

Can biorefineries be fully circular? A life cycle thinking perspective on agro-industrial biorefineries

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Agro-industrial biorefineries are central to the circular bio-economy, but their circularity cannot be inferred solely from product recovery or process efficiency. Biorefineries integrating physicochemical pretreatments, biological conversion and extraction should be designed and assessed through a Life Cycle Thinking (LCT) perspective. Two major sources of non-circularity are contaminants present in biomass feedstocks and inhibitory or persistent compounds generated during processing. These compounds can impair enzymatic hydrolysis, anaerobic digestion, nutrient recovery, digestate quality and the safe reintegration of residual streams into agricultural soils. Although many unit operations have reached technological maturity, integrated assessments linking upstream decisions with downstream environmental performance remain limited. A fully circular biorefinery should therefore be defined by its ability to preserve residual-stream suitability for biological valorisation and safe environmental reintegration. Integrating Life Cycle Assessment, Material Flow Analysis, Substance Flow Analysis and Safe-and-Sustainable-by-Design provides a comprehensive framework for identifying trade-offs and supporting environmentally safe, resource-efficient biorefineries.

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Beyond resource recovery: defining circularity in agro-industrial biorefineries

The transition from a linear economy towards a circular bioeconomy has transformed agro-industrial residues from disposal burdens into strategic feedstocks for integrated biorefineries [1,2]. Agricultural and food-processing residues are generated in large, heterogeneous quantities. They can be converted into fuels, chemicals, energy, biofertilizers, animal feed, and other value-added products, thereby reducing waste generation and dependence on fossil resources [3]. In this context, biorefineries are increasingly recognised as key enabling platforms for the circular bioeconomy, particularly when biomass is valorised through cascading strategies that prioritise the recovery of high-value products before energy production and final nutrient recycling [2,4,5].

This circularity perspective should extend beyond the biorefinery's physical boundaries to the agricultural and industrial systems that generate the residues. Upstream practices should be designed to minimise hazardous inputs, facilitate biomass separation and preserve the suitability of residual streams for subsequent valorisation [3,6]. Source control is therefore a central circular economy principle: preventing contamination at the production stage is generally more effective, less costly, and more reliable than attempting to remove contaminants through downstream treatment [7,8]. In this review, a fully circular biorefinery is defined as a system that maintains biomass-derived resources in productive use through cascading valorisation while preserving residual-stream suitability for further biological conversion and safe environmental reintegration, without contaminant transfer or burden shifting. Circularity is therefore related to, but distinct from, resource efficiency, environmental sustainability and safety. Resource efficiency concerns the effective use and recovery of materials and energy, whereas environmental sustainability addresses the broader life-cycle impacts associated with such resource use and recovery. Safety concerns the absence or acceptable control of hazards associated with recovered products and residual streams and represents a prerequisite for their recirculation. Full circularity requires these dimensions to be considered jointly, because high resource recovery alone

cannot close material loops if it results in unacceptable environmental impacts or unsafe residual streams.

Accordingly, recovering several products from the same biomass at high efficiency does not necessarily make a biorefinery circular [1,5], particularly when such recovery entails high chemical or energy inputs, emissions, contaminated side streams, or residual wastes unsuitable for further use [4,9].

This limitation is particularly relevant when physico-chemical pretreatments or extraction steps precede biological conversion, as upstream processes can alter microbial activity, residual biomass quality, and the feasibility of safely returning nutrients to agricultural soils [10–12]. Evaluating these interactions requires a system-wide perspective rather than optimisation of isolated unit operations. Figure 1 illustrates how upstream process decisions propagate through the value chain and ultimately determine residual stream quality and the feasibility of safely closing material loops. Life Cycle Thinking (LCT) provides an appropriate framework by considering feedstock selection, pretreatment, conversion, product recovery, residue management and the environmental fate of residual streams. Recent methodological reviews emphasise the need to evaluate end-of-life management, uncertainty analysis, and future circularity options, rather than focusing on individual conversion technologies [9].

Adopting a Life Cycle Thinking perspective is therefore essential for distinguishing genuine circularity from simple process optimisation and for identifying the trade-offs among product recovery, biological conversion,

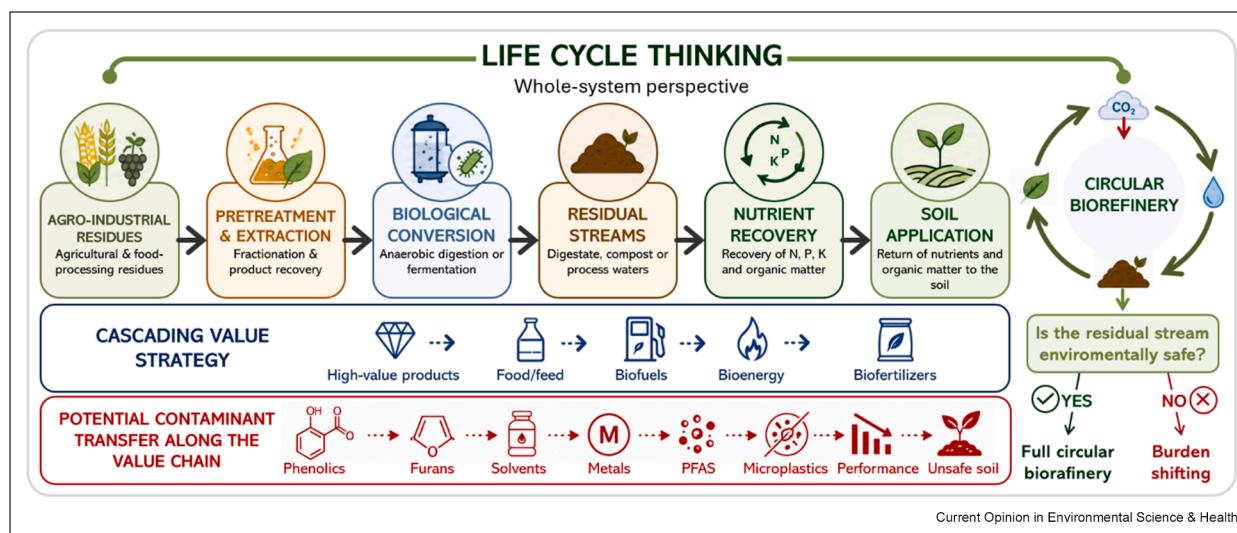
nutrient recycling, and environmental reintegration [1,13]. Rather than evaluating individual technologies in isolation, LCT identifies the decision points at which upstream process choices determine downstream environmental performance, residual-stream quality, and the feasibility of closing material loops.

The literature included in this review was identified through a targeted search in Scopus and Google Scholar databases, primarily covering studies published between 2021 and 2026. Particular emphasis was placed on studies published in 2024–2026 to capture the most recent developments in this rapidly evolving field, while earlier studies were included when necessary to provide relevant background or supporting evidence. The main search terms included combinations of “biorefinery”, “circular economy”, “Life Cycle Thinking”, “Life Cycle Assessment”, “anaerobic digestion”, “pretreatment”, “contaminants”, “digestate”, and “nutrient recovery”. Peer-reviewed studies were selected based on their relevance to the scope and specific topics addressed in the review.

Sources of non-circularity in biorefineries: biomass-derived and process-induced contaminants

This section examines the life-cycle decision points where contaminants and process trade-offs compromise circularity. From a Life Cycle Thinking perspective, these decision points become environmental hotspots because contaminants generated or introduced upstream may propagate across successive processing stages, ultimately affecting downstream biological conversion, nutrient recovery and residual-stream quality.

Figure 1



Conceptual representation of a Life Cycle Thinking approach for agro-industrial biorefineries. Circularity is achieved only when upstream process choices preserve the quality of residual streams, enabling safe nutrient recovery and environmental reintegration while preventing contaminant transfer and burden shifting.

Two interacting sources of contamination constrain full biorefinery circularity: compounds originally present in the biomass and compounds generated, solubilised, concentrated or introduced during processing. Even before pretreatment, lignocellulosic and agro-industrial residues differ markedly in the content of phenolics, tannins, organic acids, and other inhibitory constituents, depending on biomass origin, harvest conditions, and storage [14]. Pretreatment further reshapes this profile. Acidic and thermal treatments can promote the formation of furans, weak acids and soluble phenolics, whereas alkaline pretreatments may increase the release of lignin-derived phenolics, such as vanillin, syringaldehyde, 4-hydroxybenzaldehyde, pinicaldehyde, ferulic acid, and cinnamic acid [14,15]. Inhibitor formation is therefore not only a feedstock property; it is also a design variable that can be partially controlled through pretreatment severity, residence time, pH, chemical choice and downstream washing [15].

The main contaminant classes discussed in this review are summarised in Table 1. Heavy metals and trace elements constitute another source of non-circularity. Although some are essential microbial cofactors, excessive bioavailable concentrations can inhibit anaerobic digestion (AD) and compromise digestate reuse [16,17]. Solvents used to recover high-value compounds, whether conventional (e.g., ethanol, n-hexane) or marketed as “green” alternatives (e.g. D-Limonene, Cyrene, 2-methyloxolane), may carry over into residual biomass destined for AD. Recent batch test studies showed strongly solvent-specific responses; D-Limonene severely impacted the process, whereas ethanol and n-hexane improved biomethane production at low concentrations under the tested conditions [12]. These results indicate that solvent “greenness” or renewability does not necessarily predict AD compatibility.

Inhibitors may also persist, transform, and interact throughout the entire process chain. A full-scale diagnostic of a sludge treatment plant identified humic-metal complexes, rather than a single isolated compound, as the dominant persistent inhibitory factor limiting circularity [18]. This illustrates why contaminant speciation, complexation and mixture effects must be considered together when determining whether residual streams remain suitable for biological valorisation and subsequent environmental reintegration. Identifying where contaminants originate and how they propagate along the value chain is fundamental for prioritising interventions within a Life Cycle Thinking framework.

Process integration challenges: when upstream valorisation affects downstream biological conversion

Physical, chemical and extraction-based treatments illustrate a central Life Cycle Thinking principle:

optimising individual unit operations does not necessarily improve overall biorefinery performance because pretreatment decisions propagate through downstream biological conversion, nutrient recovery and residual-stream quality [32,33]. Depending on operating conditions, furans, phenolics, weak organic acids, pseudo-lignin and residual chemicals may inhibit enzymatic hydrolysis, fermentation or AD [11,34]. From a Life Cycle Thinking perspective, pretreatment represents one of the earliest design decisions because its effects propagate throughout downstream biological conversion, nutrient recovery and residual-stream quality.

These consequences become evident when pretreated biomass is subjected to biological valorisation. Both feedstock recalcitrance and pretreatment severity influence AD performance [35]. Lignin can limit enzyme accessibility and adsorb cellulases, thereby reducing hydrolysis and subsequent acetogenic and methanogenic conversions; conversely, severe hydrothermal or acid pretreatment may generate furfural and hydroxymethylfurfural, as well as related inhibitors that decrease methane production [11,27].

Pretreatment effectiveness is strongly feedstock-dependent, and improved fractionation does not necessarily translate into enhanced anaerobic biodegradability [36]. Residual solvents, extracted bioactive compounds, and other process-derived chemicals may persist along the chain, affecting microbial community stability, methane or fermentation yields, nutrient recovery, and the quality of residual streams. Maximising extraction yield is therefore insufficient if the processed biomass subsequently loses biological valorisation potential or becomes unsuitable for safe recycling.

Closing the loop: residual streams, nutrient recovery and safe land application

Within a Life Cycle Thinking framework, residual streams provide the ultimate test of circularity: a biorefinery can be considered circular only if digestate, compost, biochar and recovered nutrients can be safely returned to soil or other regulated land-based applications without shifting environmental burdens. The relationships among upstream process decisions, downstream bottlenecks, circularity impacts, and the assessment tools are summarised in Table 2.

Performance-based analysis of 23 full-scale digesters identified threshold concentrations of TAN, potassium and boron beyond which phytotoxicity occurred regardless of feedstock origin. Once these thresholds were exceeded, end-of-pipe treatments could not restore digestate quality, highlighting the importance of preventive feedstock and process management [37].

Table 1

Main contaminant classes encountered in agro-industrial biorefineries, their origin, representative examples, impacts on anaerobic digestion and circularity, and mitigation and management strategies.

Contaminant class	Origin and representative examples	Main effects on AD and circularity	Mitigation and management strategies	Refs.
 Phenolic compounds (lignin-derived)	Naturally present in lignin-rich feedstocks, tannins and polyphenols, or generated during severe acid, alkaline and thermal pretreatments. Representative compounds include vanillin, syringaldehyde, hydroxybenzaldehydes, ferulic acid, cinnamic acid and phenyl acids.	Toxicity to acetogens and methanogens; membrane and enzyme inhibition; slower hydrolysis, longer lag phases and reduced methane production. Toxicity may increase under alkaline or thermophilic conditions.	Control of pretreatment severity; washing or overliming; biological detoxification; co-digestion; adsorption using biochar or activated carbon; use of acclimated inocula.	[11] [19]
 Furans and carbohydrate-derived degradation products	Generated by acid and thermal degradation of cellulose and hemicellulose, particularly in sugar-rich feedstocks. Main products include furfural, 5-hydroxymethylfurfural (5-HMF), levulinic acid and related dehydration products.	Interference with redox reactions and central metabolism; accumulation of intermediates; delayed methanogenesis and reduced methane production. Partial microbial detoxification may occur at low concentrations.	Milder acid and thermal conditions; optimisation of pH and residence time; chemical detoxification such as overliming; microbial adaptation and gradual loading.	[20]
 Heavy metals and trace elements	Introduced through agro-industrial residues, manures, sewage sludge, industrial by-products, additives and co-substrates. Relevant elements include Cd, Cu, Zn, Ni, Cr and Pb, as well as essential trace elements such as Co, Mo, Se and Fe.	Essential cofactors at trace concentrations, but toxic at elevated levels through protein, membrane and enzyme disruption. Excess concentrations inhibit methanogenesis, reduce biogas production and may compromise digestate reuse; bioavailability depends strongly on speciation and complexation.	Feedstock screening and monitoring; control of pH, sulfide and metal speciation; use of sorbents or complexing agents; balanced micronutrient dosing; exclusion or pretreatment of highly contaminated streams.	[17] [21] [22]
 Residual solvents (extraction carryover)	Carry-over from the extraction of high-value compounds because of incomplete solvent recovery, phase separation or washing. Relevant solvents include D-Limonene, Cyrene, 2-methyloxolane, ethanol, methanol and n-hexane.	Strongly solvent- and concentration-dependent effects. D-Limonene may severely inhibit or suppress methane production, whereas ethanol and n-hexane may shorten lag phases or increase BMP. Other solvents may induce microbial adaptation or undergo partial biotransformation.	Selection of AD-compatible solvents; integration of extraction and biological conversion design; efficient solvent recovery, washing and phase separation; inoculum acclimation; minimisation of highly inhibitory solvent carry-over.	[12] [23]
 Humic substances and metal-organic complexes	Formed or accumulated in sludge treatment lines and systems with long residence times. Humic and fulvic substances may interact with Fe, Cu, Zn and other metals, producing persistent humic-metal complexes and aggregates.	Persistent and potentially poorly reversible inhibition of methanogenesis; reduced biogas recovery; impaired digestate quality and increased ecotoxicological risk. Effects may become particularly relevant at full scale.	Full-scale monitoring and multidimensional diagnostics; control of metal inputs and humic accumulation; adsorption or precipitation; optimisation of sludge treatment lines; alternative valorisation of humic-rich streams.	[24] [25]

Table 1 (continued)

Contaminant class	Origin and representative examples	Main effects on AD and circularity	Mitigation and management strategies	Refs.
 Lignin (structural and soluble)	Naturally present as a structural component of lignocellulosic biomass and partially solubilised or transformed during pretreatment, extraction and fractionation. Relevant forms include native lignin, soluble fragments and lignin–solvent complexes.	Physical shielding of polysaccharides, adsorption of enzymes and microbial cells, low biodegradability and possible toxicity of soluble fractions. These effects reduce hydrolysis, accessible volatile solids and effective methane potential.	Selective lignin removal and separate valorisation; tailored pretreatment; lignin-tolerant microbial consortia; surfactants or mediators to limit lignin–enzyme interactions; integrated lignin recovery.	[26] [27]
 Volatile fatty acids and aromatic acids	Generated during acidogenesis and accumulated under organic overloading, process imbalance or inhibition. Relevant compounds include acetate, propionate, butyrate and longer-chain VFAs, together with phenylacetic and phenylpropionic acids.	Readily converted substrates at moderate concentrations, but inhibitory when accumulated. Excess VFAs cause acidification and proton stress, while phenyl acids may specifically inhibit CO ₂ -reducing methanogens and delay methane production.	Control of organic loading rate and hydraulic retention time; alkalinity and pH management; staged feeding; dilution or removal of highly acidified streams; microbial adaptation.	[28]
 Ammonia and salt stress	Ammonia is released from protein-rich feedstocks such as manure, food waste and fish residues, while salts may be introduced or concentrated through feedstocks and nutrient-recovery operations. Relevant species include TAN (NH ₄ ⁺ /NH ₃), Na ⁺ , K ⁺ and Cl [−] . Introduced through sewage sludge, food waste, industrial residues, contaminated compost and digestate, often because of upstream product use. Relevant contaminants include PFAS, microplastics and associated additives, antibiotic residues and antibiotic resistance genes (ARGs).	Free ammonia disrupts intracellular pH and inhibits methanogens, particularly at high pH and temperature. High ionic strength and salinity impair microbial activity, aggregation and process stability, potentially causing partial failure. High persistence and limited biodegradability; transfer to digestate and agricultural soils; possible disruption of microbial communities; uncertain long-term ecological and health risks that may prevent safe land application.	Balanced feedstock mixing and C/N ratio; control of pH and temperature; ammonia stripping or dilution; gradual microbial adaptation; nutrient-recovery configurations that avoid recycling concentrated salt loads into AD.	[29–31]
 Emerging contaminants			Upstream source control and SSbD; suspect and non-target screening; restrictions on contaminated feedstocks and land application; adsorption, oxidation or thermal treatment for highly contaminated streams.	[7] [8,22]

Beyond threshold-based phytotoxicity, the agronomic value of residual streams depends on their effects on soil structure, water retention and microbial activity, which require appropriate control of nutrient loads, salinity and contaminants. Post-digestion treatments, such as composting, pelletisation and biochar production, may reduce phytotoxicity and improve handling, but also generate trade-offs. For example, composting concentrates valuable nutrients such as phosphorus and potassium (20–62%), while simultaneously increasing zinc concentrations by up to 146% [38].

Biochar exposes a fundamental gap between laboratory conditions and field reality: controlled incubations achieve near 99.8 % carbon persistence, whereas field

studies document annual losses of 17–93% [39,40]. Some biochar feedstocks contain phytotoxic Zn, Cd, and Cr [45], underscoring the importance of field validation before claiming circularity.

Upstream substrate selection also drives downstream safety. Agricultural substrates may require nutrient supplementation or co-digestion, but the choice of co-substrate can introduce hidden burdens. Wastewater treatment sludges, for example, often used in co-digestion with agro-industrial streams, accumulate heavy metals and persistent organics at unpredictable levels [45], the composition varying across treatment plants and time, creating unmanageable environmental and health hazards that cannot be controlled through

Table 2

Decision-support framework linking upstream process choices to downstream circularity outcomes in agro-industrial biorefineries.

LIFE-CYCLE decision POINT	Primary GOAL	Downstream bottlenecks & risks	Specific impacts on circularity	Assessment tools & frameworks
 Feedstock selection	Maximise biomass valorisation Preserve biomass quality Reduce contaminant inputs [2,3,5]	Biomass variability Native phenolics Heavy metals Organic acids [14–17]	Variable biodegradability Microbial inhibition Lower methane yield Reduced digestate quality [11,17,27]	Source control SSbD Substance flow analysis (SFA) [6,7]
 Pretreatment	Improve biomass accessibility Enhance fractionation Increase product recovery [11,14,15]	Furans Phenolics Pseudo-lignin Weak acids [11,20,27]	Enzyme inhibition Lower biodegradability Reduced methane production Inhibitory carry-over [26,27,36]	Life cycle assessment (LCA) Ex-ante environmental assessment [1,9]
 Extraction strategy	Recover high-value compounds Minimise solvent losses [3,12]	Residual solvents Bioactive carry-over Solvent persistence [12,23]	AD inhibition Microbial community shifts Reduced biomethane [12,23]	BMP tests Solvent fate assessment SFA [12,41]
 Process integration	Cascade valorisation Optimise overall process efficiency [4,36,42]	Inhibitor carry-over Trade-offs between unit operations Burden shifting [9,11,12]	Reduced conversion efficiency Lower nutrient recovery Poor residual stream quality [26,27,42]	Life cycle Thinking (LCT) Circularity indicators [1,6,9]
 End-of-life management	Close nutrient loops Safe environmental reintegration [10,37]	PFAS Microplastics ARGs Heavy metals Phytotoxicity [7,8,22,43]	Soil contamination risk Reduced agronomic value Failure to achieve true circularity [10,37,44]	LCA + MFA + SFA SSbD Agronomic & ecotoxicological indicators [1,6,9,10]

process adjustments. Livestock manure generally offers a predictable contaminant profile and lower variability, although availability and competing agronomic uses can constrain supply. Carbon-based amendments may boost digestion efficiency [46], but they also introduce additional material flows that circularity assessments should account for. For this reason, feedstock sourcing, end-product valorisation and safety should be evaluated within the same decision framework rather than as separate stages.

The quality of compost and digestate is primarily determined by upstream feedstock selection, traceability and process control rather than by downstream treatment alone. Although source-segregated agro-industrial residues generally contain fewer anthropogenic contaminants than mixed municipal biowaste, persistent pollutants—including heavy metals, pesticide residues, pharmaceuticals and emerging contaminants such as microplastics—may still survive processing and be transferred to agricultural soils. Consequently, integrated quality management throughout the biorefinery, from source separation to contaminant monitoring, is

essential to ensure safe nutrient recycling and genuine circularity [47].

Life Cycle Thinking for designing fully circular biorefineries

Whether a biorefinery can be considered circular depends on how upstream decisions affect downstream biological conversion, residual stream quality, and environmental reintegration. LCT provides the systems-level framework for linking feedstock selection, pretreatment, conversion, residue management and end-of-life resource recovery. By identifying environmental hotspots, contaminant pathways and resource-efficiency trade-offs, LCT enables ex-ante optimisation of process configurations, embedding circularity as a design criterion rather than a retrospective performance indicator [9]. In this context, Safe-and-Sustainable-by-Design (SSbD) is particularly relevant for agro-industrial biorefineries because it extends circularity assessment beyond product recovery, requiring that feedstock selection, pretreatment, solvent use, biological conversion, and residual-stream management be designed to

minimise hazards, contaminant transfer, and burden shifting throughout the life cycle [6].

Operationalising this perspective requires more than Life Cycle Assessment alone. While LCA quantifies environmental impacts across the system, Material Flow Analysis (MFA) follows the circulation of biomass, carbon and nutrients, whereas Substance Flow Analysis (SFA) identifies the pathways, accumulation and fate of contaminants introduced or generated during processing. When combined with circularity indicators, these tools can evaluate whether recovered products and residual streams remain suitable for safe recirculation, rather than merely shifting impacts across life-cycle stages.

A practical illustration of this integrated approach is provided by Blumenthal et al. [48], who combined MFA and LCA to compare the current decentralised management of sewage sludge, agri-food residues and OFMSW with a centralised biorefinery recovering PHA, struvite and energy. Their analysis showed that greater resource recovery did not uniformly translate into improved environmental performance: although the biorefinery reduced climate-change impacts by 22%, its higher chemical demand generated trade-offs in other impact categories, while the choice of PHA extraction route strongly affected the overall environmental performance. Extending this approach with SFA would enable the fate and transfer of specific contaminants to be tracked across recovered products and residual streams, while SSbD could use these combined MFA, SFA and LCA outputs to guide the selection of process configurations that maximise resource recovery without compromising environmental performance or downstream safety. This illustrates how full circularity can be operationally assessed through combined criteria for resource recovery, life-cycle impacts, contaminant transfer and residual-stream quality.

Circularity ultimately depends on whether recovered nutrients remain agronomically functional without transferring contaminants to agricultural soils [10]. End-of-life quality is therefore not a secondary outcome, but an integral part of biorefinery performance. Ex-ante Life Cycle Assessment indicates that advanced liquid digestate treatments, such as microalgae–bacteria-based processes, may reduce environmental impacts compared with direct land application by improving nutrient recovery, although their performance remains highly scenario-dependent [49,50]. At the same time, the persistence of contaminants, including heavy metals and microplastics in digestate, highlights the need to evaluate nutrient recovery and contaminant fate simultaneously rather than independently to support genuinely circular biorefinery design [49].

Current assessment methods still leave important gaps. Environmental evaluations often overlook end-of-life

stages, contaminant pathways, mixture effects and the quality of residual streams, although these elements ultimately determine whether biological cycles can be safely closed. Future research should develop digital, predictive decision-support frameworks that integrate process modelling with LCA, MFA, SFA, contaminant fate analysis, and SSbD principles to enable ex-ante optimisation of circular biorefinery configurations under realistic industrial conditions.

Ultimately, the value of Life Cycle Thinking lies not only in quantifying impacts but also in supporting design decisions that prevent the propagation of burdens across the entire biorefinery life cycle.

Conclusions

Agro-industrial biorefineries cannot be considered fully circular because they maximise biomass valorisation or recover multiple products. Circularity depends on how process decisions affect the entire value chain, from feedstock pretreatment to the environmental fate of residual streams. The evidence reviewed here shows that contaminants generated or transferred during processing can compromise biological conversion, nutrient recovery, and the safe reuse of digestate and other by-products. Life Cycle Thinking provides a framework for identifying these interactions and integrating process efficiency with environmental safety from the earliest stages of technology development.

Future research should therefore prioritise predictive and integrated assessment frameworks that combine process performance, contaminant fate, and end-of-life quality to support the design of genuinely circular agro-industrial biorefineries. Particular attention should be given to the soil–plant interface, including the long-term agronomic performance and bioavailability of recovered nutrients, their effects on soil quality and plant nutrition, and the potential accumulation and transfer of contaminants following repeated land application.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT (OpenAI) and Grammarly to improve the manuscript's readability, language, and clarity. After using this tool, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the published article.

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References

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest

** of outstanding interest

- Liu Y, Lyu Y, Tian J, et al.: **Review of waste biorefinery development towards a circular economy: from the perspective of a life cycle assessment.** *Renew Sustain Energy Rev* 2021, **139**, 110716.
- Yaashikaa PR, Senthil Kumar P, Varjani S: **Valorization of agro-industrial wastes for biorefinery process and circular bio-economy: a critical review.** *Bioresour Technol* 2022, **343**, 126126.
- Volpato Maroldi W, de Andrade Arruda Fernandes I, Demczuk Junior B, et al.: **Waste from the food industry: innovations in biorefineries for sustainable use of resources and generation of value.** *Bioresour Technol* 2024, **413**, 131447.
- This review provides a comprehensive and up-to-date overview of food industry biorefineries, highlighting recent innovations in biomass valorisation, cascade processing and resource recovery within the circular bioeconomy.
- Arias A, Estévez-Rivadulla S, Rebolledo-Leiva R, et al.: **Boosting the transition to biorefineries in compliance with sustainability and circularity criteria.** *J Environ Chem Eng* 2024, **12**, 113361.
- Summarises practical approaches for integrating sustainability and circularity criteria into biorefinery design, complementing the Life Cycle Thinking perspective adopted in this review.
- Arias A, Feijoo G, Moreira MT: **Biorefineries as a driver for sustainability: key aspects, actual development and future prospects.** *J Clean Prod* 2023, **418**, 137925.
- Larrea-Gallegos GM, Hofer S, Hofstätter N, et al.: **Integrate & balance aspects for safe and sustainable innovation: needs analysis on SSbD categories and product development stage requirements to cover the entire life cycle.** *Comput Struct Biotechnol J* 2025, **29**:201–221.
- Introduces a Safe-and-Sustainable-by-Design framework supporting the integration of safety, sustainability and circularity considerations from upstream process design to end-of-life management.
- Bünemann EK, Reimer M, Smolders E, et al.: **Do contaminants compromise the use of recycled nutrients in organic agriculture? A review and synthesis of current knowledge on contaminant concentrations, fate in the environment and risk assessment.** *Sci Total Environ* 2024, **912**, 168901.
- Provides a comprehensive assessment of contaminant occurrence, environmental fate and associated risks in recycled nutrient streams, offering an important framework for evaluating safe nutrient recycling within circular bioeconomy systems.
- Harirchi S, Lak M, Dalkilic K, et al.: **Impact of emerging contaminants on inhibited steady-state anaerobic digestion: a review of the fate and degradation characteristics of antibiotics, PFAS, and microplastics.** *Rev Environ Sci Biotechnol* 2026, **25**:32.
- Gaffey J, Collins MN, Styles D: **Review of methodological decisions in life cycle assessment (LCA) of biorefinery systems across feedstock categories.** *J Environ Manag* 2024, **358**, 120813.
- Critically evaluates methodological choices in Life Cycle Assessment of biorefineries and identifies current limitations and future research needs for robust system-wide sustainability assessment.
- Choi HJ, Tahmid M, Barrera L, et al.: **Nutrient separation systems: current progress and future opportunities.** *ACS EST Eng* 2026, **6**:567–596.
- Guo H, Zhao Y, Chang J-S, et al.: **Inhibitor formation and detoxification during lignocellulose biorefinery: a review.** *Bioresour Technol* 2022, **361**, 127666.
- Pedullà A, Ferreri M, Bonaccorsi L, et al.: **Impact of emerging and traditional solvents on anaerobic digestion in biorefinery processes.** *ACS Sustainable Chem Eng* 2025, **13**: 4729–4739.
- Philippini RR, Shafiei-Alavijeh R, Peeters E, et al.: **Life cycle assessment in biorefineries: foundations, methodologies, and future directions.** In *Biorefineries in circular bioeconomy: reactor configurations analysis [Internet]*. Edited by Chandel AK, Sundaramurthy S, Singapore: Springer Nature; 2025:297–334, https://doi.org/10.1007/978-981-95-3913-0_12 [cited 2026 July 22].
- Poddar BJ, Nakhate SP, Gupta RK, et al.: **A comprehensive review on the pretreatment of lignocellulosic wastes for improved biogas production by anaerobic digestion.** *Int J Environ Sci Technol* 2022, **19**:3429–3456.
- Fan J, Lu Y, An N, et al.: **Pretreatment technologies for lignocellulosic biomass: research progress, mechanisms, and prospects [Internet]** *BioRes* 2025, **20** [cited 2026 July 16].
- Sadeghpour A, Javid M, Koduru S, et al.: **Heavy metals in bio-energy crop production, biomass quality, and biorefinery: global impacts and sustainable management strategies.** *Biores Bioprod* 2025, **1**:2.
- Pires RHM, Tomasino MP, Simon S, et al.: **Impact of trace elements (total and labile fraction) on the anaerobic digestion activity and microbial community structure.** *Ecotoxicol Environ Saf* 2025, **289**, 117461.
- Song Q, Yu Y, Wang X, et al.: **Humic–metal complexes as dominant anaerobic digestion inhibitor: multidimensional diagnostic framework for 16,200-tonne full-scale sludge treatment plant.** *Bioresour Technol* 2025, **437**, 133145.
- Wunderer M, Unterkircher M, Schmidhofer A, et al.: **Phenyl acid induced inhibition of methanogenesis in CO₂ reducing organisms.** *Environ Microbiol Rep* 2025, **17**, e70082.
- Wu X, Xia A, Feng D, et al.: **Intensifying anaerobic digestion of 5-hydroxymethylfurfural via granular activated carbon supplementation.** *Int J Hydrogen Energy* 2024, **52**:71–82.
- Salazar-Batres KJ, Moreno-Andrade I: **Review of the effects of trace metal concentrations on the anaerobic digestion of organic solid waste.** *Bioenergy Res* 2025, **18**:24.
- Liu H, Yuan X, Yao Y, et al.: **Microplastics, antibiotics, and heavy metals in anaerobic digestion systems: a critical review of sources, impacts, and mitigation strategies.** *Recycling* 2025, **10**:116.
- Szaja A, Montusiewicz A, Cydzik-Kwiatkowska A, et al.: **Enhancing methane production through co-digestion of sewage sludge, citrus waste and brewery spend grain with natural zeolite: mechanisms and microbiome analysis.** *GCB Bioenergy* 2025, **17**, e70029.
- He Z-W, Wang F, Zou Z-S, et al.: **Recent advances and perspectives in roles of humic acid in anaerobic digestion of waste activated sludge.** *Chem Eng J* 2023, **466**, 143081.
- Liu Q, Xu Y, Li Y, et al.: **Carbon quantum dots in-situ relieve humic acids inhibition on methanogens while significantly increasing the abundance of Methanosarcinaceae.** *J Clean Prod* 2023, **419**, 138258.
- Correa S, Passos F, Rallini M, et al.: **Ionic liquid pre-treatment of olive pomace for lignin recovery enhances microbial-driven methane production during co-digestion with pig slurry.** *J Environ Chem Eng* 2026, **14**, 122339.
- Sun Z, Liu Q, Li Y, et al.: **Deciphering the impact of lignin on anaerobic digestion: focus on inhibition mechanisms and methods for alleviating inhibition.** *ACS Omega* 2024, **9**: 44033–44041.

28. Mu L, Wang Y, Xu F, et al.: **Emerging strategies for enhancing propionate conversion in anaerobic digestion: a review.** *Molecules* 2023, **28**:3883.
 29. Yang J, Zhang J, Du X, et al.: **Ammonia inhibition in anaerobic digestion of organic waste: a review.** *Int J Environ Sci Technol* 2025, **22**:3927–3942.
 30. Bucci L, Ghiotto G, Zampieri G, et al.: **Adaptation of anaerobic digestion microbial communities to high ammonium levels: insights from strain-resolved metagenomics.** *Environ Sci Technol* 2024, **58**:580–590.
 31. James A, Shi Y, Hussain SS, et al.: **Mitigation of ammonia inhibition during anaerobic digestion: a comprehensive update.** *AEE* 2025, **1**. 0–0.
 32. Li H, Wu H, Yu Z, et al.: **CO₂-Enabled biomass Fractionation/Depolymerization: a highly versatile pre-step for downstream processing.** *ChemSusChem* 2020, **13**: 3565–3582.
 33. Zhao L, Sun Z-F, Zhang C-C, et al.: **Advances in pretreatment of lignocellulosic biomass for bioenergy production: challenges and perspectives.** *Bioresour Technol* 2022, **343**, 126123.
 34. Kumar V, Yadav SK, Kumar J, et al.: **A critical review on current strategies and trends employed for removal of inhibitors and toxic materials generated during biomass pretreatment.** *Bioresour Technol* 2020, **299**, 122633.
 35. Gallipoli A, Angelini F, Angelini S, et al.: **Thermally enhanced solid–liquid separation process in food waste biorefinery: modelling the anaerobic digestion of solid residues** [Internet]. *Front Bioeng Biotechnol* 2024 [cited 2026 July 30];12.
 36. Oliva A, Tan LC, Papirio S, et al.: **Effect of methanol-organosolv pretreatment on anaerobic digestion of lignocellulosic materials.** *Renew Energy* 2021, **169**:1000–1012.
 37. Anacleto TM, Oliveira HR, Carraro G, et al.: **Performance-based criteria for safe and circular digestate use in agriculture.** *Sci Rep* 2025, **16**:3369.
- Introduces performance-based criteria linking digestate quality with safe agricultural reuse, providing practical thresholds for closing nutrient loops in circular biorefineries.
38. Li F, Feng B, Zha X, et al.: **Insights into physiochemical and biological characteristics of pig manure during anaerobic digestion and sheep manure during composting.** *Fermentation* 2025, **11**:307.
 39. Lyu J, Zimmerman AR: **Large losses of pyrogenic carbon (Biochar) and native soil carbon during a 15-Month field Study in North Florida, USA.** *Agriculture* 2025, **15**:300.
 40. Schmidt H, Abiven S, Cowie A, et al.: **Biochar Permanence—A policy commentary.** *GCB Bioenergy* 2025, **17**, e70092.
 41. Martinez-Burgos WJ, Bittencourt Sydney E, Bianchi Pedroni, Medeiros A, et al.: **Agro-industrial wastewater in a circular economy: characteristics, impacts and applications for bio-energy and biochemicals.** *Bioresour Technol* 2021, **341**, 125795.
 42. Castro LEN, Barroso TLCT, Sganzerla WG, et al.: **Subcritical water hydrolysis of grape pomace as a sustainable pre-treatment for anaerobic digestion in a biorefinery concept.** *Fuel* 2024, **363**, 130899.
 43. Ali AM, Bruvold AS, Nesse AS, et al.: **Suspect and non-target screening of contaminants of emerging concern in Norwegian biogas digestates.** *Environ Chem Ecotoxicol* 2025, **7**: 2241–2250.
 44. Bernal MP: **An overview of conventional and emerging aspects of compost: quality indicators for agricultural uses, emerging contaminants and technological innovations.** *Front Sustain Food Syst* 2026, **10**, 1785912.
 45. Fazzino F, Paone E, Pedullà A, et al.: **A new biorefinery approach for the full valorisation of anchovy residues: use of the sludge generated during the extraction of fish oil as a nitrogen supplement in anaerobic digestion.** *Appl Sci* 2021, **11**, 10163.
 46. Pedullà A, Calabrò PS: **Investigation into the effect of carbon-based materials on batch anaerobic digestion of citrus processing By-Products.** *Gases* 2026, **6**:6.
 47. Mancuso G, Habchi S, Maraldi M, et al.: **Comprehensive review of technologies for separate digestate treatment and agricultural valorisation within circular and green economy.** *Bioresour Technol* 2024, **409**, 131252.
- Critically reviews digestate treatment technologies and their integration into circular nutrient management, supporting the discussion on residual-stream quality.
48. Blumenthal E, Estévez S, Fatone F, et al.: **Decentralised treatment versus integrated biorefinery recovery of poly-hydroxyalkanoates and struvite from urban and organic waste: a life cycle assessment approach.** *J Water Proc Eng* 2026, **81**, 109279.
 49. Penaranda D, Casagli F, Morales M, et al.: **Ex-ante LCA for circular resource management of liquid digestate, by predictive modeling of algae–bacterial processes.** *J Ind Ecol* 2025, **29**:1568–1582.
 50. Pascu LF, Petre VA, Cimpean IA, et al.: **Managing PFAS in sewage sludge: exposure pathways, impacts, and treatment innovations.** *J Xenobiot* 2025, **15**:135.