Review of Integrated Supply Chain Strategies for Agro-forestry Residues

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Establishing an economically efficient supply chain for biomass feedstock is a critical prerequisite for achieving large-scale bioenergy development under China's "dual carbon" strategy. Focusing on agro-forestry residue feedstocks, this paper systematically reviews the technologies and models for the key stages of their collection, storage, and transportation (CST) system. The inherent physicochemical characteristics of biomass, such as low bulk density and high moisture content, constitute a fundamental physical bottleneck that constrains its economic viability. To this end, pretreatment technologies, with densification at their core, are widely recognized as a critical technological stage for enhancing logistics efficiency and achieving value addition. In contrast to the technological optimization of individual stages, systemic integration strategies—such as establishing a hybrid "decentralized-centralized" supply chain model and employing multi-modal transport—represent a more effective pathway to achieving whole-chain cost reduction and efficiency enhancement. Through a systematic integration of research in this field, this paper emphasizes that the key to resolving CST bottlenecks lies in adopting a whole-chain perspective that involves the deep coupling of essential pretreatment technologies with innovative supply chain organizational models.

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INTRODUCTION

Amidst the escalating challenge of global climate change, the establishment of a low-carbon energy system predominantly based on renewable sources has emerged as a global consensus. The United Nations Sustainable Development Goals (SDGs) explicitly identify renewable energy technologies as a pivotal pathway for poverty alleviation, ensuring clean energy access, advancing industrialization, and combating climate change (Awogbemi and Von Kallon 2025). Among the diverse portfolio of renewable sources, biomass energy is assuming an increasingly significant role, distinguished by its unique characteristic as the only carbon-based renewable resource convertible into solid, liquid, and gaseous fuels (Mohamed *et al.* 2020; Wu *et al.* 2024). As of the end of 2020, global installed renewable energy capacity reached 2799 GW, with biomass energy constituting 5% (127 GW), ranking it as the fourth-largest renewable energy source, subsequent to hydropower, wind, and solar power (Farghali *et al.* 2023; Zhang *et al.* 2025). Particularly within the strategic framework of China's "dual carbon" targets (carbon peaking and carbon neutrality), biomass energy is considered an integral component for achieving the deep decarbonization of the energy structure, because of its resource abundance, renewability, and its characteristic of near-zero carbon emissions over its lifecycle (Wang *et al.* 2024).

Biomass resources, particularly agro-forestry residues, constitute a significant energy source in rural regions. This fact is underscored by looking at China, a major agricultural nation where the average annual yield of crop straw is estimated to be 700 million tons (Liu *et al.* 2020; Sun *et al.* 2020). However, the effective realization of biomass energy's potential is constrained by inherent bottlenecks within its feedstock supply chain. In contrast to the highly standardized and centralized nature of fossil fuels, biomass feedstocks, especially agro-forestry residues, are generally characterized by low energy density, wide geographical dispersion, and strong seasonal supply variations (Wang *et al.* 2023; Wu *et al.* 2023). These attributes directly contribute to the prohibitively high costs, low efficiency, and organizational complexity associated with their collection, storage, and transportation (CST), which collectively represent a primary impediment to the large-scale commercialization of the entire biomass energy industry (Lautala *et al.* 2015). Research indicates that CST costs can account for upwards of 50% of the total cost in biomass power generation (Nunes *et al.* 2020). Consequently, research focused on the optimization of the biomass CST system is of paramount importance for the establishment of an economically efficient and reliable energy supply chain.

In light of this, this paper employs a literature review methodology to systematically review and critique the research progress on biomass CST system technologies internationally. With a specific focus on the most widely utilized agro-forestry residues, this review will analyze developments from three perspectives: collection and storage, transportation, and supply chain system integration. Specifically, the paper will delve into the economic feasibility and applicability of various mechanized collection and densification technologies, and systematically review the current state of research on transportation network optimization and multi-modal transport strategies. Through a comparative analysis of the advantages and disadvantages of different technological routes, this paper aims to identify existing knowledge gaps and future research directions. The ultimate goal is to provide a theoretical reference and decision-making support for enhancing the efficiency of biomass energy utilization, reducing whole-chain costs, and promoting the sustainable development of the industry.

METHODOLOGY

Data Sources and Search Strategy

This review follows a structured literature review framework guided by the core principles of PRISMA to ensure transparency and reproducibility. In contradistinction to systematic reviews incorporating meta-analyses, this methodology prioritised transparency in literature screening, reproducibility of procedures, and the integration of core themes. The retrieval of literature was conducted using the Web of Science, Scopus, and Google Scholar databases. This combined strategy served to mitigate the limitations that are inherent in the use of a single database. The search timeframe was set from 1998 to 2025, covering both peer-reviewed journal articles and conference proceedings. Keyword combinations were constructed using Boolean operators, including ("biomass" AND "supply chain") OR ("collection" OR "storage" OR "transportation") OR ("logistics" OR "life cycle assessment"). These were then combined with synonyms and Boolean operators to construct search queries, ensuring comprehensiveness and depth. A comprehensive and accurate search query was constructed by combining the terms "agricultural and forestry residues," "collection," "storage," "logistics and transportation," "cost," and "life cycle assessment," among others, with synonyms and Boolean operators.

Study Selection and Eligibility Criteria

Following the completion of the preliminary literature search, documents that were found to be clearly unrelated to biomass collection, storage, and transportation systems were initially excluded based on their titles and abstracts. Subsequently, the remaining literature was subjected to full-text screening in accordance with predefined inclusion and exclusion criteria, as follows:

Inclusion Criteria: (1) Publication type: peer-reviewed journal articles or conference proceedings; (2) Focused on technical, economic, or environmental analyses of biomass collection, storage, or transportation processes; (3) Published in English.

Exclusion Criteria: (1) Non-peer-reviewed white papers, editorials, *etc*.; (2) Studies solely addressing biomass conversion (*e.g*., combustion mechanisms) without supply chain considerations; (3) Research with incomplete methodological descriptions or insufficient transparency.

Quality Assessment and Synthesis Approach

For each study that was selected, key information was extracted, including the type of raw material, the geographic context, the supply chain modelling methodology, and the economic or environmental evaluation metrics. It is evident that a considerable methodological heterogeneity exists among the included research, given the diverse variations in modelling techniques, case designs, and regional conditions across the selected studies. Priority was given to studies with clearly defined system boundaries that provided explicit methodologies for examining supply chain structure, costs, or energy consumption. After screening, a total of 88 studies were retained for thematic synthesis.

The integration of research findings employed a structured thematic analysis approach, primarily categorising the literature based on storage and transportation stages, supply chain configuration types, and core analytical methods. The analysis process placed particular emphasis on identifying common findings and trends across studies while discerning and explaining the sources of result differences and discrepancies arising from differing fundamental assumptions or system boundaries.

Given the diversity of modeling approaches, case-study designs, and data sources, formal quality scoring tools were not applied. Instead, studies were interpreted with attention to data transparency, system boundary definition, and methodological consistency. Findings were synthesized thematically to identify robust patterns while avoiding overgeneralization.

BIOMASS FEEDSTOCK CHARACTERISTICS AND SUPPLY CHAIN BOTTLENECKS

In contrast to standardized and readily transportable fossil fuels, the inherent properties of biomass—such as low bulk density, high moisture content, and elevated oxygen content—are the primary determinants constraining the economic viability of its CST system, and they directly engender the core technological challenges for the entire supply chain. Specifically, key parameters, such as high moisture content, low bulk density, and high ash content collectively constitute the inherent disadvantages of biomass for energy utilization (Zhang *et al.* 2025). A high moisture content not only erodes the effective heating value of the feedstock, but it also substantially increases the transportation load and elevates the risks of mildew and spontaneous combustion during storage. Low bulk density leads directly to the predicament where transport vehicles reach their volume capacity long before their weight limit, necessitating vast storage space and significantly inflating logistics costs. Furthermore, a high ash content can cause issues, such as slagging and corrosion during the energy conversion process. Ash also acts as an inert payload throughout the supply chain, reducing the system's overall efficiency. Therefore, the fundamental objective of all technologies and models discussed in subsequent sections is the targeted mitigation of these supply chain bottlenecks, which originate from the feedstock's inherent physicochemical properties (Jerzak *et al.* 2024; Bianchini *et al.* 2025).

Moisture content is a critical parameter governing the efficiency and economic viability of the biomass CST system. An understanding of the feedstock's moisture level is of pivotal importance to the optimization of the entire process chain, from collection, drying, and storage to transportation and final energy conversion. Within the biomass supply chain, high-moisture feedstocks (*e.g.*, straw, forestry residues) exhibit a significantly increased weight per unit volume at the point of collection. This not only complicates handling, requiring more labor and transport capacity, but it also directly escalates logistics costs due to the transport of substantial non-contributing water mass. Given the large quantities of biomass involved, storage often occurs in open-air or enclosed atmospheric environments, where the extent of feedstock deterioration is primarily determined by the interplay of moisture content and storage conditions (Karunanithy *et al.* 2013). Excessively high moisture levels markedly reduce the durability of biomass, promoting microbial activity, which leads to mold formation, heat accumulation, and potentially spontaneous combustion (Lee *et al.* 2020). Moreover, during the subsequent energy conversion stage, the evaporation of this moisture consumes a significant amount of energy, resulting in a reduction in the effective heating value and a direct decrease in combustion or gasification efficiency. Research indicates that for long-term safe storage, the moisture content of biomass must typically be controlled below 17.65% (on a dry basis) (Arabhosseini *et al.* 2010). Consequently, the effective control of moisture content, supplemented by appropriate pretreatment (*e.g.*, drying, densification) and optimized storage and transport conditions (*e.g.*, ventilation, moisture-proofing), is essential for overcoming the previously mentioned bottlenecks, thereby holistically improving the economic and environmental performance of the biomass utilization system.

Bulk density, defined as the mass of biomass material per unit of volume (including inter-particle voids), is a physical characteristic of paramount importance within the biomass CST system (Cai *et al.* 2017). It directly influences the loading capacity and efficiency of transportation: a higher bulk density allows for a greater mass of material to be loaded within a given volume, thus significantly enhancing transport efficiency, lowering the unit mass transportation cost, and enabling transportation over longer distances for the same level of energy consumption (Tumuluru *et al.* 2024). Furthermore, bulk density is inversely related to moisture content; as the moisture level in biomass particles rises, their bulk density tends to decrease (Theerarattananoon *et al.* 2011; Lee *et al.* 2020). This relationship not only exacerbates the transportation burden but also directly impacts storage, as lower bulk density necessitates larger storage volumes, which in turn increases the investment and operational costs of storage facilities. Consequently, the enhancement of biomass bulk density *via* pretreatment methods represents a critical pathway toward optimizing the entire CST system and improving project feasibility and economic viability.

Ash content is defined as the mass percentage of inorganic mineral residue remaining after the complete combustion of the raw material, serving as a key indicator of the fuel's combustion quality. Firstly, during the energy conversion phase, a high ash content is highly prone to causing issues, such as slagging, fouling, and corrosion in boilers, leading to reduced system thermal efficiency and increased unplanned downtime and maintenance costs. For this reason, source control and in-process reduction of feedstock ash content become primary management objectives within the CST system. From an economic perspective, the hygroscopic nature often associated with high-ash biomass can aggravate feedstock agglomeration and corrosion of storage equipment during the storage phase, directly increasing management complexity and maintenance expenditures. Additionally, during transportation, ash acts as an inert component that displaces valuable biomass, thereby reducing the effective energy density of the feedstock and ultimately manifesting as an increase in the unit energy transportation cost. Studies have shown that reducing biomass ash content through pretreatment not only enhances its net heating value but also significantly lowers the logistics and delivery costs that pervade the entire energy utilization chain (Greene *et al.* 2014).

COLLECTION AND PRETREATMENT TECHNOLOGIES

As shown in Fig. 1, The collection and pretreatment phase constitutes the primary physical link connecting biomass resource generation with its eventual energy utilization. The selection of technologies, organizational models, and operational efficiency within this phase directly dictates the economic viability and environmental sustainability of the biomass supply chain (Balingbing *et al.* 2020; He *et al.* 2025).

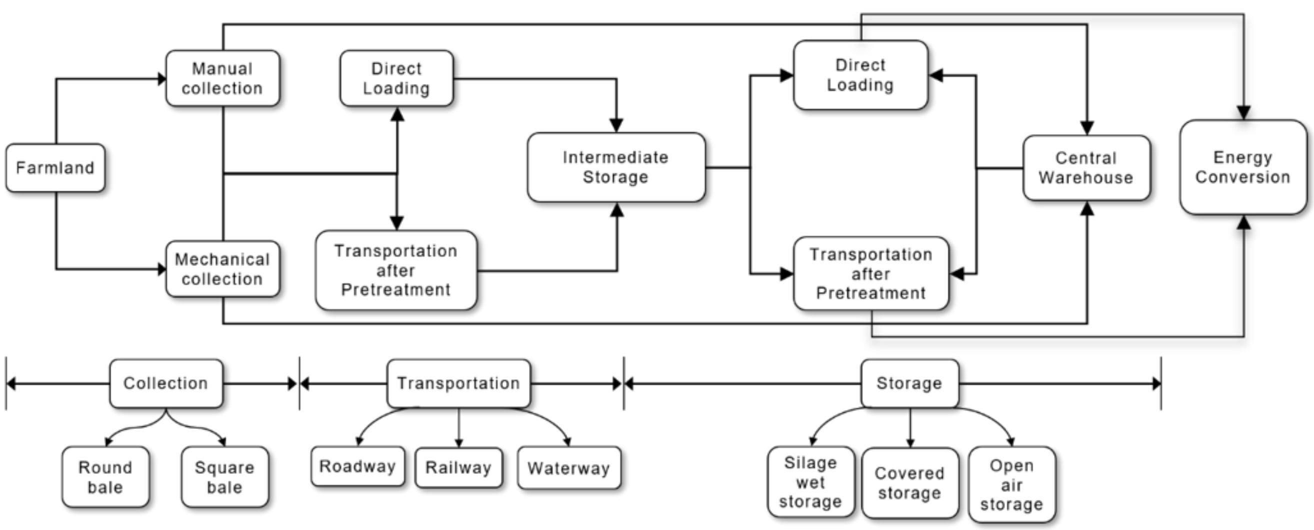

Fig. 1. Schematic diagram of the straw supply chain logistics system

The core objective of this stage is to centralize dispersed biomass resources and convert them into a stable feedstock suitable for subsequent processing in a manner that is both highly efficient and cost-effective. However, due to the inherent characteristics of biomass feedstocks, such as agro-forestry residues, namely low energy density, large volume, wide geographical dispersion, and strong seasonality, CST costs account for a significant portion of the total expenditure (Shinners and Friede 2018). Research by Nunes *et al.* (2020) has indicated that this proportion can sometimes exceed 50%. Therefore, the technological optimization and systemic integration of the collection and pretreatment phase are critical for advancing the industrialization of biomass energy (Bhatt *et al.* 2025). On this basis, this paper focuses on agro-forestry residues (primarily including straw and forest residues) as the central research object to systematically explore optimization pathways for their CST processes.

Current Status of Agricultural and Forestry Residue Collection

To address the challenge of the geographical dispersion of biomass resources, efficient collection technologies and rational organizational models are the foundational steps in constructing a supply chain. As the biomass resource with the greatest potential in China, agricultural residues (especially crop straw) present a primary challenge in terms of achieving efficient and low-cost field collection to promote the industrialization of biomass energy. For an extended period, traditional straw collection relied heavily on manual labor. However, with the continuous rise in rural labor costs, this conventional model has become inadequate for meeting the demands of large-scale industrial utilization due to its low efficiency and high expense. Against this backdrop, a transition to mechanized collection has become an inevitable trend for industrial development. Wu *et al.* (2021) conducted an economic analysis of six different supply modes in China (Fig. 2).

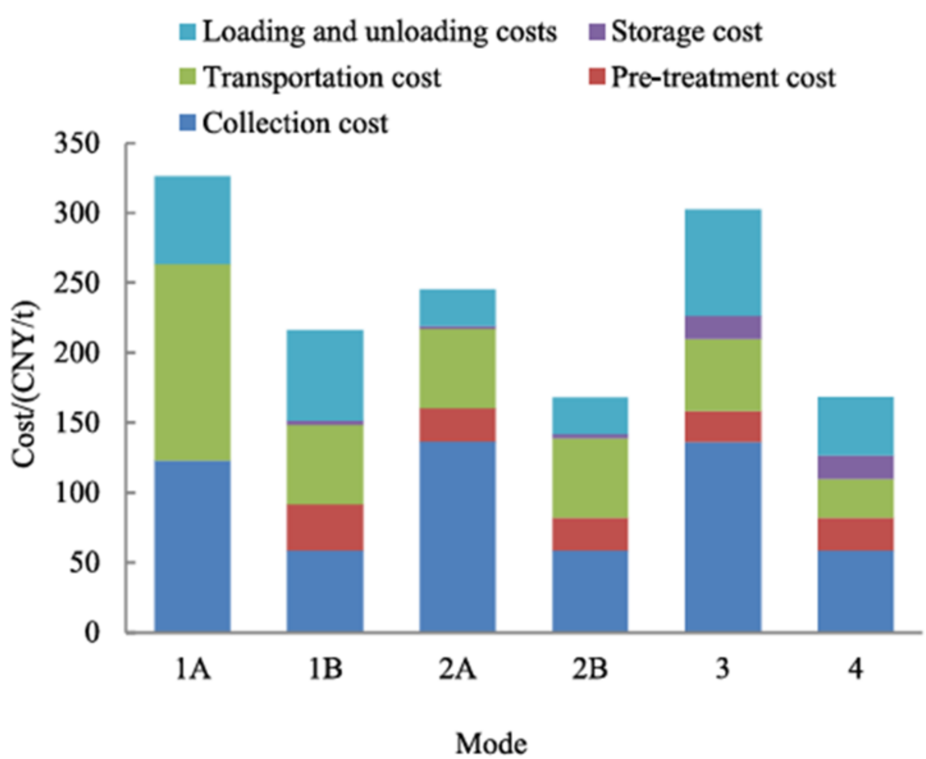

Fig. 2. Straw supply cost of different supply modes (Wu *et al.* 2021). Figure republished from Wu *et al.* (2021) with permission from Elsevier

The mechanized collection modes (Modes 1B, 2B, and 4) can significantly reduce the supply cost of straw and should thus be the primary collection method for future large-scale utilization. This provides a direct economic basis for the selection of technological routes.

Field baling, as the core technology of mechanized collection, establishes a solid foundation for subsequent storage and transportation by compressing loose straw into regular shapes. Currently, mainstream baling equipment is categorized into two major types: round balers and square balers. A study on rice straw in the Philippines by Balingbing *et al.* (2014) demonstrated that although large square balers require a higher initial investment, their capacity for continuous operation (eliminating frequent stops for tying and unloading bales) results in an effective field capacity 4.43 times that of round balers, with the unit tonnage baling cost being remarkably reduced approximately 68%. In addition to their operational efficiency, the regular geometry of square bales greatly facilitates stacking, storage, and transportation, effectively enhancing the space utilization of transport vehicles. Research by Shinners and Friede (2018) further indicated that high-density square balers can produce bales with densities up to 240 kg/m ^{3}. This high-density characteristic allows transport vehicles to fully leverage legal maximum weight limits, thereby minimizing unit transportation costs.

Beyond the selection of technological equipment, innovative and efficient collection organization models are equally crucial for addressing the resource dispersion issue prevalent in China's smallholder economy. Based on national conditions, He *et al.* (2025) proposed the principle of "relying on local authorities and mobilizing the masses", emphasizing the full utilization of rural brokers and the establishment of regional "collection and storage points". Wu's research specifically depicted a three-tier supply chain network composed of feedstock supply points, collection and storage stations, and a power plant. In this network, the collection and storage stations undertake key functions, such as field collection, baling, and preliminary storage, providing a feasible physical framework for the aforementioned models. Reliance on the conventional rural middleman model often leads to elevated transaction costs, primarily due to opaque practices and inefficient manual coordination such as bargaining. In contrast, the emergence of digital and smart agriculture offers a promising alternative. By integrating handheld mobile applications with national-level dispatch platforms, real-time matching between raw material supply and collection/transport fleets becomes possible. Such systems are designed to enable instant coordination among farmers, buyers, and processing centers. Moreover, the adoption of these digital tools has been shown to reduce transaction costs, mitigate inefficiencies associated with bargaining, and enhance the supply chain's responsiveness to market and seasonal fluctuations. Moreover, the previously mentioned study by Wu *et al.* (2021) confirmed that the combined costs of collection, transportation, and handling account for over 75% of the total cost, which, from an economic perspective, further highlights the urgency and immense potential of optimizing collection organization models.

Forestry residues primarily consist of forest harvesting residues (*e.g.*, branches, treetops, bark) and wood processing residues (*e.g.*, sawdust, shavings). Forest and agricultural residues differ markedly in their supply patterns. Agricultural residues are typically location-predictable but seasonally constrained, being available only during a narrow post-harvest window. In contrast, forest residues are generated continuously throughout the year, offering a more stable supply flow; however, their collection points constantly shift with ongoing harvesting activities, leading to variable transport routes.

Specifically, the collection of forest harvesting residues frequently faces challenges such as complex terrain and poor road accessibility. Currently, the mainstream collection models can be categorized as "in-woods processing" and "roadside processing." The "in-woods processing" model employs mobile chippers or balers to process residues directly at the harvesting site into wood chips or bundles. This method significantly reduces material volume and lowers subsequent transportation costs but places high demands on the maneuverability and adaptability of equipment in forest areas. Correspondingly, the "roadside processing" model involves first gathering the unprocessed residues to a flat area, such as a forest roadside, using forwarders, and then performing centralized chipping or baling. This model lowers the requirements for processing equipment but incurs higher initial collection and transport costs due to the need to move bulky and loose raw materials (Nunes *et al.* 2020). The collection of residues from wood processing plants is relatively straightforward as they are already centralized at the factory, typically requiring only direct loading or simple pretreatment.

Current Status of Biomass Pretreatment Technologies

Biomass pretreatment is a critical value-adding step positioned between collection and transportation/storage. Its core objective is to modify the physicochemical properties of biomass through physical, chemical, or other means to meet the requirements of subsequent storage, transportation, and energy conversion processes (Nunes *et al.* 2020).

Physical pretreatment is currently the most widely applied and technologically mature method, primarily encompassing densification and size reduction. Densification aims to significantly increase the volumetric energy density of biomass through mechanical compression. In addition to field baling, more advanced densification technologies include briquetting and pelletizing. A study by Pan *et al.* (2024) showed that briquetting rice straw could increase its bulk density by 6.4 times, correspondingly reducing storage and transportation costs 42.6%. Moreover, the denser structure of briquettes effectively slows the rate of dry matter loss during long-term storage. Pellet fuel, because of its excellent flowability and uniform shape, is particularly suitable for highly automated combustion and gasification systems (Guo *et al.* 2015). Size reduction is a prerequisite for most pretreatment processes, commonly achieved through chipping and grinding. In their research on process integration, Shinners and Friede (2018) found that although adding a pre-cutting function to the baling process slightly increased baling energy consumption, it improved the efficiency of the subsequent grinding process 25% to 45% and significantly reduced the energy consumption of grinding. This result fully demonstrates the importance of system optimization from a whole-chain perspective for reducing total costs and energy consumption.

Alongside stationary processing, the model of mobile field densification—operating on a concept analogous to a "combine harvester"—is gaining widespread adoption. This approach utilizes mobile or modular units to integrate preprocessing steps such as baling or pelletizing directly at biomass collection points. Such on-site integrated collection-preprocessing systems offer significant advantages, primarily by optimizing transport loading density and thereby avoiding the inefficiencies of hauling low-density bulk or loose residues. However, this mobile model also presents challenges. The equipment typically processes lower volumes than industrial plants, relies on limited tractor-powered energy, and is highly sensitive to raw material moisture content — a parameter that is difficult to control precisely in open-field environments without integrated drying systems. Beyond technical feasibility, operational flexibility at the source is critical for economic viability. To optimize returns, local operators (*e.g*., farmers, forest managers) require the capability to switch flexibly between modes—such as selling raw bales, producing pellet fuel, or conducting on-site pyrolysis—based on real-time market prices and end-user demand. This dynamic decision-making allows upstream supply chains to adapt swiftly to economic fluctuations rather than being locked into a single, potentially low-margin pathway. Ultimately, the economic viability of such a system depends on multiple factors, including feedstock density, transport distance, and operational scale. These dependencies make it particularly well-suited for regions with dispersed biomass resources or underdeveloped transport infrastructure.

In addition to physical methods, chemical pretreatment methods have also been extensively studied. This approach is particularly applicable in bioconversion pathways. For example, alkali treatment using sodium hydroxide can effectively disrupt the recalcitrant lignocellulosic structure of straw, thereby enhancing the efficiency and yield of subsequent anaerobic digestion or alcohol fermentation (Pan *et al.* 2024). However, this method faces economic and environmental challenges, including the high cost of chemical inputs and subsequent wastewater treatment. A techno-economic analysis by Pan *et al.* indicated that although alkali treatment could yield a higher gas production rate, its high operational costs might render the project unprofitable; in contrast, simple physical briquetting technology demonstrated a superior return on investment. In the field of thermochemical pretreatment, torrefaction has also garnered considerable attention. This technology involves the low-temperature pyrolysis of biomass in an oxygen-deficient environment at 200 to 300 °C. It effectively removes moisture and some volatile components, making the biomass hydrophobic and easier to pulverize. It also has a lower equilibrium moisture content. The energy density, hydrophobicity, grindability, and combustion performance of biomass treated in this way are significantly improved, making torrefied biomass a more suitable upgraded solid biofuel for storage, transportation, and co-firing applications (Guo *et al.* 2015). A comprehensive review by Zhang *et al.* (2025) analyzed the characteristics and performance of biomass conversion under various pretreatment torrefaction atmospheres, highlighting the differential impacts of each atmosphere on the material's physical and chemical structure. The study conducted a comparative analysis of research on five primary torrefaction atmospheres: nitrogen, carbon dioxide, air, ammonia, and flue gas. It was concluded that for agro-forestry residues, flue gas represents a more industrially viable option compared to the alternatives in terms of technical performance, economic cost, and industrial feasibility (Mei *et al.* 2015; Lei *et al.* 2019; Li *et al.* 2021; Yang *et al.* 2021; Pimsamarn *et al.* 2024; Devaraja *et al.* 2025). This conclusion is supported by findings that the mass yield from flue gas torrefaction is higher than that from pure air, while the heating value shows a significant enhancement of approximately 22.7%.

In summary, biomass collection and pretreatment technologies are rapidly advancing towards higher efficiency, lower costs, and systemic integration. This evolutionary path is characterized by a progression from the selection of single technologies to the synergistic optimization of multiple technologies, which are further integrated with innovative organizational models (Mao *et al.* 2024). The resulting multi-level technological system, through synergistic effects, effectively reduces overall costs, enhances operational efficiency, and ensures the stability of feedstock supply, thereby providing critical support for the large-scale and commercial development of the biomass energy industry (Ogunrewo and Nwulu 2024). Moreover, the selection of pretreatment methods – including, but not limited to, baling, pelletizing, and pyrolysis – is subject to dynamic adjustment in accordance with specific conditions, including but not limited to feedstock type, moisture content, energy market volatility, and end-use requirements. For instance, when energy prices fail to cover densification costs or when rapid seasonal collection is required, operators often opt for simple baling and compaction. Conversely, in circumstances where there is a requirement for long-term storage or where market prices for high-quality feedstock are favourable, operators may elect to implement on-site pelletizing or drying processes. This strategic flexibility enables supply chain operators to optimise economic returns across different seasons and logistical scenarios.

In summary, while advancements in collection and pretreatment technologies—particularly densification—technically mitigate the physical limitations of biomass, technology alone cannot guarantee economic viability. The deployment of these technologies requires significant capital investment, which must be offset by logistics savings. Therefore, the challenge shifts from a purely technological issue to a strategic network design problem: how to optimally configure these processing nodes within a supply chain to maximize efficiency. This necessitates a transition from analyzing individual unit operations to evaluating supply chain organizational models, which will be discussed in the following section.

BIOMASS SUPPLY CHAIN ORGANIZATION MODELS

The organization of biomass supply chains fundamentally revolves around the trade-off between economies of scale in processing and economies of transport (Zandi Atashbar *et al.* 2018). Existing literature broadly categorizes these systems into centralized, distributed, and hybrid models, each presenting distinct economic and operational profiles.

Comparative Analysis of Structural Models

The centralized model, where raw biomass is transported directly to a large-scale refinery, benefits significantly from reduced capital investment per unit of capacity. However, Kim and Dale (2015) demonstrated that this advantage diminishes as the facility size increases. Their life cycle optimization revealed that for large-scale biorefineries (*e.g.*, >2,000 dry Mg/day), the distributed model—which employs local depots for preprocessing (*e.g.*, pelletizing)—becomes economically superior. This is because the cost savings from transporting densified feedstock outweigh the increased capital costs of building multiple depots. Similarly, Kim *et al.* (2010) highlighted that while centralized systems are cost-effective for smaller collection radii, distributed networks are essential for accessing dispersed resources, increasing the feasible supply volume by up to 177% in some scenarios.

To capture the benefits of both approaches, research has shifted towards hybrid or "hub-and-spoke" architectures. You and Wang (2011) proposed a distributed-centralized network for biomass-to-liquid (BTL) chains, showing that preprocessing biomass into intermediate products (such as bio-oil) locally can resolve the "low-density" bottleneck, allowing for long-distance transport to a centralized upgrading facility. Furthermore, Roni *et al.* (2017) expanded this concept by integrating multi-modal transport. Their multi-objective optimization showed that a hub-and-spoke system utilizing rail transport not only reduces logistics costs for long-haul distances (>75 miles) but also significantly lowers greenhouse gas (GHG) emissions and creates more local jobs compared to truck-only centralized models.

Table 1. Comparative Analysis of Biomass Supply Chain Organizational Models

Model Type	Key Characteristics	Key Advantages	Key Limitations	Ideal Context	References
Centralized Supply Chain	Direct transport of raw biomass to a central facility.	Economies of Scale: Lower specific processing costs. Simplicity: Low management complexity.	Logistics Penalty: High cost for low-density long-haul. Supply Risk: Limited collection radius.	High biomass density regions. Small-to-medium plant capacity.	Kim *et al.* (2010); Kim & Dale (2015)
Distributed / Decentralized Supply Chain	Local preprocessing (densification); transport of intermediates.	Logistics Efficiency: High transport density. Flexibility: Larger feasible supply radius	Diseconomies of Scale: High specific CAPEX. Complexity: High coordination efforts.	Dispersed resource regions. Large-scale capacity (>2000 dry Mg/d).	You & Wang (2011); Roni *et al.* (2019)
Hybrid / Hub-and-Spoke	Multi-echelon network combining distributed depots for aggregation/preprocessing and rail/barge for long-haul transport.	System Balance: Trade-off between scale and logistics. Sustainability: Low GHG (rail usage); High resilience.	Dependency: Requires rail/port infrastructure. Investment: High initial infrastructure costs.	Inter-regional logistics. Sustainability-driven targets.	Roni *et al.* (2017); Zandi Atashbar *et al.* (2018)

Notes: CAPEX = Capital Expenditure; GHG = Greenhouse Gas. The comparison is synthesized based on techno-economic analyses from the cited references.

Nevertheless, the optimal configuration remains highly context-dependent. For instance, de Jong *et al.* (2017) conducted a systematic comparative analysis using a geographically explicit optimization model (Fig. 3) and found that, within the specific context of the Swedish forestry sector, a centralized supply chain maintained a cost advantage at most production levels. This indicates that the choice of supply chain configuration cannot be generalized but requires comprehensive optimization considering multiple regional factors, including feedstock geographical distribution, production scale, and existing industrial infrastructure.

Therefore, the selection of a supply chain model is not binary but depends on regional characteristics. As summarized in Table 1, centralized models are optimal for high-density biomass regions, whereas hybrid models involving depots and multimodal transport are the prerequisite for large-scale, inter-regional bioenergy commercialization (Roni *et al.* 2019).

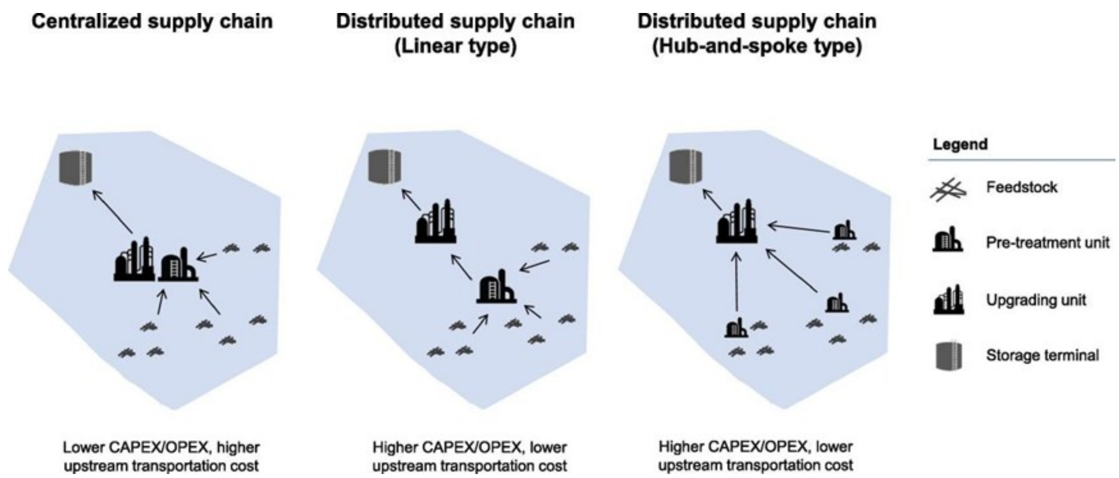

Fig. 3. A schematic image of centralized and distributed supply chain configurations (de Jong *et al.* 2017). Figure republished from de Jong *et al.* under the Creative Commons Attribution 4.0 International License (CC BY 4.0)

Strategic Optimization under Uncertainty and Sustainability

While the structural choice provides a physical baseline, the operational viability of these models is heavily constrained by multi-dimensional uncertainties. In a seminal review, Awudu and Zhang (2012) criticized the tendency of early models to rely on deterministic parameters, arguing that neglecting stochastic factors—such as yield variations, market price volatility, and policy shifts—leads to fragile supply chains. Critically, they identified a significant disparity in sustainability modeling: while economic and environmental metrics are frequently optimized, social sustainability indicators remain largely underrepresented due to quantification challenges. Similarly, at the operational level, Bochtis *et al.* (2010) emphasized that spatiotemporal constraints, such as weather-induced harvest windows, drastically compress the effective time for biomass collection, further validating the need for dynamic, prediction-based decision support tools rather than static planning.

To mitigate these stochastic risks, recent research has pivoted towards advanced stochastic and robust optimization frameworks. Azadeh *et al.* (2014) incorporated geometric Brownian motion to model biofuel price volatility, demonstrating that stochastic programming can significantly improve profit expectations under market fluctuations compared to deterministic approaches. However, addressing feedstock heterogeneity requires managing "hard" constraints that stochastic models might violate. To this end, Shabani and Sowlati (2016) proposed a hybrid "stochastic programming-robust optimization" approach. Their findings revealed that while stochastic models handle demand variations well, robust optimization is essential for managing critical quality parameters such as biomass moisture content, ensuring system feasibility even under worst-case scenarios.

Beyond parametric uncertainty, the physical resilience of the supply chain against catastrophic disruptions is becoming a critical design criterion. Soren and Shastri (2019) introduced a resiliency-focused optimization model that accounts for major disruptions, such as droughts. Their analysis showed that optimal network designs must include redundancy in depot capacity to prevent system collapse during extreme events. Although building such resilience incurs a slight increase in baseline costs, it drastically reduces the financial risks associated with biomass shortages, thereby ensuring the long-term reliability of the energy system (Rauch 2017).

Furthermore, modern supply chain design increasingly demands a holistic view of the "Triple Bottom Line" (economic, environmental, and social), necessitating multi-objective optimization. You and Wang (2011) pioneered Life Cycle Optimization (LCO) for biomass-to-liquid chains, explicitly quantifying the trade-offs between annualized costs and greenhouse gas (GHG) emissions. Their Pareto-optimal analysis indicated that distributed-centralized networks often yield better environmental performance than purely centralized ones due to reduced transport emissions. Addressing the social dimension gap, Roni *et al.* (2017) developed a multi-objective hub-and-spoke model that integrates local job creation as a key objective function. Their results highlighted a distinct trade-off: maximizing social benefits often requires a denser network of local depots, which may slightly increase unit costs but significantly enhances regional economic development and public acceptance.

Ultimately, the strategic value of these optimization efforts remains paramount. Nickerson *et al.* (2015) argued from a cost-benefit standpoint that the economic gains derived from effectively controlling front-end logistics (collection, pretreatment, transport) through such advanced optimization strategies often exceed those achieved by marginal improvements in conversion efficiencies. This reinforces the consensus that the "feedstock bottleneck" is not merely a logistical hurdle but the primary lever for competitive advantage in the bioeconomy (Lim and Lam 2016).

BIOMASS STORAGE TECHNOLOGIES

The seasonal fluctuation of biomass supply constitutes another significant challenge distinguishing it from conventional energy sources. Fuel storage at biomass power plants is a pivotal stage for ensuring a stable feedstock supply, maintaining power generation efficiency, and controlling operational costs. Therefore, scientific warehouse management functions as a 'regulator' and 'buffer' to guarantee the stable year-round operation of energy facilities. Different storage methods (*e.g.*, open-air, covered outdoor, and indoor storage) differentially impact the physicochemical properties of biomass (moisture content, higher heating value (HHV), net heating value (NHV), temperature, and dry matter loss). Consequently, the storage methods influence the subsequent combustion efficiency and operational costs of the power plant. Lara Chaves *et al.* (2022) conducted large-scale field storage experiments on seven types of biomass, concluding that initial moisture content, particle size, and leaf composition are critical factors determining storage safety and quality preservation. The study recommended that high-moisture, fine-particle, and high-leaf biomass should be stored in small piles for short durations, while dry, coarse-particle biomass can be stored in large piles for extended periods. Through implementing scientific storage management, not only can the risk of spontaneous combustion be effectively mitigated and dry matter loss reduced, but the net energy output of biomass fuel can also be enhanced, thereby optimizing the overall operational benefits of the power plant.

Based on fuel characteristics, supply stability, and power plant site conditions, current biomass power plants predominantly adopt two mainstream storage models: on-site storage and a combined on-site and off-site storage. On-site storage involves directly transporting biomass fuel to storage yards within the power plant premises for centralized management. This model is suitable for fuel types with stable, non-seasonal supply (*e.g.*, wood processing waste, rice husks), offering advantages such as fewer logistics links and lower operational costs. However, due to site constraints within the plant area, storage capacity is limited, making it challenging to accommodate large seasonal accumulations of fuel. The combined on-site and off-site storage model involves establishing a main storage yard within the plant while simultaneously setting up fixed or temporary collection stations in resource-rich rural areas to serve as off-site storage points, thereby forming a tiered CST system. This model effectively expands the feedstock collection radius and allows for flexible allocation of diverse biomass resources with varying seasonal availabilities, significantly enhancing the stability of the power plant's feedstock supply (Allen *et al.* 1998). Although combined storage incurs higher overall costs due to added transfer links compared to purely on-site storage, it reduces the risk of supply interruptions by enhancing supply reliability. Conversely, while on-site storage is less costly, it faces higher risks of supply fluctuations. Research indicates that biomass power plants are often recommended to adopt a combined on-site and off-site storage model to balance supply reliability and operational economics. Specifically, on-site storage primarily serves daily turnover and short-term security, while off-site storage is dedicated to expanding resource coverage and regulating seasonal fluctuations (Allen *et al.* 1998; Tatsiopoulos and Tolis 2003). This tiered storage strategy is crucial for achieving stable and efficient fuel supply, representing a significant guarantee for the successful operation of biomass power projects.

Centralized biomass storage can primarily be categorized into three forms: open-air storage, covered outdoor storage, and indoor storage. Open-air storage (also known as open piles) refers to storage areas without any overhead cover. This method boasts the lowest construction and maintenance costs and high land utilization; however, it is significantly susceptible to natural environmental influences and is only suitable for materials with very low storage requirements. Covered outdoor storage, equipped with a roof but not fully enclosed on the sides, can effectively reduce material loss and moisture fluctuations compared to open-air storage, offering better protection. Its cost is intermediate between open-air and fully enclosed structures, but its space utilization is limited, and its protective capabilities remain inferior to indoor storage. Indoor storage employs a fully enclosed structure (*e.g.*, silos, spherical bins, or warehouses), which maximizes material quality stability, offers high site utilization, minimizes environmental impact, and is conducive to mechanization and automation. However, it entails high investment costs and a long construction period. In practical applications, the choice of storage method must be tailored to the characteristics of the biomass feedstock. Agricultural biomass (*e.g.*, straw) typically utilizes indoor storage to ensure its quality, while more weather-resistant forestry biomass often adopts covered outdoor storage to balance cost and protection needs. Furthermore, comprehensive management measures, such as moisture-proofing, anti-corrosion, and pest control, are required during storage at both collection stations and power plants to extend the safe storage period of the feedstock.

In terms of comprehensive assessment of storage systems, Sahoo *et al.* (2018) analyzed the costs and greenhouse gas emissions of different storage solutions from techno-economic and environmental perspectives (Figs. 4 and 5). It was concluded that for wood-based materials, covered piling is the most economical option for long-term storage, while biomass pellets are better suited for silo storage. This study further revealed that dry matter loss and initial moisture content are the most critical factors influencing storage costs and energy output. Open-air piling is to be discouraged for woodchips in humid regions. Similarly focusing on quality and economic losses during storage, Darr and Shah's (2014) research emphasized that covered storage achieves a good balance between cost and dry matter loss. Specifically, the dry matter loss percentage for covered storage is approximately 5 to 7%, while employing permanent enclosed structures can reduce losses to 2 to 3%, albeit at higher construction and operational costs. The study also pointed out that initial moisture content is a key decision-making factor for selecting a storage method, with high-moisture feedstocks typically requiring special measures, such as anaerobic storage, to reduce degradation losses.

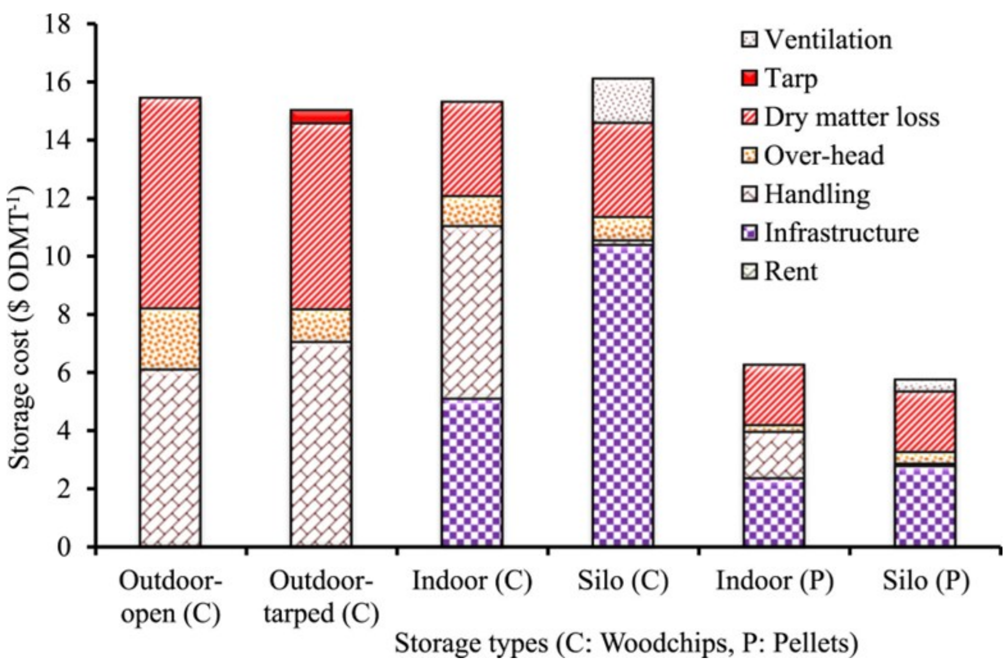

Fig. 4. Storage costs for woodchips and pellets (for six months) using selected storage systems (Sahoo *et al.* 2018). Figure republished from Sahoo *et al*. (2018) with permission from Elsevier

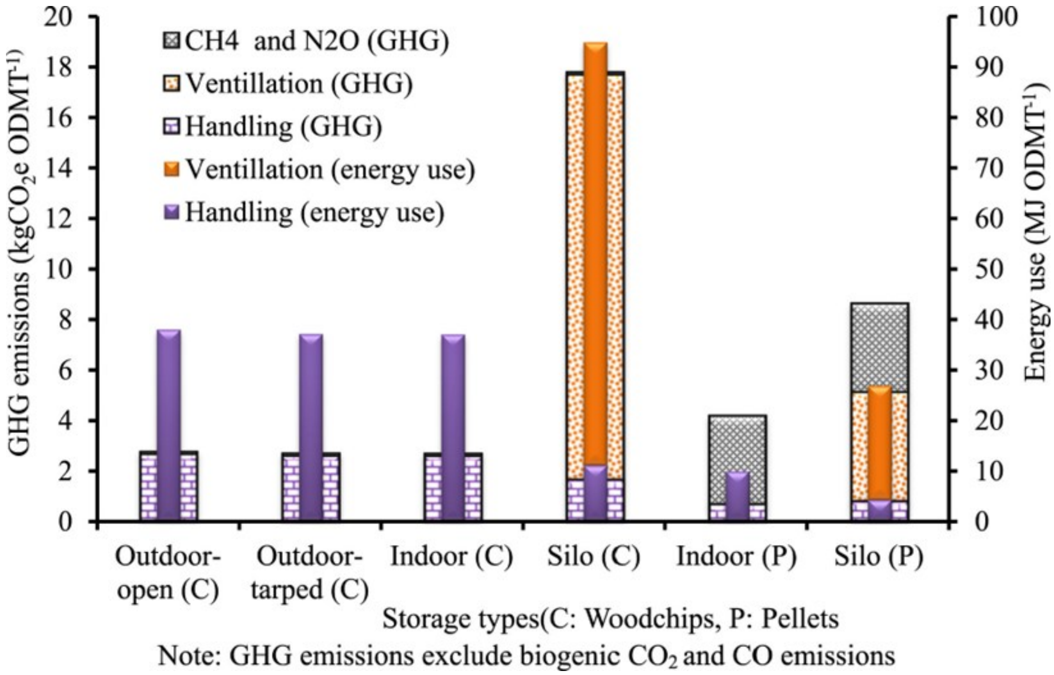

Fig. 5. Energy usage and greenhouse gas (GHG) emissions over a six-month storage period for woodchips and pellets (Sahoo *et al.* 2018). Figure republished from Sahoo *et al.* (2018) with permission from Elsevier.

Notably, in hot and humid tropical climates, storage strategies require greater specificity. Nimitpaitoon *et al.* (2023) experimentally investigated the impact of covered and uncovered conditions on the characteristics of three types of biomass: corn cobs, wood chips, and bagasse. Key indicators, such as temperature, moisture, heating value, ash content, and dry matter loss, were systematically monitored. The results demonstrated that plastic sheet covering significantly improved the storage quality of corn cobs and wood chips, but its effect on bagasse was not as pronounced, revealing substantial differences in the storage characteristics of various feedstocks and necessitating individualized management strategies. Covered storage significantly reduces moisture absorption and dry matter loss in biomass pellets, with the best effects observed for torrefied wood pellets. Over a six-month storage period, the durability reduction in the covered group was significantly lower than in the uncovered group, thereby highlighting the critical importance of dry storage conditions for maintaining the quality of biomass fuel (Nimitpaitoon and Sajjakulnukit 2022).

In conclusion, biomass storage, as a critical nexus connecting feedstock collection and energy utilization, has its technological choices and management strategies directly determining feedstock quality, supply chain stability, and whole-lifecycle costs. Existing research indicates that the scientific configuration of storage methods requires comprehensive consideration of feedstock characteristics (*e.g.*, moisture content, particle size, and ash content) and regional climatic conditions. Specifically, for high-moisture, fine-particle feedstocks, covered or indoor storage is advisable to effectively control dry matter loss and mitigate the risk of spontaneous combustion. In contrast, dry and coarse-particle feedstocks may suitably employ more economical open-air storage. At the system layout level, the combined on-site and off-site storage model can effectively ensure supply stability and enhance responsiveness to seasonal fluctuations, thus becoming a recommended strategy for most biomass power projects. Looking ahead, with the widespread application of sensing technology, the Internet of Things, and intelligent management tools, biomass storage processes are expected to achieve more refined and dynamic real-time monitoring. This will further improve storage efficiency and feedstock quality assurance capabilities, thereby providing more robust technical support for the large-scale and commercial utilization of biomass energy.

LOGISTICS AND TRANSPORTATION

Biomass feedstock transportation constitutes the core logistics link connecting collection, storage, and energy conversion. The organizational efficiency and mode selection within this phase directly determine the power generation cost, energy efficiency, and environmental sustainability of the entire supply chain. In China, biomass feedstocks are primarily sourced from agricultural straw and forestry residues, which are characterized by wide distribution but low energy density. This resource endowment leads to a transportation system that is notably diverse, regionalized, and phased. Specifically, woody biomass, due to its higher density and regular shape, is relatively convenient to transport. In contrast, agricultural residues typically require pretreatment, such as baling or pelletizing, to enhance their volumetric energy density, thereby effectively reducing unit transportation costs. A study by Lu *et al.* (2015) further demonstrated that although pelletization increases initial processing costs, it exhibits significant economic advantages in long-distance transportation (*e.g.*, over 900 km) by substantially improving loading efficiency and reducing transport frequency.

Currently, road transportation remains the predominant mode for biomass feedstocks. It is particularly suitable for short-distance and small-batch collection scenarios, with its core advantages being high flexibility and extensive coverage. In contrast, for medium- to long-distance and large-volume transportation needs, rail and waterway transport are gradually being promoted due to their low unit energy consumption and large freight capacity. Especially in the densely river-networked regions of southern China, water transport has become a vital means of effectively reducing logistics costs. The research by Lu *et al.* (2015) further quantified the applicable boundaries for different transport modes: road transport holds an economic advantage over short distances (< 100 km), whereas rail and waterway transport exhibit more significant economic and environmental benefits in long-distance haulage. The study also emphasized that enhancing material density and developing intermodal transport are two key levers for optimizing the biomass logistics system. On this basis, multi-modal transport (*e.g.*, "road + rail," "road + waterway"), by organically combining the last-mile flexibility of road transport with the large-capacity advantages of rail and waterway for trunk-line haulage, has been proven to be an effective strategy for reducing overall logistics costs (Väätäinen *et al.* 2021). Furthermore, some pioneering projects are exploring innovative transport methods such as pipeline conveyance or semi-solid slurry transport. Although these technologies are mostly in the pilot stage, they offer potential pathways for the future upgrading of the biomass logistics system.

Regarding the cost composition of the biomass feedstock transportation phase, an integrated study by Wu *et al.* (2022), based on GIS and optimization models, found that transportation and feedstock acquisition costs collectively account for over 60% of the total cost, making them the critical elements for overall cost control. The sensitivity analysis in their study further revealed that achieving economies of scale, optimizing transportation routes, and improving loading efficiency are effective strategies for mitigating the impacts of feedstock price and transport distance fluctuations.

In the economic assessment of transportation modes, Tumuluru *et al.* (2024) proposed the "Break-even Transportation Distance" (BTD) as a key evaluation metric for the three primary modes: road (truck), rail, and marine transport. The study indicated that the feedstock's bulk density and specific energy collectively determine its maximum economic transport distance, with marine transport having the highest BTD—approximately 9.2 times that of road transport—making it particularly suitable for inter-regional, large-scale logistics scenarios. It is noteworthy that torrefied biomass pellets, due to their high energy density and hydrophobicity, can achieve a further significant increase in their BTD, demonstrating excellent adaptability for long-distance transportation. The study ultimately underscored the significant value of pretreatment technologies in optimizing bulk density and overcoming volumetric constraints in transport (as illustrated in Fig. 6). The model clearly reveals that although advanced pretreatment methods such as pelletization increase initial costs, their economic transport radius far exceeds that of raw biomass by substantially increasing bulk density, giving them an unparalleled advantage in long-distance or inter-regional supply chains. This demonstrates the close cost linkage between the pretreatment and transportation phases, which must be synergistically optimized. Note that the BTD values exhibited in Fig. 6, derived from Tumuluru *et al.* (2024), are predominantly determined by bulk density and specific energy. The authors explicitly acknowledged that material degradation during long-duration transport (*e.g.*, shipping) had not been factored into the current model. In real-world logistics, raw or densified biomass is susceptible to moisture absorption and microbial decay, which results in a 'decay cost' that reduces its effective energy value over time. Conversely, torrefied biomass demonstrates enhanced hydrophobicity and biological stability. Consequently, if the costs associated with storage losses and degradation were incorporated into the calculation, the comparative advantage of torrefied biomass would likely be even more pronounced than is currently depicted, further justifying its suitability for inter-continental supply chains.

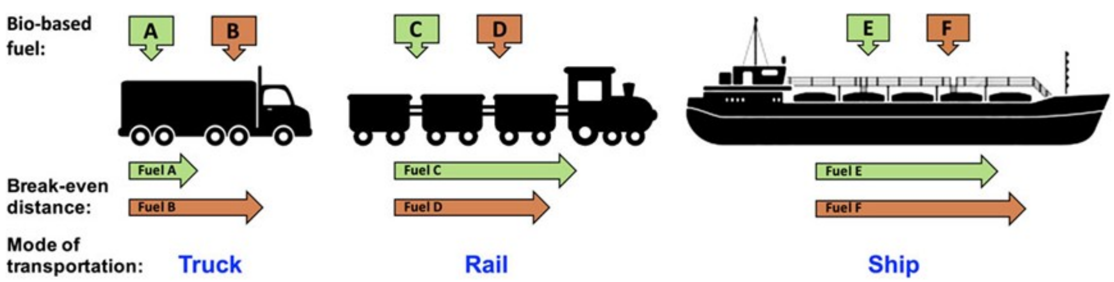

Fig. 6. Illustration of the concept of BTDs of biomass feedstocks as bio-based fuel and the modes of transportation studied (Tumuluru *et al.* 2024). Figure republished from Tumuluru *et al.* (2024) under the Creative Commons Attribution License (CC BY)

In the biomass energy system, the environmental impact of transportation is a critical consideration for its whole-lifecycle sustainability. Life Cycle Assessment (LCA) studies indicate that emissions from the transportation process account for 10% to 30% of the total emissions from biomass energy and are significantly influenced by transport mode and distance. A study by San Miguel *et al.* (2015) on short-rotation poplar plantations in Spain specifically showed that for every 10 km increase in transport distance, carbon emissions rise an average of 5%. In comparing transport modes, the carbon emission intensity of truck transport is typically higher than that of rail and waterway, but reductions of approximately 20% can be achieved by optimizing route planning and increasing vehicle load factors. The research by Lu *et al.* (2015) conducted an in-depth analysis from an energy efficiency perspective, calculating the Net Energy Ratio (NER) for different biomass types. They found that woody biomass can have an NER as high as 34, whereas agricultural residues, due to higher pretreatment energy consumption, have an NER of about 20 to 25, reflecting the profound impact of feedstock characteristics on transport energy efficiency. The environmental performance of the biomass CST system is directly linked to its lifecycle carbon neutrality and sustainability. As one of the main sources of energy consumption and greenhouse gas emissions, the transportation phase holds significant potential for emission reduction and should be given full attention and optimization.

In summary, the transportation phase of biomass feedstock is pivotal in determining the economic viability and environmental benefits of its energy utilization. Currently, road transport dominates short-haul collection due to its flexibility and extensive coverage; in contrast, rail and waterway transport demonstrate superior economic and environmental performance for medium- to long-distance, large-scale haulage. Integrated strategies, such as enhancing feedstock bulk density (*e.g.*, through baling and pelletization), optimizing transport routes, and developing multi-modal transport can effectively reduce unit logistics costs and improve system energy efficiency. Looking ahead, with the deep integration of intelligent dispatching systems, route optimization algorithms, and the Internet of Things, the biomass logistics system is poised to achieve more refined, low-carbon, and intelligent operations, thereby providing a solid foundation for the large-scale commercial application of biomass energy.

ENVIRONMENTAL SUSTAINABILITY OF CST SYSTEMS

Although biomass energy is widely viewed as a low-carbon alternative to fossil fuels at a macroscopic level, a micro-level scrutiny based on Life Cycle Assessment (LCA) indicates that its environmental performance largely depends on the operational efficiency of the upstream supply chain. Existing LCA studies show that the CST stages—from field collection to the power plant gate—typically contribute 10% to 35% of the total life cycle greenhouse gas emissions of bioenergy; in scenarios involving long-distance transport or inefficient logistics, this proportion is even higher (Ingrao *et al.* 2021; Song *et al.* 2023). To systematically identify the distribution characteristics of these environmental burdens, Table 2 summarizes the key emission sources and environmental impact mechanisms at each stage of the CST system.

At the source of the supply chain, environmental impacts originate not only from the direct fuel consumption of agricultural machinery (harvesting, baling, loading) but also involve deeper ecological costs. To pursue higher biomass collection rates, excessive straw removal can lead to soil organic carbon (SOC) depletion; the increased fossil-based fertilizer input required to maintain soil fertility constitutes significant implicit indirect emissions (Sgarbossa *et al*. 2020). In contrast, the environmental impact characteristics of the biomass pretreatment stage are more complex. Although densification technologies such as pelletizing or torrefaction can significantly reduce the carbon footprint of subsequent transportation, their processing stage is inherently energy-intensive. LCA data indicates that the emission contribution rate of this stage fluctuates significantly between

15% and 40%, reflecting its high sensitivity to feedstock moisture content and regional grid carbon intensity (Messagie *et al.* 2014).

Environmental risks in the storage stage are often underestimated. As stated in the table, in addition to the direct energy waste represented by dry matter loss, methane (CH_4) released during the anaerobic degradation of high-moisture biomass has a global warming potential far exceeding that of carbon dioxide. Therefore, moisture management and ventilation control are not only economic loss prevention measures but also key climate mitigation strategies. Within the entire CST chain, the transportation stage is usually the largest contributor to emissions (accounting for 20% to 50%), mainly attributed to the long-distance haulage of low-density materials. Studies show that the unit carbon emission intensity of transporting bulk biomass by heavy-duty trucks is significantly higher than that of rail or water transport (Reeb *et al.* 2015). This finding reveals a profound "cost-environment" synergistic effect between transportation mode optimization and the improvement of loading efficiency.

Table 2. Life Cycle Assessment (LCA) Profile and Environmental Optimization of Biomass CST Stages

Supply Chain Stage	Main Emission Sources	Dominant Environmental Impacts	Typical LCA Contribution Range	Key Influencing Factors	References
Collection	Fuel consumption by harvesters, balers, and loaders; field residue handling	Global Warming Potential (GWP) Soil Quality Degradation	10% to 30%	Mechanization level; residue density; field accessibility	Jiang *et al.* 2020; Sgarbossa *et al.* 2020; Zheng *et al.* 2022
Pretreatment	Grid electricity usage for densification (pelletizing/briquetting); Thermal energy consumption for active drying	GWP; Cumulative Energy Demand	15% to 40%	Moisture content; pretreatment intensity; Grid Carbon Intensity	Laschi *et al.* 2016; Muazu *et al.* 2017
Storage	Fugitive CH_4 emissions from anaerobic degradation in wet piles; Auxiliary energy use for storage operations	GWP; Resource inefficiency	5% to 15%	Storage duration; moisture control; climatic conditions	Jämsén *et al.* 2015; Sahoo *et al.* 2018a; Simpson *et al.* 2016
Transportation	Fuel Combustion: Diesel/Heavy Fuel Oil from trucks, trains, or barges.	GWP; Fossil resource depletion; Air pollutant emissions (NO_X, PM)	20% to 50%	Transport distance; mode selection; load factor	Beagle and Belmont 2019; Messagie *et al.* 2014

Note: Contribution ranges are synthesized from representative life cycle assessment (LCA) studies and primarily refer to the share of total life cycle greenhouse gas emissions (GWP). Reported values vary significantly depending on feedstock type, system boundary, geographic context, and methodological assumption.

In summary, constructing an efficient biomass collection, storage, and transportation system must synchronously incorporate strict environmental dimension considerations at the planning stage. Future paradigms should aim to conduct a multi-dimensional comprehensive assessment of "cost-energy-emissions" throughout the entire chain, to achieve the dual goals of economic feasibility and environmental sustainability.

POTENTIAL RISKS AND EMERGING TECHNOLOGIES

Although optimization models and LCA evaluations provide a theoretical framework for CST systems, significant practical risks remain in the process of expanding from pilot studies to industrial scalability. Currently, the core bottleneck of the biomass supply chain lies in the uncertainty of feedstock supply (Gonzalez *et al.* 2011). Unlike standardized extracted fossil fuels, the availability of agro-forestry residues is strictly constrained by seasonal cycles, meteorological conditions, and regional resource density (Stelte *et al.* 2012). Extreme weather events exacerbated by climate change may further compress the effective harvest window, intensifying the risk of "supply interruptions" for power plants (Liu *et al.* 2017). Furthermore, as the collection radius expands, coordination costs among multiple stakeholders (farmers, brokers, power plants) surge. Combined with market risks (such as fossil energy price fluctuations), this often causes actual operating costs to exceed theoretical expectations, threatening the long-term robustness of the supply chain (Gital and Bilgen 2024; Golecha and Gan 2016).

To address the aforementioned challenges, the integrated application of Emerging Technologies offers promising solutions. For instance, deploying Internet of Things (IoT) sensors in storage facilities enables real-time monitoring of environmental temperature and humidity, reducing the risks of spontaneous combustion and asset loss (Onibonoje *et al.* 2019; Parvin *et al.* 2018). Digital logistics platforms combined with intelligent prediction models can more accurately forecast feedstock supply volumes and dynamically optimize fleet routes, thereby buffering the impact of seasonal fluctuations (Gracia *et al.* 2014; Zarandi *et al.* 2024). Addressing the high cost of long-distance transport, mobile pretreatment equipment (such as truck-mounted pelletizing or pyrolysis units) achieves "decentralized densification" (Chen *et al.* 2018). This strategy of pushing processing capacity down to the feedstock source reduces dependence on fixed infrastructure and significantly improves the scalability of the system in remote areas.

It is worth noting that while these technologies alleviate some risks by enhancing information transparency and system adaptability, their economic and environmental benefits are currently mostly based on case studies. Facing the complexity of large-scale logistics networks, the actual effectiveness of these emerging technologies still requires verification through broader empirical assessments.

CONCLUSIONS AND OUTLOOK

Main Conclusions

Against the strategic backdrop of the global energy transition and China's "dual carbon" targets, this paper has systematically reviewed the key technological links and research progress within the biomass CST system. Through an in-depth analysis of the impact mechanisms of biomass physicochemical properties, the collection and pretreatment technology systems, storage optimization strategies, and logistics transportation networks, this review reveals the foundational and decisive role of the CST system within the entire biomass energy industry chain. The analysis indicates that the inherent physicochemical characteristics of biomass feedstocks constitute the core physical constraints that impede the economic viability of their energy utilization and are the fundamental reason for the economic limitations of various CST models.

Further investigation confirms that isolated technological optimizations are insufficient to address the cost challenges across the entire supply chain. Mechanized collection and pretreatment technologies, centered on high-density baling, and thermochemical modification, are not only critical for overcoming feedstock deficiencies and reducing costs at the source but are also decisive measures for lowering subsequent storage and transportation expenditures. Constructing a hybrid supply chain network of "decentralized collection–centralized processing" and developing multi-modal transport are effective pathways for achieving large-scale, long-distance, and low-cost logistics. Scientific storage management and mode selection provide essential support for coping with the seasonal fluctuations of feedstock supply and ensuring the continuous and stable operation of energy production.

Research Outlook

Although existing research has provided a solid theoretical and technological foundation for the optimization of the biomass CST system, numerous challenges remain in the progression towards industrialization, intellectualization, and decarbonization. Future research should focus on deepening and expanding in the following areas:

(1) Transition towards Intelligent and Dynamic Management: Future studies should be dedicated to integrating cutting-edge technologies, such as the Internet of Things (IoT) and Artificial Intelligence (AI) to build intelligent supply chain decision-making platforms capable of responding to market and environmental uncertainties. This will enable a transition from static optimization to dynamic, real-time dispatching.

(2) Focus on Low-Cost, High-Efficiency Pretreatment Technologies and Equipment: Emphasis should be placed on developing novel, low-energy-consumption pretreatment processes and creating mobile, modular equipment adaptable to diverse feedstock characteristics. Through advancing key value-adding steps to the resource origin, the whole-chain cost can be reduced from the source.

(3) Establishment of a Comprehensive Life Cycle Assessment Framework. There is a need to construct a multi-dimensional evaluation model that integrates economic costs, energy consumption, and environmental impacts. Such a framework would provide scientific and comprehensive decision support for the comparative selection of different technological routes and supply chain models.

(4) Promotion of Synergistic Innovation in Business Models and Policy Mechanisms: Efforts should be directed towards actively exploring new business models, such as regional energy cooperatives and third-party professional logistics. Concurrently, precisely targeted incentive mechanisms based on emission reduction performance should be designed to create a favorable market and policy environment for the large-scale application of advanced technologies.

(5) It is imperative to acknowledge that the carbon-neutrality of biomass combustion is frequently predicated on the fundamental assumption that existing ecosystems possess the capacity to rapidly reabsorb the emitted CO_2. However, in the context of ongoing environmental degradation, this absorption capacity is gradually

declining. In order to enhance the climate benefits, it is essential that future research moves beyond the singular "combustion capacity" model towards "cascading utilization" strategies. Such strategies may include the prioritization of biomass conversion into durable goods, such as bio-based building materials and furniture, with a view to establishing long-term carbon sinks. In contradistinction to wind and solar power, which are considered to provide clean energy exclusively, biomass is distinguished by its dual potential for energy conversion and physical carbon sequestration. Consequently, the development of next-generation collection, storage, and transportation systems should prioritize intelligent sorting and targeted allocation. The utilization of premium resources in the production of high-value material manufacturing is recommended, with the objective of enhancing carbon sequestration. Meanwhile, it is imperative that genuine residues are employed for the purpose of energy recovery. This approach is expected to facilitate the establishment of a more circular bioeconomy system.

In conclusion, the construction of a modern biomass feedstock supply system that is technologically advanced, economically viable, environmentally friendly, and operationally reliable is the core prerequisite for realizing the strategic value of biomass energy under China's national "dual carbon" targets. As this paper has revealed, the establishment of such a system does not rely on technological breakthroughs in individual links. Instead, the key lies in adopting a holistic mindset that synergizes "technology-model-system" to achieve "whole-chain optimization."

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