydrological, ecological, and management characteristics.

3.3.2. Sugar-rich agricultural biomass

a) Land preparation: Following the selection of a suitable feedstock category and conversion pathway, sugar-rich biomass systems—such as those relying on sugarcane (*Saccharum officinarum*) or sugar beet (*Beta vulgaris*)—require a sequence of well-coordinated agronomic practices to ensure high productivity and ecological integrity. This section outlines the upstream components for sugar-rich biomass in BECCS systems, spanning from land preparation through to harvesting and transport.

For sugar-rich crops, initial land preparation includes the selection of cultivars with elevated sugar content, tailored to regional conditions. High-sucrose varieties are critical for maximizing ethanol yield in fermentation-based BECCS routes, as they provide greater amounts of fermentable sugars per hectare and enable more efficient conversion rates. Varietal selection is typically followed by comprehensive soil testing to assess nutrient availability, pH levels, and water-holding capacity. Based on the results, site-specific nutrient regimes—especially nitrogen application—are planned to promote vigorous crop establishment (Karp et al., 2022).

b) Feedstock cultivation: During the cultivation phase, maintaining high sugar productivity requires active management of pests and diseases known to reduce sucrose accumulation. Integrated pest management (IPM) strategies and biological controls are increasingly applied to reduce pesticide dependency and environmental impact. Additionally, optimized irrigation schedules and monitoring of canopy development are essential to sustain photosynthetic efficiency and sucrose storage in the stem tissues (Amorim et al., 2011). In sugar beet systems, maintaining root quality and sugar concentration is important for downstream ethanol production, because fermentation performance depends on the availability and quality of fermentable sugars in the harvested biomass (Zabed et al., 2014).

c) Biomass provision and collection:

c1) Harvesting and collection: Sugar-rich biomass is harvested using specialized agricultural machinery adapted to either cane or beet morphology. For instance, sugarcane is typically cut at ground level with whole-stalk or chopper harvesters, depending on downstream processing needs, while sugar beet harvesting requires lifting equipment that minimizes root damage (Karp et al., 2022). The timing of harvest is critical, as peak sucrose content occurs shortly before physiological maturity.

c2) Transport: Post-harvest, biomass is loaded into covered trailers or sealed containers to minimize sucrose loss and microbial contamination during transit. Transport logistics are closely integrated with fermentation facilities to reduce storage time, limit degradation of sugar-rich biomass, and avoid unnecessary transport-related emissions (Amorim et al., 2011; IPCC, 2022).

3.3.3. Herbaceous agricultural biomass

Following the selection of the feedstock category and the transition from the general cultivation section, this module details the specific steps associated with *Herbaceous biomass*. This category includes feedstocks such as Miscanthus × giganteus, grassland residues, straw, and wetland-derived biomass, each requiring tailored preparation and harvesting practices that are represented in the BECCS process chain. Wetland biomass is treated as a specific herbaceous subcategory because of its distinct hydrological, ecological, and management characteristics.

a) Land preparation: Land preparation for herbaceous biomass typically includes soil tillage and pH adjustments to ensure balanced nutrient availability, particularly for nitrogen and phosphorus. While straw and grassland biomass often require minimal fertilization to maintain the stability of existing soil ecosystems, miscanthus cultivation is more sensitive to micronutrient deficiencies and may require targeted nutrient interventions (Kwaśniewski et al., 2022; Winkler et al., 2020). Soil conditioning before planting is therefore critical to ensure robust crop establishment.

b) Feedstock cultivation: During the establishment phase, herbaceous crops such as *Miscanthus × giganteus* are commonly planted using rhizomes at densities of approximately 16,000 per hectare. Effective mechanical weed control during the first growing season is essential to reduce competition and allow for the development of a closed canopy, which supports moisture retention and early biomass accumulation (Winkler et al., 2020; Kwaśniewski et al., 2022). Fertilization requirements vary depending on site conditions, soil nutrient status and crop development stage, and should therefore be adapted to local agronomic conditions (Winkler et al., 2020; Kwaśniewski et al., 2022).

c) Biomass provision and collection:

c1) Harvesting and collection: Herbaceous biomass is generally harvested in late winter or early spring, when moisture content falls below 30 %, improving storability and reducing transport emissions (Kwaśniewski et al., 2022). Miscanthus, for example, is harvested using forage harvesters or balers. The timing of the harvest directly influences the biomass quality, including ash content and calorific value, and is therefore a key variable in BECCS supply chain planning.

c2) Transport: Transportation of herbaceous biomass typically occurs in the form of compressed bales or shredded material. Moist biomass is prone to microbial degradation and associated emissions; for this reason, miscanthus is usually transported at moisture levels below 25 % (Kwaśniewski et al., 2022). Optimizing moisture content, bale density, and logistics coordination remains essential to minimize emissions and economic costs.

Wetland biomass (paludiculture)

Wetland biomass is treated here as a specific subcategory of herbaceous biomass due to its distinct hydrological, ecological, and management characteristics.

a) Land preparation: Wetland biomass cultivation, often referred to as *paludiculture*, focuses on the productive use of rewetted peatlands and other wet or formerly drained ecosystems. Land preparation involves rewetting previously drained areas by adjusting water levels through dike removal, ditch blocking, or controlled irrigation infrastructure. This process halts peat degradation, restores hydrological function, and prepares the site for the cultivation of wet-adapted species such as *Phragmites australis* (common reed), *Typha spp.* (cattail), or *Carex spp.* (sedges). This practice supports both biomass provisioning and climate mitigation through avoided emissions and potential carbon sequestration (Wichtmann et al., 2016; Tanneberger et al., 2021).

b) Feedstock cultivation: The cultivation of wetland biomass requires careful selection of species that are adapted to saturated conditions and capable of high biomass yields. Species such as *Typha latifolia*, *Phragmites australis*, and *Schoenoplectus lacustris* are commonly used in central Europe. These plants are typically not fertilized and rely on naturally available nutrients in the wetland ecosystem. Management focuses on water level control to optimize growth while ensuring the long-term stability of the peat body. Unlike conventional crops, these species are not re-sown annually; they regenerate vegetatively and form permanent vegetation cover (Wichtmann et al., 2016).

c) Biomass provision and collection:

c1) Harvesting and collection: Harvesting is conducted with specialized low-ground-pressure machines or amphibious vehicles, often during winter or dry periods to minimize soil disturbance and preserve the peat layer. Harvesting equipment may include adapted mowers, balers, or chippers, depending on the biomass form (e.g., whole shoots vs. shredded material). Timing and method are crucial to avoid damage to sensitive ecosystems and to maintain long-term site productivity. In many pilot projects, mobile field systems are used to cut, collect, and pre-compact biomass directly on-site (Tanneberger et al., 2021).

c2) Transport: After collection, wetland biomass is transported to processing or drying facilities. Due to its typically high moisture content, efficient logistics are essential to minimize energy losses and emissions. Transport methods include tractors with trailers, amphibious harvesters with on-board transport capability, or lightweight forwarders, depending on the site's accessibility. Proximity to utilization sites (e.g., for combustion, anaerobic digestion, or insulation material production) plays a major role in determining the feasibility and carbon balance of paludiculture systems (Tiemeyer et al., 2020).

3.3.4. Starch-rich agricultural biomass

a) Land preparation: The cultivation of starch-rich biomass, such as maize and cassava, requires site-specific land preparation techniques tailored to the crop's morphological and agronomic needs. For cassava, land clearing is followed by ridge formation or mounding to facilitate root expansion and avoid waterlogging, particularly in humid tropical environments. Soil loosening may be used to promote root and tuber development and to reduce compaction stress, depending on crop type, soil conditions, and local cultivation practice. In maize cultivation, pre-sowing tillage is used to optimize seedbed structure and moisture retention while suppressing early weed emergence. Conservation tillage techniques are increasingly recommended to reduce erosion and preserve soil carbon stocks in BECCS-compatible land-use schemes (Lal, 2020).

b) Feedstock cultivation: Starch-rich crops are cultivated with a focus on optimizing starch accumulation, which is influenced by nutrient availability, sunlight duration, planting density, pest pressure, and regional production practices. In cassava systems, cultivation intensity and fertilizer requirements vary strongly with soil conditions and local management. Maize generally requires more intensive nutrient management and is sensitive to planting time and pest pressure. For BECCS pathways, such management choices should be assessed in relation to feedstock yield, upstream emissions, and overall carbon-removal performance (Tanzer and Ramirez, 2019).

c) Biomass provision and collection:

c1) Harvesting and collection: Harvesting practices for starch-rich crops are highly mechanized in the case of maize and semi-manual to fully manual for cassava, depending on the region. Maize is typically harvested using combine harvesters that separate grains and collect cobs, which are then either stored or processed into bioethanol feedstock. Cassava roots are usually hand-harvested or uprooted using lightweight equipment to minimize tuber damage, which is critical due to the crop's rapid post-harvest deterioration (Burns et al., 2010). Efficient timing of harvest is essential to preserve starch content and reduce spoilage.

c2) Transport: Transport logistics for starch-rich biomass require particular attention to bulk density, moisture content, and degradation risk. Dried grain-based feedstocks can generally be stored and transported more easily than fresh root and tuber crops, which are more susceptible to post-harvest deterioration and therefore benefit from rapid processing or short transport routes. The choice of transport method depends on infrastructure, distance, feedstock form, and the scale of operation.

3.3.5. Forest Biomass

The use of forest-derived woody biomass within BECCS systems relies on long-term, site-specific management strategies that integrate ecological, silvicultural, and carbon-removal objectives. This section describes the key steps from land preparation to transport, following the structure outlined in the process chain.

a) Land preparation: Land preparation for forest biomass feedstocks may involve the establishment or management of forest systems on degraded, previously harvested, or underutilized lands. Site suitability depends on local ecological, logistical, and land-use conditions.

In some cases, afforestation or reforestation of marginal land is implemented, while in others, former agricultural plots are transitioned into short-rotation plantations (Berndes et al., 2016). Mechanical clearing, soil conditioning, and infrastructure development (e.g., access roads) are conducted in compliance with sustainability guidelines to minimize soil disturbance and erosion.

b) Feedstock cultivation: Cultivation in this context refers to the establishment and maintenance of forest stands optimized for biomass harvesting. Species selection plays a central role, with preference given to fast-growing, high-yield trees such as poplar, willow, or eucalyptus in temperate climates (González-García et al., 2012). Planting density, rotation length, and thinning regimes influence biomass yields, site productivity, soil carbon dynamics, and biodiversity outcomes and therefore need to be adapted to site-specific management objectives. Short-rotation coppice systems are often favored due to their rapid regrowth and compatibility with mechanized harvesting (Bentsen et al., 2014). Weed control, fertilization, and irrigation may be applied during establishment phases, especially in degraded or nutrient-poor sites, but are typically reduced in mature stands (Berndes et al., 2016).

c) Biomass provision and collection:

c1) Harvesting and collection of forest biomass is performed using specialized forestry equipment such as harvesters and forwarders, depending on stand structure, terrain, and mechanization level (Spinelli et al., 2011; Spinelli et al., 2014). Biomass may be extracted as whole trees, logs, or residues such as branches and tops. In short-rotation coppice systems, mechanized harvesting enables efficient biomass collection, although machinery use can cause soil compaction and mechanical damage and should therefore be adapted to site and soil conditions (Souch et al., 2004). Collection logistics must also account for biomass moisture content, because high moisture increases the mass transported and can reduce the economic and energetic efficiency of forest biomass supply chains (Leonello et al., 2024).

Depending on the method of processing, biomass may be chipped or bundled directly at the felling site.

c2) Transport of forest biomass typically involves trucks, trailers, or in some cases, rail systems to move the material from forest sites to conversion or storage facilities. Transport systems and loading requirements differ according to whether forest biomass is handled as roundwood, loose residues, or wood chips, and these differences affect payload and logistical efficiency (Väätäinen et al., 2021). Strategies to reduce greenhouse gas emissions during this phase include optimizing route planning, using high-capacity vehicles, and limiting transport distances through decentralized pre-processing hubs. In some cases, mobile chipping units are employed on-site to increase bulk density and reduce haulage volume (Spinelli and Marchi, 2021). Reducing the moisture content of forest biomass before transport can increase its net calorific value and improve supply-chain efficiency by reducing the amount of water transported (Acuna et al., 2012).

3.3.6. Waste Biomass

Although waste biomass is not explicitly defined as a primary category in ISO 17225-1:2021, recent frameworks increasingly recognize it as an important BECCS feedstock (ISO, 2021a).

a) Land preparation: For waste biomass sources, land preparation is generally not required in the conventional sense, as the feedstocks are by-products of urban, industrial, or agricultural processes. Waste-derived BECCS feedstocks may include biogenic municipal and industrial waste streams as well as agricultural and forestry residues, although their suitability depends on composition, competing uses, contamination, and processing requirements (Daioglou et al., 2016; Hanssen et al., 2020). Unlike forest residues, which originate from managed forestry operations, waste wood typically arises from construction, demolition, or post-industrial activities. Its utilization requires compliance with waste handling regulations, particularly regarding coatings, adhesives, or heavy metal contamination.

Waste-derived feedstocks require collection, source separation, transport, and pre-treatment systems to reduce contamination and prepare heterogeneous waste streams for subsequent material or energy recovery (Zhang et al., 2022). Sewage sludge may contain heavy metals and other contaminants that constrain its energetic utilization and require appropriate characterization and treatment before thermal conversion (Fytili and Zabaniotou, 2008). As such, the preparation phase for waste biomass focuses less on land use and more on logistical and regulatory integration.

b) Feedstock cultivation: Waste biomass is not cultivated in the conventional sense, as it is generated as a residual or by-product stream from existing agricultural, forestry, municipal, wastewater, and industrial systems (Lee et al., 2019; Daioglou et al., 2016). The quantity and availability of agricultural and forestry residues depend on primary production levels, regional conditions, competing uses, and sustainability constraints (Daioglou et al., 2016; Hanssen et al., 2020). For food waste and municipal organic waste, feedstock quality depends strongly on source separation, collection systems, preprocessing, and contamination control (Pfaltzgraff et al., 2013; Al Seadi et al., 2013). For sewage sludge and digestate, feedstock quality is influenced by the input materials and the operating conditions of wastewater treatment or anaerobic digestion processes (Fytili and Zabaniotou, 2008). Although waste biomass is not actively cultivated, these upstream systems functionally determine the availability, composition, and suitability of waste-derived feedstocks for BECCS (Daioglou et al., 2016; Hanssen et al., 2020; Lee et al., 2019).

c) Biomass provision and collection:

c1) Harvesting and collecting waste biomass requires a well-coordinated infrastructure tailored to each waste stream. Sewage sludge is typically collected via centralized wastewater treatment plants using sedimentation and dewatering technologies (Fytili and Zabaniotou, 2008). Food and organic waste are gathered through municipal or commercial collection systems, which may include source separation and anaerobic digestion pre-treatment facilities (Zhang et al., 2022). Post-consumer and industrial biogenic waste streams often require preprocessing to remove non-biodegradable or contaminated fractions, using operations such as screening, shredding, sorting, and drying where appropriate (Zhang et al., 2022).

Reliable and traceable collection systems are essential to ensure the quality and safety of the biomass stream and to comply with environmental and health regulations (Bosona et al., 2018; Friege et al., 2022; Iakovou et al., 2010).

c2) Liquid and semi-solid feedstocks such as sewage sludge and digestate require dedicated storage and transport arrangements because their high water content increases the mass transported and can affect logistics costs and environmental performance (Vilanova Plana and Noche, 2016; Kovačić et al., 2022). Solid waste streams, including source-separated organic residues and post-consumer biogenic materials, require collection and transport systems adapted to their physical form, moisture content, contamination level, and intended downstream treatment (Zhang et al., 2022). Where technically and economically feasible, pre-treatment close to the point of waste generation can reduce the amount of material transported and facilitate subsequent recovery or conversion processes (Zhang et al., 2022). Sewage sludge and other potentially contaminated fractions require appropriate characterization and treatment before further processing or energy recovery (Fytili and Zabaniotou, 2008).

3.3.7. Microalgae and aquatic biomass

a) Land Preparation: Unlike terrestrial feedstocks, microalgae and aquatic biomass do not require conventional agricultural land preparation. In this context, land preparation refers instead to the selection and establishment of suitable cultivation areas and production systems. Microalgae are commonly cultivated in open raceway ponds or closed photobioreactors, with system and site selection depending on factors such as land and water availability, solar radiation, nutrient and CO_2 supply, contamination risk, productivity requirements, and opportunities for co-location with industrial CO_2 sources (Mata et al., 2010; Tan et al., 2018). For marine macroalgae such as seaweed, site selection must additionally consider water depth, hydrodynamic conditions, nutrient availability, light, salinity, temperature, and compatibility with existing marine uses and regulatory requirements (García-Poza et al., 2020; Lojek et al., 2024).

b) Feedstock cultivation: Microalgae and other algal biomass may also be suitable for anaerobic digestion, although methane yield and process stability depend on species composition, cell-wall structure, pre-treatment requirements, and operating conditions (Ward et al., 2014; Milledge et al., 2019). Microalgae are cultivated under controlled conditions in which light intensity, temperature, pH, nutrient availability, and carbon supply influence biomass productivity and biochemical composition (Khan et al., 2018). The choice between open ponds and closed photobioreactors affects productivity, contamination control, process stability, and scalability (Brennan and Owende, 2010; Tan et al., 2018). For marine macroalgae, cultivation conditions depend on species-specific requirements and seasonal variations in light, temperature, salinity, nutrient availability, and hydrodynamic exposure (García-Poza et al., 2020; Lojek et al., 2024). Microalgal cultivation may also be coupled with wastewater treatment and the use of CO_2-containing flue gases, enabling nutrient recovery and CO_2 utilization during biomass production; however, this coupling does not constitute durable carbon dioxide removal unless the resulting biogenic carbon is subsequently captured and stored (Lage et al., 2018; Tanzer and Ramírez, 2019).

c) Biomass provision and collection:

c1) Harvesting and collection: Harvesting microalgae requires separation of the dilute biomass from the cultivation medium, commonly through sedimentation, flocculation, flotation, filtration, centrifugation, or combinations of these methods. The selection of the harvesting method depends on cell size, biomass concentration, required product quality, energy demand, and downstream conversion requirements, and harvesting and dewatering can represent a substantial share of the energy use and cost of microalgal biomass production (Tan et al., 2018). Cultivated macroalgae are harvested manually or mechanically, with the appropriate technique depending on the cultivated species, farm design, scale, accessibility, and intended downstream use (García-Poza et al., 2020). Harvest timing and intensity should account for biomass yield and composition as well as species regeneration and potential effects on associated marine ecosystems (Mac Monagail et al., 2017; Lotze et al., 2019).

c2) Transport: Because harvested microalgal biomass is highly dilute, it is generally concentrated by dewatering before transport or downstream processing. The extent of dewatering depends on the selected conversion route, since drying can improve transportability but also represents a major energy demand in microalgal biomass production, whereas wet conversion pathways may avoid energy-intensive drying steps (Zaimes and Khanna, 2013; Milledge et al., 2019). Locating cultivation, dewatering, and conversion facilities close to one another can reduce the transport of water-rich biomass and improve the overall energy and environmental performance of the supply chain (Zaimes and Khanna, 2013). Fresh macroalgae also have a high water content and deteriorate rapidly, making early dewatering or processing near the harvesting site important for reducing transported mass, costs, and associated greenhouse gas emissions (Gallagher et al., 2018; Álvarez-Viñas et al., 2019).

3.3.8. Temporary storage options

After harvesting and transport, biomass feedstocks are often subject to temporary storage prior to conversion or pre-treatment. This step serves multiple functions, including buffer capacity for seasonal harvests, supply-chain coordination, moisture control, and the preservation of biomass quality. While earlier stages in the process chain are highly feedstock-specific, temporary storage strategies tend to converge across biomass types and are therefore described collectively in this section.

Storage requirements differ substantially among sugar-rich and herbaceous feedstocks. Freshly harvested sugarcane is susceptible to rapid post-harvest deterioration and sucrose loss; storage should therefore be minimized and the material transported to processing facilities as quickly as possible (Misra et al., 2022). Sugar beet roots can be stored for longer periods, but storage duration and temperature influence respiration, microbial deterioration, sucrose losses, and processing quality (Fugate et al., 2024). For herbaceous lignocellulosic biomass, storage conditions depend primarily on moisture content: sufficiently dry material can be stored as bales under protection from precipitation, whereas high-moisture material generally requires anaerobic storage, such as ensiling, to limit aerobic microbial degradation and dry-matter losses (Smith et al., 2020; Wendt et al., 2018).

Lipid-rich algal biomass is susceptible to compositional changes and degradation during storage, particularly when exposed to elevated temperatures, oxygen, and light. Storage conditions should therefore be selected according to the intended downstream use and the required preservation of lipid and fatty-acid profiles (Lopes et al., 2024).

Forest biomass such as logs, logging residues, and wood chips may be stored temporarily before conversion to balance supply and reduce moisture content. Storage performance depends on biomass form, initial moisture content, pile dimensions, ventilation, covering, and storage duration. During storage, microbial and chemical degradation can cause dry-matter and energy losses, while moist wood-chip piles are also susceptible to self-heating and, under unfavorable conditions, fire (Jylhä et al., 2022; Ashman et al., 2018).

Storage requirements for waste-derived biomass depend strongly on the physical state, moisture content, stability, and contamination level of the material. Liquid digestate should be stored in covered or otherwise controlled systems because methane and ammonia emissions may occur during storage, while storage design and subsequent processing influence the environmental performance of digestate management (Kovačić et al., 2022; Møller et al., 2022). Sewage sludge and other contaminated waste fractions require contained storage and handling to limit odor, leachate formation, pathogen exposure, and the dispersion of hazardous substances before further treatment or energy recovery (Zaharioiu et al., 2021).

Wetland biomass from paludiculture systems may have a high moisture content at harvest, depending on species and harvest season. This affects transport, storage stability, and suitability for downstream conversion. Harvest timing and subsequent handling should therefore be aligned with the intended use, and prolonged storage of moist biomass should be avoided where deterioration and dry-matter losses cannot be adequately controlled (Schröder et al., 2015; Geurts et al., 2020).

Microalgae and aquatic biomass generally have limited storage stability because of their high water content and susceptibility to microbial and biochemical degradation. Rapid processing after harvesting is therefore preferable. For longer-term storage, the biomass usually requires preservation through dewatering, drying, or, in the case of suitable macroalgae, ensiling under controlled anaerobic conditions (Maneein et al., 2018; Milledge et al., 2019).

Across all biomass categories, storage infrastructure must be aligned with the physical and biochemical characteristics of the feedstock and the logistical requirements of downstream processes. Storage-related material losses and energy requirements can contribute to the life-cycle greenhouse gas balance of bioenergy and BECCS pathways and should therefore be included in supply-chain assessments (Cherubini et al., 2009; Hanssen et al., 2020). The different pre-treatment pathways are illustrated in Figure 4.

3.4 Pre-treatment Methods

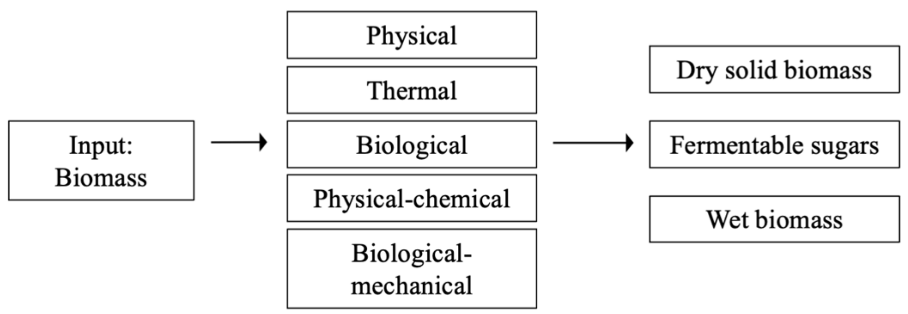

Figure 4. Feedstock-specific pre-treatment pathways. The diagram illustrates the main categories of pre-treatment processes—physical, thermal, and biological—applied to biomass feedstocks in BECCS systems. These processes transform raw biomass into standardized intermediate forms, including dry solid biomass, wet biomass, and fermentable sugars. The

resulting intermediates determine the suitability of biomass for subsequent conversion pathways.

After temporary storage, each biomass type enters a specific pre-treatment pathway. The required operations depend on physical and chemical properties and are selected to meet the input conditions of the chosen conversion process. This step ensures that moisture content, particle size, and composition are compatible with downstream requirements for processes such as fermentation, gasification, pyrolysis, anaerobic digestion, or combustion.

The process chain reflects this branching structure by listing dedicated pre-treatment routes for each feedstock category. The following sections describe the corresponding operations for each feedstock category in the order shown in the process chain: forest biomass, sugar-rich biomass, starch-rich biomass, herbaceous biomass including wetland biomass, waste biomass, and microalgae and aquatic biomass.

3.4.1 Forest Biomass – Pre-treatment

Pre-treatment requirements for forest biomass depend on feedstock properties, including moisture content, particle size, bulk density, and chemical composition, as well as on the selected downstream conversion technology. Typical physical pre-treatment operations include sorting, size reduction, drying, and, where required, densification through pelletization. Sorting and size reduction improve feedstock homogeneity and handling, while drying reduces moisture content and thereby increases the net calorific value of the material. Pelletization can increase bulk density and improve storage, transport, feeding, and handling characteristics, but it is not required for all combustion or gasification systems (Stelte et al., 2012).

Thermal pre-treatment through torrefaction may be applied when improved grindability, hydrophobicity, storage stability, and energy density are required. Torrefaction is a mild pyrolysis process generally carried out at approximately 200–300 °C under oxygen-limited or inert conditions. During the process, part of the volatile fraction is released, resulting in mass loss but an increased energy density of the remaining solid product (Prins et al., 2006; Tumuluru et al., 2011). Torrefaction can be particularly useful before gasification or co-firing because it produces a more brittle and homogeneous material that is easier to grind and handle (Prins et al., 2006; Tumuluru et al., 2011).

The process chain therefore does not prescribe one fixed pre-treatment sequence for forest biomass. Instead, the combination of sorting, size reduction, drying, pelletization, and torrefaction is selected according to the initial feedstock condition and the technical requirements of the intended conversion process (Stelte et al., 2012; Tumuluru et al., 2011).

3.4.2 Sugar-rich Biomass - Pre-treatment

Pre-treatment of sugar-rich biomass depends on whether the feedstock is processed as a sugar-containing juice or as a fibrous residue. For primary sugar crops such as sugarcane and sugar beet, the principal operations include cleaning, mechanical size reduction where required, juice extraction, clarification, and adjustment of the fermentation medium. Because sucrose and other soluble sugars are already readily fermentable, these streams generally do not require enzymatic hydrolysis before fermentation (Zabed et al., 2014; Gumienna et al., 2014).

Sugarcane is typically cleaned and mechanically crushed or milled to extract the juice, which may subsequently be clarified and conditioned before fermentation. Sugar beet roots are washed, sliced or pressed, and processed to recover sugar-containing juice. The required degree of clarification, concentration, sterilization, or nutrient adjustment depends on feedstock quality and the selected fermentation process (Zabed et al., 2014).

Fibrous by-products such as sugarcane bagasse and sugar beet pulp contain cellulose, hemicellulose, pectin, and residual sugars and therefore require different treatment. Mechanical, chemical, physicochemical, or enzymatic pre-treatment may be applied to increase carbohydrate accessibility, followed by enzymatic hydrolysis to release additional fermentable sugars before fermentation (Abo et al., 2019; Berłowska et al., 2016). Accordingly, the process chain distinguishes direct processing of sugar-rich juices from the more intensive pre-treatment required for lignocellulosic residues.

3.4.3 Starch-rich Biomass – Pre-treatment

Pre-treatment of starch-rich biomass, including maize, cassava, potatoes, and cereal grains, generally begins with cleaning and mechanical size reduction through milling, grinding, or rasping. These operations increase surface area and facilitate the release and subsequent conversion of starch. Depending on the feedstock and process configuration, the starch-containing material is then mixed with water and subjected to liquefaction, during which starch granules are gelatinized and partially hydrolysed by α-amylase into shorter-chain dextrins (Balat et al., 2008; Zabed et al., 2017).

Liquefaction is followed by saccharification, typically using glucoamylase, to convert dextrins into fermentable glucose. Saccharification may be carried out as a separate step before fermentation or combined with fermentation in a simultaneous saccharification and fermentation process. Raw-starch-hydrolysing enzymes can in some cases reduce or avoid high-temperature cooking, thereby lowering process energy requirements, although their applicability depends on feedstock properties, enzyme performance, and process design (Viktor et al., 2013; Xu et al., 2016).

The resulting sugar-rich hydrolysate is subsequently directed to fermentation. Pre-treatment severity and enzyme requirements differ among grain, root, and tuber feedstocks because starch structure, fibre content, and the presence of non-starch components influence hydrolysis efficiency and downstream conversion (Zabed et al., 2017).

3.4.4 Herbaceous Biomass – Pre-treatment

Herbaceous biomass, including feedstocks such as straw, miscanthus, grassland biomass, and wetland-derived biomass, commonly requires physical conditioning before thermochemical conversion. Typical operations include sorting, size reduction, drying, and, where required, densification through pelletization or briquetting. Size reduction improves feedstock homogeneity and handling, while drying is particularly important for combustion, gasification, and pyrolysis because high moisture content reduces net energy yield and can impair process stability. Pelletization can increase bulk density and improve transport, storage, and feeding characteristics, but it is not required for every conversion system (Bach and Skreiberg, 2016; Biswas et al., 2014; Basu, 2018; Stelte et al., 2012).

Torrefaction may be applied as an optional thermal pre-treatment to reduce moisture uptake and improve grindability, hydrophobicity, and energy density. The process is generally conducted at approximately 200–300 °C under oxygen-limited or inert conditions. Its application depends on the intended conversion route and must balance improved fuel properties against mass and energy losses during treatment (Basu, 2018; Tumuluru et al., 2011; Nunes et al., 2014).

The process chain therefore does not prescribe one fixed pre-treatment sequence for herbaceous biomass. Instead, sorting, size reduction, drying, densification, and torrefaction should be selected according to feedstock condition, ash and moisture content, logistics requirements, and the technical requirements of the intended conversion process (Bach and Skreiberg, 2016; Basu, 2018; Picchio et al., 2020).

3.4.5 Waste Biomass – Pre-treatment

Pre-treatment requirements for waste-derived biomass depend strongly on the origin, physical state, composition, moisture content, and contamination level of the waste stream. Source separation, sorting, screening, and size reduction are commonly used to remove non-biogenic or undesirable fractions and to produce a more homogeneous feedstock for subsequent material or energy recovery. Dewatering or drying may additionally be required for high-moisture streams such as sewage sludge, whereas densification is relevant only for selected dry and combustible fractions (Zhang et al., 2022; Fytili and Zabaniotou, 2008).

Organic waste intended for anaerobic digestion may undergo mechanical disintegration, thermal treatment, chemical treatment, or biological and enzymatic hydrolysis to increase solubilisation and improve the accessibility of biodegradable compounds. The effectiveness and necessity of these operations depend on the substrate: readily degradable food waste may require only limited conditioning, whereas lignocellulosic residues or structurally complex wastes can require more intensive pre-treatment before fermentation or anaerobic digestion (Hafid et al., 2017; Maitan-Alfenas et al., 2015).

Sewage sludge and contaminated waste fractions require additional characterization and treatment because heavy metals, pathogens, persistent organic pollutants, or other contaminants may restrict downstream utilization. Pre-treatment must therefore be selected for the specific waste stream and conversion pathway rather than applied as a uniform sequence across all waste-derived feedstocks (Fytili and Zabaniotou, 2008; Zhang et al., 2022).

3.4.6 Microalgae and Aquatic Biomass – Pre-treatment

Pre-treatment of microalgae and aquatic biomass depends on the organism, water content, cell-wall structure, and selected conversion pathway. Because harvested microalgal biomass is usually highly dilute, concentration and dewatering commonly precede further processing. Complete drying may be required for some thermochemical or extraction-based pathways, but it is energy-intensive and can be avoided when wet biomass is directed to processes such as anaerobic digestion or hydrothermal conversion (Milledge et al., 2019; Krishnamoorthy et al., 2022).

For biochemical conversion, cell disruption may improve the release and accessibility of intracellular carbohydrates, proteins, and lipids. Mechanical, thermal, chemical, and biological methods—including bead milling, high-pressure homogenization, ultrasonication, thermal treatment, acid or alkaline treatment, and enzymatic hydrolysis—have been investigated, but their effectiveness and energy demand vary among species and downstream applications (Krishnamoorthy et al., 2022). Enzymatic pre-treatment can increase biomass solubilisation and methane yield by disrupting resistant microalgal cell walls, although the response is species- and enzyme-specific (Córdova et al., 2019).

Untreated or minimally processed wet algal biomass may be supplied directly to anaerobic digestion where its physical properties permit pumping and mixing. More intensive dewatering, drying, or cell disruption is therefore not a universal requirement but should be selected according to feedstock properties, conversion requirements, and the balance between additional energy input and improved product yield (Milledge et al., 2019; Córdova et al., 2019).

3.5 Conversion processes: routing, transport and outputs

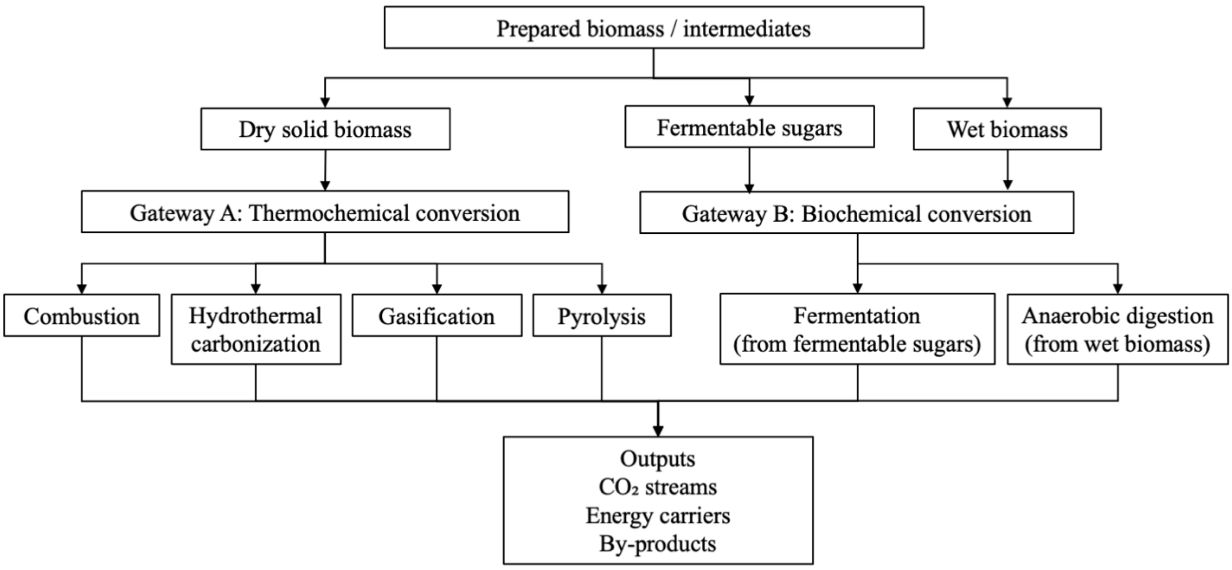

Figure 5. Conversion gateways of the BECCS process chain. The diagram distinguishes two main conversion routes: Gateway A comprises thermochemical pathways, including combustion, hydrothermal carbonization, gasification, and pyrolysis, while Gateway B represents biochemical pathways, including fermentation and anaerobic digestion. Fermentation is applied to fermentable sugars, whereas anaerobic digestion processes wet biomass. The conversion processes generate CO_2 streams, energy carriers, and by-products, which are directed to subsequent upgrading and management stages. Waste-derived fuels and residues may enter both thermochemical and biochemical pathways depending on their composition and level of pre-treatment.

Once pre-treatment has produced a feedstock compatible with the selected conversion method, the process chain divides into thermochemical and biochemical pathways. Thermochemical conversion includes combustion, gasification, pyrolysis, and hydrothermal carbonization, whereas biochemical conversion includes fermentation of fermentable substrates and anaerobic digestion of wet biodegradable biomass (IPCC, 2022). The appropriate route depends on feedstock moisture content, chemical composition, physical form, and the intended energy carrier or product.

Both pathway groups can generate energy carriers, by-products, and CO_2-containing gas streams. The concentration and composition of these streams differ among conversion technologies and determine whether CO_2 can be separated directly during product upgrading or must be captured from combustion or process gases. CO_2 intended for geological storage subsequently requires purification, dehydration, conditioning, and compression in accordance with transport and storage specifications (IPCC, 2022).

3.5.1 Thermochemical conversion (Gateway A)

Thermochemical conversion in the present framework comprises combustion, hydrothermal carbonization, pyrolysis, and gasification. These processes differ in operating conditions, product distribution, feedstock requirements, and the point at which a concentrated CO_2 stream can be generated and captured.

Combustion converts biomass in the presence of excess oxygen, producing heat and flue gas that consists predominantly of nitrogen, carbon dioxide, water vapour, excess oxygen, and smaller quantities of pollutants. In BECCS configurations, CO_2 is generally separated from the treated flue gas using post-combustion capture. The captured CO_2 is subsequently purified, conditioned, and compressed, whereas ash and other solid residues are directed to by-product management (IPCC, 2022; Fajardy and Mac Dowell, 2017).

Hydrothermal carbonization converts wet biomass into a carbon-rich solid hydrochar in hot compressed water, typically at approximately 180–250 °C under autogenous pressure. Because water remains in the liquid phase, the process can treat high-moisture feedstocks without prior energy-intensive drying. In addition to hydrochar, HTC produces an aqueous process stream containing dissolved organic compounds and a comparatively small gas fraction dominated by CO_2. The distribution and subsequent management of these streams depend on feedstock composition and process conditions (Funke and Ziegler, 2010; Libra et al., 2011). Within the process chain, hydrochar and the aqueous phase are therefore treated as product or by-product streams, while any recoverable biogenic CO_2 must undergo appropriate separation and conditioning before geological storage.

Pyrolysis thermally decomposes biomass in the absence or near-absence of oxygen and produces different proportions of biochar, condensable vapours or bio-oil, and non-condensable gases. Product yields depend strongly on temperature, heating rate, residence time, and feedstock properties. Bio-oil and gaseous products may be upgraded or combusted for energy, with CO_2 capture occurring at the subsequent combustion or upgrading stage. Biochar is directed to by-product management and may contribute to durable carbon storage only where its stability, application, and life-cycle performance meet the relevant carbon-removal criteria (Bridgwater, 2012; IPCC, 2022).

Gasification converts biomass at high temperature with a controlled amount of oxygen, air, steam, or combinations of these agents, producing synthesis gas composed mainly of carbon monoxide, hydrogen, carbon dioxide, methane, water vapour, and minor contaminants. The raw gas requires cleaning to remove particles, tar, sulphur compounds, alkali species, and other impurities. Where hydrogen-rich products are targeted, a water–gas shift reaction may be used to convert carbon monoxide and water into hydrogen and CO_2, thereby producing a more concentrated pre-combustion CO_2 stream suitable for separation, conditioning, and storage. Char, tar, ash, and slag are transferred to by-product management according to the specific gasification system (Woolcock and Brown, 2013; IPCC, 2022).

3.5.2 Biochemical conversion (Gateway B)

Biochemical conversion in the present framework comprises fermentation and anaerobic digestion. Fermentation processes soluble sugars derived from sugar-rich, starch-rich, or hydrolysed lignocellulosic biomass, whereas anaerobic digestion is particularly suited to wet biodegradable feedstocks and organic residues, including manure, sewage sludge, food waste, and algal biomass (Mata-Alvarez et al., 2014; Milledge et al., 2019; Ward et al., 2014).

During alcoholic fermentation, microorganisms convert fermentable sugars primarily into ethanol and CO_2. The resulting fermentation gas contains a comparatively high concentration of biogenic CO_2 and generally requires less complex separation than dilute combustion flue gas. Before transport and geological storage, however, the stream must still be dehydrated, purified where necessary, conditioned, and compressed. The ethanol product is directed to product upgrading, while residual organic streams may be processed further or supplied to anaerobic digestion (Fajardy and Mac Dowell, 2017; IPCC, 2022).

Anaerobic digestion converts biodegradable organic matter through successive microbial stages into biogas and digestate. Feedstock composition, solids content, inhibitors, and operating conditions influence process stability and methane yield (Mata-Alvarez et al., 2014; Ward et al., 2014). Biogas consists primarily of methane and CO_2 together with water vapour and trace compounds such as hydrogen sulphide, ammonia, and siloxanes. During biogas upgrading, contaminants are removed and CO_2 is separated to produce biomethane. Where the separated biogenic CO_2 is intended for geological storage, it must be further purified and conditioned to meet transport and storage specifications, while digestate is transferred to by-product management (Ryckebosch et al., 2011; IPCC, 2022).

3.6. Product Upgrading and CO_2 Streams

This module comprises the cleaning, separation, purification, dehydration, conditioning, and compression steps required to prepare biogenic CO_2 streams for transport and geological storage. The necessary treatment depends on the origin and composition of the gas stream: fermentation and biogas upgrading can produce relatively concentrated CO_2 streams, whereas combustion flue gas generally contains more dilute CO_2 together with water vapour, oxygen, nitrogen, and impurities. Product specifications for transport and storage therefore determine the required degree of purification and conditioning (Boot-Handford et al., 2014; Leung et al., 2014).

Hydrothermal carbonization produces hydrochar, an aqueous phase, and a comparatively small gas fraction that commonly contains CO_2 together with smaller quantities of other gases. The composition and quantity of this gas stream depend on feedstock properties and operating conditions. Where recovery of biogenic CO_2 from hydrothermal carbonization is technically justified, the gas must be characterized and subjected to an appropriate separation and conditioning process before transport and storage (Funke and Ziegler, 2010; Libra et al., 2011).

Gasification produces a raw synthesis gas containing primarily carbon monoxide, hydrogen, carbon dioxide, methane, water vapour, particulates, tar, sulphur compounds, and other contaminants. Gas cleaning and conditioning are required before further product synthesis or CO_2 separation. Where hydrogen-rich products are targeted, a water–gas shift reaction can increase the hydrogen and CO_2 fractions, after which CO_2 may be separated as a pre-combustion stream and conditioned for transport and geological storage (Boot-Handford et al., 2014; Leung et al., 2014).

Parallel to CO_2 handling, the upgrading stage refines the remaining energy carriers to specification for fuel use or grid integration.

Biogas from anaerobic digestion can be upgraded to biomethane by removing CO_2, water vapour, hydrogen sulphide, and other trace components. The separated biogenic CO_2 may subsequently be purified and conditioned for transport and geological storage where its composition and the upgrading configuration permit recovery (Ryckebosch et al., 2011; Fajardy and Mac Dowell, 2017). Gasification-derived synthesis gas can be cleaned and conditioned for the production of hydrogen, methanol, or Fischer–Tropsch fuels, depending on the selected process configuration and product requirements (Boot-Handford et al., 2014). Hydrochar produced through hydrothermal carbonization may be used as a solid fuel or directed to other material applications, although its suitability depends on its composition, stability, and contaminant content (Funke and Ziegler, 2010; Libra et al., 2011).

This stage connects directly to the subsequent CO_2 transport and storage module, where transport infrastructure, storage-site requirements, permanence, and leakage-risk management are addressed in greater detail (IPCC, 2022). The downstream integration of CO_2 compression, transport, and storage is illustrated in Figure 6. The figure highlights how technical infrastructure is linked with governance, monitoring, and verification requirements across the final stages of the BECCS process chain.

3.7. CO_2 Transport and Storage

The downstream integration of CO_2 compression, transport, and storage is illustrated in Figure 6. The figure highlights the connection between technical infrastructure and monitoring, reporting, and verification (MRV) requirements in the final stage of the BECCS process chain. This final stage completes the BECCS system by linking biomass conversion processes to permanent carbon storage and associated regulatory frameworks.

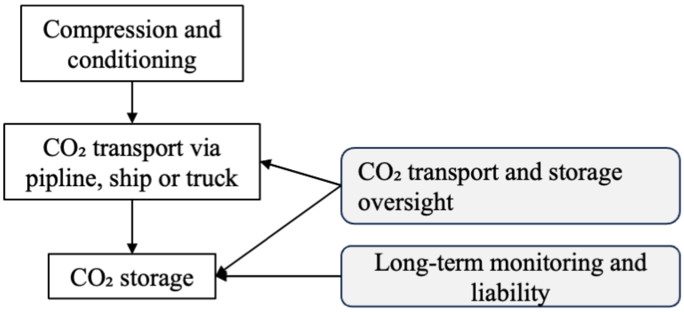

Figure 6. CO_2 transport and storage pathways in BECCS systems. The figure illustrates the downstream process from CO_2 compression and conditioning to transport via pipeline, ship, or truck, and subsequent geological storage. In parallel, governance and monitoring elements—including transport and storage oversight as well as long-term monitoring and liability—are represented as cross-cutting components that ensure system integrity and permanence.

After compression, captured CO_2 is directed to transport and storage infrastructure that enables transfer from conversion facilities to suitable geological storage sites. Pipelines are generally preferred for continuous transport of large CO_2 volumes because of their capacity and technological maturity, while ship transport can provide greater flexibility for offshore, coastal, or cross-border storage routes. For smaller and more dispersed CO_2 sources, transport by truck or rail may be considered, although these modes generally have lower capacities and higher unit costs than large-scale pipeline or ship transport (IPCC, 2022; Onyebuchi et al., 2018).

Geological storage generally takes place in deep saline formations or depleted hydrocarbon reservoirs at depths where pressure and temperature maintain CO_2 in a dense or supercritical phase. Following injection, CO_2 can be retained through structural and stratigraphic trapping, residual trapping, dissolution in formation fluids, and longer-term mineral trapping (IPCC, 2022; Ajayi et al., 2019). Deep saline formations provide the largest estimated global storage resource, whereas depleted oil and gas reservoirs may offer advantages because their geological properties and production histories are often comparatively well characterized (IPCC, 2022). Reactive formations such as basalt may additionally support mineral trapping of injected CO_2, although their practical applicability depends on geological setting, water availability, injection design, and site-specific reaction conditions (Bui et al., 2018).

Across all pathways, the upgrading stage links directly to the transport-and-storage module through conditioning and compression, which prepare CO_2 streams to meet the composition, pressure, and phase requirements of the selected transport and storage system (IPCC, 2022). This connection establishes the link between conversion facilities and geological storage, enabling the long-term removal of biogenic CO_2 from the atmosphere. As governance and MRV requirements increase at the storage stage, issues such as well integrity, reservoir performance, leakage detection and storage permanence are addressed under dedicated regulatory frameworks and are treated in detail in the cross-cutting MRV section of this paper.

3.8 Societal Dimensions

Societal dimensions are considered cross-cutting elements within the BECCS process chain. Unlike technical modules that operate sequentially, participation and societal perspectives intersect with multiple stages of the system. During land preparation and cultivation, participatory planning can help identify land-use conflicts, distributional effects, and locally perceived benefits and risks (Bellamy et al., 2017; Morrow et al., 2020). In the conversion and product-upgrading phases, societal and institutional conditions may influence technology choices, infrastructure siting, and the distribution of employment and economic benefits. For CO_2 transport and storage, early stakeholder engagement, transparent communication, and clearly defined responsibilities are important for addressing concerns regarding safety, monitoring, and long-term liability (Fridahl, 2017; Morrow et al., 2020). Societal dimensions are therefore treated as a transversal component of the process chain that complements technical assessment with questions of legitimacy, participation, justice, and governance (Morrow et al., 2020).

3.9 MRV considerations across the BECCS process chain

Monitoring, reporting and verification (MRV) constitute a cross-cutting component of the BECCS process chain and support the credibility, transparency, and traceability of carbon-removal claims. The process chain is designed as a jurisdiction-independent framework and therefore does not prescribe one specific MRV methodology, certification scheme, or regulatory system. Instead, it identifies the stages at which MRV-relevant information arises and can be linked to project-specific accounting rules, standards, and legal requirements.

MRV boundaries for BECCS must encompass the principal carbon and greenhouse-gas flows across the full system. Relevant information includes the origin and sustainability of biomass feedstocks, changes in land-based carbon stocks where applicable, emissions from cultivation, harvesting, processing and transport, material and energy inputs during pre-treatment and conversion, the quantity and composition of captured CO_2, losses during conditioning and transport, and the amount of CO_2 retained in geological storage. Defining system boundaries and consistently quantifying these flows are necessary to determine whether a BECCS configuration results in net atmospheric carbon dioxide removal rather than merely transferring emissions between stages of the system (IPCC, 2022; ISO, 2017).

At the biomass-provision stage, MRV-relevant information includes feedstock type, geographical origin, production or collection method, competing uses, moisture content, transported mass, and associated supply-chain emissions. Chain-of-custody documentation can support the traceability of biomass and help distinguish purpose-grown biomass from agricultural, forestry, municipal, or industrial residues. Where land-use change or changes in ecosystem carbon stocks may occur, the selected accounting approach must also define an appropriate baseline and include relevant direct and indirect emissions within the project boundary (IPCC, 2022).

During pre-treatment, conversion, product upgrading, and CO_2 capture, MRV should document material and energy balances, biogenic and fossil carbon inputs, conversion efficiencies, auxiliary energy demand, CO_2-stream composition, capture efficiency, and uncaptured emissions. The biogenic and fossil fractions of mixed feedstocks or waste streams must be distinguished where both contribute to the captured CO_2. By-products such as digestate, ash, slag, tar, hydrochar, and biochar should also be included in material-flow documentation where their treatment, use, decomposition, or disposal can influence the overall greenhouse-gas balance. The process chain indicates the points at which these data arise but does not prescribe a single calculation method for all technologies and project configurations (IPCC, 2022; ISO, 2017).

For CO_2 transport and geological storage, MRV-relevant information includes the quantity and composition of the transported CO_2 stream, energy use and emissions associated with compression and transport, injection volumes, reservoir pressure and behaviour, well integrity, potential leakage pathways, and the long-term containment of stored CO_2. Monitoring strategies and measurement frequencies must be adapted to the characteristics and risks of the individual transport and storage system. International standards such as ISO/TR 27915:2017 and ISO 27914:2026 provide common technical principles for quantification, verification, risk management, and geological storage, but they do not replace the legal requirements applicable within a particular jurisdiction (ISO, 2017; ISO, 2026).

The regulatory examples discussed here illustrate selected frameworks applicable at the time of writing and should not be interpreted as universally applicable or permanently fixed MRV requirements. Within the European Union, Regulation (EU) 2024/3012 establishes a voluntary Union certification framework for permanent carbon removals, carbon farming, and carbon storage in products, while Directive 2009/31/EC provides the legal framework for the environmentally safe geological storage of CO_2. Their implementation is supplemented by applicable Union and national legislation, certification methodologies, permitting procedures, and monitoring obligations. Projects outside the European Union must instead comply with the rules of the jurisdiction in which biomass production, CO_2 capture, transport, and storage take place (Regulation (EU) 2024/3012; Directive 2009/31/EC).

In the United States, the Environmental Protection Agency regulates wells used for geological sequestration under the Underground Injection Control Class VI programme. Facilities reporting geological sequestration under the Greenhouse Gas Reporting Program are subject to Subpart RR requirements, including approved monitoring, reporting, and verification plans and reporting of injected and sequestered CO_2. These provisions illustrate how the general MRV functions represented in the process chain can be translated into jurisdiction-specific permitting, monitoring, and reporting requirements; they are not components of the universal process-chain structure itself (US EPA, 2026a, b).

By identifying where MRV-relevant data arise along the BECCS process chain, the framework can support the development of transparent project-specific monitoring plans, carbon balances, and certification procedures. It does not replace dedicated MRV protocols, life-cycle assessments, legal permitting processes, or carbon-removal certification methodologies. The modular structure instead enables current standards and jurisdiction-specific requirements to be mapped onto the relevant process stages without altering the underlying framework when regulations, accounting rules, or certification systems change.

3.10. By-Product Management

By-product management is linked to the conversion module within the process chain and represents secondary material flows that accompany energy carriers and CO_2 streams but do not constitute the core geological carbon-removal pathway. These flows include ash from combustion, char, tar and slag from gasification, biochar and condensable liquids from pyrolysis, hydrochar and aqueous process streams from hydrothermal carbonization, digestate from anaerobic digestion, and residual nutrient-rich fractions from fermentation (Mata-Alvarez et al., 2014; Woolcock and Brown, 2013; Funke and Ziegler, 2010; Libra et al., 2011).

The environmental relevance of these by-products depends on their composition, stability, contaminant content, and subsequent treatment or use. Digestate may be used as an organic fertilizer or soil amendment where nutrient value, hygiene requirements, and contaminant limits are compatible with applicable regulations and agronomic needs (Mata-Alvarez et al., 2014; Kovačić et al., 2022). Ash, slag, tar, hydrochar, and process water require separate handling or treatment because their suitability for reuse, disposal, combustion, or material applications depends on process conditions and contaminant loads (Woolcock and Brown, 2013; Funke and Ziegler, 2010; Libra et al., 2011).

Biochar occupies a particular position because it may function either as a by-product of pyrolysis or, under suitable conditions, as a durable carbon storage pathway. Its contribution to carbon removal depends on feedstock origin, production conditions, carbon stability, application pathway, and life-cycle performance, and should therefore be assessed separately from geological storage of captured CO_2 (Lehmann and Joseph, 2015; IPCC, 2022). In the process chain, by-product management therefore supports environmental performance and resource efficiency but remains distinct from the primary BECCS removal pathway based on CO_2 capture, transport, and geological storage.

4. Discussion

4.1 Technical integration and efficiency trade-offs

The modular process chain highlights that technical feasibility in BECCS is determined not only by conversion efficiencies but also by the integration of supporting processes across the system. For wet feedstocks, hydrothermal carbonization can reduce the need for energy-intensive drying, but the overall efficiency of HTC-based pathways depends on process heat demand, recovery of usable energy carriers, management of aqueous and gaseous process streams, and integration with low-carbon energy inputs (Funke and Ziegler, 2010; Libra et al., 2011). Similar integration challenges occur in biochemical pathways, where biogas upgrading, fermentation CO_2 capture, and downstream CO_2 conditioning must be aligned with transport and storage specifications (Fajardy and Mac Dowell, 2017; Ryckebosch et al., 2011). More broadly, the system-level performance of BECCS depends on matching feedstock properties, pre-treatment intensity, conversion technology, CO_2 capture route, and transport-and-storage infrastructure rather than optimizing individual modules in isolation (IPCC, 2022; Fajardy and Mac Dowell, 2017).

4.2 Governance and societal legitimacy

A recurring challenge across BECCS pathways relates to societal acceptance and legitimacy. Public trust in CO_2 transport corridors and geological storage sites has been shown to be important for deployment (Morrow et al., 2020). Moreover, concerns around land-use competition, biomass sourcing, and fairness strongly shape societal perceptions of BECCS (Fridahl, 2017; Gough and Mander, 2019). Governance frameworks must therefore be reflexive and adaptive, embedding participatory processes from early stages onward (Bellamy et al., 2017). The modular process chain makes such entry points visible by integrating decision nodes for feasibility, desirability, societal considerations, and MRV. In the European context, policy frameworks such as the Renewable Energy Directive III are relevant for biomass sustainability criteria, while the Union certification framework for permanent carbon removals provides a more specific reference point for certification of carbon-removal activities (Directive (EU) 2023/2413; Regulation (EU) 2024/3012). These examples illustrate how governance and certification requirements can be mapped onto the process chain without making them fixed components of the framework itself.

4.3 Research gaps and innovation pathways

Despite significant progress in system integration, several uncertainties remain. Life-cycle assessment and carbon accounting for BECCS must include compression energy, transport-related emissions, carbon losses, and storage integrity in order to avoid overestimating net carbon dioxide removal (IPCC, 2022; Tanzer and Ramírez, 2019). Methodological uncertainty is particularly relevant for emerging or less standardized pathways, including hydrothermal carbonization, pyrolysis-based systems, heterogeneous waste streams, and aquatic biomass pathways, where system boundaries, feedstock variability, by-product treatment, and permanence assumptions can strongly influence the reported removal outcome (Tanzer and Ramírez, 2019; Smith et al., 2021).

Aquatic biomass exemplifies both opportunity and uncertainty. Microalgae can be technically compatible with fermentation and anaerobic digestion, but its role in BECCS depends on cultivation energy demand, harvesting and dewatering requirements, nutrient supply, and the subsequent capture and durable storage of biogenic carbon (Khan et al., 2018; Milledge et al., 2019; Tanzer and Ramírez, 2019). Macroalgae and other aquatic feedstocks may represent future innovation pathways, but they should be treated cautiously in BECCS assessments until carbon accounting, permanence, supply-chain emissions, and MRV requirements are sufficiently resolved (Tanzer and Ramírez, 2019; Smith et al., 2021).

Similar gaps exist for heterogeneous waste streams, where variable composition, contamination risks, moisture content, competing uses, and pre-processing requirements influence whether residues can be valorized as BECCS feedstocks or require treatment as problematic waste fractions (Zhang et al., 2022; Fytili and Zabaniotou, 2008). Further uncertainty arises from BECCS cost estimates, which remain highly sensitive to feedstock availability, conversion configuration, capture efficiency, energy prices, infrastructure access, and the availability of suitable transport and storage systems (IPCC, 2022; Wollnik et al., 2024). More robust estimates will likely emerge as integrated BECCS facilities become operational and future assessments can draw on project-level performance data rather than primarily on modelling assumptions.

4.4 Contribution of the modular process chain

Compared to narrowly focused assessments, the process chain provides a structured representation that brings technical, logistical, and contextual considerations into a single, transparent framework. Its modular design clarifies how upstream feedstock choices influence downstream conversion, upgrading and storage options, and it indicates where MRV and governance considerations become relevant along the chain. Rather than analyzing or quantifying trade-offs, it offers a scaffold that helps users organize assumptions and identify decision points across different project scales and regional contexts. This function aligns with recent calls for tools that improve transparency and facilitate dialogue between conceptual modelling, sustainability constraints and governance requirements (Kazlou et al., 2024).

By combining peer-reviewed literature with stakeholder insights, the process chain offers a structured lens that can support interdisciplinary dialogue and scenario-oriented discussions. It is particularly useful in participatory planning contexts, where clarity, adaptability and transparency help align expectations and identify early decision points for BECCS deployment. The modular representation also makes it easier to connect the chain with national system analyses, which increasingly emphasize the importance of transparent, assumption-based frameworks that reflect real system constraints such as biomass availability, conversion efficiencies, sustainability considerations and public acceptance.

4.5 Observed barriers and lessons learned from BECCS deployment

4.5.1 Peer-reviewed evidence from global BECCS deployment

Peer-reviewed analyses of BECCS deployment show a persistent implementation gap between modelled global potentials and real-world deployment. Current assessments indicate that BECCS deployment remains far below the gigaton-scale removals assumed in many mitigation scenarios, while engineered carbon-removal methods still contribute only a small fraction of current global carbon dioxide removal (Fajardy and Mac Dowell, 2017; Lamb et al., 2024).

These findings underline that technological feasibility does not automatically translate into deployment feasibility, particularly in regions where infrastructural, regulatory, and social constraints interact strongly with biomass availability and conversion configurations. National system analyses for Germany similarly highlight that only a subset of bioenergy facilities is technically or geographically suitable for CO_2 capture and storage, despite significant biogenic carbon flows (Thrän et al., 2025).

One of the most mature categories of BECCS applications is fermentation-based CO_2 capture in the bioethanol industry. The Illinois Industrial CCS project in Decatur, Illinois, illustrates this pathway by capturing CO_2 from a corn ethanol facility and storing it in the Mt. Simon Sandstone. This example also shows that bioethanol-based BECCS depends not only on concentrated fermentation-derived CO_2 streams, but also on suitable geological storage, monitoring, favourable siting conditions, and policy incentives for scale-up (Sanchez et al., 2018).

A second body of evidence concerns biomass-fired heat and power systems coupled with post-combustion CO_2 capture. These configurations are technically plausible because post-combustion capture can be integrated downstream of biomass combustion, but their climate performance depends strongly on feedstock sourcing, supply-chain emissions, conversion efficiency, and land-use dynamics. Critical assessments of forest-biomass use highlight uncertainties related to lifecycle emissions, carbon debt, and biodiversity risks, indicating that BECCS can deliver net-negative, near-neutral, or even net-positive climate outcomes depending on system design and biomass sourcing assumptions (Searchinger et al., 2018; Ter-Mikaelian et al., 2015; Sanchez et al., 2018).

Nordic district heating systems provide an additional peer-reviewed evidence base for BECCS integration. Studies evaluating the Stockholm Exergi concept suggest that large-scale BECCS at CHP facilities could deliver significant removals when paired with low-carbon electricity systems and offshore CO_2 storage, although high specific costs and uncertainties about long-term revenue streams remain central barriers (Zetterberg et al., 2021; Hanssen et al., 2020). Similar evaluations in the pulp and paper industry indicate that biogenic CO_2 streams can be integrated into capture processes, but that system-wide climate benefits are highly sensitive to energy balances, process configurations and the end-use of by-products (Karlsson et al., 2021).

Across peer-reviewed work, key systemic barriers recur: (1) competition for sustainable biomass, particularly residues; (2) geographical mismatch between emitters and storage sites; (3) high capital and operating costs under uncertain policy conditions; (4) lack of harmonized MRV frameworks and certification methodologies for carbon removal, including the implementation of the Union certification framework established under Regulation (EU) 2024/3012; and (5) social acceptance challenges rooted in earlier CCS controversies (Gough and Mander, 2019; Tanzer and Ramírez, 2019; European Union, 2024). These findings collectively indicate that the primary barriers to BECCS deployment are not technological but systemic, spanning infrastructure, governance, sustainability criteria, and public legitimacy.

A further line of evidence stems from the IPCC Sixth Assessment Report (IPCC, 2022), which—although not peer-reviewed in the strict academic sense but subject to an extensive multi-stage scientific review—provides the most authoritative synthesis of BECCS pathways. The IPCC identifies lifecycle emissions, land-use dynamics and regional resource constraints as key determinants of BECCS sustainability, and that robust governance, MRV and land-sector safeguards are essential to deliver durable removals as synthesized in IPCC AR6 WGIII.

4.5.2 Context from real-world deployment experience.

In addition to peer-reviewed analyses, real-world CCS and BECCS-related initiatives provide contextual information on practical, institutional, and regulatory aspects of deployment. These examples are not used here as primary scientific evidence, but as descriptive context that helps illustrate how barriers identified in the peer-reviewed literature can appear during implementation.

Large-scale CCS projects such as Sleipner and Quest indicate that geological CO_2 storage can be operated under long-term monitoring and regulatory oversight, while projects such as Petra Nova illustrate how capture and storage systems can be affected by economic conditions, operational reliability, and policy uncertainty. Although these cases are not BECCS projects, they are relevant to BECCS because biomass-based systems would depend on similar CO_2 transport, storage, monitoring, liability, and financing structures.

Early CCS- and BECCS-related proposals in Germany, including storage-related debates in Brandenburg and Schleswig-Holstein, further illustrate that technically assessed projects may fail to progress when public trust, regional governance, storage safety concerns, and long-term responsibility remain unresolved. These examples should therefore be interpreted as contextual implementation experience rather than as evidence for BECCS performance. They support the broader conclusion from the peer-reviewed literature that deployment barriers are systemic and include institutional coordination, infrastructure development, liability arrangements, and social legitimacy.

Conclusions

Achieving net-zero and net-negative emissions pathways requires rapid and sustained emission reductions as well as the deployment of carbon dioxide removal approaches that provide durable storage (IPCC, 2022). BECCS is widely discussed as one carbon dioxide removal option because it combines biomass-based energy conversion with CO_2 capture and geological storage, but its realization depends on the alignment of technological, ecological, logistical, and societal conditions (Fuss et al., 2018; IPCC, 2022).

This paper introduced a modular process chain that structures BECCS into transparent and systematically assessable stages, ranging from feasibility and desirability assessment through feedstock selection, biomass provision, pre-treatment, conversion, product upgrading, and CO_2 transport and storage. Developed within the German CDR-Atlas initiative, the process chain integrates insights from the scientific literature and stakeholder dialogue to provide a structured framework for early-stage planning and participatory assessment of BECCS pathways. Rather than prescribing specific deployment trajectories, simulating system dynamics, or quantifying life-cycle performance, the framework offers a transparent logic for organizing assumptions, parameters, and stakeholder perspectives across different implementation contexts.

The process chain makes visible how upstream choices, such as feedstock category and biomass-provision strategy, affect downstream conversion, CO_2 capture, product upgrading, transport, storage, by-product management, and MRV considerations. In doing so, it highlights that technological feasibility alone is insufficient for successful BECCS deployment. Transparent governance structures, institutional coordination, robust MRV, and long-term liability arrangements remain central conditions for translating BECCS concepts into credible carbon-removal pathways (Morrow et al., 2020; IPCC, 2022). Overall, the modular process chain provides an adaptable framework that supports interdisciplinary assessment, early-stage planning, and governance-oriented analysis of BECCS systems without replacing dedicated life-cycle assessment, techno-economic modelling, project-specific MRV protocols, or legal permitting processes.

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Appendix 1. Extended Terminology and Process Definitions

Anaerobic digestion describes the microbial breakdown of wet organic materials such as manure, food waste, sewage sludge, or algae in oxygen-free environments, producing biogas. The CO_2 fraction in raw biogas can be separated during biogas upgrading and, where purity and conditioning requirements are met, directed to geological storage; however, robust process control and methane-emission monitoring are required to minimize fugitive methane emissions (Mata-Alvarez et al., 2014; Ryckebosch et al., 2011; IPCC, 2022).

Combustion refers to the direct burning of biomass in the presence of oxygen to generate heat or power. When coupled with CO_2 capture systems—typically post-combustion chemical scrubbing—this process can deliver net negative emissions if total life-cycle emissions remain below the amount of CO_2 captured (Fajardy and Mac Dowell, 2017).

Fermentation is a biochemical pathway in which sugar- or starch-rich biomass, such as sugarcane or maize, is converted by microorganisms into ethanol. During ethanol fermentation, CO_2 is released as a concentrated by-product stream. Because fermentation CO_2 is typically of high purity compared with dilute flue gas streams, it is technically well suited for capture, conditioning, transport, and geological storage within BECCS systems (Sánchez and Cardona, 2008; Xu et al., 2010; Laude et al., 2011).

Feedstocks in this study are grouped into four main categories. Agricultural biomass includes herbaceous crops, sugar-rich crops, and starch-rich crops cultivated as dedicated energy crops rather than as residues. Forest biomass covers wood residues and plantation material. Wetland biomass refers to paludiculture feedstocks such as reeds. Waste biomass encompasses municipal, industrial, and agricultural residues. Aquatic biomass comprises microalgae and seaweed. Each feedstock type aligns with specific conversion methods, for instance algae in anaerobic digestion or sugarcane in fermentation (Milledge et al., 2019).

Gasification is a thermochemical process in which biomass is heated under low-oxygen conditions at temperatures typically above 700 °C, producing a synthesis gas composed mainly of carbon monoxide, hydrogen, and CO_2. This syngas can be upgraded into fuels or chemicals, while the CO_2 fraction is available for capture and permanent storage (Basu, 2018).

Hydrothermal carbonization (HTC) mimics natural coalification by converting wet biomass under moderate temperatures (180–280 °C) and elevated pressure into hydrochar. This process is particularly suitable for high-moisture feedstocks such as sewage sludge, agricultural residues, and algae (Cavali et al., 2023).

Monitoring, Reporting and Verification (MRV) denotes the systematic measurement, documentation, and independent validation of CO_2 removals along the BECCS chain. Robust MRV frameworks are essential for transparency, performance assessment, and storage integrity. They must address the entire process chain, from biomass carbon accounting through capture efficiencies and transport losses to geological storage permanence (IPCC, 2022).

Pre-treatment processes prepare biomass for conversion and can be categorised into physical (size reduction, drying), physicochemical (steam explosion, acid treatment), mechanical (extrusion, pressing), biological (fungal or enzymatic treatments), and thermal (torrefaction, HTC). These steps improve feedstock properties and increase conversion efficiency (Mata-Alvarez et al., 2014).

Pyrolysis refers to the thermal decomposition of biomass in the absence of oxygen. Depending on process temperature and residence time, it yields varying proportions of biochar, bio-oil, and syngas. The biochar fraction can contribute to long-term carbon sequestration, although permanence and stability are strongly influenced by feedstock type and process parameters (Lehmann and Joseph, 2015; Woolf et al., 2021).

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