COMPARING CELLULOSE ISOLATION ROUTES FROM LIGNOCELLULOSIC AND AGRO-FOOD BIOMASS: A STRUCTURED REVIEW OF YIELD, PURITY AND CRYSTALLINITY

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Abstract

Cellulose from agricultural, food-processing and forest residues underpins microcrystalline cellulose, cellulose nanocrystals and other bio-based materials, but primary studies test different isolation routes on different feedstocks and report outcomes on non-equivalent bases. This structured review maps isolation routes for lignocellulosic and agro-food biomass in 57 studies published in 2018–2026 (50 from an author-compiled collection and 7 from targeted searches) and compares them on cellulose yield, purity, crystallinity index (CrI), thermal stability and process sustainability. Data were extracted by a single AI-assisted reviewer and synthesised narratively because outcome definitions differed. Alkaline treatment (47 studies), oxidative bleaching (31) and acid steps (22) dominated, and 28 studies (49%) used at least one non-conventional technology. Yield was reported in 22 studies, purity in 20 and CrI in 36. Isolation raised CrI in all 13 studies that reported paired values (median +14.0 percentage points). Reported purity ranged from 43.3% to 96.7% (median 81.9%), the highest values following enzyme-assisted pretreatment, microwave-assisted formic acid extraction and microwave subcritical water extraction. Only four studies quantified energy or environmental performance. No route was superior across outcomes, so choice should follow the target product, and standardised yield bases, CrI methods and sustainability metrics are needed. The evidence set was not retrieved by a complete database search, so the findings are a structured synthesis of a defined set of studies.

Keywords:

Cellulose isolation; lignocellulosic biomass; agro-food waste; crystallinity index; deep eutectic solvents

1. Introduction

Cellulose is the most abundant biopolymer and is increasingly sourced from residues of agriculture, food processing and forestry rather than from virgin wood or cotton. Isolating it requires removing lignin, hemicelluloses, extractives, pectin, waxes and, in some feedstocks, silica, without excessive loss or degradation of the cellulose. The isolated product is used directly as a fibre or filler and is the starting point for MCC (Fouad et al., 2020), CNC and microfibrillated cellulose. The route chosen determines how much cellulose is recovered and also its purity, crystallinity, thermal behaviour and the chemical and energy burden of the process.

The classical route combines alkaline extraction with oxidative bleaching (Amensisa et al., 2024; Melesse et al., 2022; Qasim et al., 2020) and, for microcrystalline or nanoscale products, acid hydrolysis. It has been supplemented by microwave-assisted (Wang et al., 2019) and ultrasound-assisted (He et al., 2022) steps, high-pressure homogenisation (HPH) (Pirozzi et al., 2022), pulsed electric field (PEF) pretreatment (Putranto et al., 2025a), deep eutectic solvents (DES) (Prasetyaningsih et al., 2025), ionic liquids (Neubert et al., 2020), organosolv systems (Aggarwal et al., 2021), enzymatic (Lou et al., 2022) and TEMPO-mediated (Nascimento et al., 2023) routes and ozone treatment (Pujokaroni et al., 2020). Each is usually introduced in a study of a single feedstock, so a reader choosing a route must piece together evidence gathered under different conditions and outcome definitions. This review compares routes across feedstock classes while keeping the outcome definitions of the primary studies visible. It asks which routes and feedstocks have been studied since 2018 (RQ1), how routes compare on cellulose yield and purity (RQ2) and on crystallinity index and thermal stability (RQ3), to what extent process sustainability is quantified (RQ4) and where the main evidence gaps lie (RQ5). The consequences of the way the evidence set was assembled are set out in Sections 2.1 and 4.5.

2. Materials and Methods

2.1 Design and evidence set

This is a structured review of a defined evidence set that follows the principles of synthesis without meta-analysis (SWiM). It is not a PRISMA-compliant systematic review, and its protocol (questions, eligibility criteria, extraction fields and appraisal items) was written before extraction but not registered. The 57 studies comprise 50 from an author-compiled collection of full-text articles and 7 from targeted web searches run in September 2026, which combined cellulose, isolation or extraction terms, a technology name and a feedstock and aimed at combinations that were thin in the collection (oil palm biomass, PEF-assisted and microwave-assisted routes); for these seven only abstracts were read. Because the collection was curated rather than retrieved by a defined database search, the review is not exhaustive and presents no PRISMA flow diagram. One included study was authored by the first author of this review (Pujokaroni et al., 2020) and was handled with the same procedure as the others.

2.2 Eligibility, extraction, appraisal and synthesis

We included original experimental studies (English, 2018–2026; journal or proceedings papers) on lignocellulosic or agro-food biomass whose primary objective was to isolate or purify cellulose, including MCC, CNC and microfibrillated cellulose, and that reported at least one of yield, cellulose content or purity, crystallinity index (CrI), thermal stability or energy or environmental metrics. Commercial pulps, microbial cellulose, textile waste, reviews and studies aimed only at saccharification, derivatisation or composite fabrication were excluded; waste pulp fibre (Wang et al., 2019) and post-isolation treatment with the isolation composition reported (Pujokaroni et al., 2020) were accepted. For each study we extracted feedstock, route and conditions, technique tags and outcomes as reported, without converting yield or purity to a common basis. Each study was assigned to one primary route family by its most distinctive step: alkaline and alkaline–bleaching (ALK), acid-based (ACID), bleaching-agent comparisons (BLE), green solvents (GS; DES, ionic liquids, organosolv), energy-assisted (EA; microwave, ultrasound, steam or hydrothermal treatment, HPH, PEF) or enzymatic, TEMPO or ozone routes (ENZ).

Eligibility checking and extraction were done by one reviewer assisted by an AI language model (Claude, Anthropic), which was also used to compute statistics, generate the figures and draft the manuscript; all outputs remain the responsibility of the authors, and no second human reviewer has yet checked them. The 50 studies read in full were scored with a four-item screening proxy (0–4 points: at least three characterisation techniques; replication or statistics indicated by a keyword screen; a quantitative yield, purity or CrI value; full journal article), which describes reporting robustness rather than risk of bias and was not used to exclude or weight studies. Results were synthesised narratively with counts, medians and ranges, and within-study comparisons were weighted above comparisons across studies.

3. Results

3.1 Characteristics of the included studies

The 57 studies were published in 2018–2026 (peak: 11 in 2022 and 10 in 2023; 2026 is a partial year); 54 were journal articles and three were conference papers. Feedstocks were cereal, sugar and pseudo-cereal crop residues (n = 14), non-wood fibre, grass and herbaceous plants (n = 13), palm-family biomass (n = 12), fruit, seed, vegetable and food-processing by-products (n = 11), woody and forest biomass (n = 4) and multi-feedstock studies (n = 3); six concerned oil palm (Almafie et al., 2026; Prasetyaningsih et al., 2025; Pujokaroni et al., 2020; Putranto et al., 2025a; Putranto et al., 2025b; Rahmi et al., 2026). By primary route, alkaline routes led (n = 18), followed by energy-assisted (17), acid-based (9), green-solvent (7), bleaching-agent comparisons (3) and enzymatic, TEMPO or ozone routes (3).

3.2 Isolation routes and outcome reporting

Alkaline treatment featured in 47 of the 57 studies (82%), oxidative bleaching in 31 (54%) and acid steps in 22 (39%). Twenty-eight studies (49%) applied at least one non-conventional technology: steam explosion, hydrothermal or pressure treatment in eight, DES in six, microwave in five, ultrasound in four, organosolv in four, PEF in three, enzymes, TEMPO or ozone in three, and ionic liquids and HPH in one each. All three PEF studies, four of the six oil palm studies and one of the five microwave studies came from the supplementary searches, which affects how prominent these technologies appear (Section 4.5).

Yield was reported in 22 studies, cellulose content or purity in 20 and CrI in 36; five studies reported none of the three quantitatively. The quantities called yield are not interchangeable: they include cellulose yield on dry feedstock (Prasetyaningsih et al., 2025), solid-fraction recovery (Casanova et al., 2023) and CNC yield (Putranto et al., 2025b), so values must be read within their own definitions. Of the 50 full-text studies, 20 scored 4 points, 22 scored 3, seven scored 2 and one scored 1; replication or statistical analysis was the item most often missed (met by 28 of 50).

3.3 Cellulose yield and purity

After full multi-step isolation, cellulose yields clustered between roughly 25% and 55% for most lignocellulosic feedstocks: 37.3% for coffee husk and 26.5% for brewery spent grain (Amensisa et al., 2024), 39.4–53.5% for forest residues (Manzano Vela et al., 2024), 55.2% for wheat straw (Yu et al., 2021) and 37% for oil palm empty fruit bunch (Putranto et al., 2025a). Higher values were reported for oil palm trunk at the DES optimum (91.29%) (Prasetyaningsih et al., 2025) and for ultrasound-alkali isolation from coconut shell (65.3% against 24.7% for the conventional product), where the higher recovery came with lower CrI and thermal stability (Mohan et al., 2024).

The 23 purity values reported by 20 studies ranged from 43.3% to 96.7% (median 81.9%); four were 90% or higher and four were below 70%. The highest followed immobilised xylanase–laccase pretreatment of corn stalk (96.7%, against 85.5% without it) (Lou et al., 2022), microwave-assisted formic acid extraction of waste pulp (93.2%) (Wang et al., 2019), microwave subcritical water followed by microwave NaOH treatment of soybean hulls (91.5%) (Rigoletto et al., 2026) and NaOH–KOH treatment with H_2O_2–acetic acid purification of oil palm empty fruit bunch (91.5%) (Almafie et al., 2026). Green-solvent routes spanned the widest range (43.3–86.8%): DES delignification of wheat straw gave 43.77–69.53% cellulose with 16.13–35.49% residual lignin (Jančíková et al., 2023), and on bagasse [bmim][HSO_4] gave 78.4% cellulose but only 50.6% recovery, whereas [bmim][OAc] gave 43.3% with 81.0% recovery (Neubert et al., 2020).

3.4 Within-study comparisons

Comparisons by the same authors on one feedstock under one protocol give the cleanest evidence on route effects (Table 1). Replacing a chlorine-based bleaching agent by hydrogen peroxide cost little in one comparison (α-cellulose 79% against 81.4%) (Qasim et al., 2020), whereas the choice among H_2O_2, NaOCl and sodium perborate changed CrI from 26.83% to 42.36% in another (Benali et al., 2024). In pomelo fruitlets the ultrasound-assisted alkaline H_2O_2 route gave higher purity and yield than the acidic–alkaline route (He et al., 2022), but with equal 2 h steps in olive stones conventional heating slightly outperformed microwave, ultrasound and hot-water variants (yield 41% against 39%, 30% and 18%) (Macarez et al., 2025). Autohydrolysis outperformed DES and organosolv routes on sugarcane bagasse (solid fraction 63.5%, cellulose about 70%, E-factor 0.30) (Casanova et al., 2023).

Table 1. Within-study comparisons of isolation routes or conditions. Values are as reported by the original authors and use the authors' own definitions of yield and purity.

Study	Feedstock	Comparison	Main reported outcomes
Macarez et al. (2025)	Olive stones	Same HCl–NaOH–H_2O_2 sequence under four heating modes (hot water, ultrasound, microwave, conventional; 2 h per step)	Yield 18, 30, 39 and 41%; CrI 37, 40, 44 and 45%, in the order hot water, ultrasound, microwave, conventional
Mohan et al. (2024)	Coconut shell	Alkali plus bleaching (ABC) versus ultrasound-alkali isolation (UAIC)	Yield 24.7% (ABC) and 65.3% (UAIC); CrI 50.3% (ABC) and about 46% (UAIC); lower thermal stability for UAIC
He et al. (2022)	Pomelo fruitlets	Acidic–alkaline H_2O_2 (CAA), alkaline H_2O_2 (CA) and ultrasound-assisted alkaline H_2O_2 (CUA)	CAA yield 8.64%, purity 65.42%; CUA yield about 15%, purity 82.71%, CrI 44.26% (highest)
Qasim et al. (2020)	Wheat straw	Alkaline H_2O_2 (AHP) versus acidified $NaClO_2$ (ASC)	α-Cellulose 79% (AHP) and 81.4% (ASC); CrI 66.87% and 66.60%
Nascimento et al. (2023)	Banana pseudostem	Alkaline–acid versus enzymatic hydrolysis versus TEMPO oxidation	Yield 25.25% (TEMPO) and 14.58% (enzymatic); CrI 13.50% (alkaline–acid) and 68.98% (enzymatic); stability about 200 °C (TEMPO) and 250 °C (enzymatic)
Casanova et al. (2023)	Sugarcane bagasse	DES, organosolv and hydrothermal routes versus acid and alkaline hydrolysis	Autohydrolysis best: solid fraction 63.5%, cellulose about 70%, CrI 60.4%; E-factor 0.30, PMI 20.5

Note: ABC, alkali plus bleaching; AHP, alkaline hydrogen peroxide; ASC, acidified sodium chlorite; CAA, CA and CUA, acidic–alkaline, alkaline and ultrasound-assisted alkaline H_2O_2 treatments; UAIC, ultrasound-alkali isolation.

3.5 Crystallinity index

CrI was reported in 36 of 57 studies, and 13 gave values for both the untreated material and the isolated product (Figure 1) (Aggarwal et al., 2021; Almafie et al., 2026; Amior et al., 2023; Ganapathy et al., 2019; Hozman-Manrique et al., 2023; Ke et al., 2023; Lou et al., 2022; Melesse et al., 2022; Moramarco et al., 2025; Qasim et al., 2020; Senthamaraikannan & Kathiresan, 2018; Singh & Rout, 2024; Van et al., 2022). Isolation raised CrI in all 13, by a median of 14.0 percentage points (mean 17.1; range 3.8–43.1). The smallest increments came from alkali treatment of fibres that had already been extracted (+3.8 to +5.5 points) (Ganapathy et al., 2019; Senthamaraikannan & Kathiresan, 2018; Singh & Rout, 2024); the largest came from multi-step sequences: oil palm empty fruit bunch, 31.18% to 74.23% (+43.1) (Almafie et al., 2026); corn stalk with enzyme pretreatment (+26.0) (Lou et al., 2022); banana stem (+24.9) (Van et al., 2022); and soybean hulls (+23.0) (Moramarco et al., 2025). Not every modification raised CrI: ultrasound-alkali isolation of coconut shell gave a lower value than the conventional product (about 46% against 50.3%) (Mohan et al., 2024), NaOH above 8% converted cellulose I to cellulose II in *Pennisetum purpureum* (Tuan Rohadi et al., 2020), and cellulose from restaurant food waste had a CrI of 16% against 61% for commercial cellulose (Garnett et al., 2024).

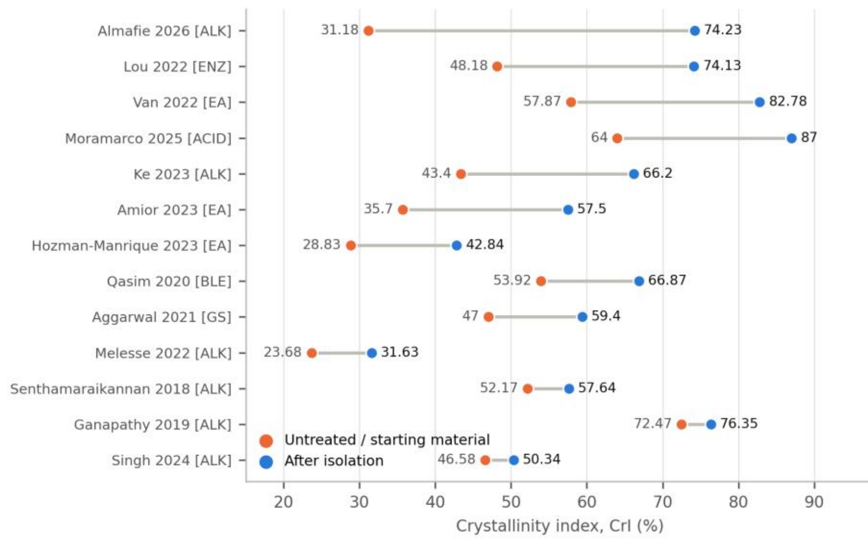

Figure 1. Crystallinity index (CrI) of the untreated material and of the material after isolation in the 13 studies that reported both. Bracketed codes give the route family (Section 2.2). The 'after isolation' value is the end point of each study's own sequence, so the pairs are descriptive and not a like-for-like effect size.

3.6 Thermal stability and sustainability

Thermal behaviour was reported in a minority of studies, and removal of hemicellulose and lignin generally coincided with decomposition at higher temperatures (T_{onset} of 206.1–225.7 °C for DES-isolated oil palm trunk cellulose) (Prasetyaningsih et al., 2025). Exceptions were linked by the authors to the isolation method: TEMPO-oxidised cellulose was stable to about 200 °C against about 250 °C for enzymatically isolated cellulose (Nascimento et al., 2023), and ultrasound-alkali cellulose from coconut shell was less stable than its conventional counterpart, attributed to cavitation (Mohan et al., 2024). Only four studies (7%) quantified energy or environmental performance: autohydrolysis of bagasse had an E-factor of 0.30 and a process mass intensity of 20.5 (Casanova et al., 2023); PEF-assisted DES pretreatment of oil palm empty fruit bunch used 98% less energy and was 60 times faster than conventional heating (Putranto et al., 2025a), with pretreatment energy of 0.4–2.1 kWh/kg in a follow-up CNC study (Putranto et al., 2025b); and microwave subcritical water followed by microwave NaOH treatment had lower toxicity-related impacts than a multi-step hydrolysis route (Rigoletto et al., 2026).

4. Discussion

4.1 Principal findings

For RQ1, the literature is dominated by alkaline delignification, oxidative bleaching and acid steps, about half of the studies added a non-conventional technology, and woody and forest biomass was rare (n = 4). For RQ2, cellulose contents above 80% were reported for alkaline–bleaching, microwave, organosolv, enzyme-assisted and other energy-assisted routes, whereas yields after full isolation were mostly 25–55% and were defined differently between studies. For RQ3, isolation raised CrI in all 13 paired studies (median +14.0 percentage points) and thermal stability usually followed the removal of non-cellulosic components. For RQ4, energy or environmental performance was quantified in only four studies. The gaps that answer RQ5 are given in Section 4.4.

4.2 Why route rankings are not transferable

Outcomes trade off in ways that a single headline number hides. In ionic liquid treatment of bagasse, the highest cellulose content (78.4%) came with the lowest recovery (50.6%) (Neubert et al., 2020); in coconut shell, the highest yield coincided with lower CrI and thermal stability (Mohan et al., 2024); and in restaurant food waste, a reproducible yield came with a CrI of 16% (Garnett et al., 2024). In contrast, enzymatic pretreatment and ultrasound-assisted alkaline peroxide raised purity and CrI together in corn stalk and pomelo fruitlets (He et al., 2022; Lou et al., 2022). Definitions add a second layer of non-comparability: a reported yield can describe a single step rather than the whole process, as in the forest residue study, where 80.83% was the recovery of bleached pulp whereas the overall cellulose yield was 39.4–53.5% (Manzano Vela et al., 2024). Feedstock composition and the CrI calculation method add further differences. For these reasons we do not rank routes across studies.

4.3 Technologies and route selection

Assisted heating is not automatically better. With identical 2 h steps, microwave, ultrasound and hot-water variants did not exceed conventional heating on yield or CrI in olive stones (Macarez et al., 2025), although ultrasound raised CrI in *Ziziphus jujuba* fibres from 35.7% to 57.5% (Amior et al., 2023). Advantages of microwave and PEF concern time and energy at least as much as product quality, and the PEF claims (60 times faster, 98% less energy (Putranto et al., 2025a)) rest on abstract-level data from one research group. DES and other green solvents show the widest range of outcomes: acidic DES outperformed basic DES (Prasetyaningsih et al., 2025), but the CrI of a DES-derived MCC (59.21%) was below that of commercial MCC (69.45%) (Rahmi et al., 2026). Read with these caveats, the evidence suggests that multi-step sequences combining alkaline delignification, bleaching and an acid or oxidative purification step reached the highest final CrI (74–87%) (Almafie et al., 2026; Lou et al., 2022; Moramarco et al., 2025; Van et al., 2022); that organosolv and ionic-liquid fractionation can recover lignin alongside cellulose at a recovery–purity cost (Neubert et al., 2020; Yu et al., 2021); and that autohydrolysis, PEF-assisted and microwave-assisted routes have reported energy or solvent advantages (Casanova et al., 2023; Putranto et al., 2025a; Rigoletto et al., 2026), each resting on one to three studies. These are observations, not validated selection rules.

4.4 Evidence gaps and reporting recommendations

The main gaps are that head-to-head comparisons of non-conventional and conventional routes under one protocol are scarce; woody and forest biomass is underrepresented; energy, solvent and environmental metrics are rare and no techno-economic analysis was extracted; work is almost always at laboratory scale; and replication is inconsistently reported. We suggest that future studies (1) report yield as grams of cellulose per 100 g dry feedstock and, separately, recovery of the cellulose present in the starting material; (2) report the composition of raw and isolated material and the CrI method; (3) give dispersion measures from replicates; (4) include a conventional comparator on the same feedstock; and (5) report energy and reagent use per kilogram of cellulose (kWh/kg, E-factor, PMI).

4.5 Limitations

Identification. The studies came from an author-compiled collection and supplementary searches rather than a defined database search, so completeness cannot be claimed; studies favoured by the collection and the topics targeted by the supplementary searches (oil palm, PEF, microwave) are over-represented, and publication bias could not be assessed. **Selection and extraction.** Eligibility checks and extraction were carried out by one reviewer with AI assistance and have not been independently verified, and seven studies were extracted from abstracts only. One included study was authored by the first author of this review (Pujokaroni et al., 2020), a potential source of selection bias, and alkali-treated natural-fibre studies were included where composition or CrI was reported, which raises the alkaline count. **Appraisal and synthesis.** The four-item proxy is not a validated risk-of-bias tool; heterogeneity in yield and purity definitions, CrI methods and feedstocks precluded meta-analysis, and the CrI pairs compare different end points.

5. Conclusion

Across 57 studies, cellulose isolation from lignocellulosic and agro-food biomass is dominated by alkaline, bleaching and acid routes, with non-conventional technologies present in about half of the studies. Isolation reliably raised CrI (median +14.0 percentage points in 13 paired comparisons) and several routes reached cellulose contents above 90%, but yields were typically 25–55% and outcomes traded off in several head-to-head comparisons. Process sustainability was quantified in only four studies. Route choice should therefore follow the target product and process constraints rather than a universal ranking. Future studies should adopt common yield bases, report composition and the CrI method, include a conventional comparator and quantify energy and reagent use; extending the search to bibliographic databases with independent screening and extraction would turn this structured synthesis into a full systematic review.

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Conflict of Interest

The authors declare no other conflict of interest.

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