

# Biomass Energy in the Low-Carbon Transition: Pathways, Performance, and Limits

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## ABSTRACT

Biomass is one of the few renewable resources capable of supplying dispatchable heat, power, and transport fuels while also valorizing agricultural, forestry, and municipal residues. This review synthesizes biomass feedstock classes, dominant conversion routes, environmental performance, and techno-economic trends using literature published between 2000 and 2025. Agricultural residues, forestry by-products, energy crops, algae, and the biodegradable fraction of municipal solid waste are assessed against conversion suitability, efficiency, cost, and lifecycle greenhouse-gas performance. Thermochemical routes such as combustion, gasification, and pyrolysis are compared with biochemical routes including anaerobic digestion and fermentation. The analysis shows that residue- and waste-derived feedstocks generally offer the strongest sustainability case, whereas dedicated crops remain sensitive to land and water constraints. Mature options such as combustion and anaerobic digestion are already commercially relevant, while gasification, pyrolysis, and biorefinery concepts offer higher product flexibility but still face capital and scale-up barriers. Biomass can make a meaningful contribution to decarbonization when deployment prioritizes sustainable sourcing, logistics optimization, and integration with carbon capture. Future progress depends on region-specific feedstock strategies, stable policy support, and system configurations that couple energy production with waste management and negative-emission potential.

## 1. Introduction

Biomass has re-emerged as a strategically important component of the renewable-energy transition because it can provide stored, dispatchable energy in forms that are compatible with existing heat, power, and fuel infrastructures [1], [2], [3]. Unlike variable renewable resources, biomass contains chemically bound solar energy that can be converted when required, which makes it relevant for dispatchable heat and power services [4], [5], [6]. Its role in industrial heat, combined heat and power, and transport-fuel supply has therefore attracted renewed analytical attention [7], [8], [9], [10]. This renewed interest is also linked to wider decarbonization debates over resource flexibility, fuel substitution, and system resilience [11], [12], [13], [14], [15].

The term biomass covers a heterogeneous resource base that includes agricultural residues, forestry by-products, dedicated energy crops, algae, and the biodegradable fraction of municipal solid waste [16], [17], [18]. This breadth is a strength because it enlarges the resource pool, but it is also a constraint because moisture, ash, elemental composition, and degradation behavior vary strongly among feedstocks [19], [20], [21], [22]. Seasonal availability, logistics density, and competing end uses further shape which resources are practical in a given region [23], [24], [25], [26]. As a result, feedstocks cannot be evaluated as interchangeable energy carriers and instead require context-specific assessment [27], [28], [29], [30].

Biomass conversion technologies are generally grouped into thermochemical and biochemical pathways [31], [32], [33]. Combustion remains the most mature route for direct heat and power generation, whereas gasification and pyrolysis expand the product slate toward

syngas, hydrogen-rich gas, bio-oil, and char [34], [35], [36], [37]. In parallel, anaerobic digestion and fermentation enable the production of biogas and liquid biofuels from wet or sugar-rich feedstocks [38], [39], [40], [41]. The technical suitability of each route depends strongly on feedstock structure, pre-treatment requirements, process control, and the intended end use [42], [43], [44], [45].

Claims of biomass carbon neutrality must, however, be treated cautiously [46], [47], [48]. The climate benefit depends on land-use counterfactuals, cultivation practices, supply-chain emissions, methane leakage, and the fate of co-products or captured carbon [49], [50], [51], [52]. Residues and waste streams often offer the most defensible climate case, whereas dedicated crops can lose much of their advantage when land-use change, irrigation burden, or long transport distances are introduced [53], [54], [55], [56]. This is why recent low-carbon transitions literature increasingly links biomass performance to broader system-integration and carbon-management frameworks rather than to combustion emissions alone [57], [58], [59], [60].

Economic competitiveness is similarly context dependent. Feedstock aggregation, drying, densification, storage, and transport can dominate the cost structure of biomass systems, particularly where resources are spatially dispersed [17], [25], [43]. At the same time, biomass offers value beyond fuel substitution by supporting rural economies, waste management, and negative-emission strategies such as bioenergy with carbon capture and storage (BECCS) [18], [31], [46]. These attributes justify a broader assessment framework than cost per unit energy alone [27], [40], [57].

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## Nomenclature

### Abbreviation

LCA – Life Cycle Assessment  
 GHG – Greenhouse Gas  
 BECCS – Bioenergy with Carbon Capture and Storage  
 MSW – Municipal Solid Waste  
 CHP – Combined Heat and Power  
 RDF – Refuse-Derived Fuel  
 HHV – Higher Heating Value  
 LHV – Lower Heating Value  
 DOE – Department of Energy

### Symbol

$\eta$  – Efficiency  
 $\rho$  – Density  
 Q – Heat energy

Against this background, the present review critically examines biomass as a multi-pathway energy resource by comparing feedstock categories, conversion performance, environmental implications, and deployment conditions through a common analytical lens [32], [39], [48]. The objective is not merely to summarize the literature, but to clarify where biomass performs well, where it remains constrained, and which system configurations are most likely to deliver credible low-carbon benefits at scale [41], [49], [58].

Policy and market structure ultimately determine whether technical promise translates into deployment [19], [56], [59]. Regions that combine reliable feedstock access with stable renewable-energy incentives, waste-diversion policies, and carbon-management frameworks have consistently delivered stronger biomass uptake than regions where support mechanisms remain fragmented or short lived [47], [52], [53], [54]. This policy dependence is particularly important when biomass projects are evaluated alongside carbon-management pathways and other long-horizon transition options [55], [60].

## 2. Methodology

This review followed a structured evidence-synthesis approach combining systematic literature retrieval, comparative screening, and data normalization. Publications from 2000 to 2025 were gathered from major academic databases and institutional repositories, with emphasis on peer-reviewed journal articles, review papers, techno-economic analyses, lifecycle-assessment studies, and policy reports relevant to biomass feedstocks and conversion technologies [47].

Search terms were organized around three clusters: feedstock descriptors (for example, agricultural residues, forestry residues, energy crops, algae, and municipal solid waste), process descriptors (combustion, gasification, pyrolysis, anaerobic digestion, fermentation, and biorefinery), and evaluation descriptors (efficiency, emissions, lifecycle assessment, CAPEX, OPEX, and policy). Studies were retained when they reported quantitative or clearly interpretable evidence on resource availability, process performance, climate implications, or deployment experience [48], [49], [50].

**Table 1.** Biomass feedstock categories and their energy potential

Feedstock Type	Typical Sources	Energy Potential (MJ/kg)	Key Challenges
Agricultural residues	Rice husk, wheat straw, corn stover	12–17	Seasonal availability, logistics
Forestry residues	Wood chips, sawdust, bark	16–20	Transportation cost, sustainability
Energy crops	Switchgrass, miscanthus, jatropha	14–19	Land-use competition, water demand

The selected literature was then classified by feedstock class, conversion pathway, and scale of evidence, distinguishing laboratory

studies from pilot-scale and commercial demonstrations. To improve comparability, reported performance metrics were converted into common descriptors wherever possible, including efficiency ranges, energy yield, lifecycle climate performance, and indicative cost bands. Priority was given to studies providing explicit boundary conditions, transparent assumptions, and operationally meaningful data [51], [52], [53].

A comparative feedstock framework was used to assess resource categories in terms of availability, energy usefulness, mobilization burden, and sustainability risk. Agricultural residues, forestry by-products, energy crops, algae, and municipal solid waste were evaluated not as interchangeable resources, but as regionally contingent options whose attractiveness depends on collection density, moisture level, competing uses, and environmental safeguards [52], [53], [54].

**Table 2.** Comparison of thermochemical and biochemical conversion pathways

Conversion Pathway	Key Process	Products	Efficiency (%)
Combustion	Direct oxidation	Heat, electricity	20–40
Gasification	Partial oxidation	Syngas, H <sub>2</sub> , CH <sub>4</sub>	40–55
Pyrolysis	Thermal decomposition	Bio-oil, char, gas	35–50
Anaerobic digestion	Microbial breakdown	Biogas (CH <sub>4</sub> , CO <sub>2</sub> )	30–45
Fermentation	Enzymatic conversion	Ethanol, butanol	25–40

For the process comparison, thermochemical and biochemical pathways were reviewed using conversion efficiency, product flexibility, feedstock tolerance, and deployment maturity as the primary analytical criteria. Thermochemical routes were additionally interpreted through heating-value behavior and process severity, whereas biochemical routes were examined through substrate quality, biodegradability, and conversion yield. Economic evidence was screened through reported CAPEX, OPEX, and levelized-cost indicators, while environmental evidence was interpreted through lifecycle greenhouse-gas accounting and resource-use implications [51], [52], [53], [54], [55], [56].

A complementary policy and case-study layer was incorporated to connect technical findings with real deployment conditions. Documents from international agencies and national policy frameworks were reviewed to identify the influence of renewable-energy mandates, fuel standards, feed-in tariffs, and carbon-pricing mechanisms. Case examples from Europe, Brazil, the United States, and Asia were used to highlight how regulatory continuity and feedstock geography shape commercial outcomes [56], [57], [58], [59].

The visual analyses presented in Figures 1-6 were reconstructed from the representative ranges discussed in the manuscript and summarized in Tables 1-3. Rather than duplicating the original chart forms, the revised figures were designed to emphasize positional trade-offs, performance envelopes, climate ranges, regional concentration, and value-chain integration. This allowed the same evidence base to be communicated through more discriminating graphical forms [60].

Finally, data triangulation was used throughout the review to reduce dependence on isolated values or unusually optimistic case studies. When the literature reported wide ranges, those ranges were preserved instead of collapsed into a single number, and outliers were interpreted in light of scale, feedstock quality, and methodological assumptions. The result is a review methodology intended to remain descriptive where evidence is fragmented and comparative where the evidence is sufficiently mature [61].

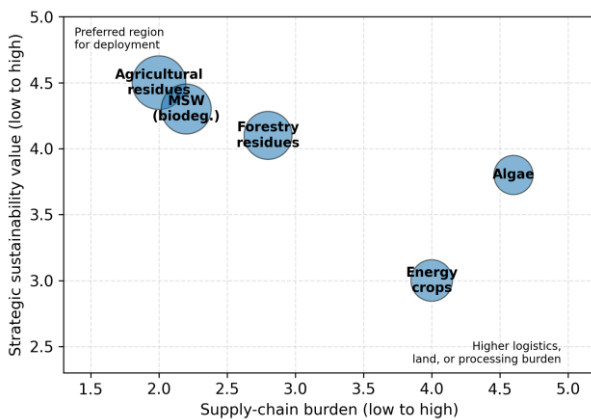
**Table 3.** Economic indicators of biomass energy systems

Technology	CAPEX (USD/kW)	OPEX (USD/MWh)
Combustion (CHP)	2,000–4,000	20–35
Gasification	3,500–6,000	25–40
Pyrolysis	4,000–7,000	30–50
Anaerobic digestion	1,500–3,500	15–30
Fermentation	2,000–5,000	20–35

**3. Results**

The reviewed literature shows that biomass cannot be treated as a single technology or a single resource; its performance depends on the combination of feedstock quality, conversion route, logistics, and end-use objective. The results therefore point to a portfolio logic in which residue streams, waste management systems, and regionally abundant resources shape the most credible deployment pathways.

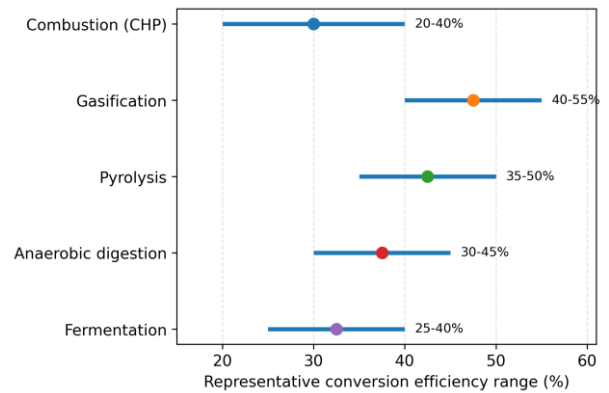
Feedstock availability remains the first differentiator. Agricultural residues appear particularly attractive because they combine high aggregate availability with relatively low land-use penalty, provided that sustainable removal rates are respected. Forestry residues also retain strong value where established collection systems already exist, while the biodegradable fraction of municipal solid waste offers an additional waste-management benefit. By contrast, dedicated energy crops and algae can be strategically important, but they generally involve higher mobilization burdens, stronger dependence on local conditions, or greater processing complexity. Figure 1 positions these feedstocks within a supply-chain-burden versus strategic-value matrix derived from the evidence summarized in Table 1 [62], [63], [64].



**Fig. 1.** Feedstock positioning matrix comparing strategic sustainability value and supply-chain burden for the principal biomass resource classes discussed in the review.

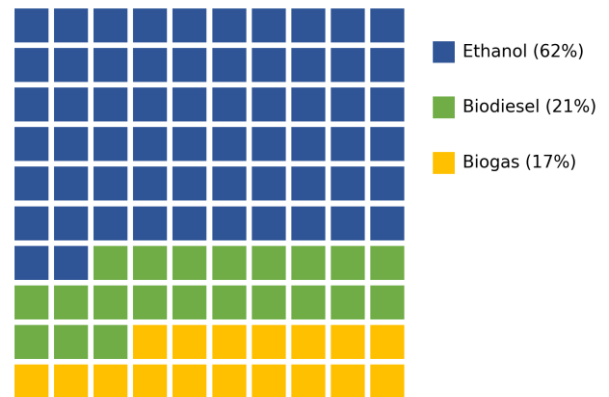
Process performance differs markedly across conversion routes. Combustion remains the most mature option for direct heat and combined heat-and-power applications, but gasification and pyrolysis provide broader product flexibility and can support syngas, hydrogen-rich intermediates, and liquid-fuel upgrading routes. Anaerobic digestion and fermentation remain highly relevant where wet biomass or sugar-rich substrates dominate. Figure 2 recasts the efficiency evidence as performance envelopes, showing that gasification occupies the highest representative efficiency band among the pathways compared, while combustion and fermentation retain lower but commercially proven operating windows [65], [66], [67].

*Energy Conversions*



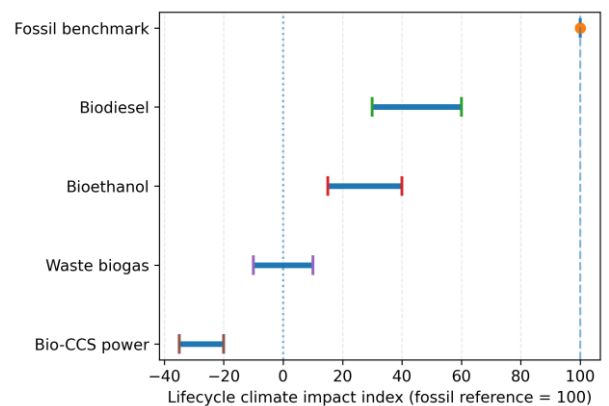
**Fig. 2.** Representative efficiency envelopes for major biomass conversion pathways, reconstructed from the ranges summarized in Table 2.

The product mix associated with biomass deployment is similarly uneven. Liquid biofuels continue to be dominated by ethanol, followed by biodiesel, while biogas occupies a smaller but strategically important share because it is closely linked to waste treatment, decentralized energy supply, and methane management. Figure 3 replaces the earlier pie representation with a waffle layout so that the relative dominance of ethanol can be read more directly and compared visually with the smaller contributions of biodiesel and biogas [66].



**Fig. 3.** Indicative composition of global biofuel output shown as a waffle chart to emphasize the relative dominance of ethanol over biodiesel and biogas.

Environmental performance is one of the strongest arguments for biomass, but the evidence is conditional rather than uniform. Bioethanol and biodiesel commonly outperform fossil gasoline and diesel on a lifecycle basis, while waste-derived biogas can approach carbon neutrality or become strongly favorable when avoided methane emissions are credited. The most aggressive climate benefit appears in biomass systems coupled with carbon capture, which can cross into net-negative territory. Figure 4 expresses these outcomes as normalized climate-performance ranges relative to a fossil benchmark, making clear that biomass pathways do not cluster around a single emissions value [67], [68].



**Fig. 4.** Normalized lifecycle climate-performance ranges of selected biomass pathways

Economic results reveal a similar pattern of differentiation. Mature systems such as combustion and anaerobic digestion show the most familiar cost structure, whereas gasification, pyrolysis, and integrated biorefinery schemes remain more capital intensive despite their superior product flexibility. That flexibility is still important because it allows one biomass stream to generate fuels, heat, electricity, chemicals, and captured carbon value within a single configuration. Figure 5 therefore reframes the biorefinery concept as a node-link architecture that makes the logic of multi-product valorization more explicit than a linear schematic [68].

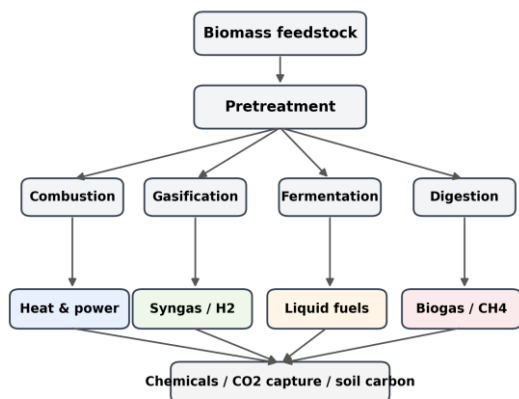


Fig. 5. Integrated biorefinery architecture showing how a common biomass platform can be diversified into heat, power, fuels, and carbon-management products.

Deployment is highly uneven across regions. Europe is strongly associated with biogas and decentralized biomass utilization, Brazil remains closely linked to ethanol, the United States shows stronger biodiesel and biomass-power activity, and China and India are accelerating in biomass power and waste-to-energy. Africa, by contrast, still relies more heavily on traditional biomass than on modern conversion infrastructure. Figure 6 converts this narrative into a regional heatmap, highlighting that biomass development is shaped as much by policy continuity and infrastructure as by resource availability alone [65], [66], [67], [68], [69].

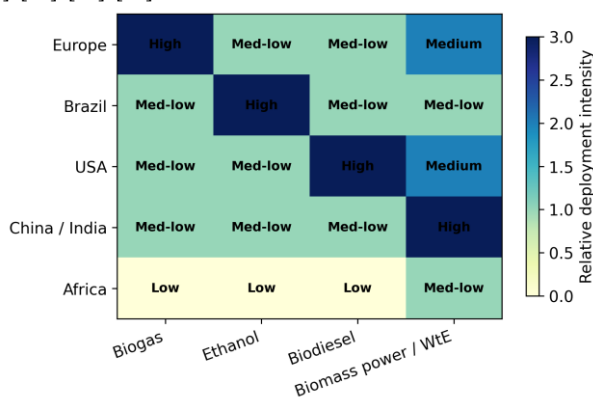


Fig. 6. Regional heatmap of modern biomass deployment intensity by technology family, based on the narrative synthesis presented in the results section.

Taken together, the results indicate that the strongest near-term role for biomass lies in residue- and waste-based systems, especially where conversion can be integrated with heat recovery, distributed energy, or carbon capture. Advanced routes remain important, but their long-term contribution depends on reducing capital intensity, improving feedstock logistics, and aligning deployment with robust sustainability governance.

#### 4. Discussion

The revised synthesis confirms that biomass occupies a distinctive

position in the energy transition: it is renewable, storable, dispatchable, and convertible into multiple products, yet its success depends more heavily on sourcing and system design than many other low-carbon options [70], [74]. Biomass should therefore be understood as a conditional solution rather than a universally beneficial one.

A consistent pattern across the evidence is that waste-derived and residue-based feedstocks offer the most credible route to sustainable deployment [71], [72]. Agricultural residues, forestry by-products, and the biodegradable fraction of municipal solid waste avoid much of the land competition associated with purpose-grown crops and can simultaneously address waste-management burdens. Their limitations are logistical rather than conceptual, which means that improvements in aggregation, densification, and regional supply planning can unlock substantial value.

Dedicated energy crops and algae remain relevant, but chiefly under more selective conditions [76], [80]. Energy crops may support stable fuel supply where land, water, and governance constraints are manageable, while algae retains long-term appeal because of its high areal productivity and non-arable cultivation potential. Even so, both routes require stronger evidence on cost, resource intensity, and large-scale operational reliability before they can be treated as mainstream rather than niche options.

The technology comparison also carries an important systems message [73], [85]. Mature pathways such as combustion and anaerobic digestion are not necessarily inferior simply because they occupy lower efficiency bands than gasification in certain studies. Their value lies in operational robustness, simpler integration, and existing commercial experience. By contrast, gasification, pyrolysis, and advanced upgrading routes offer broader product flexibility and potentially higher value creation, but they demand tighter process control, better feedstock conditioning, and larger capital commitments.

This is why the biorefinery concept deserves particular attention [74], [81]. Biomass economics improve when projects are not forced to depend on a single revenue stream. Heat, power, liquid fuels, gaseous fuels, chemicals, carbon products, and captured CO<sub>2</sub> can all contribute to value stacking, thereby improving resilience against feedstock-price volatility and commodity-market swings. The conceptual shift from single-output plants to integrated biomass platforms is therefore central to future competitiveness.

Even with that systems advantage, logistics remains one of the most stubborn barriers to scale [79], [83]. Biomass is geographically dispersed, seasonally variable, and often bulky relative to its energy content. Collection, drying, pre-treatment, storage losses, and transport distances can erode both economic and environmental performance. In practice, this means that a technically attractive pathway may still underperform if feedstock mobilization is poorly matched to plant scale or location.

Land-use governance is another decisive boundary condition [71], [76]. A biomass pathway that appears attractive at plant level may look far less favorable once indirect land-use change, biodiversity pressure, irrigation demand, or soil-carbon depletion is included. This reinforces the argument for a hierarchy in which residues and wastes are prioritized first, marginal-land strategies are evaluated cautiously, and food-crop displacement is treated as a major warning sign rather than a secondary concern.

Policy design can either stabilize or undermine the sector [78], [84]. Long-term renewable-fuel standards, feed-in tariffs, carbon pricing, landfill diversion rules, and certification schemes have all played decisive roles in the regions where biomass deployment accelerated. The opposite is also true: policy discontinuity increases investment risk and can quickly weaken project pipelines, even where the technical resource base is strong.

Regional differentiation should therefore be treated as an analytical requirement, not a contextual footnote [80], [82]. Europe, Brazil, the United States, and parts of Asia illustrate how different feedstocks and policy packages produce different biomass identities: biogas-centered, ethanol-centered, biodiesel-centered, or biomass-power-centered. A strategy that succeeds in one region cannot be transplanted mechanically into another without accounting for infrastructure, climate, market access, and competing resource demands.

Public legitimacy also matters [79], [83]. Biomass projects are often evaluated not only by lifecycle metrics but by perceptions of land conversion, forest use, air emissions, odor, traffic, and fairness in benefit distribution. Certification frameworks and transparent accounting are

therefore essential, particularly for projects that claim carbon neutrality or negative emissions. Without social and regulatory credibility, even technically sound projects may struggle to scale.

The present review also has limitations. Because the literature spans laboratory studies, pilot plants, commercial facilities, and policy assessments, not all reported metrics are strictly comparable. Some pathways are represented by mature operational data, while others rely more heavily on projected performance or selective demonstration cases. Preserving ranges instead of forcing artificial precision is therefore a methodological strength, but it also means that cross-pathway rankings should be interpreted cautiously [74].

Overall, the discussion points toward a clear strategic conclusion: biomass is most persuasive when it is waste-led, regionally grounded, and integrated into systems that reward co-products, heat recovery, and carbon management [70], [81]. Under those conditions, it can make a durable contribution to decarbonization; outside them, its performance can deteriorate quickly.

Biomass should also be interpreted within the wider low-carbon systems literature, where flexibility, storage, water-energy coupling, process control, heat recovery, ventilation, hydrogen carriers, microbial conversion, and sustainable fuels are increasingly treated as interacting design questions rather than isolated topics. Built-environment airflow and facade studies likewise reinforce the importance of systems integration when positioning biomass within future energy portfolios [75], [77].

## 5. Conclusion

This review reassessed biomass energy through the combined lenses of feedstock quality, conversion performance, environmental impact, and deployment practicality [62], [65], [69]. The evidence shows that biomass remains one of the most versatile renewable resources because it can supply heat, electricity, gaseous fuels, liquid fuels, and negative-emission potential within a single broad technology family.

Not all biomass resources are equally attractive. Agricultural residues, forestry by-products, and biodegradable waste streams emerge as the strongest near-term options because they can be mobilized with lower land-use conflict and stronger waste-valorization benefits [62], [63]. Energy crops and algae retain longer-term relevance, but their role is more conditional and region specific [64].

Among conversion pathways, combustion and anaerobic digestion remain the most established, while gasification, pyrolysis, and integrated biorefinery schemes offer broader product flexibility and future strategic value [65], [66], [68]. The choice of technology should therefore be guided by feedstock form, product target, logistics radius, and the ability to recover value from heat, co-products, or captured carbon.

Environmental performance is favorable in many biomass applications, but only when lifecycle boundaries are defined rigorously [67]. Residue- and waste-based systems often provide the strongest climate case, and coupling biomass with carbon capture can extend that benefit into net-negative territory [69]. However, unsustainable cultivation and poorly designed supply chains can erode or even negate those gains [68].

Economic competitiveness likewise depends on system context. Biomass performs best where policy support is stable, feedstocks are locally available, and projects are configured to capture multiple value streams rather than one commodity alone [70], [78], [84]. This makes integration, regional planning, and governance as important as process efficiency.

In summary, biomass is neither a universal remedy nor a marginal option. It is a high-potential but highly contingent component of low-carbon energy systems, and its long-term success will depend on prioritizing sustainable feedstocks, improving logistics, advancing integrated biorefineries, and embedding deployment within credible policy and carbon-accounting frameworks [71], [81].

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