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Review

Fractionation-Based Valorization and Circular Biorefining of Biomass and Biowaste: Component Separation, Conversion Processes, and Criteria for Systems Assessment

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Abstract

Biomass and biowaste are heterogeneous renewable carbon resources whose moisture content, structural recalcitrance, ash, contaminants, and supply conditions constrain conversion pathways. This framework-oriented, semi-systematic narrative review searched the Web of Science Core Collection and Scopus from 1 June to 30 June 2026 using 98 targeted search combinations and supplementary reference screening. The evidence base comprised primary studies, reviews, process simulations, techno-economic analyses, life cycle assessments, and pilot-, demonstration-, and commercial-scale reports. Because feedstocks, operating conditions, functional units, and system boundaries differed substantially, the evidence was synthesized qualitatively and selected quantitative results were retained as context-specific examples rather than pooled performance ranges. The review organizes established assessment dimensions into a six-module conceptual pathway-screening framework comprising feedstock characterization, selective separation, process integration, product portfolios, systems assessment, and engineering implementation. The synthesis shows that separation severity should be determined by downstream stream-quality requirements rather than maximum component recovery or purity. Process integration and multiproduct utilization can improve carbon and energy use but may increase purification, wastewater-treatment, and quality-control burdens. Recycling benefits depend on impurity accumulation, recovery demand, market capacity, and product qualification. Illustrative applications to air-dried cereal straw and dewatered municipal sewage sludge show that dry lignocellulosic and wet contaminant-bearing feedstocks require different separation, conversion, product, and recycling strategies. The principal contribution is the sequential linkage of established assessment dimensions through stream-quality requirements, incremental system consequences, and complete-chain engineering constraints. The framework supports conditional pathway screening but does not replace feedstock-specific TEA, LCA, or continuous engineering validation.

Keywords: biomass; biowaste; fractionation-based valorization; circular biorefining; techno-economic analysis; life cycle assessment

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Academic Editor: Amit K. Jaiswal

Received: 24 July 2026
Revised: 21 August 2026
Accepted: 26 August 2026
Published: 3 September 2026

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1. Introduction

Biomass and biowaste are important renewable carbon resources. They include agricultural and forestry residues, energy crops, livestock manure, industrial biobased by-products, and municipal organic solid waste. These resources contain cellulose, hemicellulose, lignin, proteins, lipids, and recoverable elements, including nitrogen and phosphorus. They can therefore be used to produce fuels, chemicals, and functional materials while enabling the recovery of energy and nutrients [1–5]. Nevertheless, some biowastes continue to be managed by open burning, landfilling, or inefficient combustion, resulting in material and energy losses as well as increased greenhouse gas emissions and environmental pollution [6]. Biomass is also characterized by compositional heterogeneity, substantial variation in moisture content, structural recalcitrance, geographically dispersed supply, and pronounced seasonality. Treating biomass solely as a waste-management burden or a low-value energy feedstock therefore fails to fully utilize the value of its constituent components and structural attributes [7,8].

Existing reviews have examined feedstock characterization, pretreatment and conversion technologies, specific feedstocks and products, and systems-level dimensions including TEA, LCA, TRL, feedstock logistics, and market conditions [9–13]. These studies have established the relevance of these dimensions to the technical, economic, environmental, and engineering assessment of biorefineries. However, they have not consistently organized them into an explicit pathway-screening sequence linking feedstock properties and front-end separation to stream quality, downstream conversion compatibility, product portfolios, residual-stream management, and engineering implementation [11–13]. This gap is relevant for heterogeneous and compositionally variable feedstocks because conversion rates and selectivities obtained with model substrates or in batch experiments may not be maintained under high-solids feeding, impurity accumulation, continuous operation, and downstream product-separation conditions. Comparisons among TEA and LCA studies are also constrained by differences in functional units, system boundaries, energy mixes, and coproduct treatment methods [12], while technology maturity, logistics, product standards, and market capacity further affect the feasibility of complete process pathways [13].

In this review, fractionation-based valorization refers to the selective separation and targeted utilization of components or process streams according to feedstock composition, structural characteristics, impurity load, and intended use [14–16]. Stream quality encompasses not only purity but also component concentration, structural integrity, moisture state, reactivity, and the levels of inhibitors, ash, salts, and contaminants. Circular biorefining refers to the recovery and utilization of carbon, energy, water, solvents, and nutrients through integrated component separation and conversion while controlling the transfer and accumulation of salts, ash, heavy metals, inhibitors, and other contaminants [17–19]. Circularity is therefore not equivalent to maximizing recycling rates or achieving completely closed-loop operation. Similarly, process-level carbon recovery is not equivalent to life cycle greenhouse gas mitigation.

Accordingly, pathway design is treated as a sequence of linked decisions within six modules: feedstock characterization, selective separation, process integration, product portfolios, systems assessment, and engineering implementation. First, feedstock-processing boundaries are defined according to moisture content, biodegradability, lignocellulosic structure, ash content, contaminant load, and supply conditions. The need for separation and its appropriate severity are then determined according to downstream requirements for component concentration, structural integrity, and impurity levels. The resulting streams are subsequently matched with biochemical, thermochemical, catalytic, or materials-oriented processes according to their composition, moisture state, and tolerance

to impurities. Marketable products, internal energy recovery, and residual-stream utilization are then configured accordingly. Finally, the engineering applicability of the complete pathway is evaluated on the basis of TEA, LCA, TRL, supply-chain conditions, and product qualification and market access [20–22].

On this basis, three principles are proposed for pathway assessment. First, separation severity should be determined by downstream stream-quality requirements rather than by maximizing the removal, recovery, or purity of any individual component. Second, additional conversion, product, and recycling units should be introduced only when their incremental benefits offset the associated increases in capital expenditure, operating costs, separation and purification burdens, and quality-control requirements. Third, the extent of material recycling should be jointly constrained by impurity accumulation, net environmental performance, and product qualification and market access. These principles extend performance assessment beyond individual unit operations to the screening of complete biorefinery systems.

This review adopts a framework-oriented, semi-systematic narrative-review approach. Relevant publications were identified through searches of the Web of Science Core Collection and Scopus and through reference-list screening, and literature screening and evidence extraction were conducted by multiple authors and subsequently reviewed. Representative quantitative results were retained when the feedstock, operating conditions, measurement basis, and relevant system boundary could be identified and were used to illustrate context-specific process performance and trade-offs; otherwise, the applicable conditions, evidence scale, principal influencing factors, and engineering limitations were synthesized qualitatively. Results based on inconsistent functional units, system boundaries, feedstock definitions, product specifications, or coproduct treatment methods were not subjected to direct quantitative ranking. The interpretation of evidence is consequently conditioned by differences in study objectives, feedstock definitions, experimental scales, functional units, system boundaries, and reporting practices. Evidence from laboratory batch studies was distinguished from evidence obtained using actual feedstocks under continuous pilot-, demonstration-, or commercial-scale operations. The qualitative compatibility categories and maturity descriptors used in the pathway-screening synthesis were assigned by Q.L. and reviewed by W.Z. against the studies recorded in Supplementary Table S2; no numerical scoring or formal evidence weighting was applied. Claim-to-source mapping is provided through the references associated with individual table entries and Supplementary Table S2, which records the publication type, feedstock or intermediate stream, principal process or pathway, experimental or assessment scale, operating mode, principal evidence contributed, corresponding analytical-module assignment, and relevant section(s) of the main text. The complete search strategy, study-selection process, eligibility criteria, data-extraction fields, and evidence-synthesis methods are provided in the Supplementary Materials.

The main aim of this review is to synthesize how feedstock properties, front-end separation, stream quality, conversion compatibility, product portfolios, residual-stream management, and engineering conditions jointly constrain fractionation-based and circular biorefinery pathways. The review is broad at the pathway level but focuses on the interfaces among these elements rather than providing exhaustive coverage of individual reaction mechanisms, catalysts, microorganisms, reactor designs, products, or regional policies. Its contribution beyond existing reviews lies in organizing established assessment dimensions into a sequential pathway-screening framework, using stream quality to connect separation severity with downstream requirements, evaluating additional conversion and recycling units relative to an explicit baseline, and defining engineering implementation for the complete integrated chain rather than the core reactor alone. Sections 2–5 and 6.1–6.4, synthesize the relevant evidence, Sections 6.5 and 6.6 present and illustrate the framework,

respectively, Section 7 summarizes the conclusions, and Section 8 discusses limitations and research priorities. The framework supports conditional pathway screening rather than replacing feedstock-specific TEA, LCA, or engineering design, and the relationships among its six modules are summarized in Figure 1.

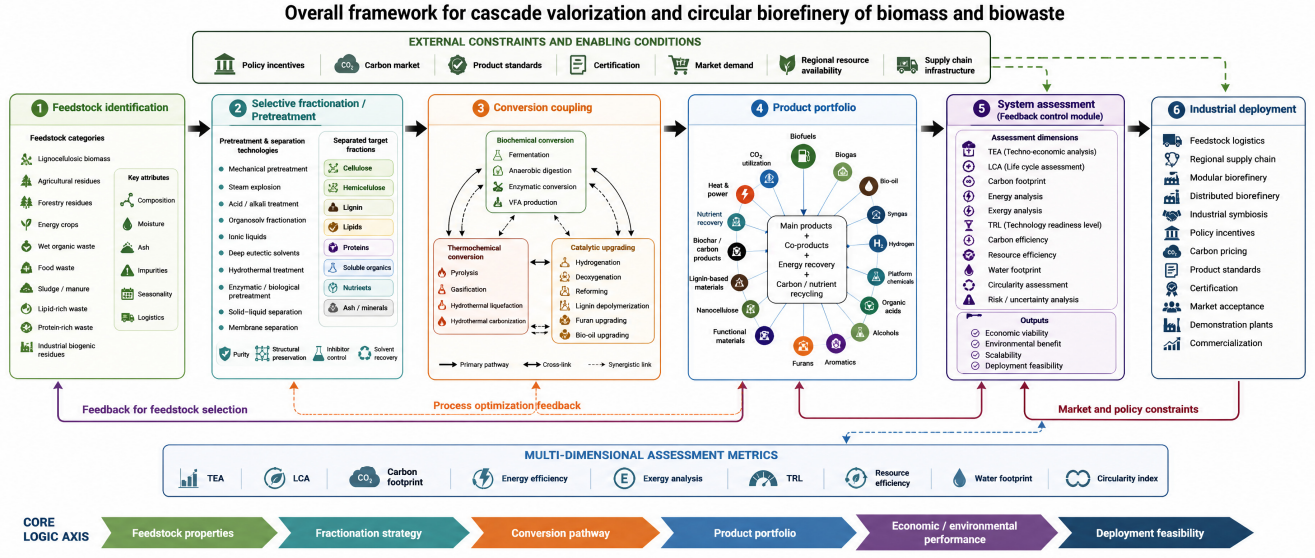


Figure 1. Six-module conceptual framework for the fractionation-based valorization and circular biorefining of biomass and biowaste. The framework links feedstock characterization, selective separation, process integration, product portfolios, systems assessment, and engineering implementation through material and energy allocation and assessment feedback. Circularity is represented by separate indicators rather than a composite index. The figure is a conceptual synthesis of the reviewed literature and does not represent a complete process-flow, mass-balance, energy-balance, or stoichiometric model.

2. Feedstock Characteristics and Their Implications for Biorefinery Pathways

The composition, moisture content, structural recalcitrance, ash content, contaminant load, and supply conditions of biomass and biowaste jointly determine the requirements for front-end processing and conversion. Classification by source is useful for identifying general characteristics; however, feedstocks within the same category may differ substantially because of variations in cultivar, geographic origin, harvesting practices, storage conditions, and upstream processing [23]. Pathway selection should therefore be based on measured feedstock properties rather than solely on feedstock category or source name.

2.1. Composition and Utilization Constraints of Biomass and Biowaste

Agricultural and forestry residues consist primarily of cellulose, hemicellulose, and lignin and can be used for component fractionation, saccharification, materials production, and thermochemical conversion. Their moisture content and structural characteristics vary with feedstock type and storage conditions. Air-dried straw and wood-processing residues are generally easier to store than fresh bagasse and some freshly harvested residues, which have higher moisture contents. These feedstocks are also characterized by low bulk density, pronounced seasonality, and geographically dispersed availability. The quantities that can be practically recovered are constrained by collection radius, storage losses, and competing uses [24–26].

Municipal organic solid waste, food waste, livestock manure, and municipal sludge generally contain substantial amounts of water, readily degradable organic matter, lipids, proteins, nitrogen, and phosphorus. Their principal advantages include relatively high

biodegradability and, for some sources, geographically concentrated generation. However, compositional variability, susceptibility to rapid degradation during storage, high salinity, and extraneous impurities complicate collection and treatment. Plastics and grit may interfere with sorting and equipment operation, whereas heavy metals, pathogens, and antibiotic residues may affect product safety and migrate into or become enriched in solid residues and nutrient products [27–29].

The properties of energy crops and industrial biobased by-products depend on their tissue composition and upstream production processes, respectively. Feedstocks such as sweet sorghum can yield sugar-rich juice and a lignocellulosic residue, whereas miscanthus and switchgrass more closely resemble agricultural and forestry residues [30]. Black liquor, industrial lignin, crude glycerol, distillers' residues, and molasses are generated at relatively concentrated locations but may contain salts, alkalis, methanol, fatty acid soaps, and other impurities. These constituents may cause corrosion, inhibit microbial activity, or deactivate catalysts [31]. The upstream production process and impurity composition of these feedstocks should therefore be characterized before targeted conversion.

Table 1 summarizes the typical composition, resource advantages, utilization constraints, and potential utilization pathways of the principal feedstock categories. The properties presented in the table are intended for preliminary pathway screening. Engineering design should be based on feedstock-specific measurements and adjusted according to the moisture content, ash content, contaminant levels, and supply conditions of the relevant feedstock batches.

Table 1. Compositional characteristics, utilization constraints, and potential utilization pathways of major biomass and biowaste feedstocks.

Feedstock Category	Representative Sources	Major Recoverable Components	Moisture Characteristics	Resource Advantages	Principal Constraints	Potential Utilization Pathways	References
Agricultural residues	Straw, corn cobs, and bagasse	Cellulose, hemicellulose, and lignin	Varies with feedstock type and storage conditions; air-dried straw generally has a relatively low moisture content, whereas fresh bagasse has a relatively high moisture content	Abundant and widely available; can provide multiple organic carbon streams	Low bulk density, pronounced seasonality, and high logistics and storage costs	Component fractionation, sugar-platform production, materials production, pyrolysis, and gasification	[4,5,7,9,24,26,32]
Forestry residues	Logging residues, including branches, and wood-processing chips and fines	Cellulose, hemicellulose, and lignin	Low to moderate, depending on storage and drying conditions	Do not directly compete with food production; relatively high lignin content	Geographically dispersed, structurally dense, and resistant to degradation	Saccharification, lignin separation, aromatic-chemical production, pyrolysis, and gasification	[4,5,7,25,32]
Municipal organic waste	Kitchen waste, catering waste, and fruit and vegetable waste	Readily degradable organic matter, lipids, and proteins	High, generally above 60%	Relatively concentrated generation, high biodegradability, and substantial nutrient content	Susceptibility to rapid degradation, high heterogeneity, and the presence of extraneous impurities and salts	AD, VFA fermentation, HTL, and HTC	[4,5,9,27–29]

Table 1. *Cont.*

Feedstock Category	Representative Sources	Major Recoverable Components	Moisture Characteristics	Resource Advantages	Principal Constraints	Potential Utilization Pathways	References
Sludge and livestock manure	Municipal sludge, livestock manure, solid digestate, and liquid digestate	Organic matter, proteins, nitrogen, phosphorus, and ash	High, generally above 70%	Generated in large quantities; suitable for wet processing and nutrient recovery	Ammoniacal nitrogen, pathogens, heavy metals, and antibiotic residues	AD, hydrothermal conversion, and nitrogen and phosphorus recovery	[4,5,27–29]
Energy crops	Sweet sorghum, miscanthus, and switchgrass	Fermentable sugars and lignocellulose	Varies with tissue type and harvesting conditions	High biomass productivity; some species can be cultivated on marginal land	Land and agricultural inputs, collection and storage costs, and seasonality	Fermentation of sugar-rich liquids, saccharification of lignocellulosic residues, materials production, and energy recovery	[4,5,30]
Industrial biobased by-products	Black liquor, industrial lignin, crude glycerol, distillers' residues, and molasses	Lignin, glycerol, soluble sugars, and organic acids	Liquid or process-dependent	Concentrated generation; some streams have relatively high organic carbon concentrations	High salinity, corrosivity, impurity enrichment, and composition that depends on upstream processing	Fermentation after preliminary purification, catalytic upgrading, resin production, and carbon-material production	[4,5,9,29,33]

Note: The moisture characteristics presented in the table represent typical conditions. The moisture percentages are expressed on a wet basis and are intended only for feedstock classification and preliminary pathway screening. Actual moisture content depends on harvesting, storage, dewatering, and regional climatic conditions. AD, anaerobic digestion; VFA, volatile fatty acids; HTL, hydrothermal liquefaction; HTC, hydrothermal carbonization.

2.2. Major Components and Their Conversion Characteristics

The crystalline structure of cellulose and its intermolecular hydrogen-bonding network limit its accessibility to enzymes and catalysts. Lignin coverage and cell-wall architecture further increase structural recalcitrance [34]. For saccharification, front-end processing should increase cellulose accessibility. By contrast, when cellulose is intended for the production of nanocellulose, membranes, or composite materials, its degree of polymerization, crystalline structure, and fiber morphology should be preserved [35]. The same cellulose fraction therefore has different quality requirements in biochemical and materials-oriented pathways.

Hemicellulose is relatively susceptible to hydrolysis into oligosaccharides, xylose, and arabinose. However, excessive treatment can generate furfural, 5-hydroxymethylfurfural, and organic acids [36]. When oligosaccharides are the target products, excessive hydrolysis should be avoided. When fermentation is the intended pathway, monosaccharide release must be balanced against substrate concentration and inhibitor levels. Hemicellulose streams should therefore not be evaluated solely on the basis of solubilization yield.

The structure and reactivity of lignin depend on both feedstock origin and separation history. Acidic, high-temperature, or oxidative conditions may induce lignin condensation, thereby reducing the abundance of cleavable aryl ether bonds and impairing subsequent catalytic depolymerization [31,37]. Lignin with a low degree of condensation is more suitable for producing aromatic chemicals and polymer precursors. By contrast, highly condensed lignin or lignin containing substantial impurities is generally more suitable for carbon-material production or energy recovery [38].

Lipids, proteins, and readily degradable organic matter can be utilized through biochemical, catalytic, or energy-conversion processes; however, associated compounds may limit process stability. Free fatty acids and long-chain fatty acids may interfere with transesterification and inhibit AD, whereas saponification may reduce transesterification performance. Ammonia released during protein degradation may inhibit biochemical processes and increase the denitrogenation burden associated with thermochemically derived liquid products [28,32].

Ash and inorganic salts do not directly contribute organic carbon but can substantially affect reactor operation and product quality. Elements such as K, Na, Cl, Si, and Ca may cause slagging, corrosion, bed agglomeration, or catalyst deactivation [39,40]. Salts, heavy metals, pathogens, and antibiotic residues may also restrict the use of digestate, char-based materials, and nutrient products [41–43]. Feedstock characterization should therefore encompass organic components, inorganic elements, and contaminants relevant to process operation and product safety.

2.3. Feedstock Variability and Preliminary Pathway Screening

Moisture content, biodegradability, structural recalcitrance, ash content, and contaminant load are the principal parameters for preliminary pathway screening. Organic wastes with high moisture contents and high biodegradability are relatively well suited to AD or volatile fatty acid (VFA) fermentation. Sludge, some algal biomass, and digestate containing substantial recalcitrant fractions may be suitable for hydrothermal liquefaction (HTL) or hydrothermal carbonization (HTC) [27–29]. Lignocellulosic feedstocks with relatively low moisture contents can be directed to component fractionation, materials production, saccharification and fermentation, or thermochemical conversion, depending on the target product [32,44].

The qualitative feedstock categories used for preliminary screening should be translated into measurable descriptors before pathway selection. Moisture and ash contents should be reported as mass fractions with the wet- or dry-basis definition stated explicitly. Biodegradability can be characterized using biochemical methane potential, volatile-solids destruction, chemical-oxygen-demand removal, or substrate-specific hydrolysis and fermentation yields under defined conditions. Lignocellulosic structure can be described using dry-basis cellulose, hemicellulose, and lignin contents together with indicators relevant to the intended process, such as crystallinity, enzymatic digestibility, degree of polymerization, or the abundance of cleavable lignin bonds. Salinity and contamination should be reported using electrical conductivity or total dissolved solids, concentrations of relevant ions and metals in milligrams per liter or milligrams per kilogram, and feedstock-specific pathogen or organic-contaminant measurements. Supply conditions should include the recoverable quantity, seasonal variation, storage loss, collection radius, and transport distance. Accordingly, terms such as “high moisture content” or “high ash content” indicate preliminary screening categories rather than universal numerical thresholds. Their practical significance depends on the feed envelope of the receiving unit, mechanical dewatering performance, waste-heat availability, ash composition, product specifications, and regional operating conditions.

Feedstocks with high salinity or extraneous contaminants generally require sorting, solid–liquid separation, or desalination to reduce corrosion, microbial inhibition, and product-safety risks [32,41,44]. For high-ash feedstocks, water washing, ash separation, or feedstock blending may also be required, depending on the concentrations and mineral phases of K, Na, Cl, Si, and other relevant elements. These measures can mitigate slagging, bed agglomeration, and catalyst deactivation [39,40].

Co-processing can improve the composition and processing characteristics of some feedstocks. For example, co-digestion can adjust the carbon-to-nitrogen ratio and micronutrient supply, whereas biochar or hydrochar may provide surfaces for microbial attachment and facilitate electron transfer [29]. However, co-processing also alters the input, distribution, and potential accumulation of salts, metals, and other contaminants. Its performance should therefore not be evaluated solely on the basis of gas yield or conversion rate.

Feedstock composition also varies among batches, seasons, and storage periods. Near-infrared spectroscopy, Raman spectroscopy, thermogravimetric analysis, and online sensors can be used to estimate moisture, cellulose, hemicellulose, lignin, and ash contents and to support feedstock blending, feed adjustment, and process control [28,41,45]. The reliability of these analytical models depends on the extent to which their training datasets represent the actual feedstocks and operating conditions. These models should therefore be validated using independent samples and data obtained under continuous operating conditions. Figure 2 and Table 2 provide a preliminary framework for pathway screening based on feedstock properties. Final pathway selection should also consider plant scale, waste-heat availability, product requirements, and the results of TEA and LCA.

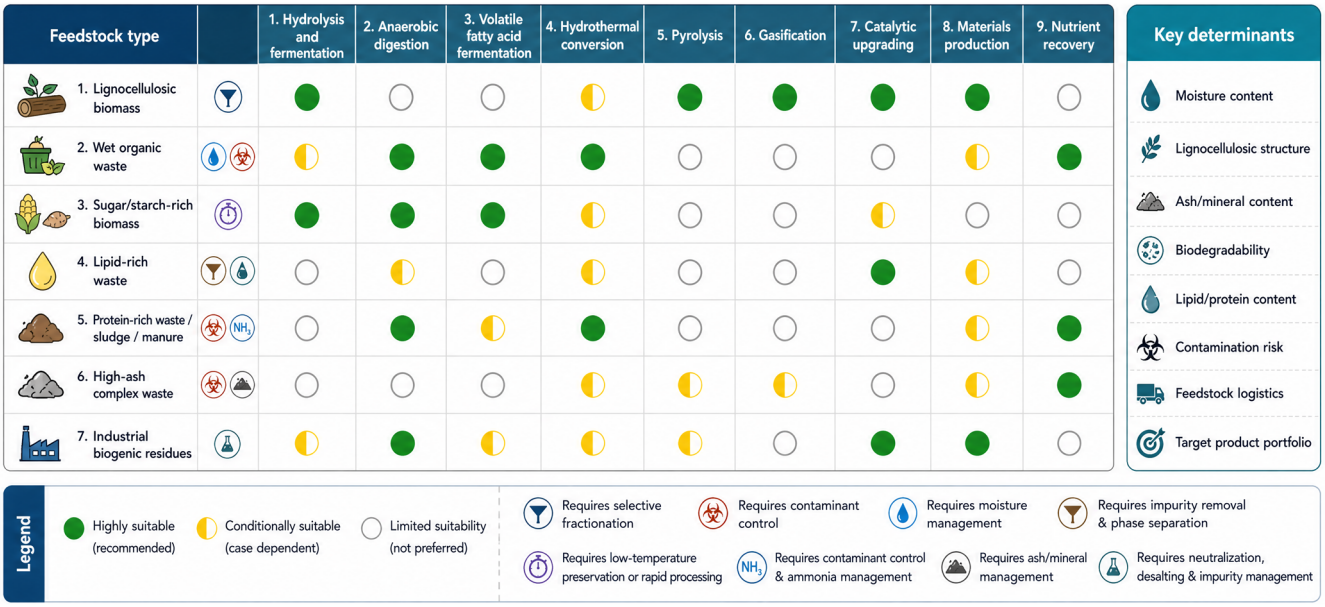


Figure 2. Qualitative relationships between feedstock properties and preliminary biorefinery-pathway selection. The categories "highly suitable", "conditionally suitable", and "limited suitability" represent the authors' literature-based synthesis of relative feedstock–process compatibility rather than numerical ratings or exclusive pathway assignments.

Table 2. Matrix for preliminary selection of biorefinery pathways based on feedstock properties.

Key Feedstock Properties	Representative Feedstocks	Priorities for Front-End Processing	Relatively Suitable Conversion Pathways	Major Product Categories	Principal Constraints	References
Low moisture content, structural recalcitrance, and high lignocellulose content	Straw, wood chips, and logging residues	Size reduction, increased polysaccharide accessibility, and control of lignin condensation	Saccharification and fermentation, lignin depolymerization, materials production, pyrolysis, and gasification	Sugar-derived products, aromatic chemicals, fibrous materials, biochar, and energy products	Pretreatment energy demand, inhibitor formation, enzyme costs, and solvent recovery	[16,32,35–38,44,45]

Table 2. *Cont.*

Key Feedstock Properties	Representative Feedstocks	Priorities for Front-End Processing	Relatively Suitable Conversion Pathways	Major Product Categories	Principal Constraints	References
High moisture content and high biodegradability	Kitchen waste, fruit and vegetable waste, and some food-processing wastewaters	Sorting, homogenization, solid–liquid separation, and adjustment of the carbon-to-nitrogen ratio	AD, VFA fermentation, and co-digestion	Biogas, organic acids, and nutrient products	Rapid acidification, compositional variability, inhibition by ammonia or salts, and treatment of liquid streams	[19,27–29]
High moisture content with substantial recalcitrant fractions	Sludge, some algal biomass, and digestate	Dewatering, homogenization, and, where necessary, desalination and contaminant control	HTL and HTC, potentially integrated with AD	Biocrude, hydrochar, biogas, and nutrient products	High-pressure feeding, aqueous-stream treatment, and enrichment of heteroatoms and contaminants	[27–29]
High free-sugar or starch content	Sweet sorghum juice, molasses, and starch-rich wastes	Mild extraction, solid–liquid separation, and controlled storage	Fermentation, VFA fermentation, and AD	Ethanol, lactic acid, other organic acids, and biogas	Susceptibility to degradation during storage, substrate or product inhibition, and product-separation requirements	[29,30,36]
High lipid content	Waste cooking oil, lipid-rich food waste, and oil-processing by-products	Impurity removal, dewatering, and mitigation of interference from salts and free fatty acids	Transesterification, hydrodeoxygenation, HTL, or controlled co-digestion	Biodiesel, hydrocarbon fuels, biogas, and coproduct glycerol	Saponification, inhibition by long-chain fatty acids, hydrogen consumption, and catalyst deactivation	[4,5,10,12,29]
High protein, nitrogen, phosphorus, and ash contents	Sludge, livestock manure, and some food wastes	Solid–liquid separation, ammonia control, and control of pathogens and heavy metals	AD, HTC, HTL, and nutrient recovery	Biogas, hydrochar, and nitrogen and phosphorus products	Ammonia inhibition, contaminant partitioning, and product qualification and market access	[27–29,39–42]
High salinity, high ash content, or high contamination risk	Saline organic by-products, some sludges, and mixed organic wastes	Sorting, water washing and desalination, ash separation, or stabilization	Thermochemical or hydrothermal conversion after pretreatment, and mineral recovery	Energy products, hydrochar, and mineral products	Wastewater-treatment burden, corrosion, slagging, and residual-stream management	[14,33,39–42,44]
Concentrated sources with compositions that depend on upstream processing	Black liquor, industrial lignin, crude glycerol, distillers' residues, and molasses	Compositional analysis, neutralization, desalination, membrane separation, or controlled depolymerization	Catalytic upgrading, fermentation, materials production, and energy recovery	Platform chemicals, aromatic products, resin precursors, and carbon materials	Preliminary purification, product-purification costs, compositional variability, and waste-liquid treatment	[4,5,9,31,33]

Note: The pathways listed represent relative priorities based on feedstock properties and are not the only possible process options. Specific configurations should be adjusted according to regional resource availability, the energy mix, product markets, contaminant-control requirements, and the results of TEA and LCA. AD, anaerobic digestion; VFA, volatile fatty acids; HTL, hydrothermal liquefaction; HTC, hydrothermal carbonization; TEA, techno-economic analysis; LCA, life cycle assessment.

3. Component Separation for Fractionation-Based Valorization

Front-end separation can alter component distributions, molecular structures, moisture states, and impurity loads, thereby affecting subsequent biochemical, thermochemical, catalytic, and materials-oriented processes. Its performance should not be evaluated solely in terms of delignification, sugar release, or solid recovery. Component concentrations, structural preservation, inhibitor formation, impurity partitioning, residual solvents, and downstream conversion performance should also be considered.

3.1. Separation Objectives and Stream Quality

Steam explosion and hydrothermal treatment can disrupt cell-wall structures and promote hemicellulose solubilization, thereby increasing cellulose accessibility [46,47]. For isothermal steam-based treatment, thermal severity is commonly expressed as

$$\log R_0 = \log_{10}\left[t \exp\left(\frac{T-100}{14.75}\right)\right]$$

where t is the residence time in minutes and T is the treatment temperature in degrees Celsius. This parameter facilitates comparison of the combined effects of temperature and residence time but does not account for feedstock composition, particle size, catalyst concentration, liquid-to-solid ratio, or mass-transfer limitations. Acid-catalyzed systems additionally require consideration of pH or acid loading, and severity values calculated using different definitions should not be compared directly.

Acid, alkaline, and solvent-based fractionation can generate streams with distinct compositions and properties through hemicellulose hydrolysis, delignification, or disruption of lignin–carbohydrate complexes [48–51]. However, increasing treatment severity may cause sugar degradation, pseudo-lignin formation, and lignin condensation. Sugar degradation generates furans and organic acids, thereby increasing the detoxification burden associated with subsequent fermentation [46,47]. Lignin condensation reduces the abundance of cleavable bonds and impairs subsequent selective depolymerization [48,52]. Salts generated during acid–base neutralization and the associated liquid waste streams may also enter downstream aqueous streams, increasing the burdens associated with separation and water treatment.

Fractionation emphasizes the partitioning of individual components among process streams and the suitability of the resulting streams for subsequent utilization. Lignin-first fractionation combined with in situ stabilization can limit the condensation of reactive lignin fragments and increase the subsequent yield of aromatic monomers [52,53]. Mild acid, hydrothermal, or solvent-based treatments can regulate hemicellulose solubilization, cellulose enrichment, and lignin recovery [49–51]. The suitability of the resulting streams depends on downstream conversion processes and product requirements and cannot be determined solely by the recovery of an individual component.

Fermentation substrates generally require high fermentable-sugar concentrations and low levels of inhibitors, salts, and residual solvents. Oligosaccharide production requires control of hydrolysis severity to avoid excessive conversion to monosaccharides and degradation products. Lignin depolymerization and polymer production are sensitive to the degree of condensation, molecular-weight distribution, and functional-group composition of the lignin stream. Fiber-based material production places greater emphasis on preserving the degree of polymerization and fiber morphology. Solids intended for pyrolysis or gasification are less dependent on the preservation of molecular structure but require control of moisture content, ash content, and key inorganic elements. Separation severity should therefore be limited to that required to meet target-stream quality specifications rather than increased to maximize component removal, recovery, or purity.

For engineering assessment, stream quality should be expressed using measurable, use-specific descriptors, including component concentration in grams per liter or mass fraction, component recovery, moisture and ash contents, particle or fiber characteristics, molecular-weight distribution, degree of polymerization, abundance of target functional groups or cleavable bonds, inhibitor and residual-solvent concentrations, ionic strength or salinity, and concentrations of regulated contaminants.

3.2. Principal Separation Technologies and Their Applicable Conditions

Mechanical processing can reduce particle size and improve mixing and mass transfer. It generally requires no chemical reagents or only small quantities of them, but provides limited selectivity among components. High-intensity mechanical processing also increases electricity consumption, dust generation, and equipment wear. Steam explosion and liquid hot-water treatment can promote hemicellulose solubilization and structural disruption; however, severe conditions increase sugar degradation, pseudo-lignin formation, and lignin condensation [46,47].

Acid treatment is used primarily for hemicellulose hydrolysis. Its principal limitations include equipment corrosion, the formation of furan inhibitors, salt generation during neutralization, and the treatment of acidic waste streams. Alkaline and oxidative treatments can promote delignification but increase the burdens associated with alkali recovery, black-liquor utilization, and wastewater treatment [48,49]. The system-level performance of these methods depends not only on component release but also on chemical recovery and the subsequent utilization or treatment of the resulting liquid streams.

Organosolv fractionation can produce cellulose-rich solids and relatively reactive lignin and is therefore suitable for some feedstocks with high lignin contents. However, operation at elevated temperature and pressure, solvent flammability, and solvent-recovery requirements increase engineering complexity [49,50,54]. Ionic liquids have a high capacity to dissolve lignocellulosic components and disrupt hydrogen-bonding networks, but their application is constrained by cost, high viscosity, antisolvent requirements, and limited biocompatibility [55].

The acidity, polarity, and viscosity of deep eutectic solvents (DESs) can be adjusted by varying their composition. Under specific conditions, DESs can selectively separate lignin or hemicellulose [55,56]. Some DES systems can limit lignin condensation or improve subsequent enzymatic hydrolysis [53,56,57]. Nevertheless, high viscosity, large liquid-to-solid ratios, solvent-recovery requirements, and limited stability over repeated cycles remain important barriers to scale-up. Moreover, low vapor pressure does not necessarily correspond to a low life cycle environmental burden.

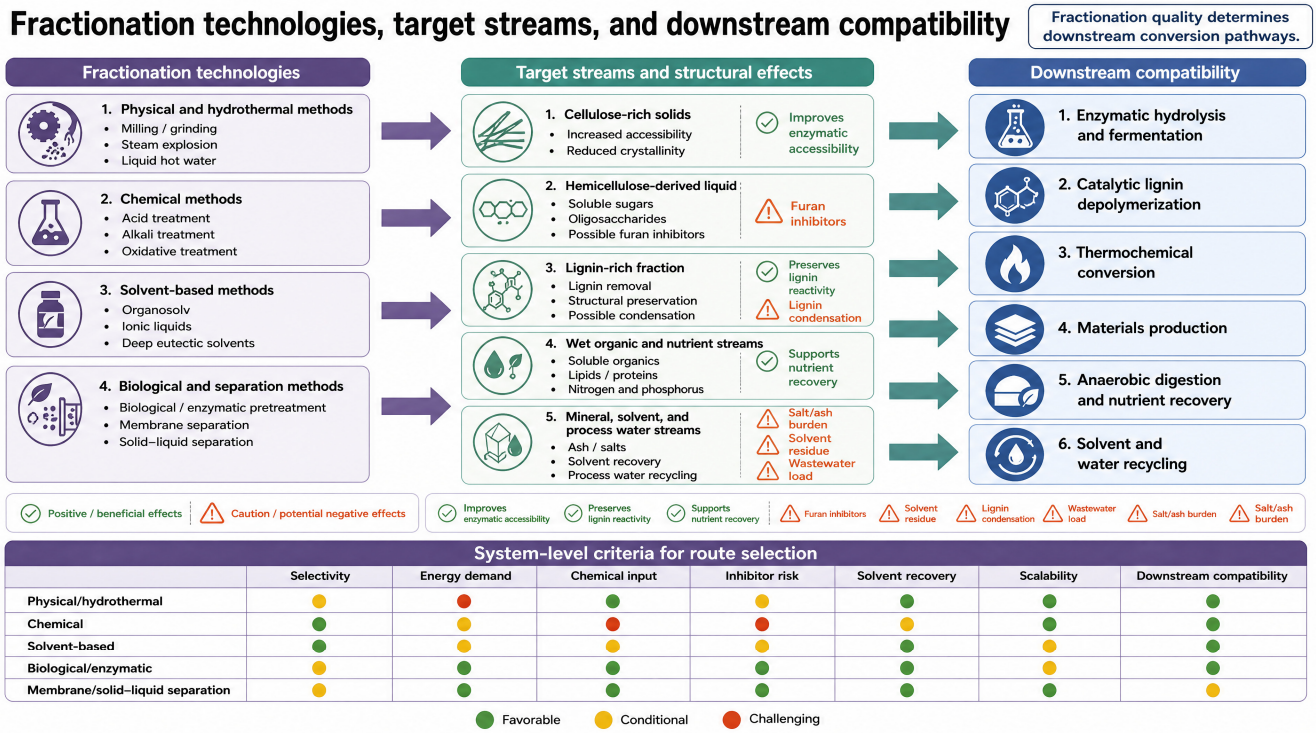
Biological and enzymatic treatments operate under mild conditions and generally generate fewer furan inhibitors. However, their applicability is limited by long processing times, losses of fermentable carbon, contamination-control requirements, and enzyme costs [58–60]. Membrane and solid–liquid separation can be used to concentrate sugars, organic acids, solvents, lignin fragments, and nutrients. Nevertheless, membrane fouling, cleaning requirements, and the management of concentrate streams must be incorporated into process design [61]. The effects of the major component-separation technologies on stream composition and subsequent conversion processes are illustrated in Figure 3.

3.3. Separation Severity, System Burdens, and Downstream Compatibility

Separation processes consume heat, electricity, chemicals, solvents, and process water and can contribute to biorefinery costs and environmental impacts through utility demand, reagent production, solvent losses, recovery operations, and residual-stream treatment. Greater treatment severity may increase component release but can also increase inhibitor formation, equipment corrosion, chemical consumption, and liquid-waste generation [62,63]. Milder conditions favor structural preservation but may increase the difficulty of downstream conversion or purification. Separation and downstream processing should therefore be evaluated within the boundaries of the complete process to identify and avoid burden shifting between unit operations.

The feasibility of pathways based on organic solvents, ionic liquids, and DESs depends strongly on solvent-recovery efficiency and stability over repeated cycles. Solvent losses

increase replenishment costs and upstream environmental burdens, whereas evaporation, distillation, or antisolvent-based recovery may require additional heat, electricity, water, or separation agents [64–66]. Water, salts, lignin fragments, and solvent-degradation products may also accumulate during recycling, thereby altering viscosity, separation selectivity, and downstream compatibility. Consequently, single-pass separation and solvent-recovery metrics do not adequately represent long-term operating performance.



	Selectivity	Energy demand	Chemical input	Inhibitor risk	Solvent recovery	Scalability	Downstream compatibility
Physical/hydrothermal	●	●	●	●	●	●	●
Chemical	●	●	●	●	●	●	●
Solvent-based	●	●	●	●	●	●	●
Biological/enzymatic	●	●	●	●	●	●	●
Membrane/solid–liquid separation	●	●	●	●	●	●	●

Figure 3. Schematic relationships among component-separation technologies, resulting streams, and downstream conversion processes. The terms "recommended", "favorable", and "challenging" represent the authors' qualitative synthesis of the cited literature rather than numerical ratings. The figure does not constitute a complete process-flow, mass-balance, or stoichiometric model.

Process-water recycling can reduce freshwater demand, but organic acids, phenolic compounds, salts, and metals may gradually accumulate during repeated use. Practical systems generally require purification, bypass treatment, partial discharge, or a combination of these measures rather than completely closed-loop operation [67,68]. Membrane separation, low liquid-to-solid ratios, and continuous operation can reduce some thermal-separation and water-use burdens. However, membrane service life, cleaning requirements, and the management of concentrate streams must still be assessed [61,67].

Separation should therefore be evaluated within the boundaries of the complete biorefinery. Additional separation is likely to provide a system-level advantage only when it increases the yield of usable streams, preserves the structural characteristics required for target products, or reduces the burdens associated with downstream conversion and purification [69,70]. The applicable conditions, downstream effects, and scale-up issues associated with the major component-separation technologies are summarized in Table 3.

Table 3. Applicable conditions, downstream effects, and scale-up issues associated with major component-separation technologies.

Separation Method	Principal Function	Applicable Feedstocks	Main Characteristics	Principal Limitations	Effects on Subsequent Conversion	Scale-Up Issues	References
Mechanical and physical processing	Particle-size reduction and increases in specific surface area and fiber accessibility	Agricultural and forestry residues and structurally recalcitrant biomass	Requires no chemical reagents or only small quantities of them and can be readily integrated with other processes	Limited component selectivity and high energy demand under intensive processing conditions	Improves mixing, mass transfer, and enzymatic accessibility	Electricity consumption, dust, noise, and equipment wear	[48,49]
Steam explosion and liquid hot-water treatment	Hemicellulose solubilization and structural disruption	Agricultural and forestry residues and other lignocellulosic feedstocks	Requires relatively low chemical inputs and has an established basis for scale-up	Formation of furan inhibitors and pseudo-lignin and condensation of lignin	Improves enzymatic hydrolysis of cellulose, although the liquid stream may require detoxification	High-pressure feeding, treatment uniformity, heat recovery, and corrosion	[46–48,62]
Acid treatment	Hemicellulose hydrolysis and release of monosaccharides or oligosaccharides	Lignocellulosic feedstocks	Rapid reaction and relatively effective hemicellulose removal	Sugar degradation, corrosion, formation of neutralization salts, and generation of acidic waste streams	Increases cellulose accessibility, although the resulting inhibitors may affect fermentation	Acid recovery, corrosion-resistant materials, detoxification, and liquid-waste treatment	[48,49,51,62,63]
Alkaline and oxidative treatment	Lignin removal and increase in cellulose accessibility	Agricultural residues and some feedstocks with high lignin contents	Effective delignification and established application across multiple lignocellulosic feedstocks	Alkali consumption, black-liquor generation, salt loading, and oxidative by-products	Favors enzymatic hydrolysis but may alter lignin structure	Alkali recovery, black-liquor utilization, and process-water recycling	[48,49,51,62,63]
Organosolv fractionation	Lignin separation and cellulose enrichment	Forestry residues and feedstocks with high lignin contents	Provides relatively extensive component separation and generally yields reactive lignin	Elevated temperature and pressure, solvent flammability, and solvent-recovery requirements	Favors enzymatic hydrolysis, lignin depolymerization, and materials production	Solvent recovery, explosion protection, corrosion control, and long-term continuous operation	[48–50,52,54,66]
Deep eutectic solvents	Selective separation of lignin or hemicellulose	Agricultural and forestry residues and some industrial biobased by-products	Adjustable composition, low vapor pressure, and tunable separation selectivity	High viscosity, large liquid-to-solid ratios, and substantial solvent-recovery requirements	May yield lignin with a low degree of condensation and improve some enzymatic-hydrolysis processes; residual solvent may inhibit fermentation	Mass transfer, solvent recycling, impurity accumulation, and moisture control	[48,53,55–57,64,65,67,68,71]
Ionic liquids	Reduction in cellulose crystallinity or dissolution of lignocellulosic components	Structurally recalcitrant lignocellulosic feedstocks	High dissolution capacity and effective disruption of hydrogen-bonding networks	High cost, high viscosity, antisolvent requirements, and limited biocompatibility	Promotes enzymatic hydrolysis of cellulose, although residual ionic liquids may inhibit enzymes and microorganisms	Antisolvent recovery, solvent purification, and impurity accumulation	[48,49,55,68]

Table 3. *Cont.*

Separation Method	Principal Function	Applicable Feedstocks	Main Characteristics	Principal Limitations	Effects on Subsequent Conversion	Scale-Up Issues	References
Biological and enzymatic treatment	Modification of lignin and hemicellulose structures	Lignocellulosic feedstocks under suitable moisture conditions	Mild reaction conditions and generally limited inhibitor formation	Long processing times, loss of fermentable carbon, enzyme costs, and contamination risk	Can improve compatibility with biochemical conversion	Microbial-strain stability, contamination control, processing time, and enzyme recovery	[48,49,55,58,59]
Membrane and solid–liquid separation	Concentration of sugars, organic acids, solvents, lignin fragments, and nutrients	Pretreatment liquids, fermentation broths, hydrothermal aqueous streams, and solvent systems	Can concentrate products and recover some solvent and process water	Membrane fouling, declining selectivity, cleaning requirements, and management of concentrate streams	Reduces some downstream thermal-separation burdens	Membrane service life, cleaning costs, and stability during continuous operation	[61,67,68]

Note: The separation performance of each technology depends on feedstock composition, treatment severity, and target products. In addition to component recovery, assessments should consider structural preservation, inhibitor formation, impurity partitioning, solvent and process-water recycling, and downstream conversion performance.

4. Conversion Processes and Product Distributions

The streams generated by front-end separation differ in composition, moisture content, biodegradability, structural characteristics, and impurity levels and are therefore suited to different conversion processes. Conversion pathways should be designed with due consideration of reaction performance, product separation and upgrading requirements, and the treatment or utilization of residual streams. The relationships among the principal feedstock components, conversion processes, and products are illustrated in Figure 4.

4.1. Applicability of Biochemical, Thermochemical, and Catalytic Conversion Processes

Biochemical conversion is suitable for fermentable-sugar solutions, organic waste liquids, and wet organic matter with relatively low inhibitor concentrations. Fermentation can produce alcohols, organic acids, and other biobased chemicals, whereas AD and VFA fermentation are suitable for food waste, sludge, and organic liquid streams [72,73]. Key performance indicators include substrate utilization, product yield, final product concentration, volumetric productivity, and process stability. The principal engineering constraints include mixing at high solids contents; inhibition by ammoniacal nitrogen, salts, furans, and phenolic compounds; and the separation of products from dilute aqueous streams.

Thermochemical processes are suitable for lignocellulosic feedstocks, lignin-rich residues, and some complex wet streams that are resistant to biodegradation. Pyrolysis and gasification generally require control of feedstock moisture content, whereas HTL and HTC can directly process high-moisture feedstocks [72–74]. The influence of moisture content on process performance also depends on the feasibility of mechanical dewatering, the availability of waste heat, and the extent of heat integration [75]. Thermochemical processes should be evaluated in terms of phase-specific product distributions, carbon and energy recovery, ash behavior, and product-upgrading requirements.

Catalytic processes can be applied to lignin depolymerization, the conversion of sugar-derived platform molecules, and the upgrading of pyrolysis oil and biocrude [76,77]. Lignin monomer yields depend strongly on the separation history and degree of condensation of the lignin stream. The hydroprocessing of pyrolysis oil and biocrude is constrained by hydrogen consumption, heteroatom removal, and carbon losses. K, Na, and Ca in

ash can alter the rates and pathways of cracking, gasification, and catalytic reactions. However, excessive accumulation of these elements may cause catalyst deactivation or bed agglomeration [78,79]. Si can also react with oxygen carriers or bed materials to form low-melting-point silicates, thereby increasing the risks of slagging and long-term deactivation [80,81]. These effects depend on elemental concentrations, mineral phases, temperature, and reaction atmosphere and should be evaluated using actual feedstocks under long-term operating conditions.

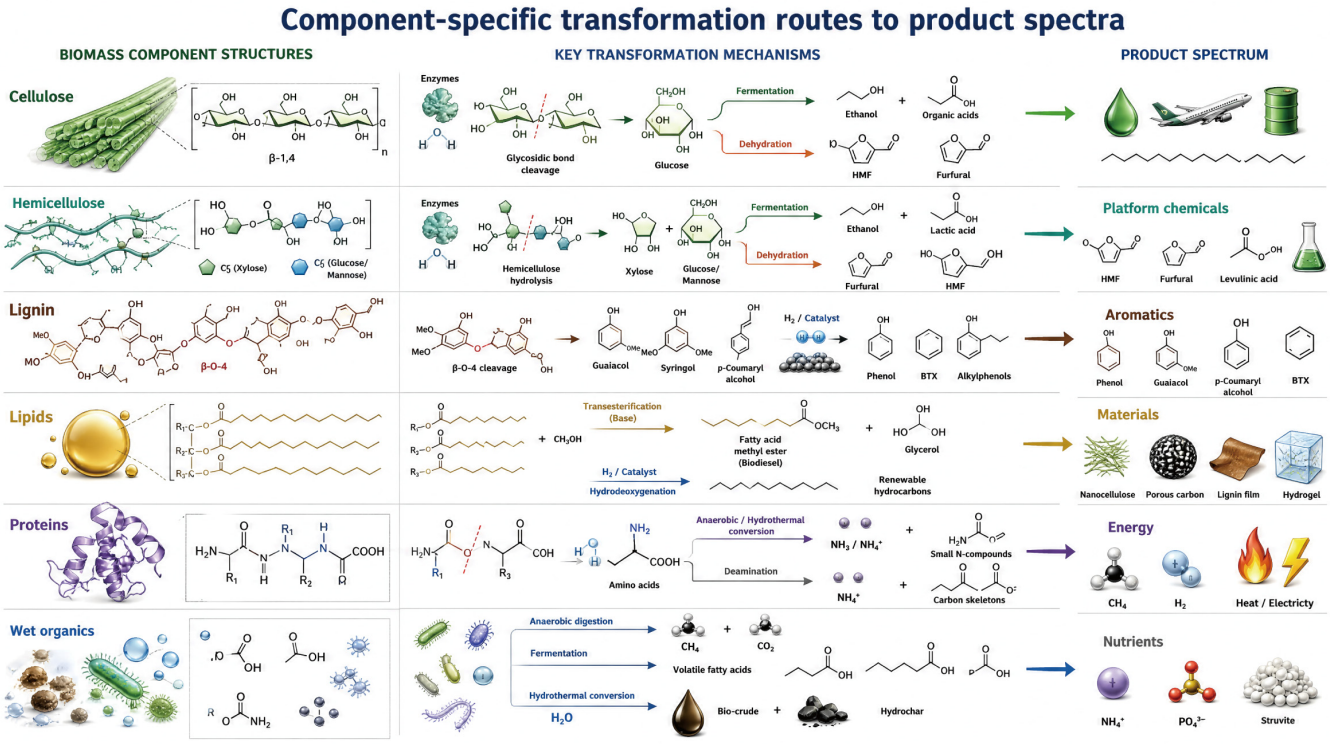


Figure 4. Schematic literature-based relationships among major biomass and biowaste components, conversion processes, and product categories. The relationships do not represent complete mass or stoichiometric balances.

4.2. Product-Oriented Conversion Pathways

Energy products include biogas, pyrolysis oil, biocrude, syngas, and solid fuels. Their evaluation should focus on the yield of final products that meet the relevant specifications, net energy recovery, product stability, and production cost rather than solely on primary-product yields at the reactor outlet [82,83]. Pyrolysis oil and biocrude generally require stabilization and heteroatom removal, particularly the removal of oxygen and nitrogen. Syngas must be purified to remove tar, particulates, sulfur- and chlorine-containing compounds, and other trace contaminants before it can be used for fuel or chemical synthesis.

The production of platform and aromatic chemicals places stringent requirements on reaction selectivity, product concentration, and separation performance. C5 and C6 sugars can undergo fermentation or catalytic conversion to produce alcohols, organic acids, furfural, 5-hydroxymethylfurfural, levulinic acid, and other products [84]. Lignin with a low degree of condensation can be converted into phenolic compounds and aromatic intermediates, with the product distribution depending on the abundance of cleavable bonds and the catalytic conditions [85]. Reaction-stage selectivity has practical engineering significance only when it can be translated into an adequate yield of specification-compliant final products after downstream separation and upgrading.

Materials-oriented pathways exploit the polymeric structures, morphologies, pore characteristics, and surface functional groups of cellulose, lignin, and carbonaceous ma-

terials [86]. The production of nanocellulose and lignin-based polymers requires relatively mild separation conditions to preserve the degree of polymerization and chemical reactivity [87,88]. The potential applications of biochar and hydrochar are constrained by their pore characteristics, carbon stability, ash contents, and contaminant levels [89]. Materials production should also be evaluated in terms of process inputs, service life, and end-of-life management [90].

4.3. Integration of Biochemical, Thermochemical, and Catalytic Processes

The principal purpose of process integration is to allocate carbon and energy according to stream properties. Following selective separation, sugar streams can be directed to fermentation, lignin streams to catalytic conversion or materials production, recalcitrant solids to hydrothermal or thermochemical conversion, and nutrient-rich liquid streams to AD or nutrient recovery. Such configurations can reduce interference among components but increase the requirements for separation, storage, stream transfer, and logistics management.

In a study of agave residues, an acid hydrolysate was detoxified and used in a two-stage biochemical process for hydrogen and methane production, whereas the residual solid fraction was subsequently subjected to microwave-assisted pyrolysis [91]. This configuration increased the utilization of both liquid and solid streams but also introduced additional requirements for hydrolysate detoxification and compatibility between process units. The study illustrates an integrated configuration in which liquid and solid streams are directed separately to biochemical and thermochemical processes. However, its results should not be extrapolated directly to feedstocks with different compositions and impurity levels.

Aromatic intermediates generated through the chemical or catalytic depolymerization of lignin can be further converted by engineered microorganisms through a biological funneling strategy [92,93]. This configuration uses chemical processing to deconstruct complex macromolecules and microbial conversion to increase product selectivity. However, phenolic compounds, aldehydes, salts, and residual solvents in lignin-depolymerization liquids can reduce biocompatibility and increase stream-purification requirements.

In pathways that apply biochemical conversion before thermochemical processing, fermentation or AD preferentially converts readily degradable components, after which the residual solids are subjected to HTC, pyrolysis, or gasification to recover the remaining carbon and energy [94,95]. The feasibility of these pathways depends on the moisture content, ash content, and contaminant distribution of the residues. Combustible gases, waste heat, biogas, and recovered nutrients can also be used across process units. However, the recycling of material streams should be constrained by the accumulation of salts, ammoniacal nitrogen, and inhibitors, as illustrated in Figure 5.

4.4. Carbon Allocation, Product Selectivity, and Final Product Upgrading

Conversion pathways should account for the allocation of feedstock carbon among target products, energy carriers, solid products, and gaseous products. Combustion of residual streams can increase process energy self-sufficiency but reduces the amount of carbon retained in marketable products and solid materials. Biochar and hydrochar can increase solid-phase carbon recovery, but their environmental benefits depend on carbon stability and end use [95–97]. Process-level carbon recovery describes the distribution of feedstock carbon within the process system and should not be interpreted as an indicator of life cycle greenhouse gas mitigation.

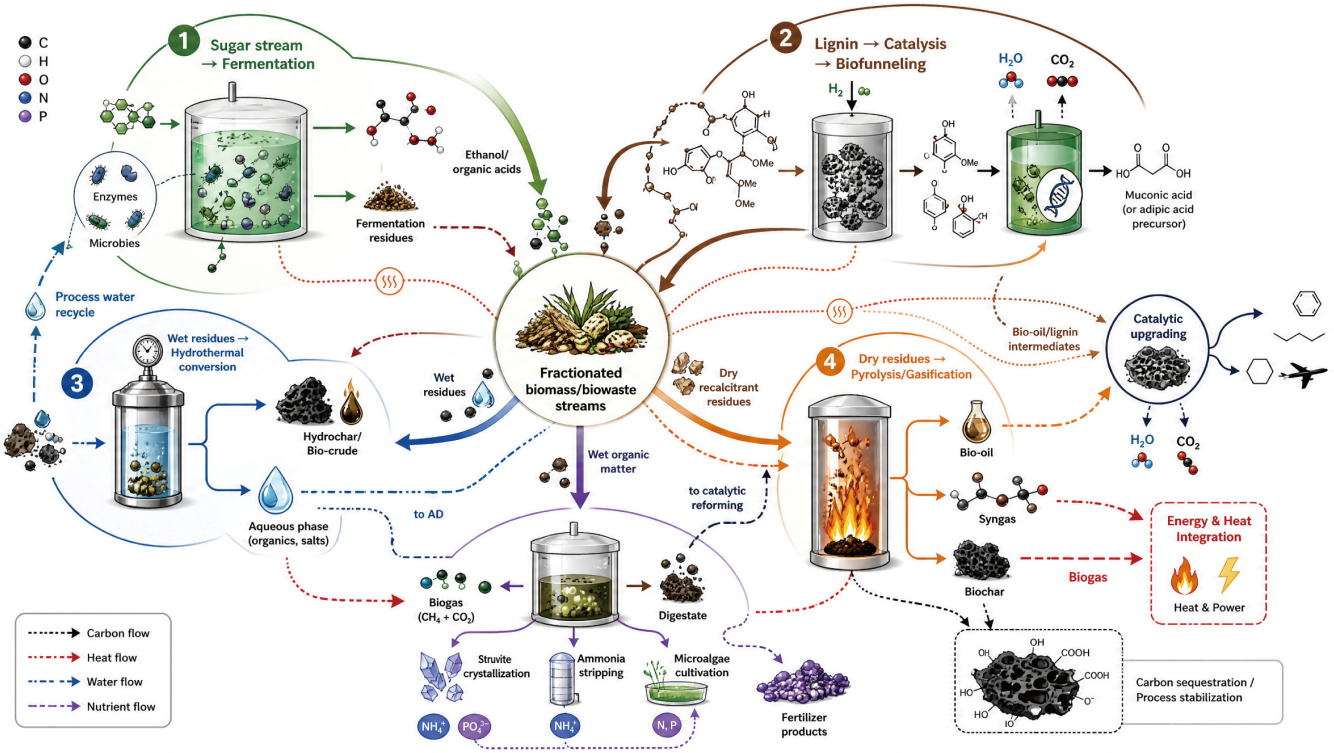


Figure 5. Schematic literature-based configurations integrating biochemical, thermochemical, and catalytic processes through stream allocation, residual-stream conversion, energy recovery, water recycling, and nutrient recovery. The configurations do not represent complete mass, energy, or stoichiometric balances.

Product selectivity should be evaluated in conjunction with downstream separation and upgrading. When fermentation products are present at low final concentrations in aqueous media, distillation, extraction, or membrane separation may become the principal sources of energy consumption and production cost [98]. Pyrolysis oil generally has a high oxygen content, high acidity, and limited thermal stability. HTL biocrude may contain substantial amounts of nitrogen-containing compounds and inorganic impurities and therefore requires further stabilization and upgrading [77,83]. Syngas from gasification must be purified to remove tar, particulates, sulfur- and chlorine-containing compounds, and other trace impurities before it can be used for fuel or chemical synthesis [83]. Catalytic lignin depolymerization commonly produces mixtures of structurally similar aromatic compounds. The difficulty of separating these compounds may offset the benefits of high reaction-stage selectivity [76,93,99]. Pathway assessment should therefore be based on the yield and quality of final specification-compliant products rather than on primary-product yields before separation and upgrading. The applicable conditions, evidence basis, implementation boundaries, and principal limitations of the major biomass-conversion pathways are summarized in Table 4.

Table 4. Applicable conditions, evidence basis, implementation boundaries, and principal limitations of major biomass-conversion pathways.

Conversion Pathway	Applicable Streams	Major Products	Key Performance Criteria	Evidence Basis and Maturity Boundary	Principal Engineering Limitations	Typical Integration Configurations	References
Biochemical fermentation	Liquid streams with relatively high fermentable-sugar concentrations and low inhibitor levels	Ethanol, higher alcohols, organic acids, and biobased chemicals	Sugar utilization, product yield, final product concentration, volumetric productivity, and separation energy demand	Core fermentation using sugar- and starch-based feedstocks is commercially established. Evidence for lignocellulosic hydrolysates ranges from laboratory batch or fed-batch studies to pilot, demonstration, and selected commercial applications. The maturity of the complete chain remains specific to the feedstock, product, and downstream recovery process.	Enzyme costs, inhibitor effects, mixing at high solids contents, microbial-strain stability, and separation of low-concentration products	Detoxification, in situ product separation, and AD or thermochemical utilization of residues	[84,96,98,100,101]
Anaerobic digestion	High-moisture, readily degradable organic wastes and organic liquid streams	Biogas, liquid digestate, and solid digestate	Organic loading rate, methane yield, volumetric biogas production rate, ammoniacal nitrogen concentration, and VFA concentration	AD is commercially established for actual organic wastes, generally under semicontinuous or continuous operation. Integrated chains involving controlled VFA production, hydrothermal conversion, selective nutrient recovery, or high-value products are supported mainly by laboratory, pilot, demonstration, or site-specific engineering evidence.	Hydrolysis rate, inhibition by ammonia and long-chain fatty acids, process fluctuations, methane leakage, and liquid-digestate treatment	Co-digestion, biogas upgrading, nutrient recovery, and HTC of solid residues	[83,91,94,96,102]
Hydrothermal liquefaction	Sludge, microalgae, and other complex high-moisture streams	Biocrude, aqueous-phase organics, gases, and solid residues	Biocrude yield, carbon and energy recovery, heteroatom content, and aqueous-stream treatment burden	HTL has been studied with actual wet feedstocks in laboratory batch reactors and continuous pilot- or demonstration-scale systems. Complete chains incorporating biocrude upgrading and aqueous-stream utilization remain primarily at the pilot or demonstration stage.	High-pressure feeding, corrosion, oil–water separation, biocrude upgrading, and aqueous-stream treatment	AD or reforming of the aqueous stream, biocrude hydroprocessing, and nutrient recovery	[72,83,96,102]

Table 4. *Cont.*

Conversion Pathway	Applicable Streams	Major Products	Key Performance Criteria	Evidence Basis and Maturity Boundary	Principal Engineering Limitations	Typical Integration Configurations	References
Hydrothermal carbonization	Digestate, sludge, and other high-moisture solids	Hydrochar and organic-rich aqueous streams	Solid and carbon yields, energy densification, carbon stability, and contaminant partitioning	HTC has been studied with actual wet feedstocks in laboratory batch, pilot, demonstration, and selected engineering-scale systems. Evidence for complete chains incorporating aqueous-stream management, nutrient recovery, and hydrochar qualification remains feedstock- and product-specific.	Aqueous-stream treatment, salt and metal enrichment, product standards, and continuous feeding	AD, aqueous-stream treatment or recycling, nutrient recovery, and hydrochar utilization	[94,95,102]
Fast pyrolysis	Low-moisture, relatively low-ash lignocellulosic feedstocks and dried residues	Pyrolysis oil, biochar, and combustible gas	Phase-specific product yields, carbon distribution, oxygen content and stability of the liquid product, and net energy recovery	Continuous fast-pyrolysis units using actual biomass have reached demonstration and commercial scales. Complete fuel-production chains incorporating long-term stabilization and extensive upgrading of pyrolysis oil remain less mature than the core conversion process.	Feedstock drying, pyrolysis-oil instability, coke formation, ash effects, and deoxygenation costs	Catalytic pyrolysis, oil hydroprocessing, use of combustible gases for process heat, and biochar utilization	[77,95,96,102,103]
Gasification	Low-moisture, recalcitrant solids and carbon-rich residues	Syngas	Carbon conversion, cold-gas efficiency, H_2/CO molar ratio, and tar and particulate concentrations	Continuous biomass gasification using actual feedstocks is commercially established for selected heat- and power-generation applications. Integrated chains producing hydrogen, liquid fuels, or chemicals generally remain at pilot, demonstration, or selected engineering scales because they require additional gas cleaning and synthesis.	Tar formation, ash variability, slagging, bed agglomeration, and syngas purification	Fischer–Tropsch or methanol synthesis, combined-cycle systems, hydrogen production, and waste-heat recovery	[75,78–81,96,97,102]

Table 4. *Cont.*

Conversion Pathway	Applicable Streams	Major Products	Key Performance Criteria	Evidence Basis and Maturity Boundary	Principal Engineering Limitations	Typical Integration Configurations	References
Catalytic lignin depolymerization	Lignin streams with a low degree of condensation and controlled ash and sulfur contents	Phenolic monomers and aromatic intermediates	Monomer yield, selectivity, hydrogen consumption, solvent recovery, and catalyst lifetime	Evidence is based mainly on laboratory batch studies using isolated lignins or model compounds, with limited continuous-flow or early pilot validation. Complete chains incorporating catalyst regeneration, solvent recovery, and aromatic-product separation have not reached commercial implementation.	Secondary condensation, coke formation, catalyst deactivation, hydrogen and solvent requirements, and product separation	Lignin-first fractionation, in situ stabilization, and biological funneling	[76,85,93,99]

Note: The maturity descriptions are the authors' qualitative synthesis of the feedstock type, operating mode, scale, core-unit boundary, and integrated-chain evidence reported in the cited literature. No numerical maturity score or formal evidence weighting was applied, and the descriptions do not constitute uniform TRL assignments for broad technology categories. Stable-operation duration and inclusion of product upgrading are recorded in Supplementary Table S2 when explicitly reported in the original studies. AD, anaerobic digestion; VFA, volatile fatty acids; HTL, hydrothermal liquefaction; HTC, hydrothermal carbonization; TRL, technology readiness level; H_2/CO, molar ratio of hydrogen to carbon monoxide.

5. Circular Biorefining and Multiproduct Utilization

Circular biorefining integrates feedstock fractionation, stream conversion, product separation, residual-stream utilization, and process-energy recovery within a single system. Compared with single-product pathways, circular biorefineries allocate carbon flows according to component and stream properties and use solid residues, process liquids, combustible gases, and waste heat to reduce material and energy losses. However, adding conversion and recovery units also increases capital requirements, operational complexity, and product-separation burdens. The system-level performance of a circular biorefinery therefore depends on whether its individual streams can be allocated to mutually compatible product and energy pathways rather than simply on the number of process units or products included.

5.1. Configurational Differences Between Two Representative Circular Biorefinery Systems

Lignocellulosic feedstocks and high-moisture organic wastes represent two types of circular biorefinery systems subject to distinct constraints. For lignocellulosic feedstocks, the principal objective of selective separation is to generate cellulose, hemicellulose, and lignin streams that meet the requirements of saccharification, catalytic conversion, or materials production. For high-moisture organic wastes, the emphasis is generally on wet conversion, process-water management, and nutrient recovery, together with the control of salts, pathogens, heavy metals, and other contaminants. Both systems can generate multiple products and recycled streams, but they differ in their front-end processing objectives, interfaces between process units, and requirements for product qualification and market access (Figure 6).

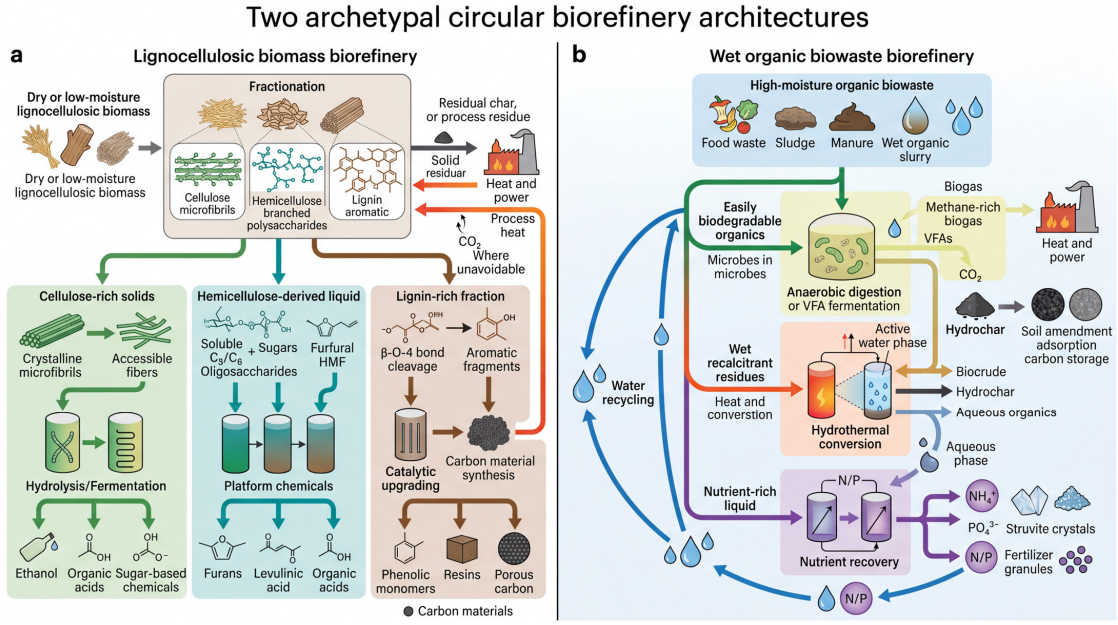


Figure 6. Schematic literature-based circular-biorefinery configurations for lignocellulosic feedstocks and high-moisture organic wastes. The configurations show principal product and residual-stream pathways rather than complete process designs or mass and energy balances.

In lignocellulosic systems, streams are generally allocated according to their quality. Cellulose-rich solids can be directed to saccharification and fermentation or materials production, whereas hemicellulose-derived liquid streams can be used to produce oligosaccharides, fermentation products, or platform chemicals [104,105]. Depending on their degree of condensation, molecular-weight distribution, ash content, and sulfur content, lignin streams can be used for catalytic depolymerization or the production of polymers

and carbon materials. Lignin with poor structural integrity, high impurity levels, or limited potential for further separation may instead be used to generate process energy [106,107]. The principal limitations of these systems arise from pretreatment severity, enzyme and solvent consumption, changes in lignin structure, and product-purification requirements. Further intensification of separation may not provide corresponding system-level benefits for components that occur at low concentrations, are difficult to purify, or have limited market capacity.

High-moisture organic-waste systems generally begin with sorting, homogenization, and, where necessary, solid–liquid separation. Readily degradable streams can then be directed to AD or VFA fermentation, whereas recalcitrant wet solids can be processed by HTL or HTC. Nitrogen, phosphorus, and other usable components may also be recovered from liquid streams [108,109]. These pathways can reduce the need for energy-intensive drying. However, hydrothermal and biochemical processes redistribute organic matter, nitrogen-containing compounds, salts, and contaminants among solid, liquid, and gaseous streams. The subsequent treatment or utilization of the resulting aqueous streams and solid products should therefore be incorporated into system design.

Integration between these two types of systems should be based on stream compatibility. Residues from saccharification, fermentation, or AD may be directed to hydrothermal or thermochemical conversion depending on their moisture content, ash content, and contaminant levels. Aqueous streams from hydrothermal processing should be recycled to biochemical units only when their biodegradability, salinity, ammoniacal nitrogen concentration, and inhibitor levels are within the tolerance ranges of the receiving processes. Streams containing high concentrations of salts or metals, or substantial amounts of recalcitrant organic compounds, should be purified, stabilized, or discharged under controlled conditions. System configuration should therefore begin with the identification of the principal carbon flows and limiting impurities, followed by the selection of marketable products, options for internal energy recovery, and residual-stream management pathways.

5.2. Residual Streams and Energy Recovery

The performance of circular biorefineries depends not only on the yields of the principal products but also on the treatment or utilization of solid, liquid, and gaseous residual streams and the recovery of waste heat. If residual streams are managed exclusively through end-of-pipe treatment, the burdens associated with wastewater and solid-waste treatment may increase, and demand for externally supplied energy may also rise. Conversely, extensive recycling without adequate quality and safety controls may lead to impurity accumulation.

Solid residues generally contain unconverted organic carbon, lignin, microbial biomass, and ash. Residues with relatively low moisture contents and suitable heating values can be subjected to pyrolysis or combustion, whereas high-moisture residues may be processed by HTC to recover residual carbon and energy [110,111]. The resulting biochar and hydrochar may be used as adsorbents, microbial carriers, catalyst supports, or soil amendments [112–115]. Their suitability for these applications is nevertheless constrained by carbon stability, ash and salt contents, and contaminant levels. Chars derived from sludge, manure, and mixed organic wastes may contain elevated concentrations of heavy metals and phosphorus and must comply with the relevant standards before entering markets for land application or materials [116].

Pretreatment liquids, aqueous streams from hydrothermal processing, and fermentation effluents may contain organic acids, sugar-degradation products, phenolic compounds, nitrogen-containing organic compounds, and inorganic salts. Biological treatment, adsorption, membrane separation, oxidation, or catalytic processes can be used to reduce pollutant

loads and recover some of the organic matter and nutrients [117–119]. The feasibility of process-water recycling depends on impurity accumulation and downstream tolerance, as discussed in Section 3.3. When purification costs or accumulation risks become excessive, bypass treatment, controlled discharge, or a combination of these measures should be adopted.

Contaminant transfer should be evaluated using element- or compound-specific mass balances rather than product-phase concentrations alone. An increased concentration of metals, phosphorus, salts, or other contaminants in digestate, hydrochar, biochar, ash, or an aqueous stream may result from a reduction in the total mass of the receiving phase and does not by itself establish the fraction of the input contaminant transferred to that phase. A phase-specific mass balance requires the yield of each solid, liquid, and gaseous stream and the concentration of the relevant element or compound in each stream on a consistent basis. Where these data are available, the assessment should report the input mass, mass recovered in each measured phase, unaccounted fraction, and mass-balance closure. Concentration data should be interpreted together with phase yields because a high concentration in a low-yield phase may represent a smaller fraction of the input mass than a lower concentration in a high-yield phase. For volatile or transformable constituents, physical partitioning should also be distinguished from chemical conversion, volatilization, and analytical non-recovery. Where studies report only concentrations or selected product phases, the results should be interpreted as evidence of potential enrichment or partitioning rather than as a complete contaminant mass balance [116–119]. Biogas produced by AD can be used for combined heat and power generation or upgraded to biomethane. Combustible gases and waste heat from pyrolysis and gasification can be used for process heating, steam generation, or electricity production. Internal energy recovery can reduce the demand for purchased electricity and heat but may also reduce the quantities of marketable fuels or other carbon-based products. The appropriate allocation should therefore be determined according to energy quality, product value, the regional energy mix, and life cycle emissions. For streams that are dilute, technically difficult to recover, or associated with substantial contamination risks, the benefits of resource recovery should be compared with the associated purification and quality-control burdens rather than assuming that all residual streams should be recycled [120].

5.3. Multiproduct Configurations and Their Economic and Environmental Implications

Multiproduct pathways can distribute costs through stream valorization, product sales, equipment sharing, and residual-stream utilization. However, increasing the number of products does not necessarily improve system performance [121]. The benefits of a multiproduct configuration depend on recoverable stream yields, product purity, market capacity, separation burdens, and quality-control requirements.

One possible configuration is to use structurally well-preserved or relatively pure streams for chemicals and materials, direct larger carbon flows to basic chemicals, fuels, or biogas, and use residues that cannot be further valorized economically for process-energy generation or char production [122]. The system-level contribution of a high-value product should be evaluated according to its achievable yield, purification cost, and market capacity rather than its nominal selling price alone.

A study of the coproduction of cellulose nanofibers, xylo-oligosaccharides, and polyphenols from pineapple-leaf waste showed that a multiproduct configuration could outperform a single-product pathway under specific assumptions regarding product prices and recovery rates [123]. A sugarcane biorefinery using lactic acid as a platform product similarly showed that product portfolios involving acrylic acid, polylactic acid, or lactate esters could alter both the minimum selling price and life cycle emissions [124]. These

findings indicate that the potential advantages of multiproduct pathways arise from component valorization and cost sharing but are highly sensitive to product prices, yields, plant scale, and system boundaries.

Reaction conditions and residual-stream management can also alter the product portfolio and the allocation of carbon among marketable products, process-energy carriers, and residual streams [125,126]. Additional downstream processes require further inputs of enzymes, catalysts, and solvents, as well as additional separation and purification equipment. Their incremental benefits should therefore offset the associated capital, operating, and environmental burdens. Combustible gases and waste heat used internally do not generate marketable products but can reduce utility demand [127]. Product portfolios should consequently be evaluated on the basis of the incremental economic and environmental performance of the complete system rather than on the number or variety of products.

Across the reviewed evidence, there is broad agreement that feedstock moisture state should influence the initial choice between dry and wet processing, that separation conditions affect the suitability of carbohydrate and lignin streams for downstream use, and that product recovery and residual-stream treatment can alter the performance inferred from reactor-level yields. The evidence is less consistent regarding the system-level advantages of intensive fractionation, multiproduct configurations, and extensive stream recycling. Laboratory studies commonly report increased component accessibility, recovery, or product yield under controlled batch conditions, whereas process simulations and TEA or LCA studies show that these gains can be offset by solvent recovery, product purification, hydrogen or enzyme demand, wastewater treatment, and limited coproduct markets. Differences among studies also arise from feedstock composition, solids-loading basis, product specifications, plant scale, energy mix, system boundaries, and coproduct treatment. Consequently, the qualitative recommendations in Sections 2–5 identify conditional relationships supported by the literature rather than universal performance rankings. Figure 7 conceptually summarizes the literature-based allocation of biorefinery streams among product portfolios, process-energy recovery, and residual-stream utilization.

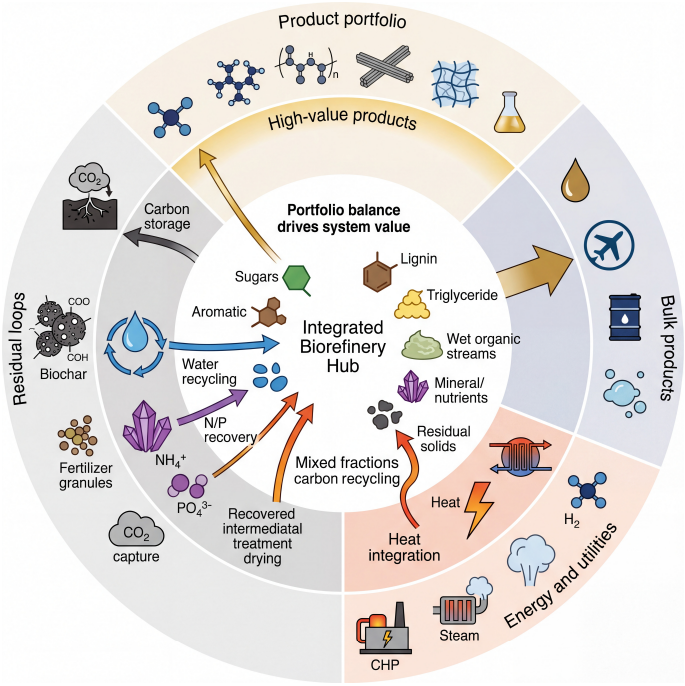


Figure 7. Conceptual literature-based allocation of biorefinery streams among product portfolios, process-energy recovery, and residual-stream utilization. The allocations do not imply complete carbon balances or fixed product distributions.

6. Systems Assessment and Conditions for Engineering Implementation

Systems assessment is required to determine whether candidate pathways can progress from laboratory research to pilot-scale, demonstration-scale, and commercial implementation. Technology maturity should be assessed, and techno-economic analysis (TEA) and life cycle assessment (LCA) should be conducted within consistent system boundaries encompassing feedstock handling, component separation, conversion, product upgrading, and residual-stream utilization. Supply-chain conditions, product standards, market capacity, and policy frameworks also affect pathway costs, environmental performance, and feasible deployment scale.

Selected quantitative examples are summarized in Table 5 to illustrate how specific operating conditions affect pretreatment severity and inhibitor formation, solvent recovery over repeated cycles, high-solids processing and stream concentration, and the cost burden of additional pretreatment. The examples retain the feedstock definitions, measurement bases, operating conditions, and evidence scales reported in the original studies because results obtained under inconsistent experimental and system boundaries should not be compared directly.

Table 5. Selected quantitative examples supporting the pathway-screening discussion.

Evidence Topic	Feedstock and Process	Conditions and Measurement Basis	Selected Quantitative Result	Evidence Basis and Reference
Pretreatment severity and inhibitor formation	Lignocellulosic biomass subjected to steam-explosion pretreatment	Severity factor integrating treatment temperature and residence time	In the cited review, a severity factor of 3.6 was described as an approximate intermediate condition between preserving cellulose-fiber integrity and applying more severe treatment for cellulose conversion. Reported severity factors for lignin recovery ranged from 3.2 to 4.4, and 3.8 was identified as applicable to several of the biomass types reviewed. Conditions above 3.6 were associated with greater cellulose disruption and with the formation of furfural and 5-hydroxymethylfurfural. These values represent a review-based synthesis rather than universal treatment thresholds	Review-based synthesis of steam-explosion studies [47]
Solvent recovery over repeated cycles	Pine wood fractionation using a choline chloride–urea natural deep eutectic solvent recovered by ultrafiltration and bipolar-membrane electrodialysis	Membrane-based solvent recovery followed by three reuse batches	The highest solvent-recovery ratio was 97.7%, and the lowest specific energy consumption for solvent recovery was 8.4 kWh kg^{-1}. The regenerated solvent was reused for three fractionation batches, with hemicellulose and lignin removal efficiencies of approximately 25.4% and 18.1%, respectively. The calculated recovery cost was approximately 3.0% of the solvent-purchase price	Laboratory multicycle fractionation and membrane-recovery study [67]
Solids loading and stream concentration	Enzymatic hydrolysis of alkali-treated and ball-milled corn stover	Enzymatic hydrolysis at 20% solid content; the original study reported the loading as solid content	At 20% solid content, alkaline treatment followed by ball milling produced a total sugar concentration of 182.86 g L^{-1} and a glucose yield 16.64% higher than that obtained using ball milling alone. The corresponding modeled minimum sugar selling price was USD 496.92 t^{-1}	Laboratory high-solids hydrolysis integrated with process simulation and TEA [128]
Cost burden of additional pretreatment	Acid washing before hydrothermal carbonization of microalgal biomass	Comparison of direct hydrothermal carbonization, acid pretreatment without acid recovery, and acid pretreatment with acid recovery and recirculation	Direct hydrothermal carbonization produced 418.08 kg h^{-1} of hydrochar with a minimum selling price of USD 2.83 kg^{-1}. Acid pretreatment reduced hydrochar production to 264.45 kg h^{-1} and increased the minimum selling price to USD 9.92 kg^{-1}, with HCl consumption accounting for 90.9% of annual operating costs. Acid recovery and recirculation reduced the minimum selling price to USD 7.41 kg^{-1}, although it remained higher than that of direct hydrothermal carbonization	Process simulation integrated with TEA and LCA [62]

Note: The values are reported using the feedstock definitions, operating conditions, measurement bases, and system boundaries of the original studies. They represent selected study-specific examples rather than pooled performance ranges. Review-based synthesis, laboratory multicycle experiments, laboratory experiments integrated with process simulation, and modeled TEA and LCA results are identified separately. TEA, techno-economic analysis; LCA, life cycle assessment.

6.1. Technology Readiness Level and Scale-Up

High conversion rates obtained with model substrates or in batch experiments may not be maintained when actual feedstocks are processed under continuous operating conditions. Variability among feedstock batches, high-solids feeding, complex rheological behavior, impurity accumulation, catalyst or microbial deactivation, and fluctuations in product quality may all reduce performance during scale-up [129]. Engineering validation should therefore encompass feedstock handling and feeding, reaction, product separation and upgrading, and waste-stream management rather than focus exclusively on the core reactor.

Lignocellulosic pretreatment and enzymatic hydrolysis generally require a relatively high solids content to increase product concentrations. However, increasing the solids content can impair mixing, heat transfer, and mass transfer [128,130]. Wet, fibrous, or heterogeneous feedstocks also complicate continuous conveying and pumping and increase the risk of equipment blockage. In microalgal pathways, cultivation, harvesting, dewatering, and cell disruption may consume more energy and incur greater costs than the subsequent conversion process [131].

Engineering validation should be based on complete mass and energy balances for the integrated pathway rather than on conversion and product yields from the core reactor alone. The mass balance should include fresh feedstocks, water, solvents, catalysts, nutrients, gases, recycled streams, products, emissions, wastewater, solid residues, and purge streams. Carbon, nitrogen, phosphorus, sulfur, ash-forming elements, relevant metals, and target contaminants should be tracked across solid, liquid, and gaseous streams, and balance closure should be reported for the complete operating period. The energy balance should distinguish heating, cooling, drying, evaporation, distillation, pumping, compression, agitation, reaction, product upgrading, and waste-treatment requirements. Heat integration should be evaluated using the temperature and temporal availability of heat sources and sinks rather than by assuming that all recovered heat can offset an equivalent quantity of external energy [132].

Recycle loops should be evaluated under repeated-cycle or steady-state conditions. For water, solvents, nutrients, and other recycled media, the recovery efficiency, make-up requirement, purge fraction, recovery energy demand, and changes in stream composition should be reported. The purge rate should be determined from the balance between impurity input, formation, removal, and the maximum concentration tolerated by the receiving process or permitted in the final product. Completely closed-loop operation should not be assumed when salts, ash, metals, inhibitors, solvent-degradation products, or recalcitrant organic compounds accumulate. Long-term continuous operation should additionally be evaluated using campaign duration, throughput, capacity factor or operating availability, product-quality variation, planned and unplanned shutdowns, and changes in catalyst activity, membrane flux, solvent composition, corrosion, fouling, and equipment blockage [129,133]. Experience from commercial projects indicates that satisfactory performance of the core reaction cannot substitute for validation of feedstock handling, heat and material integration, recycle-loop control, product upgrading, residual-stream management, and equipment reliability [134].

Technology maturity should be assessed for a specific combination of feedstock, process configuration, target product, operating mode, scale, and system-integration boundary. Although core AD, pyrolysis, and gasification processes have reached commercial implementation for selected applications, this maturity does not necessarily extend to integrated chains incorporating additional conversion, product upgrading, nutrient recovery, or residual-stream management. Table 4 therefore distinguishes the evidence basis and maturity boundary of the core conversion unit from those of the complete integrated chain, while detailed operating evidence is provided in the Supplementary Materials.

6.2. Techno-Economic Analysis and Cost Structure

TEA should be based on complete material and energy balances and should clearly specify plant capacity, cost year, discount rate, equipment lifetime, capacity factor, feedstock prices, and product prices. Increasing conversion in an individual unit operation or increasing product yield may not reduce the minimum selling price if either change simultaneously increases the requirements for high-pressure equipment, solvent recovery, hydrogen consumption, or product purification [135].

For pathways based on agricultural and forestry biomass, the principal cost components generally include collection, transportation, storage, and pretreatment. Increasing plant capacity can reduce specific capital costs but may also increase feedstock transport distances and competition for available resources [136]. Distributed densification, drying, or primary conversion can reduce the burden associated with transporting low-density feedstocks over long distances, but such configurations increase the number of processing nodes and the requirements for intermediate-product handling and quality control. Centralized and distributed configurations should therefore be compared according to regional feedstock density, transport infrastructure, and existing processing facilities.

High-pressure hydrothermal processing, evaporation, distillation, hydrogenation, and solvent recovery may constitute major capital or operating burdens. Enzymes, catalysts, hydrogen, and solvents contribute to variable costs, although their relative contributions depend on unit prices, consumption rates, recovery efficiencies, catalyst or enzyme lifetimes, and plant capacity [137,138]. Internal use of residual streams and combustible gases for process energy can reduce purchased-utility requirements but may also decrease the quantities of marketable carbon products. Scenario analysis is therefore required to determine an appropriate balance between process energy self-sufficiency and product sales.

Multiproduct pathways can offset costs through coproduct revenues and equipment sharing but are sensitive to product prices, market capacity, and the need for additional separation and purification equipment [139,140]. Carbon credits, waste-treatment revenues, and policy subsidies should be reported separately from product revenues, with distinct scenarios including and excluding policy support [136,141]. Sensitivity and uncertainty analyses should, at a minimum, cover feedstock costs, product prices, plant capacity, product yields, energy prices, and key recovery efficiencies.

6.3. Life Cycle Assessment, Carbon Footprint, and Resource Efficiency

The use of biobased feedstocks does not necessarily result in lower life cycle environmental impacts. Pathway performance depends on feedstock origin, the energy mix, chemical consumption, transportation, land use, process-water requirements, coproduct treatment, and the products or services displaced by biorefinery outputs. For waste-derived feedstocks, the allocation of upstream burdens and the avoided treatment pathway—such as landfilling or incineration—can substantially affect LCA results [142]. Assessments of energy crops and woody feedstocks should additionally consider land use, fertilizer application, irrigation, and changes in soil organic carbon [143].

Separation and product purification can become environmental hotspots when they require energy-intensive drying, distillation, high-pressure hydrogenation, solvent recovery, or repeated water-treatment operations. Freeze-drying, high-temperature distillation, high-pressure hydrogenation, and some solvent-based processes can increase energy consumption, global warming potential (GWP), and other environmental impacts [142,144]. Process-water and solvent recovery can reduce the demand for freshwater and virgin solvents; however, the energy and materials required for recovery, as well as the effects of impurity accumulation, should also be included within the system boundary.

Circularity is assessed in this review using a set of separate material-, energy-, and product-related indicators rather than a single composite index. Process-level carbon recovery describes the fraction and distribution of feedstock carbon among specified products, energy carriers, gaseous streams, and solid residues within the process boundary. Internal energy recovery describes the useful heat, electricity, or fuel recovered and used within the biorefinery relative to the stated process-energy demand or feedstock-energy basis. Water and solvent recycling should be reported as the quantities recovered and reused relative to the corresponding process requirements, together with freshwater or solvent replenishment, purge rates, recovery energy demand, and changes in recycled-stream quality. Nutrient recovery describes the fractions of input nitrogen, phosphorus, or other target nutrients recovered in products that meet the requirements of their intended uses. These indicators should be interpreted together with the accumulation and discharge of salts, ash, metals, inhibitors, and other contaminants and with the quantities of products that satisfy applicable quality requirements. GWP is assessed separately because it quantifies greenhouse gas emissions over the life cycle and depends on upstream inputs, the energy mix, transportation, coproduct treatment, displaced products, and end-of-life assumptions. A pathway can therefore have high process-level carbon, energy, water, solvent, or nutrient recovery without necessarily achieving lower life cycle greenhouse gas emissions. Resource-efficiency assessment may additionally include cumulative energy demand, water consumption, land use, acidification, eutrophication, and ecotoxicity [145,146]. Materials-oriented products require further assessment of service life, carbon stability, contaminant release, and end-of-life management [147].

These indicators are interpreted according to a resource-management hierarchy comprising prevention of avoidable resource use and residual-stream generation, retention or reuse of qualified materials, recovery of chemicals and nutrients, recovery of useful energy from streams unsuitable for material use, and treatment or controlled disposal of the remaining residues. This hierarchy does not imply that material recycling is preferable under all conditions [148]. A lower-tier option may be selected when a higher-tier option is technically incompatible with the stream, fails applicable product or safety requirements, increases life cycle burdens, or lacks a viable market. Circularity assessment should therefore report both the destination of each material stream and the technical, environmental, and product-quality conditions governing that destination.

LCA studies should specify whether an attributional or consequential approach is applied. Attributional LCA describes the environmental burdens assigned to a defined product system, typically using data representative of the processes supplying that system and an explicit procedure for allocating shared inputs and emissions. Consequential LCA estimates the environmental changes caused by a decision and therefore requires assumptions concerning marginal suppliers, market responses, alternative waste-management routes, and the products or services displaced by biorefinery outputs. Avoided-product or avoided-treatment credits should identify the counterfactual pathway, displacement ratio, product-quality equivalence, geographic and temporal context, and substituted technology. These assumptions should be tested through sensitivity or scenario analysis because they can change both the magnitude and direction of the results [149].

Biogenic carbon should be tracked consistently across biomass uptake, conversion, product use, storage, and end-of-life stages rather than assumed to be intrinsically carbon neutral. The assessment should account for changes in land and soil carbon stocks where relevant, methane and other non-CO_2 emissions, the duration and stability of carbon storage in materials or chars, and the eventual release or disposal of biogenic carbon. For wastes and residues, the assignment of upstream burdens and the assumed counterfactual treatment pathway should be reported explicitly. Process-level carbon recovery is a mass-

balance indicator within the selected process boundary and does not account by itself for fossil energy and material inputs, methane leakage, displaced products, carbon-storage duration, or end-of-life emissions. A high process-level carbon recovery should therefore not be interpreted as favorable life cycle performance without a complete LCA [150].

Cross-study comparisons are meaningful only when the LCA approach, functional unit, system boundary, energy mix, upstream feedstock burdens, biogenic-carbon accounting, and coproduct treatment methods are sufficiently consistent. Functional units based on the mass of product, energy delivered, or quantity of feedstock processed are appropriate for different assessment objectives; results based on different functional units should not be compared directly. For multiproduct systems, subdivision should be applied where technically feasible. When shared burdens cannot be subdivided, the study should state whether mass, energy, or economic allocation, system expansion, or substitution is used and should report the allocation factors, displaced products, substitution ratios, and principal assumptions. Results based on alternative allocation or substitution methods should be examined through sensitivity analysis when coproduct treatment materially affects the conclusions [151].

6.4. Supply Chains, Product Qualification and Market Access, and Policy Conditions

The engineering implementation of biorefineries is affected by the quantity of feedstock that can be collected sustainably, storage losses, transport distances, competing uses, and available infrastructure [152,153]. Biomass-resource assessments should distinguish theoretical potential from technical or collectible, sustainable, and economically available supply because collection constraints, environmental requirements, competing uses, and supply costs can substantially reduce practical availability [154,155]. Designing plant capacity solely on the basis of theoretical resource availability may therefore result in feedstock shortages or increased procurement costs.

The effects of transportation depend on transport mode, feedstock moisture content, regional resource density, plant capacity, and the products displaced by biorefinery outputs. No single transport-distance threshold is applicable across all regions and pathways [156]. Centralized plants can benefit from economies of scale, whereas distributed pretreatment can reduce the transportation burden associated with low-density feedstocks. These configurations should be compared according to regional resource availability, transport infrastructure, and existing industrial facilities [153,157,158].

Product qualification should be assessed against the requirements applicable in the intended market because fuel specifications, fertilizer regulations, waste-derived-product rules, and certification schemes differ among regions. For example, EN 14214:2012+A2:2019 [159] specifies a minimum ester content of 96.5% by mass, a maximum water content of 500 mg kg^{-1}, a maximum acid value of 0.50 mg KOH g^{-1}, and a maximum sulfur content of 10 mg kg^{-1} for fatty acid methyl ester used in diesel engines or heating fuel. Lipid-derived streams that do not meet these requirements may require additional dewatering, esterification, washing, adsorption, or distillation, and the associated losses and costs should be included in pathway assessment. Fuel-quality compliance should also be distinguished from sustainability certification, which addresses feedstock origin, traceability, and life cycle greenhouse gas performance rather than fuel composition alone [160,161].

Requirements for biochar, digestate, and recovered nutrients depend on both product category and jurisdiction. European Union rules for CE-marked fertilising products specify eligible component materials and category-specific requirements for contaminants, pathogens, nutrient content, and labeling, whereas national rules may govern products placed on domestic markets outside this harmonized framework. Biochar certification

schemes additionally consider feedstock eligibility, carbon stability, polycyclic aromatic hydrocarbons, heavy metals, and other product properties; these schemes should not be treated as equivalent to legal authorization in every region. Digestate derived from manure, separately collected biowaste, sewage sludge, or mixed municipal waste may be subject to different input-material, sanitation, pathogen, metal, and end-of-waste requirements. Similarly, recovered phosphate salts such as struvite can enter fertilizer markets only when the source material, production process, nutrient composition, and contaminant levels satisfy the applicable requirements. These conditions can change pathway selection by requiring source segregation, sanitation, contaminant removal, product blending, or alternative management of noncompliant streams. Products that do not meet the requirements of their intended markets should not be counted as qualified coproducts in TEA or as displaced commercial products in LCA [162].

Carbon pricing, renewable-fuel mandates, tax incentives, and waste-treatment subsidies can improve project economics, but policy stability affects long-term investment decisions [156,157]. For pathways that depend on policy-derived revenues, scenarios with and without policy support should be reported separately. Existing regional wastewater-treatment plants, district-heating networks, refineries, fertilizer-production facilities, and power infrastructure may provide opportunities for shared feedstock handling, product upgrading, and utility provision.

6.5. Pathway Screening and Incremental Assessment

On the basis of the preceding analysis, candidate biorefinery pathways should be evaluated sequentially in terms of feedstock compatibility, stream quality, continuous operation, incremental economic and environmental consequences relative to an explicit baseline, circular utilization, and product qualification and market access. They should not be ranked solely according to unit-level conversion performance, primary-product yield, or theoretical product value (Figure 8).

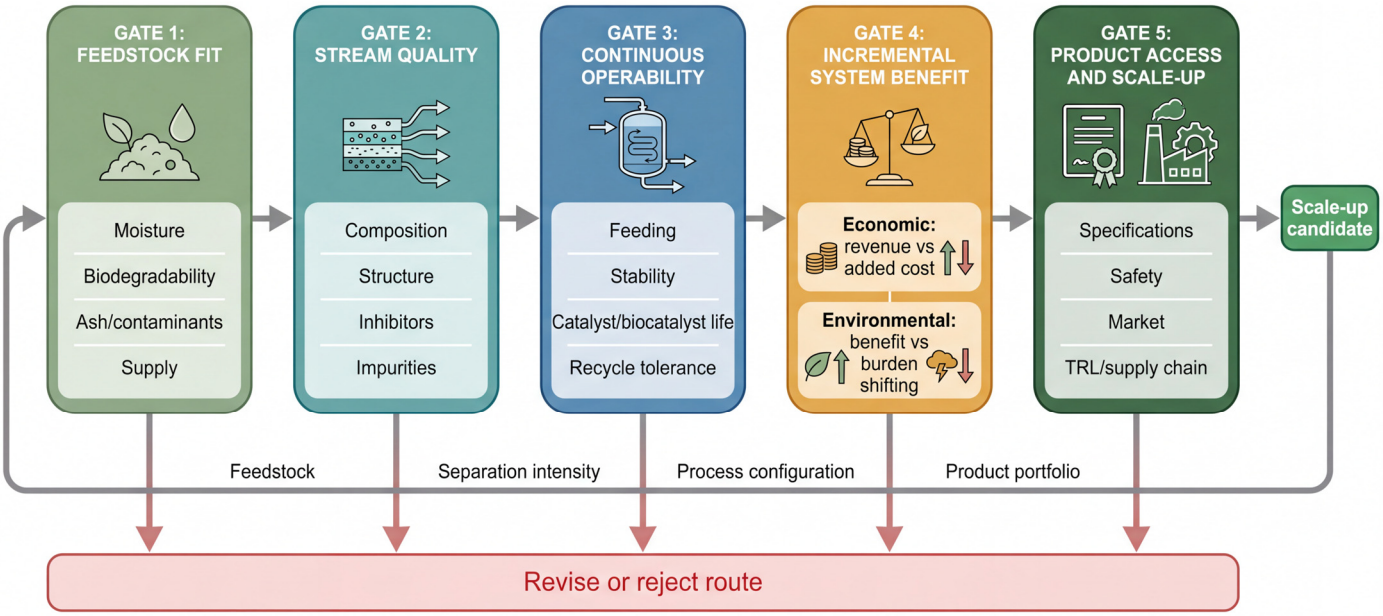


Figure 8. Author-derived conceptual framework for sequential pathway screening and engineering feedback in circular biorefineries. The screening stages cover feedstock compatibility, stream quality, continuous engineering performance, incremental economic and environmental consequences, circular utilization, and product qualification and market access. The framework is not a quantitatively validated scoring model.

Feedstock compatibility depends on moisture content, biodegradability, structural characteristics, ash content, contaminant load, and supply stability. For pathways that require energy-intensive drying, extensive purification, or long-distance transportation of low-density feedstocks, the associated front-end processing and logistics burdens should be included in the assessment.

Stream quality should be evaluated according to the intended downstream use. Fermentation substrates should be assessed in terms of fermentable-sugar concentration, inhibitor levels, and salt content. Lignin streams intended for catalytic conversion should be evaluated according to their degree of condensation, abundance of cleavable bonds, ash content, and sulfur content. Materials-oriented streams should retain the required degree of polymerization, morphology, or functional groups. Thermochemical feedstocks should meet process-specific requirements for moisture content, ash content, and key inorganic elements. If low-severity separation already satisfies downstream requirements, further increases in purity or recovery generally lack a system-level justification.

Assessment under continuous operating conditions should cover actual feedstocks, feeding at high solids contents or loading rates, complete mass and energy balances, heat integration, recycle-stream make-up and purge requirements, catalyst or biocatalyst service life, fluctuations in product quality, and multicycle recycling of solvents and process water. Slagging, corrosion, membrane fouling, equipment blockage, unplanned shutdowns, and impurity accumulation should also be considered. Unit-level performance demonstrated with model substrates or in batch experiments cannot, by itself, establish the engineering applicability of a complete pathway.

Incremental system benefits should be assessed relative to an explicitly defined baseline pathway. The baseline should provide the same principal function as the candidate pathway and should use a consistent feedstock basis, plant capacity, functional unit, cost year, energy mix, and system boundary. Depending on the assessment objective, the baseline may be the existing waste-management route, a single-product biorefinery, or the same process configuration without the additional separation, conversion, or recycling unit being evaluated.

The economic assessment should compare the additional annual revenues from products and marketable energy, utility savings, and avoided treatment or disposal costs with the annualized additional capital expenditure, operating expenditure, and costs associated with product testing, contaminant control, certification, and market access. All economic terms should use consistent currency bases, price years, capacity factors, and annualization methods. Carbon credits, policy subsidies, and waste-treatment compensation should be examined in separate scenarios rather than incorporated into the primary economic result without distinction. This relationship is intended as an accounting structure for defining the incremental terms that should be included; it does not replace a complete TEA.

Environmental changes should be assessed for the same baseline, functional unit, and system boundary and should be reported separately for GWP, cumulative energy demand, water consumption, acidification, eutrophication, and the toxicity indicators included in the selected life cycle impact-assessment method. A candidate pathway can be described as a Pareto improvement only when at least one predefined environmental indicator improves and no other assessed indicator worsens after uncertainty is considered. When some indicators improve and others worsen, the result should be reported as a trade-off rather than as an overall environmental improvement. Its interpretation should consider the goal and scope of the assessment, the absolute and relative magnitude of each change, data and model uncertainty, regional water and energy conditions, and regulatory or product-safety constraints. Indicators associated with mandatory limits, such as contaminant release or product-safety requirements, should be treated as constraints rather than offset by

improvements in other categories. If normalization, weighting, or a composite score is used to support a decision, the unaggregated results, weighting basis, and sensitivity of the conclusion to alternative weights should also be reported. This procedure provides a conceptual structure for incremental environmental assessment and does not replace a complete LCA [163].

The assessment of circular utilization and product qualification should consider both process compatibility and product quality. Recycling a stream should not result in the continued accumulation of salts, inhibitors, ash, metals, or recalcitrant organic compounds. Fuels, materials, fertilizers, and chemicals produced within the system should meet the quality, safety, performance, traceability, and feedstock-origin requirements applicable in their intended regional markets. Streams that fail to meet the requirements for their stated uses should not be counted as qualified coproducts when economic or environmental system benefits are calculated. If any assessment criterion is not satisfied, the feedstock source, separation severity, conversion process, contaminant-control strategy, product portfolio, intended market, or plant capacity should be adjusted accordingly. Only pathways that satisfy all relevant criteria should proceed to further pilot-scale, demonstration-scale, or commercial-scale development. Figure 8 summarizes the sequential pathway-screening framework, while Table 6 specifies the measurable bases, decision rules, and revision options for each screening stage.

Table 6. Measurable bases and revision rules for sequential pathway screening.

Screening Stage	Measurable Basis	Decision Rule	Revision Following a Negative Result
Feedstock compatibility	Moisture and ash contents with stated basis; component composition; biodegradability; salinity; relevant contaminant concentrations; recoverable annual supply; seasonal variability; storage loss; collection radius	The measured feedstock properties must remain within the feed envelope and contaminant tolerance of the proposed handling and conversion units, and the recoverable supply must support the selected plant capacity	Apply source segregation, blending, dewatering, washing, stabilization, or alternative storage; select another conversion route; reduce plant capacity; or change the feedstock supply region
Stream quality	Component concentration and recovery; inhibitor, salt, ash, residual-solvent, and contaminant concentrations; moisture state; structural descriptors required by the receiving process or product	Each stream must meet the acceptance specifications defined by the receiving conversion unit or target product; additional purity is not required once these specifications are met	Adjust separation severity, washing, detoxification, concentration, solvent recovery, or stream allocation; redirect a noncompliant stream to a more tolerant process
Continuous engineering performance	Throughput, mass- and energy-balance closure, campaign duration, operating availability, product-quality variation, catalyst or biocatalyst stability, membrane flux, corrosion, fouling, blockage, and recycle-loop composition	The integrated pathway must maintain the predefined throughput and product specifications over the stated campaign while meeting mass- and energy-balance and equipment-reliability requirements	Modify feeding and solids handling, heat integration, reactor configuration, catalyst or membrane management, purge rate, redundancy, maintenance schedule, or operating scale

Table 6. *Cont.*

Screening Stage	Measurable Basis	Decision Rule	Revision Following a Negative Result
Incremental economic and environmental consequences	Annualized incremental revenue and cost relative to the baseline; GWP, cumulative energy demand, water consumption, acidification, eutrophication, and toxicity indicators using a consistent functional unit and system boundary	The additional unit should provide non-negative incremental economic value under the defined scenario and meet the predefined environmental decision rule without violating regulatory or safety constraints	Remove or simplify the additional unit; alter heat or utility integration; change product allocation, recovery efficiency, plant scale, or baseline configuration; or report the result as an unresolved trade-off
Circular utilization	Carbon, energy, water, solvent, and nutrient recovery; fresh make-up; purge fraction; impurity accumulation; recovery energy demand; quantity of qualified recovered products; residual disposal	Recycle loops must approach a controllable composition without exceeding process or product limits, and recovered outputs must have a qualified use that provides a system-level advantage over treatment or disposal	Increase purification or purge, reduce the recycling ratio, change the receiving unit, redirect the stream to energy recovery or treatment, or discontinue recycling
Product qualification and market access	Applicable product specifications; contaminant and pathogen limits; feedstock-origin and traceability requirements; production volume relative to accessible market capacity	The product must satisfy the requirements of the intended regional market and have sufficient accessible demand at the planned production scale	Add product upgrading or contaminant removal; change product grade, use, or intended market; reduce production scale; redirect the stream to an alternative use; or treat it as a residual stream

Note: Numerical thresholds are pathway- and region-specific and should be obtained from the receiving-unit operating envelope, product specifications, applicable regulations, project design basis, and predefined TEA and LCA decision criteria. The table provides measurable decision rules rather than universal acceptance values.

6.6. Illustrative Application of the Framework to Two Contrasting Feedstocks

To illustrate the sequential application of the proposed framework, two contrasting feedstocks are considered: air-dried cereal straw as a relatively dry lignocellulosic residue and dewatered municipal sewage sludge as a high-moisture organic waste. These cases are illustrative pathway-screening exercises rather than quantitative process designs or claims of universally optimal configurations. The specific pathway selected for either feedstock would require confirmation using measured feedstock properties, product specifications, regional supply conditions, continuous-operation data, and consistent TEA and LCA boundaries. Table 7 summarizes how the six framework modules lead to different processing decisions for the two cases.

For air-dried cereal straw, the principal feedstock constraints are lignocellulosic recalcitrance, seasonal and geographically dispersed supply, low bulk density, and the possible presence of alkali metals, chlorine, silica, and soil-derived impurities [24,26,34,39,40]. If the intended product portfolio comprises a fermentation product and a lignin-derived product, front-end treatment must increase cellulose accessibility and recover a usable hemicellulose stream without generating inhibitor concentrations that exceed the tolerance of the selected microorganism. At the same time, the treatment should limit lignin condensation if the lignin stream is intended for catalytic depolymerization or polymer production [36,37,46–53]. Separation severity should therefore be increased only until the cellulose-rich and lignin-rich streams satisfy their respective downstream requirements.

Greater delignification or hemicellulose solubilization would not be justified if it increases sugar degradation, solvent-recovery demand, salt loading, or lignin condensation without improving the yield of specification-compliant final products. The cellulose-rich solid can be directed to enzymatic hydrolysis and fermentation, the hemicellulose-derived liquid can be used for fermentation or oligosaccharide production when its concentration and inhibitor levels are suitable, and the lignin stream can be directed to catalytic or materials-oriented utilization when its structure and purity are adequate. Lignin or solid residues that do not meet these requirements can instead be used for process-energy generation or thermochemical conversion. Solvent and process-water recycling should include purification or partial discharge to prevent the accumulation of organic acids, phenolic compounds, salts, and degradation products [64–68].

Table 7. Sequential application of the six-module framework to two contrasting illustrative feedstocks.

Framework Module	Air-Dried Cereal Straw	Dewatered Municipal Sewage Sludge	Principal Decision Resulting from the Framework
Feedstock characterization	Relatively low moisture content; high cellulose, hemicellulose, and lignin contents; structural recalcitrance; low bulk density; seasonal and dispersed supply; possible K, Cl, Si, ash, and soil contamination	High residual moisture content; biodegradable and recalcitrant organic matter; high nitrogen, phosphorus, and ash contents; possible pathogens, heavy metals, salts, and organic contaminants	Straw requires attention to structural accessibility, ash chemistry, and logistics, whereas sludge requires wet handling, contaminant characterization, and nutrient and ash balances
Selective separation	Size reduction followed by hydrothermal, chemical, or solvent-based fractionation according to the required sugar concentration, inhibitor level, cellulose accessibility, and lignin structural quality	Screening, grit removal, homogenization, mechanical dewatering, and solid–liquid separation; extensive molecular fractionation is generally not the initial priority	Separation severity is governed by downstream stream quality for straw but by dewatering, contaminant partitioning, and process compatibility for sludge
Process integration	Enzymatic hydrolysis and fermentation of carbohydrate streams; catalytic or materials-oriented use of qualified lignin; thermochemical or energy use of unsuitable residues	AD of readily biodegradable organic matter; possible HTC or HTL of dewatered digestate or recalcitrant wet solids; treatment or utilization of hydrothermal aqueous streams	Straw favors component-specific biochemical, catalytic, and thermochemical allocation, whereas sludge favors sequential wet biochemical and hydrothermal processing
Product portfolio	Fermentation products, oligosaccharides or sugar-derived products, lignin-derived chemicals or materials, process energy, and possibly char	Biogas, recovered phosphorus or other nutrient products, hydrochar or biocrude, and process energy	Products are retained only when stream yield, purification requirements, structural quality, contaminant levels, and market capacity support their qualification and sale

Table 7. *Cont.*

Framework Module	Air-Dried Cereal Straw	Dewatered Municipal Sewage Sludge	Principal Decision Resulting from the Framework
Systems assessment	Major variables include feedstock collection and storage, enzyme and solvent consumption, inhibitor control, product concentration, solvent recovery, process-water treatment, and residue utilization	Major variables include dewatering, methane leakage, high-pressure processing, aqueous-stream treatment, ammonia management, contaminant fate, and qualification of nutrient and char products	TEA and LCA priorities differ because the dominant burdens arise from structural fractionation and logistics for straw but from water management and contaminant control for sludge
Engineering implementation	Continuous high-solids feeding, mixing, solvent recycling, catalyst or enzyme lifetime, and seasonal feedstock supply require validation	Continuous wet feeding, reactor stability, ammonia inhibition, corrosion, solids handling, pathogen control, and multicycle aqueous-stream recycling require validation	Both pathways require validation using actual feedstocks under continuous operation, but their principal scale-up risks are different
Recycling strategy	Recover solvent and water when their quality remains compatible with fractionation and fermentation; use lignin-rich or solid residues internally when higher-value utilization is not justified; apply purification or partial discharge when impurities accumulate	Recycle centrate or hydrothermal aqueous streams only within the tolerance limits of AD or other receiving processes; recover nutrients when qualified; apply purification, bypass treatment, or partial discharge to control ammonia, salts, metals, and recalcitrant organics	Circularity is constrained by different limiting impurities and should not be evaluated solely by the percentage of material recycled

Note: The configurations are illustrative and are not intended to represent universally optimal pathways. Final pathway selection requires feedstock-specific compositional data, defined product specifications, regional logistics and market information, continuous-operation evidence, and TEA and LCA conducted using consistent baselines and system boundaries. AD, anaerobic digestion; HTL, hydrothermal liquefaction; HTC, hydrothermal carbonization; TEA, techno-economic analysis; LCA, life cycle assessment.

For dewatered municipal sewage sludge, the principal constraints are high residual moisture content, heterogeneous organic matter, substantial nitrogen, phosphorus, and ash contents, and the possible presence of pathogens, heavy metals, salts, and organic contaminants [27–29,41–43]. The front-end objective is therefore not extensive molecular fractionation but the removal of grit and extraneous materials, homogenization, mechanical dewatering, and, where required, the separation of liquid and solid streams according to their contaminant and nutrient contents. Because thermal drying would impose an additional energy burden, wet conversion should initially be considered. Readily biodegradable organic matter can be converted by AD, whereas dewatered digestate or other recalcitrant wet solids can be considered for HTC or HTL when the additional carbon and energy recovery offsets the requirements for high-pressure operation and aqueous-stream treatment [72–74,94,95]. The potential product portfolio includes biogas, recovered phosphorus or other nutrient products, and hydrochar or biocrude. However, nutrient products and solid carbon products should be counted as marketable coproducts only when contaminant concentrations and product properties satisfy the relevant requirements. Otherwise, stabilization, alternative use, energy recovery, or controlled disposal is required.

Recycling of centrate, hydrothermal aqueous streams, or recovered process water to AD should be limited by ammoniacal nitrogen, salinity, metals, recalcitrant organic compounds, and inhibition of the receiving biological process. Purification, bypass treatment, and partial discharge may therefore provide a more feasible strategy than complete water recycling [67,68,117–119].

The comparison shows that the same framework does not prescribe a single conversion train. For the relatively dry lignocellulosic residue, the principal decision is how much structural fractionation is required to produce carbohydrate and lignin streams compatible with their intended downstream uses. For the high-moisture sludge, the principal decision is how to minimize drying and extensive separation while controlling the partitioning of nitrogen, phosphorus, ash, metals, and other contaminants among gas, liquid, and solid streams. The corresponding circularity strategies also differ: the straw pathway emphasizes solvent recovery, process-water management, and internal use of lignin-rich residues, whereas the sludge pathway emphasizes aqueous-stream treatment, nutrient recovery, contaminant control, and conditional qualification of char or nutrient products. In both cases, an additional separation, conversion, or recycling unit should be retained only if it improves the predefined economic or environmental indicators relative to the baseline pathway without causing unacceptable burden shifting or preventing product qualification and market access.

7. Conclusions

The reviewed evidence shows that biorefinery pathway selection should begin with measured feedstock and stream properties rather than feedstock names or reactor-level conversion yields. Moisture state, biodegradability, lignocellulosic structure, ash composition, contaminants, and supply conditions determine front-end handling and conversion compatibility. Because separation changes component concentration, molecular structure, inhibitor levels, salt loading, and residual-stream composition, its severity should be determined by the requirements of the receiving process and final product.

The system-level advantages of process integration, multiproduct utilization, and recycling are conditional on stream yields and quality, purification and utility requirements, impurity accumulation, market capacity, and regional conditions. The illustrative straw and sludge applications show that the framework produces different priorities for structurally recalcitrant dry feedstocks and contaminant-bearing wet wastes rather than prescribing a single conversion train. Engineering feasibility must be assessed for the complete integrated chain because commercial maturity of a core reactor does not establish equivalent maturity for feedstock preparation, product upgrading, process-water management, and residual-stream treatment.

8. Limitations and Perspectives

The interpretation and application of this review are subject to several evidence and scope constraints. The available evidence differs in feedstock definition, measurement basis, operating scale, functional unit, system boundary, and coproduct treatment, which restricts direct quantitative comparison among studies. By design, the broad pathway-level scope involves selective rather than exhaustive treatment of individual reaction mechanisms, catalysts, microorganisms, reactor designs, and product-specific markets. The qualitative classifications used in the framework are literature-based screening judgments rather than outputs of a numerical scoring model, and the illustrative straw and sludge applications do not replace feedstock-specific TEA, LCA, process optimization, or engineering design. These constraints define the following research priorities.

(1) Separation and downstream conversion should be jointly optimized. In addition to reporting delignification, sugar release, or solid recovery, separation studies should characterize component concentrations, molecular structures, inhibitor levels, salt and ash contents, and residual solvents. The suitability of the resulting streams should then be validated in relevant fermentation, catalytic-conversion, or materials-production processes. Solvent recycling should be evaluated through multicycle experiments to quantify recovery losses, solvent-composition changes, and compatibility with downstream processes [67]. Process-water recycling should likewise be assessed over repeated cycles with attention to inhibitor and salt accumulation, purification demand, and purge requirements [68].

(2) Mass- and energy-balance analysis using actual feedstocks under continuous operating conditions should be strengthened. Research should cover feedstocks from different batches and seasons, feeding at high solids contents or loading rates, continuous conveying, heat integration, and the long-term stability of catalysts, enzymes, and microbial systems. Complete balances should be established for carbon, nitrogen, phosphorus, ash, salts, target contaminants, energy inputs, energy recovery, purge streams, and residual outputs across the integrated pathway.

(3) The comparability of process data and systems assessments should be improved. Experimental and modeling studies should clearly report feedstock composition, moisture-content basis, reaction conditions, product specifications, plant capacity, duration of continuous operation, and the disposition of residual streams. TEA and LCA studies should additionally report the cost year, functional unit, system boundary, energy mix, coproduct treatment method, baseline pathway, principal assumptions, and uncertainty range [164–167].

(4) The applicability boundaries of additional process and recycling units should be defined explicitly. Separation or recycling severity should be reduced, product uses should be reconsidered, or the corresponding unit should be omitted when intensive separation costs exceed the value generated by stream upgrading, when recycling causes continued accumulation of inhibitors or other impurities, when market capacity is insufficient to absorb the planned production volume, or when contaminant levels prevent compliance with applicable product requirements.

(5) Plant configurations should be determined according to regional resource availability, infrastructure, and market conditions. The economies of scale associated with centralized plants should be balanced against transport distances, seasonality, storage losses, and competing feedstock uses. Distributed pretreatment can reduce the long-distance transportation of low-density feedstocks but increases the number of processing nodes and the requirements for intermediate-stream management and quality control [153,157,158]. Machine learning, process simulation, and multiobjective optimization can link feedstock properties and stream quality with system-level indicators, but these models should be validated using independent feedstock samples and data obtained from continuous operation and scale-up studies [168,169].

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/biomass6050072/s1, Supplementary Note S1: Literature Search, Study Selection, and Evidence Synthesis; Figure S1: Workflow for Literature Identification, Study Selection, Evidence Extraction, and Synthesis; Table S1: Recorded Search Combinations and Their Standardized Database-Specific Forms; Table S2: Evidence Map of the Main Publications Included in the Review.

Author Contributions: Conceptualization, Q.L.; methodology, Q.L.; validation, Q.L. and W.Z.; formal analysis, Q.L.; investigation, Q.L., X.S., L.L., Y.T. and W.X.; resources, W.Z.; data curation, Q.L., X.S.,

L.L., Y.T. and W.X.; writing—original draft preparation, Q.L.; writing—review and editing, Q.L. and W.Z.; visualization, Q.L.; supervision, W.Z.; project administration, W.Z.; funding acquisition, W.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Fundamental Research Funds for the Central Universities of China (2662026DKPY006).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article. The structured evidence matrix used for the literature synthesis is provided in Supplementary Table S2.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic Digestion
DES	Deep Eutectic Solvent
GWP	Global Warming Potential
HTC	Hydrothermal Carbonization
HTL	Hydrothermal Liquefaction
LCA	Life Cycle Assessment
TEA	Techno-Economic Analysis
TRL	Technology Readiness Level
VFA	Volatile Fatty Acids

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