



## REVIEW ARTICLE

# Systematic Literature Review on Sustainable Value Chain Transformation of *Arenga pinnata* in Tropical Bioresource Systems



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## ABSTRACT

Aren (*Arenga pinnata*) has emerged as a multifunctional tropical species. It has the potential to contribute to sustainable value chain development, the circular bioeconomy, and rural livelihoods. Nevertheless, existing literature remains fragmented and addresses ecological, technological, and governance dimensions in isolation. This study systematically reviews the literature on the sustainable value chain transformation of *A. pinnata* within tropical bioresource systems. It identifies factors influencing its transition from a traditional multipurpose palm to a strategic bioresource platform. A systematic literature review was conducted through a structured process. The steps included search, screening, eligibility assessment, data extraction, and thematic synthesis. The review combined empirical studies with broader literature on circular bioeconomy, value chain restructuring, social sustainability, and governance. The analysis covered four thematic domains: upstream resource systems, midstream processing and upgrading, downstream diversification, and market or institutional alignment. The review shows that *A. pinnata* can drive transformative change. This is due to its multifunctionality, ecological adaptability, and diverse product pathways. Upstream research highlights its role in agroforestry, biodiversity-linked landscapes, and livelihood systems. Midstream studies identify opportunities for product stabilization, fermentation, and process improvement. Downstream investigations show promising use in thermoplastic starch, composites, functional biomaterials, and circular by-products. However, integration among these advances is weak. Technical innovation often outpaces commercialization and governance. Value distribution, coordination, and inclusion also remain underdeveloped. The study concludes that the sustainable transformation of *A. pinnata* requires integrating resource sustainability, technological upgrading, and market or institutional alignment. This review offers an integrated framework for understanding aren-based transformation and identifies priorities for future research on commercialization, circularity, and inclusive tropical bioresource development.

## 1. Introduction

*Arenga pinnata* is increasingly recognized as a multifunctional tropical species with strategic importance for the development of sustainable value chains, rural livelihoods, and a circular bioeconomy. Traditionally, it has been used for palm sugar, palm flour, fruit products, fiber, and household goods. Recent research shows that it also provides foodstuffs, fermented products, renewable energy raw materials, composites, thermoplastic starches, and other bio-based materials (Aulia et al., 2024; Ghozali et al., 2023; Ilahi et al., 2025; Sarkar et al., 2022; Sulistyowati et al., 2025). This diversity of applications suggests that *A. pinnata* has broader significance as a tropical biological resource beyond its traditional status as a rural commodity (Azhar et al., 2021).

The debate over a sustainable bioeconomic transition underscores the need for this transition. Contemporary bioeconomic literature advocates a more efficient use of biomass in diverse circular systems (Sherwood, 2020). In these systems, materials are continuously reused and recycled across the food, feed, materials, chemicals, and energy sectors (Vermeir et al., 2020). Such systems aim to reduce waste and improve sustainability. *A. pinnata* is relevant to this discussion. It has characteristics suitable for cascading use and multiple outputs (Abdullah and Hussein, 2021). Research on thermoplastic starch from palm sugar, applications of palm fiber bio-composites, mesoporous aerogels from endosperm palms, and palm by-products in secondary systems suggest that such species can support diverse product portfolios rather than a single product chain (Tarchoun, 2022).

The importance of *A. pinnata* goes beyond downstream applications. The species is rooted in rural production systems, agroforestry, and the economy of non-timber forest products (Hadish, 2018). Socio-ecological studies show that palm production depends on access to land, local knowledge, biodiversity, and village-level processing, such as palm sugar and flour (Withaningsih et al., 2019). Ecological evidence also suggests *A. pinnata* supports diverse vegetation and plays a role in the ecology of the broader landscape. Furthermore, palms are featured in discussions on the development and restoration of tropical oil palms, linking cultivation, conservation, and reforestation (Abdullah et al., 2024).

Despite this growing interest, the literature remains fragmented (Harahap et al., 2026). One research body views palm as an underutilized or ethnobotanically valuable species with diverse socio-economic uses. Another explores socio-ecological production systems, agroforestry, and resource use related to biodiversity. The third examines the processing and quality of products, including edible coatings, fermentation, and the potential of functional foods. The fourth body discusses the use of advanced materials, including composites, starch-based materials, and specialized adsorbents. Nevertheless, another group offers a broader conceptual framework for circular bioeconomics, value chain transformation, social sustainability, and governance, but does not specifically focus on these areas.

This fragmentation results in significant research gaps. While the literature suggests that palm has ecological significance, processing potential, and value for innovation, it rarely explains how these elements interact within a sustainable value chain. Product-focused studies often end up at the technical feasibility stage. Socio-ecological research remains at the local description. Bioeconomic studies provide theoretical insights that are rarely based on specific evidence (Castro and Lechthaler, 2022). As a result, the literature lacks a unified explanation of how *A. pinnata* can shift from a versatile species to a resilient, high-value, and sustainability-oriented tropical bioresource system (Chamberlain and Smith-Hall, 2024).

This article addresses this gap by conducting a systematic literature review of the sustainable value chain transformation of *A. pinnata* in tropical bioresource systems. This review is guided by the proposition that sustainable transformation depends on the interaction between resource sustainability, technological upgrades, and market or institutional alignment. This framework aligns with broader research showing that innovation alone does not ensure equitable or sustainable outcomes, and that governance, coordination, and benefit-sharing mechanisms determine who benefits from the bioeconomic transition (Clay and Sellare, 2022, 2025; Puder and Tittor, 2023; Saes et al., 2023). Therefore, this article addresses four key questions: how the literature conceptualizes the value chain of *A. pinnata* from production to diversification; which ecological, technological, and institutional factors enable or limit transformation; the extent to which *A. pinnata* has been repositioned from a traditional rural species into a strategic tropical biological resource; and the remaining research gaps. By answering these questions, this review contributes to the ongoing debate about circular bioeconomics, inclusive enhancement, and the sustainable development of underutilized tropical resources.

## 2. Materials and Methods

### 2.1. Review Design

This study used a systematic literature review to synthesize fragmented scholarship on the transformation of aren (*Arenga pinnata*) in tropical bioresource systems. A systematic review was needed because studies span various fields, including agroforestry (integration of trees and crops), food science (study of food properties), fermentation (microbial transformation of substances), materials engineering (study of materials), rural livelihoods (support of rural life), the circular bioeconomy

(resource reuse and regeneration), and value chain governance (process management from production to market). The reviewed studies differ in design and scale. They include socio-ecological case studies (interactions between society and environment), vegetation analyses (plant community surveys), engineering trials (tests of engineering solutions), product tests (evaluations of new products), and conceptual reviews (analyses of theoretical concepts). Given this diversity, a qualitative (focused on meanings and experiences), thematic (identifying common themes), and configurative (organizing sources) synthesis was chosen, rather than a statistical meta-analysis (quantitative summary of findings).

The review was organized to integrate empirical studies on *A. pinnata* with broader interpretive scholarship. Aren-focused studies contributed evidence on production systems, ecological context, product innovation, food processing, fermentation, and by-product use (Ghozali et al., 2023; Ilahi et al., 2025; Sarkar et al., 2022; Sulistyowati et al., 2025). Broader conceptual studies on circularity, biomass-based business models, value chain restructuring, socio-biodiversity, and bioeconomy upgrading were included because they offer the theoretical vocabulary needed to interpret transformation processes that are only partially visible in the existing literature itself (Achillas and Bochtis, 2020; Clay and Sellare, 2022; Feng et al., 2023; Lange et al., 2021; Puder and Tittor, 2023; Saes et al., 2023; Venkatesh, 2021).

The overall review logic followed a PRISMA-informed structure: identification, screening, eligibility assessment, and inclusion. In this study, PRISMA was used as a transparency and reporting framework to systematically document the literature selection process.

## 2.2. Search Strategy

The search strategy was designed to capture the breadth of literature relevant to aren transformation. Because aren are discussed under different labels across product and disciplinary domains, several keyword clusters were used. The first cluster included “*Arenga pinnata*,” “sugar palm,” and “aren,” together with product-related terms such as sap, palm sugar, palm flour, fruit, fiber, ijuk, starch, vinegar, thermoplastic starch, composite, probiotic, and by-product. This was necessary because some studies focus on aren-derived materials or foods without foregrounding the species name in the title.

The second keyword cluster targeted context and system conditions, including agroforestry, non-timber forest products, rural livelihoods, biodiversity, conservation, restoration, and tropical bioresources. This was especially relevant given the importance of aren in landscape-based and community-linked production systems (Azahari et al., 2024; Withaningsih et al., 2019, 2023). The third cluster addressed transformation-related concepts such as value chain, supply chain, upgrading, commercialization, value addition, circular bioeconomy, circular economy, waste valorization, sustainability, governance, and bio-based business model. These terms enabled the inclusion of conceptual work on biomass transition and sustainable upgrading that is relevant to the transformation trajectory (Achillas and Bochtis, 2020; Clay and Sellare, 2022, 2025).

The search drew on multidisciplinary databases, including Scopus, Web of Science, Google Scholar, ScienceDirect, and SpringerLink, with supplementary backward and forward citation tracing. The review window covered recent scholarship relevant to aren transformation, especially literature from 2017 to 2025, which includes ecological, technical, and governance-oriented studies from both aren-specific and broader bioeconomy fields.

## 2.3. Inclusion and Exclusion Criteria

Studies were included when they met four criteria. First, they had to examine *A. pinnata*, sugar palm, or closely related aren-based systems as a central empirical or conceptual focus. Second, they had to contribute to at least one stage of the value chain, namely upstream resource systems, midstream processing, downstream diversification, or governance and market organization. Third, they had to be relevant to sustainability, value addition, upgrading, or circular transformation. Fourth, they had to be scholarly publications, including journal articles, review articles, and academically credible proceedings.

Studies were excluded when *A. pinnata* appeared only incidentally, when the subject concerned other palm species without direct transferability, when the methodological or conceptual contribution was too limited for synthesis, or when the full text was unavailable. These criteria ensured that the final corpus captured both empirical and theoretical studies, as well as broader theoretical contributions that helped interpret the existing evidence base.

The final set included 19 references spanning socio-ecological production systems (Withaningsih et al., 2019), vegetation and ecological context (Withaningsih et al., 2023), underutilized species and ethnopharmacological attributes (Sarkar et al., 2022), reforestation-linked palm cultivation (Azahari et al., 2024), food quality and shelf-life improvement (Aulia et al., 2024), probiotic and fermentation potential (Ilahi et al., 2025), by-product use (Sulistiyowati et al., 2025), biomaterials and materials science applications (Bahrain et al., 2017; Ghozali et al., 2023; Savov et al., 2023; Tarigan et al., 2020), and conceptual literature on circular bioeconomy and governance (Achillas and Bochtis, 2020; Clay and Sellare, 2022, 2025; Feng et al., 2023; Lange et al., 2021; Puder and Tittor, 2023; Saes et al., 2023; Venkatesh, 2021).

#### 2.4. Screening and Selection Procedure

The screening procedure followed four stages. First, records were identified using the predefined keyword combinations. Second, duplicate entries were removed. Third, titles and abstracts were screened against the eligibility criteria. Fourth, full texts were examined for substantive relevance to the aren value chain transformation.

The selection process required interpretive judgment because not all relevant studies explicitly used the same terminology. For instance, some technical studies on thermoplastic starch or mesoporous applications were clearly relevant to aren-based diversification even when they did not frame their contributions as a value chain issue (Ghozali et al., 2023; Tarigan et al., 2020). Similarly, broader conceptual studies on bioeconomy transition and social sustainability were retained when they provided analytical tools necessary to interpret aren transformation, even if they were not specific to *A. pinnata* (Puder and Tittor, 2023; Saes et al., 2023). This balance between empirical specificity and conceptual relevance was necessary to construct a meaningful synthesis.

#### 2.5. Data Extraction and Coding

A structured review matrix was used to extract comparable information from each study. The matrix included author, year, region, study objective, study design, value chain stage, resource or product focus, sustainability dimension, key findings, and implications. Additional coding fields included the transformation mechanism, type of upgrading, governance relevance, and circularity potential. These additions enabled comparison of highly diverse studies within a single analytical framework.

Studies such as Azahari et al. (2024) and Withaningsih et al. (2019, 2023) were coded mainly under upstream sustainability and ecological context. Aulia et al. (2024), Ilahi et al. (2025), and Sulistiyowati et al. (2025) were coded under midstream processing and secondary valorization. Bahrain et al. (2017), Ghozali et al. (2023), Savov et al. (2023), and Tarigan et al. (2020) were coded under downstream product diversification and materials innovation. Conceptual studies such as Achillas and Bochtis (2020), Clay and Sellare (2022, 2025), Feng et al. (2023), Lange et al. (2021), Puder and Tittor (2023), Saes et al. (2023), and Venkatesh (2021) were coded under circularity, governance, upgrading, and sustainability assessment.

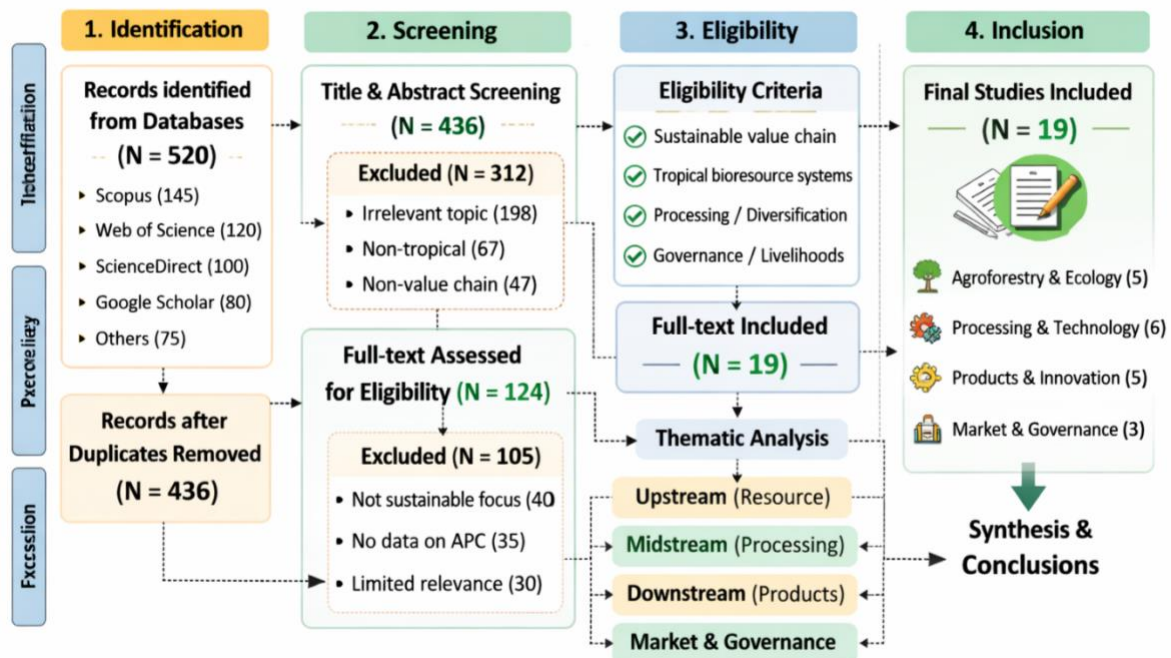
#### 2.6. Quality Appraisal

Because the studies differed widely in design and quality, quality appraisal was conducted using a fit-for-purpose approach rather than a single checklist. For socio-ecological studies, the appraisal emphasized contextual depth, analytical clarity, and the connection between local findings and value chain implications. For technical and experimental studies, the appraisal focused on methodological transparency, relevance of indicators, and plausibility of application claims. For conceptual and review-based works, the appraisal emphasized coherence, analytical relevance, and interpretive value.

This flexible appraisal approach was essential, as the review sought to be integrative rather than exclusionary. Studies were not excluded solely on the basis of differing epistemological traditions. Instead, quality assessment determined the relative weighting of each study in the final synthesis.

## 2.7. Data Synthesis

The final synthesis was thematic. The literature was organized into four main domains: upstream resource base, midstream processing upgrading, downstream diversification, and market structure and governance. The synthesis proceeded in two steps. First, studies were descriptively mapped by year, topic, and value chain stage. Second, they were interpreted comparatively to identify recurring patterns, complementarities, tensions, and research gaps.



**Fig. 1.** PRISMA-style flow diagram of the literature identification, screening, eligibility assessment, and inclusion process used in the systematic review of sustainable value chain transformation of *Arenga pinnata*.

This approach enabled the literature to be reorganized around the core analytical triad used in this review: resource sustainability, technological upgrading, and market or institutional alignment. In this way, the Methods section directly supported the broader objective of explaining aren transformation as a systemic rather than product-specific process.

## 3. Results and Discussion

### 3.1. Conceptualizing Sustainable Value Chain Transformation

Sustainable value chain transformation denotes a structural shift in the production, processing, valorization, and governance of biological resources that results in value creation, which is economically viable, environmentally responsible, and socially inclusive. Within bioresource systems, transformation extends beyond productivity growth or downstream product innovation, requiring coordinated change across multiple value chain stages and actor groups. This broader perspective is consistent with scholarship on the circular bioeconomy and sustainable upgrading, which emphasizes that value addition must be linked to system efficiency, waste reduction, inclusive participation, and resilient governance structures (Achillas and Bochtis, 2020; Clay and Sellare, 2025; Venkatesh, 2021).

In this review, the concept is especially relevant because *A. pinnata* is associated with multiple forms of value creation. Its sap supports sugar and fermentation pathways, its starch can be transformed into thermoplastic materials, its fibers can be used in composites, and its by-products may be incorporated into secondary or circular production uses (Bahrain et al., 2017; Ghozali et al., 2023; Ilahi et al., 2025; Sulistyowati et al., 2025). However, these uses do not automatically constitute transformation. Transformation occurs only when they are connected through resource sustainability, technological capability, and institutional or market coordination.

### 3.2. Tropical Bioresource Systems Perspective

#### 3.2.1. *Arenga pinnata* as a landscape-embedded species

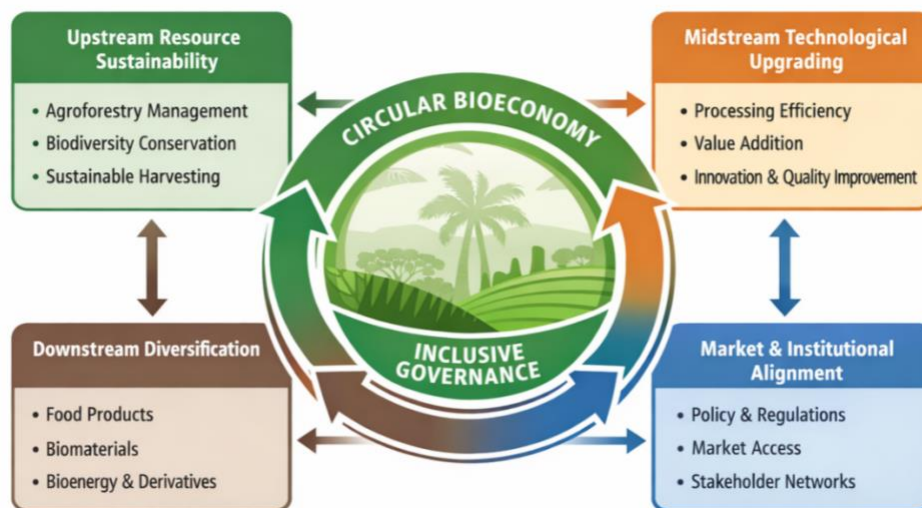
A tropical bioresource systems perspective views biological resources as part of a coupled socio-ecological system rather than simply as a raw material source. This perspective is supported by the literature, which shows that *A. pinnata* is closely tied to agroforestry, biodiversity-rich landscapes, and rural production settings (Azahari et al., 2024; Withaningsih et al., 2019, 2023). The value of the species depends not only on its biological traits but also on how local communities access land, maintain knowledge, organize labor, and connect ecological resources to production systems.

This perspective is further reinforced by scholarship on underutilized species, which highlights that the numerous usable parts of the palm make it particularly suitable for diversified, locally embedded use systems (Sarkar et al., 2022). Thus, *A. pinnata* is best understood as a multifunctional landscape resource with both ecological and economic significance.

#### 3.2.2. From traditional use to circular transformation

The tropical bioresource systems perspective also helps explain how *A. pinnata* may transition from traditional use systems to circular and higher-value pathways. The circular bioeconomy literature argues that sustainably sourced biomass should be managed through diversified, cascading resource flows rather than single-output extraction systems (Feng et al., 2023; Lange et al., 2021). This is especially relevant to *A. pinnata*, because food products, biomaterials, residues, and bio-based process streams are all represented in the literature.

However, circular transition is not only a technical matter. It also depends on coordination, infrastructure, and institutional design. Without these conditions, innovation may remain isolated and benefits may be captured unevenly. This concern is particularly relevant in *A. pinnata* systems, where local producers often operate under limited capital and weak market access (Withaningsih et al., 2019). The integrated relationships among these dimensions are illustrated in Fig. 2, which presents the theoretical framework for interpreting sustainable value chain transformation in *A. pinnata*-based bioresource systems.



**Fig. 2.** Integrated theoretical framework for analyzing sustainable value chain transformation of *Arenga pinnata* in tropical bioresource systems.

### 3.3. Relevant Theories and Analytical Lenses

Several complementary analytical lenses inform this review. Socio-ecological systems thinking helps explain how production is linked to landscape conditions and local knowledge. Livelihoods frameworks clarify the role of *A. pinnata* in household welfare, local resilience, and community-based production. Value chain and governance perspectives explain how upgrading, coordination, and value capture are distributed among actors (Clay and Sellare, 2022; Puder and Tittor, 2023). Innovation systems thinking helps interpret trajectories of process and product development, including edible

coatings, probiotic potential, thermoplastic starch, and composite materials (Aulia et al., 2024; Ghozali et al., 2023; Savov et al., 2023). Circular bioeconomy theory serves as an integrative lens, connecting resource stewardship, valorization, residue use, and sustainability outcomes (Achillas and Bochtis, 2020; Lange et al., 2021; Venkatesh, 2021).

### 3.4. Historical Development of *Arenga pinnata* Research

The literature suggests a gradual broadening of academic scholarship on *A. pinnata*. Earlier attention focused on traditional uses and the multifunctionality of the species in rural contexts. Later work shifted toward socio-ecological production systems and ecological relevance (Withaningsih et al., 2019, 2023). More recent studies increasingly examine technically and industrially relevant applications, including food stabilization, fermentation, composites, and starch-based materials (Aulia et al., 2024; Bahrain et al., 2017; Ghozali et al., 2023; Ilahi et al., 2025; Tarigan et al., 2020). This broadening has been accompanied by stronger conceptual engagement with circularity, socio-biodiversity, and governance, which together support the repositioning of *A. pinnata* as a strategic tropical bioresource.

### 3.5. Major Scholarly Streams and Ongoing Debates

The literature identifies several scholarly streams in the study of *A. pinnata*: the species as an underutilized resource, a socio-ecological livelihood asset, a food and fermentation system, a materials feedstock, and a candidate for circular bioeconomy transformation. These streams generate several ongoing debates. One debate concerns whether *A. pinnata* should be regarded primarily as a traditional rural species or as a strategic bioresource for circular development. Another concern is whether commercialization and technical upgrading can proceed without compromising local embeddedness. A third debate questions whether economic upgrading necessarily results in social and environmental upgrading; broader scholarship suggests that it does not (Clay and Sellare, 2025; Puder and Tittor, 2023). These unresolved debates underscore the need for the thematic synthesis that follows.

### 3.6. Review of Themes

The literature selection process that underpins this thematic synthesis is presented in **Fig. 1**, which summarizes the identification, screening, eligibility assessment, and inclusion stages used in the review. To support the interpretation of the evidence, the reviewed studies are also organized into summary tables corresponding to the four analytical domains discussed in this section (**Tables 1–4**). These tables complement the narrative synthesis by presenting the main studies, thematic focus, key findings, and implications for sustainable value chain transformation in a more systematic form.

#### 3.6.1. Theme 1 — Upstream Resource Base

The upstream literature presents *A. pinnata* as a multifunctional and ecologically adaptable species with strong relevance to agroforestry, biodiversity-based production, and non-timber forest product systems. Socio-ecological studies show that production depends on land access, local ecology, and inherited knowledge, and that different product systems, such as palm sugar and palm flour, follow distinct socio-technical pathways (Withaningsih et al., 2019). Vegetation research strengthens this argument by showing the ecological significance of *A. pinnata* in biodiverse landscapes (Withaningsih et al., 2023). Work on tropical palm cultivation and restoration adds a broader strategic dimension by linking sugar palm to discussions of reforestation and sustainable land use (Azahari et al., 2024). Scholarship on underutilized species further reinforces the resource base by emphasizing the economic value of almost every part of the palm (Sarkar et al., 2022).

These findings confirm that *A. pinnata* possesses a strong upstream foundation for value chain development. However, the literature seldom explains how ecological resource strength is translated into downstream competitiveness or coordinated market systems. Resource sustainability, therefore, emerges as a necessary but insufficient condition for transformation. The main findings from the upstream literature, including agroforestry relevance, ecological embeddedness, and resource-related constraints, are summarized in **Table 1**.

**Table 1.** Theme 1 — upstream resource base: agroforestry, cultivation, conservation, and land suitability

Author(s) and year	Country/region and agroecological setting	Upstream focus	Method/design	Key findings on productivity/resource sustainability	Reported constraints or risks	Implications for value chain transformation
Withaningsih et al. (2019)	West Bandung, Indonesia/heterogeneous village landscape/forest-edge bioresource setting	Socio-ecological production systems for palm sugar and palm flour	Case study: socio-ecological analysis	Distinct production systems emerge from local ecological conditions, biodiversity availability, and knowledge transmission	Limited capital, limited market access, variable access to land/trees, dependence on local biological materials	Upstream sustainability is landscape-embedded; future upgrading depends on securing resource access, skills continuity, and local ecological resilience
Azahari et al. (2024)	Indonesia/tropical palm systems	Palm cultivation, reforestation, and NTFP relevance	Conceptual/review-type synthesis	Sugar palm is a significant tropical palm with restoration and reforestation relevance	Restoration claims are strategic rather than fully <i>A. pinnata</i> -specific causal evidence; governance and land context matter	<i>A. pinnata</i> can be positioned as a restoration-linked bioresource, but only if ecological and institutional conditions are aligned
Sarkar et al. (2022)	India/underutilized <i>Arenga</i> systems	Multipurpose use and underutilization	Review	Nearly all parts of the palm have economic utility; the species remains under-commercialized	Limited scaling and commercialization despite multifunctionality	A strong upstream resource base exists, but transformation requires connection to processing and market systems
Withaningsih et al. (2023)	West Java, Indonesia/biodiverse vegetation setting	Ecological dominance/landscape role	Vegetation analysis	<i>A. pinnata</i> can be a dominant species in biodiverse landscapes	Ecological prominence alone does not ensure value chain integration	Ecological embeddedness supports the tropical bioresource systems perspective and justifies conservation-sensitive upgrading
Achillas and Bochtis (2020)	General/comparative bioeconomy framing	Circular business models, biomass sourcing	Conceptual review	Sustainable biomass systems require closed-loop logic and efficient organization	Weak coordination and poor business model design can undermine biomass systems	Upstream development must be linked to circular business model logic
Lange et al. (2021)	General/circular bio-based economy	Biomass portfolios and sectoral integration	Conceptual review	Diverse biomass resources gain more value through sectoral partnerships and multiple outputs	Fragmented sectors slow transition	Upstream <i>A. pinnata</i> resources should be connected to multi-output and cross-sector chains rather than single-product systems

### 3.6.2. Theme 2 — Midstream Processing Upgrading

The midstream literature focuses on processing quality, stabilization, fermentation, and resource conversion. Studies on *A. pinnata* fruit dodol show that edible coating can improve shelf life, microbial properties, and product quality, thereby increasing commercial viability (Aulia et al., 2024). Research on bacteria isolated from palm vinegar suggests that *A. pinnata* fermentation streams may support probiotic applications and additional value-added uses (Ilahi et al., 2025). Broader bioeconomy- and energy-oriented literature indicates that sap-based processes may also support renewable-energy or fermentation pathways when supported by adequate organization and logistics (Lange et al., 2021).

These studies indicate that midstream technological upgrading can improve product quality and diversify outputs. However, they also reveal a disconnect between technical success and systemic adoption. Literature on circular processing and business models suggests that efficiency gains are most impactful when integrated with coordinated systems and residue utilization, rather than achieved through isolated process improvements (Achillas and Bochtis, 2020; Feng et al., 2023). Thus, while midstream innovation is important, it does not by itself result in value chain transformation. The reviewed evidence on processing interventions, fermentation pathways, and implications for circular processing is summarized in **Table 2**.

**Table 2.** Theme 2 — midstream processing upgrading: sap quality, sugar processing, and bioethanol conversion

Author(s) and year	Product/process focus	Processing technology or intervention	Quality/performance indicators	Main findings and comparative advantage	Scalability/barriers to adoption	Sustainability implications
Withaningsih et al. (2019)	Palm sugar and palm flour	Traditional tapping, grating, precipitation, and local processing systems	Process differentiation by product pathway	Palm sugar and palm flour involve distinct socio-technical systems and labor organization	Small-scale production, limited capital, limited access to markets and inputs	Midstream upgrading must reflect local production realities rather than assume one standard pathway
Aulia et al. (2024)	<i>A. pinnata</i> fruit dodol	Edible coating treatment for shelf-life extension	Physicochemical, sensory, microbial quality; moisture-related compliance	Product quality and shelf life can be improved through processing intervention	Standards compliance and commercialization on readiness remain important barriers	Quality upgrading is crucial for market competitiveness and value addition
Ilahi et al. (2025)	Palm vinegar / probiotic candidate	Isolation and testing of <i>Acetobacter aceti</i> from palm vinegar	Acid and bile salt resistance	<i>A. pinnata</i> fermentation streams may support higher-value functional food applications	Early-stage evidence; limited commercialization on pathway	Fermentation upgrading expands <i>A. pinnata</i> beyond conventional sweetener products
Lange et al. (2021)	Sap-to-bioethanol pathway	Fermentation/bioenergy valorization framing	Feedstock suitability and transition potential	Sugar palm sap has potential as a renewable-energy feedstock	Feedstock collection, chain coordination, and infrastructure remain critical	Bioethanol pathways support diversification but depend on organized supply systems
Achillas and Bochtis (2020)	Circular processing systems	Closed-loop and circular performance logic	Efficiency and business-model fit	Processing innovation must be embedded in circular business models	Technical change alone is insufficient	Midstream upgrading should integrate process efficiency with resource looping and chain coordination
Feng et al. (2023)	Residue-centered circular integration	Biogas-centered circular bioeconomy model	Residue utilization and integrated system value	Centralized residue valorization can support local circular economies	Logistics, coordination, and infrastructure barriers are substantial	Suggests a possible model for <i>A. pinnata</i> processing residues, but implementation conditions are demanding

### 3.6.3. Theme 3 — Downstream Diversification

The downstream literature provides some of the strongest evidence of the broader relevance of the bioeconomy. Research shows that sugar palm starch can be converted into thermoplastic starch with potential packaging applications (Ghozali et al., 2023). *A. pinnata* fiber has been used in silicone biocomposites, demonstrating engineering-related properties (Bahrain et al., 2017). *A. pinnata* endosperm has also been applied in mesoporous aerogel systems, suggesting potential in specialty functional materials (Tarigan et al., 2020). Broader composite-material literature supports the relevance of natural-fiber systems to eco-friendly material development, providing conceptual reinforcement for *A. pinnata*-related applications (Savov et al., 2023). In addition, fermented by-products have been incorporated into animal feed-related uses, indicating opportunities for secondary valorization and residue-based circularity (Sulistiyowati et al., 2025).

Collectively, these findings indicate that *A. pinnata* is increasingly represented not only as a source of traditional products but also as a platform for high-value diversification. However, most studies remain laboratory-focused and do not demonstrate commercialization, life-cycle performance, or integration into inclusive markets. Consequently, the literature provides strong evidence for downstream upgrading potential but limited evidence of actual transformation. The principal studies on biomaterials, starch-based applications, fiber utilization, and other downstream diversification pathways are synthesized in **Table 3**.

**Table 3.** Theme 3 — downstream diversification: biomaterials, packaging, fiber, starch, and high-value bioresource applications

Author(s) and year	Biomaterial/product application	Feedstock used	Processing/formulation approach	Functional/material properties assessed	Commercial or industrial relevance	Research gaps/limitations
Ghozali et al. (2023)	Thermoplastic starch/packaging potential	Sugar palm starch	Extrusion method	TPS characteristics for bio-based material application	Promising for bio-based packaging alternatives	Limited market integration and scale-up evidence
Bahrain et al. (2017)	Silicone biocomposites/sealing applications	<i>A. pinnata</i> fiber	Fiber incorporation in silicone composite	Sealing capability and hyperelastic behavior	Indicates technical potential in engineering use	Product performance is shown, but broader sustainability and commercialization evidence is limited
Tarigan et al. (2020)	Mesoporous aerogel for vitamin E adsorption	<i>A. pinnata</i> endosperm	Aerogel preparation and adsorption application	Adsorption functionality	Suggests a high-value specialty material niche	Proof-of-function does not yet demonstrate industrial integration
Savov et al. (2023)	Composite-materials framing	Natural fibers/composite systems	Review of eco-friendly composite design	Design and characterization relevance	Supports the <i>A. pinnata</i> -related composite development conceptually	Not <i>A. pinnata</i> -exclusive; commercialization and LCA gaps remain
Sulistyowati et al. (2025)	By-product use in dairy concentrate	Fermented <i>A. pinnata</i> by-product	Feed formulation	Fatty acid characteristics in milk response	Demonstrates residue valorization potential	Limited integration with a full circular chain design
Venkatesh (2021)	Circular bioeconomy framing for bio-based products	Renewable biomass and waste streams	Systematic review/paradigm synthesis	Circularity, waste-to-value, and transition logic	Useful for positioning <i>A. pinnata</i> diversification in circular bioeconomy	Need for impact assessment, collaboration, and sustainability evaluation

### 3.6.4. Theme 4 — Market Structure, Business Models, Governance, and Sustainability Outcomes

The governance literature is less developed empirically in studies focusing on *A. pinnata*, but it is analytically decisive. Existing village-scale evidence indicates that *A. pinnata* value chains are constrained by limited capital, weak market access, and fragmented local organization (Withaningsih et al., 2019). Broader work on bioeconomy restructuring emphasizes that innovation and upgrading change who captures value across a chain and may increase exclusion unless supportive institutions are present (Clay and Sellare, 2022). Research on social sustainability in upgrading further argues that vulnerable actors must be explicitly considered within innovation and market transition processes (Clay and Sellare, 2025).

Additional contributions strengthen this governance critique. Socio-biodiversity scholarship argues that conventional indicators often fail to capture diversity, equity, and community-relevant outcomes in biological-resource chains (Saes et al., 2023). Comparative critical work on bioeconomy development shows that economic upgrading does not automatically produce environmental or social upgrading (Puder and Tittor, 2023). Circularity studies further indicate that residue use and closed-loop gains depend heavily on coordination and infrastructure (Feng et al., 2023). As a result, market and institutional alignment emerges as the most underdeveloped but most necessary dimension for sustainable *A. pinnata* transformation. The main governance-related studies, including those addressing value distribution, coordination, circular business models, and sustainability outcomes, are presented in **Table 4**.

### 3.6.5. Cross-Theme Interpretation

Taken together, the four themes show that the transformation of *A. pinnata* cannot be explained solely by technological innovation. Upstream studies establish the species as ecologically embedded and socially meaningful in rural production systems, but these strengths do not automatically translate into coordinated market development. Midstream studies reveal the potential of quality improvement, fermentation, and process upgrading, yet many of these advances remain technically promising rather

than institutionally grounded. Downstream studies provide strong evidence that *A. pinnata* can support diverse bio-based products and higher-value applications, but commercialization pathways and life-cycle implications remain insufficiently developed. Finally, governance-oriented studies show that value distribution, institutional coordination, and social inclusion are decisive in determining whether upgrading leads to genuinely sustainable outcomes.

**Table 4.** Theme 4 — market structure, business models, governance, and sustainability outcomes

Author(s) and year	Market/ value chain segment examined	Business model or governance structure	Main actors involved	Key findings on value distribution/ market access	Sustainability outcomes identified	Policy or managerial implications
Withaningsih et al. (2019)	Village-scale sugar and flour chains	Small-scale, locally embedded production systems	Producers, households, local resource users	Market access is limited; local constraints shape value capture	Livelihood relevance is clear, but scaling is weak	Governance support and access conditions are essential for inclusive upgrading
Clay and Sellare (2022)	Bioeconomy value chain transformation	Conceptual governance and restructuring lens	Firms, chain coordinators, producers, institutions	Value chain restructuring changes who captures value	Upgrading is not neutral; outcomes depend on governance	<i>A. pinnata</i> upgrading should be analyzed in terms of value capture and institutional design
Clay and Sellare (2025)	Innovation-value chain-social sustainability nexus	Bioeconomy upgrading lens	Vulnerable actors, firms, institutions	Innovation can shorten or reorganize chains, with risks for vulnerable actors	Social sustainability is central, not secondary	Supports inclusive-upgrading criteria for <i>A. pinnata</i> value chains
Saes et al. (2023)	Socio-biodiversity bioeconomy supply chains	Indicator and evaluation framework	Communities, value chain actors, and institutions	Standard metrics are insufficient to capture biological and cultural diversity outcomes	Equity, diversity, and bottom-up indicators are necessary	<i>A. pinnata</i> chains need broader sustainability metrics beyond output and price
Puder and Tittor (2023)	Bioeconomy development and upgrading critique	Comparative political economy perspective	States, firms, producers	Economic upgrading may fail to generate social/environmental upgrading	Highlights non-automatic sustainability outcomes	<i>A. pinnata</i> commercialization should not equate technical modernization with sustainability success
Feng et al. (2023)	Biomass-derived product systems and circular coordination	Centralized circular bioeconomy/coordination model	Residue suppliers, processors, local communities, institutions	Coordination and certification/logistics matter for market credibility	Circular outcomes depend on governance quality	Suggests that <i>A. pinnata</i> residue valorization requires collective infrastructure and policy support
Achillas and Bochtis (2020)	Circular business model performance	Closed-loop business models	Firms, system operators, policy actors	Circular performance depends on business model efficiency	Environmental and economic gains require system design	<i>A. pinnata</i> market development should integrate circular business logic from the outset

Viewed together, **Tables 1–4** demonstrate that sustainable value chain transformation depends on the interaction among three interdependent dimensions: resource sustainability, technological upgrading, and market or institutional alignment. In this respect, the empirical and conceptual relationships synthesized in **Fig. 2** provide an integrated basis for interpreting how *A. pinnata* can move from a traditionally embedded rural resource to a more coordinated, sustainability-oriented tropical bioresource system. The literature therefore supports the argument that *A. pinnata* should be understood not merely as a source of traditional products, but as a strategic tropical bioresource whose transformation potential depends on linking ecological stewardship, innovation pathways, and inclusive governance within an integrated value chain framework.

### 3.7. An Integrated Perspective on *A. pinnata* Transformation

This review demonstrates that *A. pinnata* has emerged in the literature as a promising tropical bioresource, yet the evidence base remains uneven in its explanation of transformation across the value chain. Ecological and socio-technical studies provide strong support for upstream relevance, while materials and processing research highlight substantial innovation potential. However, these research

strands remain weakly integrated, confirming that sustainable transformation cannot be understood through isolated product studies alone.

A key insight is that the ecological and livelihood significance of *A. pinnata* is well established but insufficiently linked to industrial and market outcomes. Studies on socio-ecological production systems and landscape relevance demonstrate that aren is deeply embedded in biodiversity-linked rural systems (Withaningsih et al., 2019, 2023). Literature on underutilized species and palm development further substantiates the biological and strategic value of *A. pinnata* (Azahari et al., 2024; Sarkar et al., 2022). However, these studies seldom extend their analysis to commercialization, standards, or coordination. Consequently, they clarify the importance of aren but do not fully explain the mechanisms of transformation.

A second insight is that technical innovation is progressing more rapidly than system integration. Midstream studies identify clear opportunities for improved quality, shelf life, and fermentation-related value addition (Aulia et al., 2024; Ilahi et al., 2025). Downstream research demonstrates that aren can support advanced materials and residue-based circularity (Bahrain et al., 2017; Ghozali et al., 2023; Sulistyowati et al., 2025; Tarigan et al., 2020). Review-based analyses of composite materials further reinforce the relevance of these material pathways (Savov et al., 2023). However, most of this literature remains focused on proof of concept rather than scalability, actor inclusion, or market feasibility. This dynamic accounts for the innovative character of the field, but also for the absence of a mature transformation model.

A third insight pertains to governance. The broader literature on circular bioeconomy and upgrading consistently cautions that innovation alone does not ensure inclusive or sustainable outcomes. Business-model performance, residue integration, cross-sectoral coordination, and value distribution are critical to the success of biomass systems (Achillas and Bochtis, 2020; Feng et al., 2023; Lange et al., 2021). Similarly, governance and social-sustainability research indicates that economic upgrading may exclude vulnerable actors and that value chain restructuring can alter the distribution of benefits from innovation (Clay and Sellare, 2022, 2025; Puder and Tittor, 2023; Saes et al., 2023). This argument is particularly relevant to aren, where smallholders and local communities frequently maintain the resource base.

The literature also identifies significant methodological limitations. Socio-ecological studies are typically context-rich but limited in value chain analysis. Technical studies are often methodologically rigorous yet lack governance analysis. Conceptual research provides robust interpretive frameworks but is not always grounded in *A. pinnata*-specific evidence. This fragmentation across analytical scales constitutes a major obstacle for the field. Future research should prioritize integrated studies that connect production ecology, process innovation, market coordination, and benefit-sharing within a unified framework. Comparative cross-regional analysis, techno-economic assessment, and life-cycle evaluation are particularly recommended.

Overall, the review supports an integrated perspective on *A. pinnata* transformation. The evidence indicates that *A. pinnata* holds significant potential as a strategic platform for sustainable tropical bioresource development, provided that ecological stewardship, technological upgrading, and institutional alignment are addressed as interdependent dimensions rather than isolated agendas.

#### 4. Conclusion

This systematic literature review shows that *A. pinnata* should be understood not merely as a traditional multipurpose palm, but as a strategic tropical bioresource with substantial potential for sustainable value chain transformation. The reviewed studies demonstrate strong upstream ecological and livelihood relevance, meaningful opportunities for processing and quality upgrading and promising downstream applications in biomaterials, fermentation, packaging materials, and circular residue utilization. However, the review also shows that these strengths remain only partially connected across the chain. The study answers the research questions in four main ways. First, the literature conceptualizes the aren value chain as fragmented across production, processing, diversification, and governance rather than as a fully integrated system. Second, sustainable transformation is enabled by multifunctional resource characteristics, technical innovation, and circular valorization potential, but constrained by weak coordination, underdeveloped commercialization pathways, and limited inclusive governance. Third, the literature increasingly repositions *A. pinnata* from a traditional rural species to a

broader tropical bioresource platform. Fourth, important research gaps remain in cross-stage empirical analysis, techno-economic and life-cycle assessment, and governance research focused on value distribution and smallholder inclusion. This review advances the existing body of knowledge by integrating aren-specific empirical research with broader scholarship on circular bioeconomy, sustainable upgrading, and socio-biodiversity governance. Its principal contribution is to demonstrate that sustainable transformation should be conceptualized as a systemic process involving the interaction among resource sustainability, technological upgrading, and market or institutional alignment. Future research should therefore progress beyond isolated product innovations and pursue more comparative, integrative, and policy-relevant analyses of aren-based bioresource systems.

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