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Valorization of Jackfruit Peel Waste: A Bibliometric and Critical Review of Environmental Remediation, Functional Materials, and Resource Recovery

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Abstract

Jackfruit peel is a renewable feedstock for environmental remediation and resource recovery, but research remains fragmented across applications. This review combines bibliometric mapping with critical evaluation of valorization pathways. Following a Web of Science Core Collection search on 18 September 2026, 167 publications spanning 2002–2026 were retained. R was used for descriptive and temporal analyses, and VOSviewer for keyword co-occurrence mapping. Publications from 2020–2025 accounted for 67.1% of the corpus. Three thematic clusters covered adsorption and remediation, recovery of biopolymers and bioactive compounds, and functional carbon materials. Across applications, feedstock composition, pretreatment and material structure influenced reported performance. Practical implementation remains constrained by inconsistent characterization, limited regeneration and continuous-flow validation, and insufficient safety, techno-economic and life-cycle evidence. The review connects these research patterns and limitations through a cascade framework involving phenolic and pectin recovery, cellulose utilization, and conversion of residual solids into carbon materials or energy products. Its proposed advantages require verification through mass balances, pilot-scale testing and integrated economic and environmental assessment.

Keywords: Jackfruit peel; Agricultural waste; Environmental remediation; Biomass-derived materials; Circular valorization.

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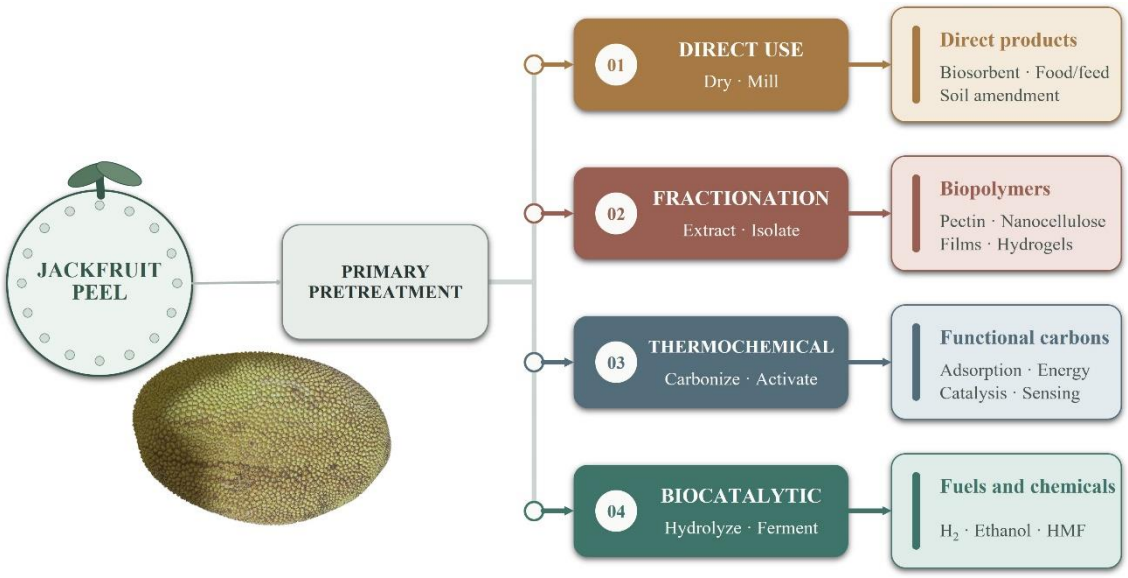
Graphical abstract



1. Introduction

Tropical fruit production and processing generate substantial quantities of lignocellulosic residues whose poor management can contribute to greenhouse-gas emissions and soil and water contamination (Thuong Huyen *et al.*, 2025). Jackfruit (*Artocarpus heterophyllus* Lam.) is widely consumed in tropical and subtropical regions, but its thick peel commonly remains a low-value processing residue. The peel provides cellulose that can be isolated by removing lignin, hemicellulose and other non-cellulosic constituents (Padhi *et al.*, 2023). It also contains extractable pectin and phenolic compounds with antioxidant activity (Zhang *et al.*, 2017; Xu *et al.*, 2018). This composition supports complementary routes for recovering biopolymers and bioactive compounds and converting residual biomass into functional materials.

Early studies established untreated peel as a dye biosorbent and demonstrated pore development through phosphoric-acid activation (Prahas *et al.*, 2008; Hameed, 2009). Microwave-assisted NaOH activation further demonstrated its suitability as a precursor for porous adsorbents (Foo and Hameed, 2012). Hydrothermal activation and magnetic modification subsequently expanded applications to heavy metals and other cationic pollutants (Wen *et al.*, 2022; Ton-That *et al.*, 2024). Porous peel-derived carbons have also been evaluated as capacitive-deionization electrodes for desalination and defluoridation (Elisadiki *et al.*, 2019; Elisadiki *et al.*, 2020). More advanced carbon structures include defect-engineered spheres for symmetric supercapacitors and porous hosts for aqueous Zn–S batteries (Patel *et al.*, 2024; Chinnalagu *et al.*, 2025). Carbon-dot/semiconductor composites have extended applications to fluorescent sensing and photocatalytic degradation (Paul *et al.*, 2026). Magnetic biochar systems have additionally linked nutrient recovery from water with the potential reuse of spent materials as soil amendments (Nayak *et al.*, 2021).

Fractionation provides a complementary route to biopolymers and functional composites. Hydrolysis chemistry influences the structure, thermal stability and rheological behaviour of peel-derived nanocellulose (Padhi *et al.*, 2025). Nanocellulose and recovered cellulose and polyphenolic fractions have been incorporated into functional packaging films (Rajasekharan *et al.*, 2023; Orsuwan and Sothornvit, 2025). Pectin/apatite composites and cellulose-nanocrystal/alginate hydrogels have been investigated for bone-related applications and drug delivery, respectively (Govindaraj *et al.*, 2018; Nyoo Putro *et al.*, 2024). Peel-derived pectin has also enabled the fabrication of biocompatible, antimicrobial nanofibres (Kumar *et al.*, 2025), while peel extracts have been applied to flame-retardant textiles (Nguyen *et al.*, 2025). Beyond materials, biochemical conversion has yielded bioethanol and hydrogen-rich gas (Vijayaraghavan *et al.*, 2006; Kumar and Uppuluri, 2026). Peel ash has been used as a catalyst for biodiesel synthesis, while untreated peel has been converted into 5-hydroxymethylfurfural (Mulkan *et al.*, 2023; Huynh *et al.*, 2026).

Previous reviews have surveyed food and material applications of jackfruit waste and its conversion into fuels, feed and other value-added products (Kalse and Swami, 2022; Pathak *et al.*, 2022). More specialized coverage has examined waste-derived polymers and composites (Hajare *et al.*, 2024). A broader biorefinery review has also addressed product diversification, economic and environmental considerations, and barriers to scale-up (Chakraborty *et al.*, 2025). These contributions provide a foundation for a more focused assessment of peel as a distinct feedstock with multiple recoverable components.

A central challenge is to relate the expanding range of applications to comparable evidence on material performance and practical feasibility. Differences in feedstock composition, pretreatment and testing conditions complicate comparisons among conversion routes. Regeneration, realistic operating conditions, environmental safety and economic performance also require consideration alongside laboratory results. The contribution of this review lies in combining peel-specific bibliometric mapping with a critical assessment of processing–structure–performance relationships and opportunities for cascade valorization. The proposed framework considers sequential recovery of phenolics, pectin and cellulose, followed by conversion of residual solids into carbon materials, catalysts or energy products.

Accordingly, this review has three objectives: (i) to map publication trends, geographical contributions and research themes through bibliometric analysis; (ii) to critically evaluate how feedstock characteristics and processing affect structure and performance across remediation, functional materials, bioconversion and direct-use applications; and (iii) to identify cross-cutting limitations and prioritize research toward integrated cascade valorization. Particular attention is given to standardized characterization, regeneration and durability, continuous-flow and pilot-scale validation, and techno-economic and life-cycle assessment.

2. Bibliometric Analysis

2.1. *Data retrieval and screening*

The literature search was conducted in the Web of Science Core Collection on 18 September 2026. A broad Topic search covered common-name variants and botanical names of jackfruit, with peel-specific eligibility assessed during screening. The following search string was used: TS=(jackfruit*OR "jack fruit*"OR "jack-fruit*"OR jakfruit*OR "jak fruit*"OR "Artocarpus heterophyll*"OR "Artocarpus integrifoli*"OR "A. heterophyll*"OR "A. integrifoli*")

The search retrieved 1,961 records. After removing one duplicate, 1,960 unique records were screened using their titles and available abstracts. Records were eligible for inclusion when they substantively addressed the valorization of jackfruit peel or equivalent outer fruit fractions as feedstocks, material precursors or research objects. Studies restricted to other plant parts or lacking a substantive connection to peel utilization were excluded. Following screening, 1,793 records were excluded, leaving a final corpus of 167 publications for bibliometric analysis. The final bibliometric corpus comprised 167 publications assigned to 2002–2026.

No a priori restrictions on publication year, language or document type were applied during screening. All retained records were indexed in English. The corpus contained 143 records carrying an Article designation, including records with additional Early Access or Proceedings Paper labels, together with 14 proceedings-only records, eight reviews and two news items. The analysis therefore describes publication activity across these document types. The 167 records were exported in plain-text format for data processing and visualization.

2.2. *Data processing and visualization*

Descriptive statistics and temporal keyword visualizations were produced in R version 4.4.3 using ggplot2. Publication years were assigned from the Early Access date when available and otherwise from the publication-year field (PY). This convention reproduced the annual counts in the retrieved Web of Science results. Years without publications were retained as zero counts, and 2026 was treated as an incomplete year ending on the search date.

Country and regional contributions were calculated from author affiliations using full counting. Each publication was counted once for every represented country or region, and its contribution was expressed relative to the 167-publication corpus. Country percentages can therefore sum to more than 100%. Publication sources were counted using the source-title field (SO), with each record assigned to one source. Additional book-series labels (SE) were excluded from this count to avoid counting the same publication twice. For the leading-source table, all ties at the tenth position were retained.

Keyword co-occurrence analysis was conducted using VOSviewer version 1.6.19, with “All keywords” selected as the unit of analysis and full counting applied. The minimum occurrence threshold was set to five. Of the 1,013 keywords identified, 44 met this threshold, and all were retained for network construction. Association strength normalization was applied. Clustering used a resolution of 1.00 and a minimum cluster size of 1, with small-cluster merging enabled. Node size represented keyword occurrence frequency, links indicated co-occurrence relationships, and colours distinguished clusters. The resulting network comprised 44 keywords organized into three clusters, with 413 links and a total link strength of 884. The clusters were interpreted based on their constituent keywords and connections.

The temporal analysis used author keywords (DE), which were available for 151 publications (90.4%). The remaining 16 records were retained in annual publication totals but contributed no author-keyword occurrences. Keywords Plus was not used to fill missing author keywords. For this analysis, formatting tags were removed, capitalization and spacing were standardized, and selected plural forms, spelling variants and unambiguous abbreviations were harmonized. Generic search-object terms, including jackfruit, jackfruit peel and *Artocarpus heterophyllus*, were excluded from the temporal display. Each keyword was counted once per publication. Terms occurring in at least three publications were eligible for display; retaining ties among the 20 highest-frequency terms produced 28 displayed keywords. Bubble area represents annual document frequency, colour represents the percentage of all publications in the corresponding year containing the keyword, and rows are ordered by mean publication year.

2.3. *Annual publication trends*

Publication output increased substantially over the study period, although growth was uneven (**Figure 1**). Only 23

publications (13.8%) were assigned to 2002–2016, with annual output ranging from zero to three. The next three years contributed 22 publications, including ten in 2018, indicating more sustained research activity from the late 2010s.

The largest concentration of publications occurred in 2020–2025, which accounted for 112 records (67.1% of the corpus). Annual output rose from 11 in 2020 to 16 in both 2021 and 2022, reached 23 in 2023, and declined to 18 in 2024 before reaching a peak of 28 in 2025. Ten publications were assigned to 2026 by 18 September. Because 2026 is incomplete, this count cannot establish a decline in annual research activity. Overall, the distribution indicates increased research attention to jackfruit-peel valorization, particularly during the most recent complete years.

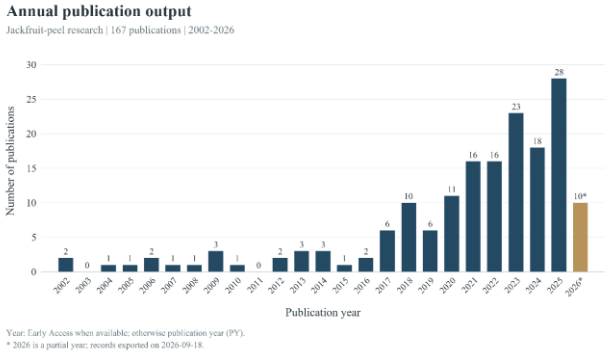


Figure 1. Annual publication output on jackfruit-peel valorization, 2002–2026. Counts were calculated from 167 publications and visualized using R version 4.4.3 and ggplot2. Records were assigned to the Early Access year when available and otherwise to the publication year. Years without publications are shown as zero. The asterisk indicates incomplete coverage of 2026 up to the search date, 18 September 2026.

2.4. *Country and regional contributions*

The corpus involved affiliations from 30 countries and regions (**Figure 2**). India contributed the largest number of publications, with 84 records (50.3%), followed by Malaysia with 34 (20.4%) and China with 23 (13.8%). Saudi Arabia contributed 13 publications (7.8%), Vietnam ten (6.0%), Indonesia seven (4.2%) and South Korea six (3.6%). These results identify a strong concentration of publication activity in Asian countries, alongside contributions from other regions.

Full counting produced 222 country or regional contributions across the 167 publications. This exceeds the corpus size because internationally co-authored papers contribute to more than one country. The percentages consequently represent each country's participation in the corpus and should not be interpreted as mutually exclusive shares.

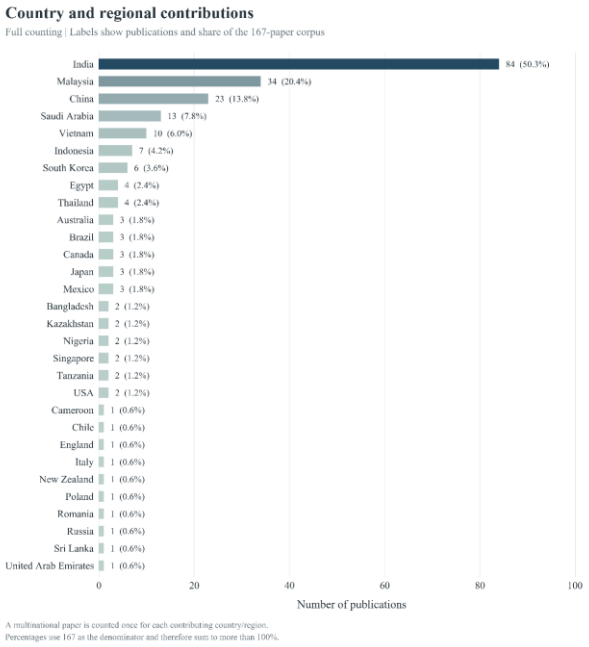


Figure 2. Country and regional contributions to jackfruit-peel research. Contributions were determined from author affiliations using full counting and visualized using R and ggplot2. Each publication was counted once for every represented country or region. Labels show publication counts and percentages of the 167-publication corpus. Percentages can sum to more than 100% because internationally co-authored publications contribute to multiple countries or regions.

2.5. *Leading publication sources*

The 167 publications were distributed across 109 source titles. **Table 1** presents the leading sources, with 16 titles retained because ten sources shared the frequency of three publications at the cutoff. *Biomass Conversion and Biorefinery* contributed nine publications (5.39%), followed by *Chemical Engineering Journal* and *Materials Today: Proceedings* with five each (2.99%). *Bioresource Technology*, *Food Chemistry* and *Journal of Environmental Chemical Engineering* each contributed four publications (2.40%).

Together, the 16 listed sources accounted for 61 publications (36.5%). Their coverage of biomass conversion, environmental engineering, food chemistry, polymers and energy storage reflects the distribution of peel-valorization research across several disciplines. The table includes conference proceedings as well as journals, consistent with the document types retained in the corpus. This dispersed source distribution supports a review that connects environmental applications with component recovery and functional-material development.

Table 1. Leading publication sources in the jackfruit-peel corpus, including all ties at the tenth position.

Rank	Publication source	Publications	Share (%)
1	Biomass Conversion and Biorefinery	9	5.39
2	Chemical Engineering Journal	5	2.99
2	Materials Today: Proceedings	5	2.99

4	Bioresource Technology	4	2.40
4	Food Chemistry	4	2.40
4	Journal of Environmental Chemical Engineering	4	2.40
7	Biomass and Bioenergy	3	1.80
7	Current Science	3	1.80
7	Diamond and Related Materials	3	1.80
7	Food Bioscience	3	1.80
7	Indian Journal of Chemical Technology	3	1.80
7	International Journal of Biological Macromolecules	3	1.80
7	Journal of Energy Storage	3	1.80
7	Journal of Food Science and Technology	3	1.80
7	Scientific Reports	3	1.80
7	Waste and Biomass Valorization	3	1.80

Note: Share = source publication count / 167 × 100. Each publication was assigned to one SO source title. Equal counts receive the same rank. Search date: 18 September 2026.

2.6. *Keyword co-occurrence and thematic clusters*

The keyword co-occurrence map displays three thematic clusters (**Figure 3**). The green cluster centres on adsorption and pollutant removal, with terms including adsorption, activated carbon, biochar, removal, methylene blue, kinetics and equilibrium. Their co-occurrence identifies sorbent preparation and the assessment of adsorption behaviour as a substantial component of the selected literature.

The red cluster concerns extraction, biopolymer recovery and bioactive constituents. Pectin, cellulose, nanocellulose, antioxidant and phenolic compounds occur alongside extraction, ultrasound, pretreatment and optimization. This grouping connects the recovery of functional peel constituents with processing conditions. The blue cluster contains biomass, pyrolysis, porous carbon, energy, water and performance, indicating a related strand involving carbon materials and their energy and water applications.

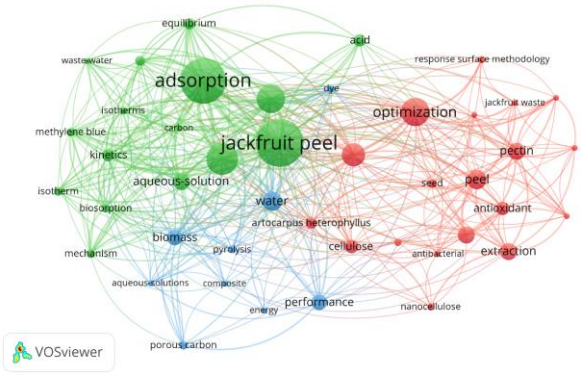


Figure 3. Keyword co-occurrence network and thematic clusters in jackfruit-peel valorization research. The network was generated using VOSviewer version 1.6.19 with All keywords, full counting, a minimum occurrence threshold of five and association strength normalization. The 44 retained keywords formed three clusters using a resolution of 1.00, a minimum cluster size of 1 and small-cluster merging. Node size represents keyword occurrence frequency, and links indicate co-occurrence relationships. Green, red and blue identify clusters associated with adsorption and remediation, biopolymer and bioactive-compound recovery, and functional carbon materials, respectively.

Connections across the three clusters show that remediation, component recovery and material development share part of their research vocabulary. These links provide a basis for examining relationships among valorization routes. Establishing whether the routes can be combined into an effective cascade process requires the critical assessment of experimental studies, including the compatibility of successive treatments and the management of residual streams.

2.7. *Temporal changes in research themes*

The author-keyword timeline shows persistent attention to adsorption alongside a wider range of recent research topics (**Figure 4**). Adsorption was the most frequently displayed keyword, occurring in 22 publications, followed by activated carbon in 12. Pectin and antioxidant each occurred in eight publications. Adsorption appeared repeatedly from 2004 to 2025 and reached its highest annual frequency of five publications in 2023. Activated carbon and pectin also occurred across multiple years, indicating continued interest in carbon preparation and the recovery of polymeric components.

Several material-related keywords were concentrated in the more recent part of the timeline. Biochar occurred in seven publications assigned to 2021–2025, while nanocellulose appeared in four publications in 2021, 2022 and 2025. Cellulose occurred in four records assigned to 2023–2025, and artificial neural network appeared in three publications in 2024–2025. These distributions suggest increasing thematic diversity, including material modification and computational approaches, alongside continuing adsorption research. Supercapacitor appeared in 2017, 2020 and 2022, showing that energy-related applications were already represented before the latest growth in publication output.

The timeline describes the occurrence of selected author keywords within this corpus. A keyword's earliest appearance does not establish when the corresponding research field began, and its absence does not demonstrate that a topic was unstudied. Interpretation is also affected by missing author keywords, small annual samples and partial coverage of 2026. Taken together, the source distribution, keyword clusters and temporal

patterns guide the following critical review of environmental remediation, functional materials and resource recovery. Assessing their contribution to integrated peel valorization requires evidence on material performance, process compatibility, environmental safety and resource efficiency.



Figure 4. Temporal distribution of author keywords in jackfruit-peel research, 2002–2026. The visualization was produced using R and ggplot2. Author keywords were available for 151 of the 167 publications. Terms occurring in at least three publications were eligible; retaining ties among the 20 highest-frequency terms yielded 28 displayed keywords. Bubble area represents the number of publications containing a keyword in each year. Colour represents its percentage of all publications in that year, with darker colours indicating higher percentages. Keywords are ordered by mean publication year. Years follow the Early Access year when available and otherwise the publication year. The asterisk indicates incomplete coverage of 2026 up to 18 September 2026.

3. Valorization and Applications of Jackfruit Peel

Jackfruit peel can be valorized through routes that differ in processing requirements, product functionality and technological maturity. Direct applications include powdered ingredients, feed supplements and biosorbents. Fractionation enables the recovery of pectin, cellulose, nanocellulose, polysaccharides and phenolic compounds. Thermochemical conversion produces biochar, activated carbon, carbon dots and other carbonaceous materials, while biological and catalytic processes convert carbohydrate-rich fractions into fuels and platform chemicals. Route selection therefore requires consideration of feedstock composition, pretreatment requirements, product performance and the management of residual streams. **Figure 5** summarizes the major pathways.

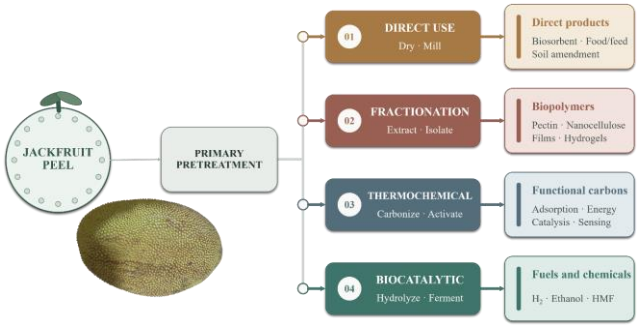


Figure 5. Major valorization pathways and applications of jackfruit peel

3.1. *Feedstock and Pretreatment*

Jackfruit peel is a heterogeneous lignocellulosic residue containing cellulose, hemicellulose, lignin, pectin, soluble polysaccharides, phenolic compounds, proteins and minerals. Their relative abundance varies with cultivar, maturity, cultivation conditions and the fruit fraction collected. This variability supports diverse applications but complicates process standardization. Cellulose provides a reinforcing framework, hemicellulose supplies hydrolysable carbohydrates, and lignin contributes to aromatic carbon. Pectin provides carboxyl and hydroxyl groups, while phenolic compounds and minerals can contribute biological or catalytic functionality.

Initial processing generally involves washing, drying, milling and sieving. These operations improve storage stability and control particle size, but their intensity should match the intended application. Excessive grinding increases energy consumption and can complicate solid–liquid separation. Harsh drying may alter heat-sensitive compounds and the properties of extracted polymers. Pretreatment studies should therefore document both the original feedstock and the changes introduced during processing. **Table 2** proposes a minimum characterization and reporting framework.

Table 2. Proposed minimum characterization and mass-balance reporting framework for jackfruit-peel valorization.

Category	Minimum information to report	Purpose
Feedstock identity	Cultivar where known, geographical origin, maturity, collection conditions and definition of the peel fraction	Establish comparability between feedstocks
Initial handling	Washing procedure, storage conditions, drying temperature and duration, moisture content and particle-size distribution	Identify changes introduced before conversion

Bulk composition	Ash, extractives, cellulose, hemicellulose, lignin and pectin; analytical methods and reporting basis	Support route selection and interpretation of yields
Structural and chemical properties	Elemental composition, thermal behaviour and surface functional groups; crystallinity where relevant	Relate processing conditions to material properties
Fraction recovery	Mass and purity of each recovered fraction, recovery basis and residual solid mass	Distinguish crude extraction yield from recovery of the target component
Process inputs	Chemical and solvent quantities, liquid-to-solid ratio, water consumption, processing time and energy demand	Identify resource-intensive operations
Residual streams	Liquid and solid residues, relevant dissolved components and losses during separation	Assess secondary waste generation and recovery opportunities
Integrated balance and reproducibility	Overall mass-balance closure, unaccounted losses, carbon balance where feasible, replicate measurements and batch variability	Evaluate sequential recovery and support scale-up

Note: Report moisture separately and specify whether composition and yield values are expressed on a wet or dry basis. Constituents measured by overlapping analytical procedures should not be added without accounting for that overlap. Extraction yield, product purity and recovery efficiency should be reported separately.

Pectin extraction is one of the most established fractionation routes. Acidic extraction releases pectic polysaccharides from the cell-wall matrix, although prolonged treatment can reduce molecular weight and increase effluent-treatment requirements. Ultrasound-assisted extraction has been optimized by adjusting the liquid-to-solid ratio, pH, treatment time and temperature (Moorthy *et al.*, 2017). Ultrasonic–microwave extraction using citric acid subsequently achieved a pectin yield of 21.5%, producing fractions with measurable antioxidant activity (Xu *et al.*, 2018). Oxalic-acid extraction has also produced pectin suitable for blending with polyvinyl alcohol and electrospinning, as illustrated in **Figure 6a**. These examples show that extraction yield should be considered alongside molecular weight, degree of esterification, purity and suitability for the intended application.

Cellulose isolation generally involves alkali treatment and bleaching to remove non-cellulosic constituents. Alkali treatment promotes fibre swelling and removal of associated components, while bleaching reduces residual lignin and coloured compounds. The isolation route illustrated in **Figure 6b** produced a cellulose yield of 25.6% and a crystallinity of 69.42%. The resulting suspension exhibited concentration-, pH- and ionic-strength-dependent rheological behaviour. Subsequent acid hydrolysis can produce nanocellulose, but the acid selected affects particle dimensions, surface chemistry, thermal stability and suspension properties. Comparative organic- and inorganic-acid treatments demonstrated that hydrolysis conditions influence these characteristics and should be selected according to the desired downstream function (Padhi *et al.*, 2025)

Alternative solvent systems have broadened the range of recoverable compounds. A choline chloride–lactic acid natural deep eutectic solvent, combined with sequential microwave and ultrasonic treatment, produced phenolic-rich extracts containing 53.16 mg gallic-acid equivalents per gram of dry peel under optimized conditions (Ly and Sothornvit, 2024). Chlorogenic acid was identified as a major constituent. Ultrasound–microwave extraction has also yielded peel polysaccharides at an optimized recovery of 24.6%, with the recovered fractions showing intestinal-health-related biological activity in the reported experiments (Cheong *et al.*, 2025). However, reduced use of conventional organic solvents does not by itself establish environmental superiority. Solvent recovery, viscosity, residual toxicity, corrosion and downstream purification requirements remain relevant.

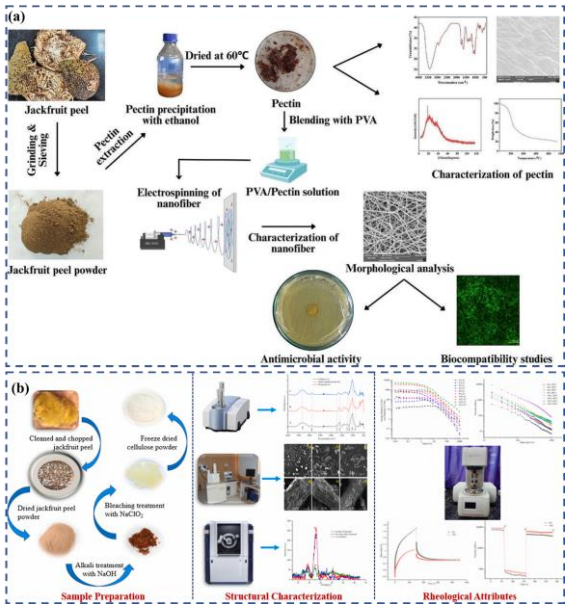


Figure 6. Representative preparation and characterization of jackfruit-peel-derived biopolymers: (a) pectin extraction, PVA/pectin nanofiber fabrication and functional evaluation (Kumar *et al.*, 2025); (b) cellulose isolation and structural–rheological analysis (Padhi *et al.*, 2023)

A limitation of current pretreatment research is the frequent optimization of individual fractions without complete accounting for the remaining material. Pectin extraction, cellulose isolation and phenolic recovery may each alter the suitability of subsequent fractions. Sequential recovery is therefore a potential integration strategy, but its benefits depend on compatibility between processing steps. Studies should quantify fraction purity, component losses, chemical consumption and residual-stream composition before claiming improved resource efficiency. The proposed cascade framework is discussed further in Section 3.6.

Table 3. Representative jackfruit-peel-derived materials for water remediation: preparation, reported conditions and performance.

Material	Preparation or reported test conditions	Target contaminant	Main reported performance	Source
Untreated peel	Batch adsorption at 30 °C; initial concentration range of 35–400 mg/L; pH range of 2–11 investigated	Methylene blue	Langmuir maximum capacity: 285.7 mg/g	(Hameed, 2009)
Activated carbon	Microwave-assisted NaOH activation	Methylene blue	Maximum capacity: 400.06 mg/g; carbon yield: 80.82%	(Foo and Hameed, 2012)
Carbonized peel	Carbonization; acetic acid evaluated for dye recovery	Rhodamine B	Reported capacity: 121.47 mg/g	(Inbaraj and Sulochana, 2006)
Activated carbon	Adsorption from aqueous solutions of phenolic compounds	Phenol and chlorophenols	Maximum capacities ranging from 144.9 mg/g for phenol to 400.0 mg/g for 2,4-dichlorophenol	(Jain and Jayaram, 2007)
Hydrothermally activated biochar	Hydrothermal activation followed by aqueous adsorption experiments	Pb(II)	Maximum capacity: 83.86 mg/g	(Ton-That *et al.*, 2024)
Magnetic activated carbon	Thermochemical and coprecipitation magnetization routes compared	Cr(VI)	Magnetization route affected surface properties, magnetic recovery and adsorption performance	(Ngan *et al.*, 2024)
Iron-functionalized peel carbon	Batch adsorption; optimum performance near pH 7	As(III) and As(V)	Removal efficiencies: 97.3% and 98.2%; reported maximum capacities: 6.41 and 6.62 mg/g, respectively; reuse assessed over five regeneration cycles	(Chetia *et al.*, 2026)
PVA/peel-derived CMC/GO/kaolin hydrogel	Optimum removal at pH 8; equilibrium reached within 90 min	Congo red	Removal efficiency: 92.3%; Langmuir maximum capacity: 200.80 mg/g	(Liu *et al.*, 2025)
Porous activated-carbon electrodes	KOH activation; NaCl solutions of 30–500 mg/L investigated; applied voltages of 1.2–2.0 V	Dissolved salt	Electrosorption capacity: 5.74 mg/g at 2.0 V	(Elisadiki *et al.*, 2019).
Microwave-produced activated carbon	NaOH activation; reported test conditions of 5 g/L salt, 0.4 g/L adsorbent, 30 °C and 4 h	Dissolved salt	Adsorption capacity: 2.588 mg/g; performance declined with repeated regeneration	(Ngo *et al.*, 2025)

Note: Values are reported on the bases used in the respective studies. Ranges indicate conditions investigated and do not imply that maximum performance occurred throughout those ranges. Removal percentages and model-derived maximum capacities are different indicators and should not be treated as interchangeable. PVA: polyvinyl alcohol; CMC: carboxymethyl cellulose; GO: graphene oxide.

3.2. *Adsorption and Remediation*

Adsorption is one of the earliest and most extensively investigated applications of jackfruit peel. Untreated peel contains oxygen-containing functional groups that can interact with dissolved contaminants, while its cellular structure provides transport pathways. Studies of peel powders have demonstrated the removal of cationic dyes without intensive conversion (Ahmed and Nasar, 2021). However, untreated biomass can exhibit variable composition, swelling, weak mechanical stability and leaching of soluble organic matter. Its suitability therefore depends on both contaminant removal and the quality of the treated water.

Table 3 summarizes representative remediation studies. The reported values describe different materials, contaminants and experimental conditions. Adsorption capacities, removal percentages and electrosorption capacities should therefore be interpreted within their respective test systems.

Carbonization and activation provide greater control over pore structure and surface chemistry than direct use of untreated peel. Phosphoric-acid activation at 450–550 °C produced activated carbons with surface areas of 907–1260 m^2/g and pore volumes of 0.525–0.733 cm^3/g (Prahas *et al.*, 2008). Microwave-assisted NaOH activation also produced high-capacity methylene-blue adsorbents. However, activation conditions must be evaluated alongside carbon yield, chemical consumption and washing requirements. Rapid microwave heating can shorten processing, but uniform heating and reproducibility require attention during scale-up.

Peel-derived carbons have been applied to both dyes and aromatic organic contaminants. The studies demonstrate adsorption of rhodamine B, phenol and chlorophenols, with performance depending on the adsorbate and carbon surface. Langmuir and pseudo-second-order models are frequently used to describe these systems. Nevertheless, good mathematical fits do not independently establish monolayer adsorption or chemisorption. Mechanistic interpretation should combine adsorption modelling with pH-dependent behaviour, surface-charge measurements, spectroscopy, pore characterization and desorption experiments.

Heavy-metal removal has encouraged the development of modified biochars and composite adsorbents. Hydrothermally activated biochar achieved a Pb(II) capacity of 83.86 mg/g, with complexation, ion exchange and intraparticle diffusion contributing to uptake (**Figure 7a**). Magnetic modification improved adsorbent separation and altered Cr(VI) adsorption behaviour, with the outcome depending on the magnetization route. Iron-functionalized peel carbon also achieved high arsenic removal near neutral pH and showed reusability over five regeneration cycles (**Figure 7b**). These materials require evaluation of metal leaching, active-phase stability and the management of contaminant-loaded solids.

Peel-derived polysaccharides provide an alternative platform for adsorbent fabrication. A composite hydrogel containing peel-derived carboxymethyl cellulose, polyvinyl alcohol, graphene oxide and kaolin achieved 92.3% Congo-red removal at pH 8, with a reported Langmuir capacity of 200.80 mg/g. Hydrogels can simplify handling compared with fine carbon powders, but their performance depends on swelling and crosslink density. Insufficient crosslinking can weaken the material, whereas excessive crosslinking can restrict diffusion and reduce access to functional groups. Adsorption performance should therefore be assessed together with wet-state mechanical integrity.

Capacitive deionization provides an electrochemical route for salt removal. KOH activation generated a series of peel-derived carbons with surface areas reaching approximately 1955 m^2/g. A selected electrode exhibited a specific capacitance of 307 F/g and an electrosorption capacity of 5.74 mg/g at 2.0 V (**Figure 7c**). A separate adsorption-based desalination study reported a salt uptake of 2.588 mg/g for microwave-produced activated carbon. These results cannot be compared directly because the operating principles and experimental conditions differ.

Across these applications, regeneration and realistic operating conditions remain central to practical feasibility. Evaluation should extend beyond single-solute batch tests to competing ions, dissolved organic matter, variable pH and repeated use. Continuous-flow studies should report breakthrough behaviour, pressure drop and material loss. For electrochemical systems, energy consumption and charge efficiency are also relevant. Concentrated brines, regeneration effluents and spent adsorbents must be included in the assessment of environmental performance.

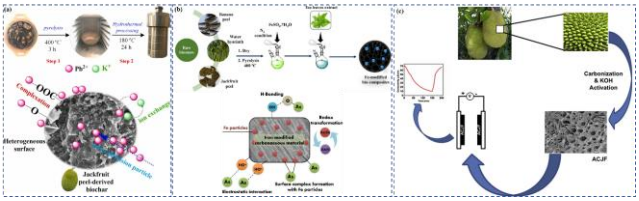


Figure 7. Representative jackfruit-peel-derived materials for water purification. (a) Pb(II) adsorption using hydrothermally activated biochar (Ton-That *et al.*, 2024). (b) Arsenic removal using iron-functionalized carbon composites (Chetia *et al.*, 2026). (c) Capacitive deionization using KOH-activated porous carbon electrodes (Elisadiki *et al.*, 2019).

3.3. *Energy, Catalysis and Sensing*

Functional carbon materials extend jackfruit-peel utilization into electrochemical storage, thermal management, catalysis and sensing. Their performance depends on pore accessibility, surface chemistry, conductivity and structural stability. Micropores can provide charge-storage sites, while larger pores facilitate electrolyte transport. Surface oxygen groups can improve wettability but may affect conductivity. High surface area alone is therefore insufficient. Pore dimensions must match the electrolyte ions, and the carbon framework must maintain adequate conductivity and mechanical stability.

Activated peel carbon has been investigated as a supercapacitor electrode. KOH activation combined with

controlled carbonization and carbon-dioxide treatment produced electrodes with specific capacitances of up to 191 F/g (Awitdrus *et al.*, 2022). More recent studies have introduced defects and heteroatoms to modify the carbon structure. The symmetric device illustrated in **Figure 8a** exhibited a specific capacitance of 177 F/g at 1 A/g in a PVA–KOH gel electrolyte and operated over a voltage window of up to 2.0 V. The study also reported an energy density of 36.1 Wh/kg. Comparisons between studies require consistent reporting of electrode configuration, active-material mass, electrolyte, mass loading and calculation basis.

Hybridization with redox-active phases can introduce additional charge-storage mechanisms. Nitrogen-doped peel carbon combined with zinc hexacyanoferrate delivered 457 C/g in a three-electrode configuration, while the corresponding asymmetric device achieved an energy density of 48.5 Wh/kg and retained 91.6% of its capacity after 5000 cycles (Palaniappan *et al.*, 2026). A nitrogen- and sulfur-codoped carbon/iron hexacyanoferrate electrode system achieved an energy density of 28.6 Wh/kg and approximately 92% capacity retention after 5000 cycles (Dhanasekar *et al.*, 2026). Bismuthene-integrated carbon spheres also showed promising electrochemical performance, including a reported capacitance of 665 F/g at 1 A/g (**Figure 8b**). These gains should be assessed against synthesis complexity, active-phase stability and end-of-life recovery.

Peel-derived carbon has also been used in hybrid energy-storage devices. A lithium-ion capacitor combining a peel-derived activated-carbon cathode with a pre-lithiated SnO_2 nanorod anode delivered a maximum energy density of approximately 187 Wh/kg and retained approximately 82% of its initial energy after 10,000 charge–discharge cycles (Sennu *et al.*, 2017). Activated peel carbon has additionally been evaluated as a sulfur host in lithium–sulfur batteries. Machine-learning models relating biomass composition and carbonization variables to performance were validated using an experimental jackfruit-peel carbon dataset (Dharmesh *et al.*, 2025). Such approaches could support precursor screening, but their reliability depends on consistent reporting of composition, processing conditions and device-testing parameters.

Thermal-energy storage provides a different use of porous carbon. Activated jackfruit-peel carbon with a surface area of 2446.88 m^2/g was impregnated with n-docosane to produce a shape-stable phase-change material. The composite exhibited melting and crystallization enthalpies of approximately 107 J/g and improved temperature regulation in a simulated lithium-ion battery pack (Luo *et al.*, 2025). The carbon framework confined the phase-change material and supported heat distribution. Further evaluation should address repeated thermal cycling, leakage under mechanical loading and flammability.

Catalytic applications can use the inorganic fraction remaining after calcination. Jackfruit-peel ash containing potassium, calcium and magnesium species was employed as a solid base catalyst for waste-cooking-oil transesterification. The optimized process produced a methyl-ester content of 98.88%, and catalyst reuse was demonstrated over three cycles (Mulkan *et al.*, 2023). This route combines the utilization of peel waste and waste cooking oil. However, ash variability, active-species leaching and sensitivity to water or free fatty acids can affect performance. Tests should distinguish surface-catalysed reactions from activity caused by dissolved alkaline species.

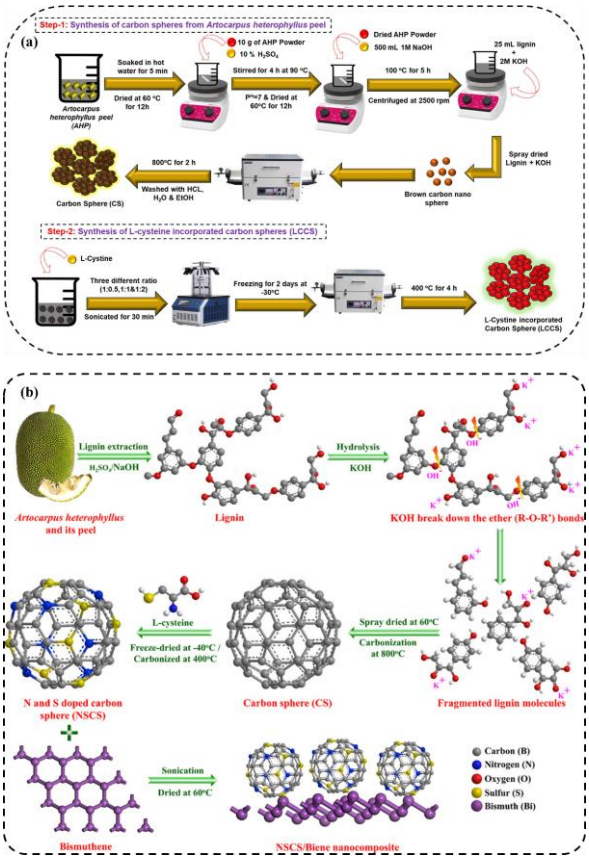


Figure 8. Preparation of jackfruit-peel-derived carbon-sphere electrodes for supercapacitors. (a) Pristine and L-cysteine-functionalized carbon spheres (Chinnalagu *et al.*, 2025). (b) Bismuthene-integrated nitrogen- and sulfur-codoped carbon-sphere composites (Murugesan *et al.*, 2025).

Engineered peel-derived carbon has also been incorporated into photocatalytic systems. Acid-modified hydrothermal carbon produced hydrogen peroxide at a reported rate of 521.7 µmol/g/h, with sulfuric-acid treatment modifying surface chemistry and charge-transfer behaviour (You *et al.*, 2025). A cerium Prussian-blue-analogue composite containing nitrogen- and phosphorus-doped peel carbon achieved removal efficiencies of 92% for ciprofloxacin, 88% for Cr(VI) and 95% for crystal violet under visible light (Vaijayanthi *et al.*, 2026). These findings support further investigation of carbon as an adsorptive and charge-transfer component. However, concentration loss should be separated into adsorption and photochemical transformation. Mineralization, transformation products and catalyst stability require independent evaluation.

Carbon dots extend peel utilization into optical sensing. Nitrogen-doped carbon dots showed fluorescence responses to environmental analytes through static quenching or, for selected compounds, hydrogen-bond-

mediated fluorescence enhancement (Paul et al*., 2025). A separate carbon-dot/copper-vanadate composite was investigated for fluorescent sensing, photocatalytic degradation and antibacterial activity (Paul* et al*., 2026). Practical assessment should address selectivity, matrix interference, photostability and batch reproducibility. Purification is also important because residual molecular fluorophores can contribute to the measured optical response.*

3.4. *Biopolymers and Composites*

Jackfruit peel can be incorporated directly into polymers as a particulate filler or fractionated into cellulose, nanocellulose and pectin before material fabrication. Direct powder incorporation requires fewer separation steps, but moisture absorption, particle agglomeration and weak interfacial bonding can limit performance. Surface treatments are therefore used to improve compatibility with polymer matrices. Treatment severity must be controlled because excessive chemical exposure can damage the reinforcing structure.

In polylactic-acid composites, bleaching improved the performance of jackfruit-skin fibres relative to untreated fibres, although high fibre loading could still reduce tensile properties compared with neat PLA (Marzuki *et al.*, 2020). Thymol incorporation introduced antibacterial functionality while creating additional trade-offs involving strength, release behaviour and microbial inhibition. Fused-deposition-modelled composites containing jackfruit-skin powder showed a 10.7% increase in ultimate tensile strength relative to pure PLA, while a hybrid coconut-shell/jackfruit-skin formulation achieved a tensile strength of 59.2 MPa (Reddy *et al.*, 2025). These results indicate that filler treatment and formulation can affect performance, but printing orientation and interlayer adhesion also need consideration.

Peel-derived components have also been incorporated into thermosetting matrices. An epoxy composite containing modified jackfruit-peel powder and mango-peel nanofibres achieved tensile and flexural strengths of approximately 150 and 156 MPa at an optimized filler loading. Hot-water conditioning reduced its mechanical performance and increased moisture uptake (S *et al.*, 2026). This illustrates a recurring limitation of lignocellulosic composites: promising dry-state properties do not necessarily translate into durability under humid or wet conditions. Evaluation should include cyclic humidity, water immersion and thermal ageing.

Nanocellulose offers greater control over reinforcement dimensions and surface properties than untreated peel powder. Jackfruit-peel nanocellulose combined with neem extract and polyethylene glycol produced antibacterial packaging films that degraded during a soil-burial test over approximately 60 days (Rajasekharan *et al.*, 2023). A soy-protein-based synbiotic film containing peel-derived nanocellulose, probiotics and jackfruit-seed extract maintained viable microorganisms and inhibited yeast and mould growth on feta cheese (Pooja *et al.*, 2026). However, biodegradation and preservation outcomes remain dependent on the test conditions and formulation. Water-vapour permeability, swelling and stability during storage should be evaluated alongside mechanical and antimicrobial performance.

An integrated fractionation approach recovered cellulose and polyphenols from jackfruit peel using a natural deep eutectic solvent. The fractions were incorporated into jackfruit-seed-flour/polyvinyl-alcohol films, where polyphenols contributed antioxidant, antimicrobial and light-barrier properties, while cellulose improved mechanical performance. Selected formulations extended olive-oil shelf life by 30 days relative to the reported controls (Orsuwan and Sothornvit, 2025). This example demonstrates complementary use of multiple peel fractions, although improved reinforcement was accompanied by increased water uptake. Material design therefore requires balancing strength, moisture resistance and active-compound release.

Pectin provides another platform for functional materials. Pectin/hydroxyapatite bionanocomposites exhibited cytocompatibility, cell adhesion and anti-inflammatory potential in the reported experimental systems (Govindaraj *et al.*, 2018). The electrospun PVA/pectin system introduced in **Figure 6a** produced fibres with an average diameter of approximately 187 nm and a tensile strength of 2.21 MPa at an optimized polymer ratio of 7:3. Antibacterial inhibition zones exceeded 16 mm against *Escherichia coli* and *Staphylococcus aureus*, and the material supported human dermal fibroblast growth. These results support further investigation for wound-related applications, but sterilization resistance, wet-state durability, degradation and in-vivo performance remain to be established.

Peel extracts have also been investigated for textile treatment. Treated cotton achieved a limiting oxygen index of 26.8%, showed self-extinguishing behaviour and retained flame-retardant performance after repeated washing (Nguyen *et al.*, 2025). The treatment was also associated with reduced toxic volatile emissions relative to the tested conventional formulation. Further work should identify the active extract constituents and clarify their interaction with cellulose. Extract consistency, colour, odour, wash durability and compatibility with industrial finishing processes will influence practical adoption.

Across these applications, moisture sensitivity and inconsistent testing conditions limit comparison. Studies should report filler origin, particle dimensions, treatment, loading, dispersion, matrix composition and conditioning history. Packaging materials additionally require barrier, migration and end-of-life assessments, while biomedical applications require application-specific biological evaluation. Biomass origin alone is insufficient to establish the environmental performance of a composite.

3.5. *Biofuels, Platform Chemicals and Direct Use*

Biological conversion uses the carbohydrate fraction of jackfruit peel as a substrate for microorganisms or enzymes. Anaerobic hydrogen fermentation produced 0.72 L of biogas per gram of volatile solids destroyed in a contact-

filter system, with a hydrogen content of 55 ± 2% and no detectable methane (Vijayaraghavan *et al.*, 2006). Performance depends on substrate accessibility, inoculum preparation and operating conditions. Although wet biomass can be processed without complete drying, the remaining liquid can retain a substantial organic load. Subsequent treatment or recovery of residual carbon and nutrients should therefore be included in process evaluation.

Bioethanol production requires sufficient access to fermentable carbohydrates. An integrated process combining steam-assisted organic-acid pretreatment, crude fungal cellulases and co-fermentation with *Saccharomyces cerevisiae* and *Kluyveromyces marxianus* achieved saccharification efficiencies above 93% and ethanol concentrations of approximately 17 g/L (Kumar and Uppuluri, 2026). Oxalic acid provided the highest digestibility among the tested organic acids. However, high saccharification efficiency does not necessarily imply a favourable overall energy balance. Dilute fermentation broths increase downstream separation requirements, making solids loading, inhibition and viscosity important development priorities.

Thermochemical conversion provides an alternative route to gaseous fuels. Supercritical-water gasification of jackfruit peel at 600 °C and 25 MPa produced 9.84 mmol H_2/g. A multimetal biochar–perovskite catalyst increased hydrogen yield to 13.5 mmol/g and gasification efficiency to 84.5%, while reducing tar formation (Nallimilli *et al.*, 2026). Processing wet biomass avoids complete feedstock drying, but high-pressure operation introduces equipment, corrosion and energy requirements. Catalyst recovery and stability should therefore be evaluated together with gas yield.

Carbohydrate-rich peel can also be converted into platform chemicals. A betaine-hydrochloride/$AlCl_3$ deep eutectic solvent converted untreated jackfruit rind into 5-hydroxymethylfurfural with a reported yield of 66.42 mol% at 135 °C. The yield was 65.23% after the first recycle, and the solvent system remained catalytically active over five consecutive runs (Huynh *et al.*, 2026). The process combined acid-catalysed carbohydrate conversion with product recovery. Its reported life-cycle assessment provides an initial environmental benchmark, but solvent manufacture, recovery, product extraction and humin management remain important determinants of overall performance.

Direct food applications use peel powder, dietary fibre, pectin, polysaccharides or phenolic extracts. Comparative analysis identified peel as a source of phenolic compounds with antioxidant and α-glucosidase-inhibitory activity (Zhang *et al.*, 2017). Incorporating peel powder into cookies increased dietary fibre and phenolic content, although high substitution levels adversely affected texture and sensory acceptance; ascorbic acid partly reduced these quality losses (Ngo *et al.*, 2024). Peel extracts have also improved the oxidative stability of soybean and sunflower oils under the reported storage and frying conditions (Koundal *et al.*, 2025). These applications require control of microbial contamination, pesticide and solvent residues, and sensory properties. Activity measured in laboratory assays should not be equated directly with a demonstrated human health benefit.

Animal-feed studies have investigated peel as a source of fibre and phytochemicals. Dietary supplementation improved selected growth, feed-conversion and meat-quality indicators in rabbits relative to the tested control diets and other jackfruit fractions (Ortega-González *et al.*, 2025). In Nile tilapia exposed to ammonia stress, supplementation at 5 g/kg feed improved selected haematological and immune indicators (Abdel-Tawwab *et al.*, 2025). Earlier fish-feeding experiments also indicated potential economic and nutritional benefits from fruit-waste diets (Sulaiman *et al.*, 2022). Commercial application nevertheless requires assessment of digestibility, nutrient consistency, antinutritional compounds, contaminants and longer-term feeding outcomes.

Agricultural applications include composting, soil amendment and nutrient recovery. Composting can stabilize readily degradable peel, while pyrolysis produces biochar with properties that depend on conversion conditions. Low levels of heavy metals and polycyclic aromatic hydrocarbons reported for a jackfruit-peel biochar support further evaluation of that material for environmental applications (Thuong Huyen *et al.*, 2025). Nutrient-loaded biochar composites have also been proposed for soil application after phosphate and nitrate recovery (Nayak *et al.*, 2021). However, reuse suitability should be established through nutrient-release measurements, plant-growth studies and assessment of soil effects. Material characterization alone does not demonstrate agronomic benefit.

3.6. *Cross-route Comparison and Cascade Valorization*

The bibliometric results identify connected research themes in adsorption and remediation, biopolymer and bioactive-compound recovery, and functional carbon materials. The temporal keyword analysis also indicates increasing attention to cellulose, nanocellulose and bioactive compounds alongside continuing adsorption research. These patterns help identify complementary routes, but publication activity does not establish technological maturity or demonstrate the feasibility of integrated processing.

The reviewed applications share several limitations: variable feedstock composition, inconsistent test conditions, incomplete mass balances and limited evidence from repeated or continuous operation. Direct food and feed use requires relatively few conversion steps but depends on safety, storage stability and nutritional consistency. Fractionation preserves selected structural or bioactive components while introducing separation and purification requirements. Carbonization and activation provide control over material properties but require accounting for energy, chemicals and washing effluents. Biological conversion can recover energy from carbohydrate fractions, although pretreatment and product separation remain important constraints. These

routes cannot be ranked using isolated yield or performance values because they provide different functions.

A proposed cascade could begin with mild recovery of phenolic compounds and pectin, followed by utilization of the cellulose-rich fraction for materials or fermentable sugars. Residual solids could subsequently be evaluated for carbon production or energy recovery. The sequence should remain flexible because each treatment can change the composition and suitability of downstream fractions. Mineral-rich residues may offer additional recovery opportunities, provided that their composition and application requirements are compatible.

Validation should proceed in a defined order. First, component and overall mass balances should establish recovery, losses and interactions between processing steps. Second, the resulting products should be compared with appropriate controls under consistent application conditions. Third, repeated or pilot-scale operation should evaluate solvent and water recycling, product consistency, effluent treatment and residue management. Techno-economic and life-cycle assessments should then compare the integrated process with credible individual-route alternatives using clearly defined system boundaries and product-allocation methods. Cascade processing could improve resource utilization, but its economic and environmental advantages require demonstration.

4. Conclusions

This review integrates bibliometric mapping with critical evaluation of processing–structure–performance relationships to provide a framework for comparing and connecting jackfruit-peel valorization routes. The evidence supports diverse applications in environmental remediation, functional materials and resource recovery, although practical implementation remains limited by feedstock variability, inconsistent testing, incomplete mass balances and insufficient durability data. The first research priority is to standardize feedstock characterization and quantify component recovery, product purity, resource consumption and residual streams. The next priority is validation under realistic conditions, including competing contaminants, repeated regeneration, long-term stability and continuous or pilot-scale operation. Safety assessment should accompany this validation, addressing leaching, migration, transformation products and end-of-life management. Techno-economic and life-cycle analyses should then compare integrated processes with credible individual-route alternatives. A flexible cascade could recover phenolics and pectin before directing cellulose-rich fractions towards materials or fermentable sugars and converting residual solids into carbon materials or energy products. However, the sequence requires verification because each treatment can alter downstream recovery and product performance. By linking research trends with complementary conversion routes and prioritized validation steps, this review provides a basis for determining when integrated utilization can deliver measurable resource-efficiency, economic and environmental benefits.

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Author contributions

Ruili Yang contributed to conceptualization, formal analysis, visualization, and methodology. Xiaoman Zhu contributed to bibliometric data collection and curation, literature synthesis, and manuscript writing and revision. Both authors reviewed and approved the final version of the manuscript.

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Generative AI statement

During the preparation of this manuscript, the authors used OpenAI ChatGPT solely for English-language editing and stylistic refinement. The authors subsequently reviewed and edited all AI-assisted content and take full responsibility for the final manuscript.

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