Circular Economy in the Oasis Ecosystem: Valorization of Date Palm By-products for Industrial Application in Southeastern Algeria — A Critical Systematic Review

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Abstract:

Southeastern Algeria's 12.2 million date palms generate over 700,000 t yr^{-1} of valorizable biomass, predominantly disposed of by open-field burning. This PRISMA-guided systematic review critically synthesises evidence from 45 sources across four valorization pathways: construction materials, activated carbon production, thermochemical energy, and agri-food biotechnology. Palm midrib fiberboards achieve tensile strength of 16.9–43.8 MPa; date-seed activated carbon reaches iodine numbers up to 787 mg g^{-1} and 86.9% COD removal; updraft gasification achieves 95% biomass conversion. An integrated bio-refinery model yields a payback period of approximately 4.0 years, 12–15% net margin, and avoidance of approximately 220,000 t CO_2eq per facility annually. Three original contributions are made: a cross-sector critical synthesis resolving inter-study contradictions; a regionally calibrated economic feasibility model; and a three-tier stakeholder policy roadmap. Life-cycle assessment data and industrial-scale pilot validation are identified as the most critical research gaps.

Keywords: date palm; circular economy; biorefinery; activated carbon; lignocellulosic composites; biomass gasification; Algeria; waste valorization

JEL Classification Codes: Q16, Q57, O13, L60, Q42

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1. Introduction:

The date palm (*Phoenix dactylifera* L.) is the structural keystone of the Saharan oasis ecosystem. Algeria hosts approximately 18–19 million palms across 170,000 ha, with southeastern wilayas—Biskra, El Oued, Ouargla, and Ghardaia—contributing 76% of national production exceeding 1.1 million tonnes annually, establishing Algeria as the world's third-largest producer (Hannachi et al., 2015; Boukhalfa et al., 2024).

As Algeria pursues economic diversification away from hydrocarbon dependency—historically representing over 90% of export earnings—valorization of agricultural residues has become a strategic national priority (USDA FAS, 2025). The national plan to plant one million new date palms by 2030 further amplifies the urgency of developing by-product valorization infrastructure (The African Dreams, 2024).

Annual maintenance generates 20–65 kg of dry vegetative residue per tree, yielding approximately 380,000 t yr-1 nationally. Including non-marketable fruit fractions (approximately 25% of harvest) and seed biomass, total valorizable bio-resources exceed 700,000 t yr-1 (Kerdouh et al., 2024; Makhlouf et al., 2022). Between 2009 and 2021, more than 911 fire incidents were recorded in Algerian palm groves (Harrouni et al., 2024), simultaneously destroying a carbon-rich feedstock and exacerbating regional air quality degradation.

Existing literature on date palm by-product valorization is consistently single-sector; no existing review integrates cross-sector evidence, addresses the southeastern Algerian economic context, or provides a stakeholder policy roadmap. This review addresses that gap through three original contributions:

1. A cross-pathway critical synthesis revealing substrate-performance interdependencies and resolving contradictions in reported data absent from existing single-sector reviews.
2. An integrated economic feasibility model for a multi-output bio-refinery calibrated to verified regional feedstock availability in southeastern Algeria.
3. A structured three-tier policy roadmap targeting government, private investors, and primary producers.

The specific objectives are: (i) to critically characterise the physicochemical properties of date palm by-products; (ii) to evaluate technical performance across four valorization sectors; (iii) to assess economic feasibility through an integrated bio-refinery model; and (iv) to develop a structured stakeholder policy roadmap.

2. Methodology:

2.1 PRISMA Framework and Search Strategy

This review was conducted following the PRISMA framework. Three electronic databases were searched: Web of Science, Scopus, and Google Scholar. Boolean string: ("date palm" OR "Phoenix dactylifera") AND ("by-product*" OR "waste" OR "residue*") AND ("valoriz*" OR "circular economy" OR "biorefinery" OR "composite" OR "activated carbon" OR "gasification"). Final corpus: 45 sources. Quality assessed via the Newcastle-Ottawa Scale (NOS); threshold: 5/9 for quantitative synthesis inclusion.

2.2 Inclusion and Exclusion Criteria

Table N°1: Inclusion and exclusion criteria applied in the systematic review.

Criterion	Inclusion	Exclusion
Publication type	Peer-reviewed articles; institutional reports (FAO, USDA, CGIAR)	Conference abstracts without full text; opinion pieces
Language	English; French (with English abstract)	Languages without English abstract
Period	2010–2024 (plus seminal foundational works)	Outdated data superseded by recent studies
Geographic scope	Algeria; MENA (for methodological benchmarking)	No relevance to arid environments
Thematic scope	Physicochemical characterisation; performance testing; economic modelling	Studies on fruit quality or post-harvest storage only
Data quality	Quantitative data with defined experimental conditions	Non-reproducible or unreported methods

Source: Authors' compilation based on PRISMA guidelines.

2.3 Economic Modelling Scope

Economic feasibility was assessed through a bottom-up integrated bio-refinery model. Capital and operational expenditure parameters were sourced from peer-reviewed techno-economic analyses and verified against institutional market data (USD 2024 equivalent). The model does not incorporate Monte Carlo sensitivity analysis—a recognised limitation discussed in section 4.

3. Results: Critical Synthesis of Valorization Evidence

3.1 Regional Context and Biomass Availability

The quadruplication of regional tree populations over three decades—driven by state-facilitated expansion using non-renewable groundwater—has transformed the landscape from scattered traditional oases into modern high-density production zones (Hannachi et al., 2015; Guendouz et al., 2024). Current waste

management encompasses three practices: (i) open-field burning (predominant; 911 incidents 2009–2021) (Harrouni et al., 2024); (ii) informal reuse as animal feed; and (iii) limited co-composting. The absence of formalised biomass collection infrastructure constitutes the primary structural barrier to industrial valorization.

Table N°2: Regional distribution of date palm population and production in southeastern Algeria.

Province (Wilaya)	Est. Tree Count	National Prod. (%)	Dominant Varieties
Biskra	>= 4,500,000	31.0	Deglet Noor, Ghars
El Oued	>= 4,000,000	27.0	Deglet Noor, Degla Baida
Ouargla	>= 2,500,000	18.0	Ghars, Deglet Noor
Ghardaia	>= 1,200,000	5.0	Traditional (diverse)
Adrar/SW	>= 3,900,000	Variable	Takarbouche, diversified

Source: Hannachi et al. (2015); Boukhalfa et al. (2024); Kherief Nacereddine et al. (2023).

3.2 Physicochemical Composition: Data Reconciliation

Date palm vegetative organs display monocotyledonous anatomy conferring anisotropic properties that differ fundamentally from dicotyledonous hardwoods (Mostefa et al., 2022a). **Critically, cellulose content for palm midrib ranges from 41.5% to 69.3%—a 27.8 percentage-point spread reflecting differences in analytical method, variety, and collection season. This inter-study variability is the most significant methodological finding of this review.**

Table N°3: Lignocellulosic composition of date palm by-product substrates (range across reviewed studies).

Substrate	Cellulose (%)	Lignin (%)	Hemicellulose (%)	Ash (%)	n
Palm Midrib	41.5–69.3	15.0–28.0	18.0–32.0	2.5–5.0	7
Leaf Sheath (Fibrillium)	35.0–45.0	25.0–30.0	20.0–25.0	5.0–8.0	4
Petioles	30.0–38.0	20.0–28.0	25.0–30.0	3.0–6.0	5
Date Seeds	13.2 (crude)	10.0–15.0	25.0–35.0	1.0–2.0	6

Source: Kerdouh et al. (2024); Makhlouf et al. (2022); Mostefa et al. (2022a); Belbachir et al. (2023); Mokhtar & Djelaili (2022).

3.3 Construction Materials and Lignocellulosic Composites

Single fibres from date palm fronds exhibit mean tensile strength of 333 MPa and elastic modulus of approximately 17.1 GPa (Agoudjil et al., 2023). The upper range of date palm board elastic modulus (9.52 GPa) substantially exceeds the commercial MDF ceiling (4.0 GPa), suggesting potential for structural applications not yet explored in the literature. Conversely, the lower range (1.72 GPa) indicates high sensitivity to processing parameters whose optimisation remains incomplete (Mostefa et al., 2022a; 2022b).

Table N°4: Comparative performance of date palm-based boards versus commercial MDF standards.

Property	Date Palm Board	MDF Standard	Assessment
Elastic modulus (GPa)	1.72–9.52	2.0–4.0	Overlapping — competitive
Tensile strength (MPa)	16.9–43.8	20.0–45.0	Overlapping — competitive
Thermal cond. (W m-1 K-1)	0.058–0.122	0.050–0.150	Fully within standard
Sound absorption (NRC)	> 0.37	0.20–0.40	Exceeds lower bound
Thermal stability onset (°C)	approx. 291	260–300	Within standard

Source: Agoudjil et al. (2023); Mostefa et al. (2022a; 2022b); Kriker et al. (2005). NRC = Noise Reduction Coefficient.

3.4 Activated Carbon for Environmental Remediation

Activated carbon (AC) from date palm waste via pyrolysis at 450 °C with H3PO4 pre-impregnation yields iodine numbers of 247–787 mg g-1 (Belbachir et al., 2023; Dib et al., 2022). **This 540-unit range across similar substrates and activation methods represents a fundamental contradiction in the literature** explained by three factors: (i) H3PO4 impregnation ratio varied from 1:1 to 3:1; (ii) pyrolysis hold time ranged from 30 to 120 minutes; and (iii) particle size was reported in only 2 of 6 studies.

Table N°5: Activated carbon performance parameters by substrate.

Precursor	Activation	Iodine No. (mg g-1)	BET (m2 g-1)	Yield (%)	Key Variable
Date Seeds (El Oued)	Pyrolysis + physical	735.2	125.86	N/R	Temperature
Petioles (SW Sahara)	Chemical (H3PO4 1:1)	247.46	N/R	51.11	Impregnation ratio
Floral Handles	Chemical (H3PO4 2:1)	786.78	N/R	39.98	Impregnation ratio
Fibrillium	Chemical (H3PO4 1.5:1)	596.43	N/R	46.99	Impregnation ratio

Source: Belbachir et al. (2023); Dib et al. (2022); Bentarfa (2022). N/R = Not reported.

Date seed-derived AC achieved COD reduction of 86.9% and nitrate removal of 47.9% in El Oued industrial effluents (Dib et al., 2022). All adsorption studies used synthetic solutions; no study tested performance against real multi-pollutant industrial wastewater—a critical translational gap.

3.5 Energy Valorization and Agri-food Biotechnology

Fixed-bed updraft gasification in Adrar experimental reactors achieved 95% biomass conversion at 174–557 °C (Kerdouh et al., 2024). All studies used laboratory-scale reactors (<10 kg hr-1); no pilot-scale data exists. A circular loop was demonstrated: AC from palm fronds catalyses biodiesel synthesis from waste cooking oil at 88% yield (Boublia et al., 2025)—the sole documented cross-sector integration in the reviewed corpus.

Date seed oil (approximately 7.8% content; oleic and lauric acid-rich) supports biodiesel production comparable to conventional diesel (Boulal et al., 2023). Co-composting with goat manure (C/N declining from approximately 60 to 20) improved soil CO2 mineralisation by 178% (Sellami et al., 2020). Non-marketable dates (approximately 25% of harvest) are processed by SMEs into date sugar, syrup, and vinegar (El Finti et al., 2024).

3.6 Cross-Sector Synthesis: Interdependencies and Strategic Insights

Table 6 maps valorization pathways by substrate. Three strategic insights emerge: (i) Date seeds are the only substrate with high-value applications across three sectors simultaneously, making them the priority for integrated processing. (ii) Floral handles have the highest documented AC iodine number (787 mg g-1) yet are absent from construction and energy literature—significant underexploration. (iii) The AC-catalysed biodiesel circular loop eliminates external catalysts, reducing process costs substantially (Boublia et al., 2025).

Table N°6: Cross-sector valorization pathway matrix by substrate type.

Substrate	Construction	Remediation	Energy	Agri-food	Priority
Palm Midrib (fronds)	*** MDF, composites	** AC catalyst	*** gasification	—	HIGH
Petioles	*** insulation boards	*** AC; 51% yield	** gasification	—	HIGH
Leaf Sheath	** composite filler	** AC; 47% yield	* co-gasification	—	MEDIUM
Date Seeds	* epoxy composite	*** AC; 737 mg g-1	** biodiesel	*** cosmetics, food	HIGH
Non-marketable Dates	—	—	*** bio-ethanol	*** sugar, syrup	MEDIUM
Floral Handles	—	*** AC; 787 mg g-1	—	—	MEDIUM

Source: Authors' synthesis. * = primary/high-value; ** = secondary; * = emerging; — = not documented.**

4. Economic Feasibility and Discussion:

4.1 Integrated Bio-refinery Model

An integrated bio-refinery was modelled for co-processing of multiple date palm by-product streams in Biskra and El Oued, producing four outputs: MDF, bio-ethanol, date seed oil, and activated carbon. Table 7 presents feedstock availability; Tables 8 and 9 present the financial model.

Table N°7: Estimated annual feedstock availability by wilaya (t yr-1).

Wilaya	Vegetative Biomass	Non-Marketable Dates	Seeds (est.)	Total
Biskra	180,000–220,000	75,000–90,000	12,000–15,000	267,000–325,000
El Oued	160,000–200,000	65,000–80,000	10,000–14,000	235,000–294,000
Ouargla	100,000–130,000	40,000–55,000	6,500–9,000	146,500–194,000
Ghardaia	45,000–60,000	15,000–25,000	2,500–4,000	62,500–89,000

Source: Hannachi et al. (2015); The African Dreams (2024); Kerdouh et al. (2024). Seed tonnage estimated as 10% of non-marketable fruit weight.

Table N°8: CAPEX and OPEX for a 150,000 t yr-1 integrated bio-refinery (USD 2024).

Expenditure Category	Estimated Cost (USD)	Basis
CAPEX: Machinery and infrastructure	$12,500,000–$15,000,000	MDF lines, fermentation, distillation (Foong et al., 2021a; CGIAR-ICARDA, 2018)
CAPEX: Land and civil works	$2,000,000–$3,000,000	Industrial zone, SE Algeria
OPEX: Raw material collection (yr-1)	$1,500,000	Farmer incentives, logistics (Farghali et al., 2025)
OPEX: Utilities and labour (yr-1)	$2,500,000	Thermal process energy, technical staff
OPEX: Maintenance and overheads (yr-1)	$800,000	Equipment upkeep
Total initial investment	approx. $16,500,000	CAPEX mid-range estimate

Source: Foong et al. (2021a); CGIAR-ICARDA (2018); Farghali et al. (2025). All values USD 2024.

Table N°9: Financial performance indicators and comparison with composting benchmark.

Financial Metric	Bio-refinery Model	Composting Benchmark (Farghali et al., 2025)
Total initial investment	$16.5 million	Lower absolute investment
Annual net profit	$4.8–$5.5 million	Lower (fertiliser commodity margins)
Payback period	approx. 4.0 years	approx. 4.0 years
Net profit margin	12–15%	8–10%
Direct employment per facility	approx. 250 technical jobs	Fewer (less processing complexity)

Financial Metric	Bio-refinery Model	Composting Benchmark (Farghali et al., 2025)
CO2eq avoided (t yr-1)	approx. 220,000	Lower
MDF import substitution	approx. $34.5M yr-1	Negligible

Source: IndexBox (2024); IMARC Group (2025); Farghali et al. (2025). All values USD 2024.

4.2 Discussion: Interpretation and Limitations

The cross-sector synthesis confirms that date palm by-products satisfy physicochemical prerequisites for valorization across all four pathways. However, the 27.8 percentage-point range in midrib cellulose content and the 540 mg g-1 spread in AC iodine numbers reveal that the literature has not established reproducible processing baselines (Makhlouf et al., 2022; Mokhtar & Djelaili, 2022). Industrial specifications must account for natural feedstock heterogeneity through blending or real-time quality monitoring—neither of which has been studied.

Four sources of model uncertainty are not quantified: (i) Algerian dinar exchange rate risk; (ii) supply-chain formalisation costs for 2,500–5,000 informal collectors; (iii) the complete absence of LCA data means CO2eq claims are mass-balance estimates rather than verified accounts; and (iv) price assumptions are point estimates without sensitivity analysis. A Monte Carlo simulation across plus or minus 20% price variation is a research priority (Foong et al., 2021b).

Any circular bioeconomy strategy must be bounded by non-renewable groundwater depletion. The expansion of irrigated area from 350,000 ha (2000) to over 1.3 million ha (2020) places severe pressure on both aquifer systems (Guendouz et al., 2024). Bio-refinery development cannot be decoupled from water governance—the water-biomass nexus constitutes an important interdisciplinary research frontier.

4.3 Three-Tier Policy Roadmap

Translating findings into actionable implementation requires coordinated intervention across three governance levels:

Table N°10: Three-tier stakeholder policy roadmap for circular bioeconomy implementation in southeastern Algeria.

Tier	Stakeholder	Key Actions	Timeline	KPI
1 — Regulatory	Central Government	(i) Designate SE Algeria as a Circular Bioeconomy Priority Zone; (ii) mandate biomass collection protocols; (iii) align	Years 1–3	No. certified bio-refineries; export volume

Tier	Stakeholder	Key Actions	Timeline	KPI
		product standards with EU norms		
2 — Investment	Private Sector / PPP	(i) Establish bio-refineries in Biskra and El Oued; (ii) co-fund LCA and pilot-scale trials; (iii) develop date seed oil value chain	Years 2–6	Investment (USD); payback achieved; jobs
3 — Production	Farmers and Cooperatives	(i) Formalise biomass collection cooperatives; (ii) transition from burning via incentive programmes; (iii) adopt co-composting at wilaya scale	Years 1–5	% farmers participating; tonnes diverted

Source: Authors' compilation. PPP = Public-Private Partnership; KPI = Key Performance Indicator.

4.4 Five Priority Research Gaps

Five priority knowledge gaps are identified, ranked by their blocking effect on investment decisions:

1. Cradle-to-gate Life Cycle Assessment (LCA) for all four valorization pathways under Algerian conditions. Environmental performance claims cannot currently be verified. Priority: CRITICAL.
2. Industrial-scale pilot trials of gasification (target: >=500 kg hr-1) and AC production to validate bench-scale conversion efficiencies. Priority: HIGH.
3. Standardised physicochemical characterisation protocols for Algerian cultivars—particularly Degla Baida and Ghars—to resolve inter-study variability documented in this review. Priority: HIGH.
4. Full techno-economic analysis incorporating Monte Carlo sensitivity modelling under Algerian fiscal, labour, and currency risk conditions. Priority: MEDIUM-HIGH.
5. Longitudinal field trials of date palm compost application to quantify effects on soil fertility and subsequent date palm yield in Saharan conditions. Priority: MEDIUM.

5. Conclusion:

This critical systematic review synthesises and evaluates evidence from 45 sources on date palm by-product valorization in southeastern Algeria within a circular economy framework. The review makes three original contributions beyond existing single-sector literature: a cross-pathway critical synthesis revealing substrate-performance interdependencies; a calibrated integrated bio-refinery economic model; and a structured three-tier policy roadmap.

The principal findings are:

1. Date palm lignocellulosic residues exhibit physicochemical properties competitive with commercial MDF; inter-study variability is too large for confident industrial specification without standardised testing protocols.

2. Activated carbon performance spans 247–787 mg g-1 iodine number; this spread is explained by inconsistent impregnation ratios and pyrolysis hold times—a finding with direct implications for process design.
3. Updraft gasification (95% conversion) and AC-catalysed biodiesel synthesis (88% yield) demonstrate technical maturity at laboratory scale only; no pilot-scale validation data exists.
4. The integrated bio-refinery model indicates economic viability (approximately 4.0-year payback; 12–15% net margin; approximately 220,000 t CO2eq avoided per facility) contingent on feedstock collection formalisation.
5. The complete absence of LCA data from the corpus is the most critical knowledge gap: environmental benefit claims cannot be rigorously substantiated.

Achieving circular bioeconomy transformation in the Algerian oasis ecosystem requires simultaneous action across technical, institutional, and policy domains. The three-tier roadmap and five identified research gaps define the minimum evidence base required before large-scale capital commitment can be made with confidence.

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