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POST-HARVEST PROCESSING AND VALUE ADDITION OF ARECANUT (*ARECA CATECHU L.*): CURRENT STATUS, CHALLENGES AND FUTURE OPPORTUNITIES

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ABSTRACT
Arecanut (*Areca catechu L.*) is one of India's most economically significant plantation crops, sustaining livelihoods across its production, processing, and marketing chain. It serves as the principal raw material for the pan masala industry. India accounts for 65.5 per cent of global arecanut production (2,542 thousand tonnes in 2022), yet there is productivity stagnation and underdeveloped post-harvest processing systems. This systematic review consolidates evidence from 49 peer-reviewed sources retrieved from Scopus, Web of Science and Google Scholar to address post-harvest physiology, processing technologies, value addition, by-product utilisation, constraints and emerging innovations in the arecanut sector, with particular reference to India. The processing of arecanut follows three principal routes: sun-dried, boiled, and white-processed forms, all predominantly manual, weather-dependent and quality-inconsistent. Enzymatic browning through polyphenol oxidase and peroxidase activity, aflatoxin contamination during improper sun-drying by Aspergillus species and insect infestation during storage are the documented primary quality deterioration mechanisms. By-product streams, including arecanut husk biochar, leaf sheaths for cellulose-based transparent packaging and separated polyphenol fractions with documented osteoporosis-ameliorating effects, represent underexploited value chains with strong published evidence for commercial viability. Emerging innovations in machine vision and deep learning-based grading (>85% classification accuracy), solar-assisted drying (40–55% energy saving), and nanocellulose extraction from sheath fibres offer transformative opportunities. Critical research gaps in universal mechanical dehusking, mandatory quality standardisation, farmer-level processing units and food safety engineering for leaf sheath plates are identified, contextualised specifically for India. This review contributes to the processing and value chain of arecanut.

KEYWORDS: arecanut; betel nut; post-harvest processing; value addition; challenges; India

INTRODUCTION
Arecanut (Areca catechu L.), a slender palm of the family Arecaceae, is one of the most consumed products in the world. It is thought that more than 600 million people globally consume the fruit drupe of its seed, which is the fourth most commonly consumed psychoactive plant food after tobacco, alcohol and caffeine (1). In India, there is a strong cultural importance for the crop that is utilised in religious ceremonies, social rituals and also in the preparation of betel quid or tambula (2). In addition to the traditional chewing industry, the pan masala industry and the processed supari industry have brought additional customers to the crop and led to a sustained surge in the demand for the crop (3,4). India is the world's largest producer, accounting for 65.5 per cent of global production of 2,542 thousand tonnes in 2022 (5). Area under cultivation has more than doubled since 2004-05, with productivity growing at only 2.66 per cent annually and area growing at 6.56 per cent over the period 2004-05 to 2019-20, confirming that output expansion has been area-driven rather than yield-driven (5). India is now a huge producer and one of the largest consumers of the same commodity. Due to this structural condition, along with the rapid increase in demand (6). The arecanut is classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC), making it more difficult to develop nutraceuticals as well as to export products (7).

The critical linkage between the farm production and consumption in the arecanut value chain is the post-harvest processing. The raw fruit after harvesting is processed through a series of unit operations (dehusking, boiling or curing, drying, grading and sorting) and marketed in the following forms, which have been discussed in the literature (8): raw fruit, canned in liquor, canned in syrup, canned in juice, boxed and canned fruit, and frozen. Although the arecanut industry is a large-scale industry, the post-harvest technology is far less advanced compared to other plantation crops like cashew and coconut, with a low rate of mechanisation, no enforced standard for national grading and high risk of aflatoxin contamination due to weather-dependent open sun drying (9,10).

Despite the substantial volume of research on arecanut physiology, processing, and by-product valorisation, several critical research gaps persist in the published literature. First, the mechanisation of dehusking operations, the single most labour-intensive and cost-dominant unit operation in both the green nut and ripe nut processing chains, remains an unresolved engineering challenge, with no published study demonstrating a universal mechanical system capable of processing both fresh tender and fully dried ripe nuts without unacceptable kernel breakage. Second, no mandatory national grading standard with instrumentally verifiable quality parameters exists for arecanut in India, leaving the entire commercial chain dependent on subjective visual assessment by traders and creating structural price asymmetry that disadvantages smallholder farmers. Third, the economic viability, institutional design, and market access constraints of farmer-level collective processing units, which could enable producers to capture a larger share of the value chain, have not been empirically evaluated in any published study. Fourth, food safety engineering protocols for arecanut leaf sheath plate manufacturing, including validated critical control points for fungal contamination reduction, are entirely absent from the published literature despite the sector's documented commercial significance. The present review addresses these gaps by synthesising published evidence on post-harvest processing, value addition, by-product utilisation, constraints, and emerging technological innovations in the arecanut sector, with particular focus on research needs in inland growing regions that are systematically underrepresented in existing literature. The central research question guiding this review is: What is the current state of published knowledge on arecanut post-harvest processing and value addition in India, and what specific technological, institutional, and policy research priorities emerge from a systematic synthesis of this literature?

LITERATURE SEARCH STRATEGY

This review follows a systematic approach to literature identification and selection. Searches were conducted across four electronic databases: Scopus, Web of Science and Google Scholar, covering publications from 2000 to 2025, with seminal foundational studies from before 2000 included where specifically relevant. The primary search terms were: ‘arecanut’ OR ‘areca nut’ OR ‘Areca catechu’ AND ‘post-harvest’ OR ‘processing’ OR ‘value addition’ OR ‘biochar’ OR ‘leaf sheath’ OR ‘nanocellulose’ OR ‘grading’ OR ‘drying’ OR ‘quality’. Secondary searches targeted specific sub-topics, including alkaloid composition, polyphenol extraction, machine vision classification, and by-product valorisation. Figure 1 represents the complete literature search protocol.

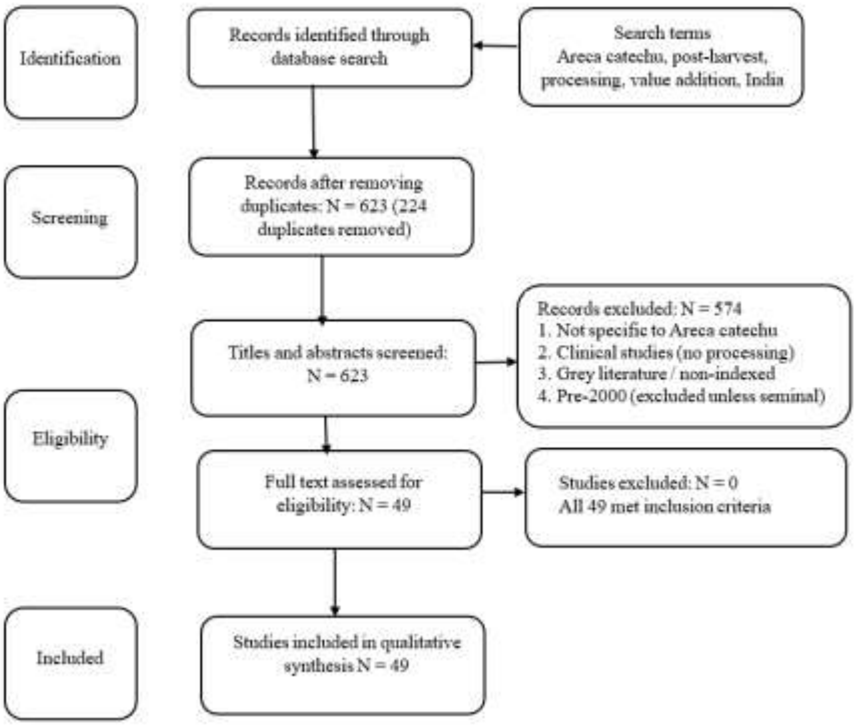

Figure 1. PRISMA flow diagram

Inclusion and Exclusion Criteria

Studies were included if they: (i) were published in peer-reviewed journals, institutional research monographs (such as ICAR-CPCRI publications), or indexed conference proceedings; (ii) specifically addressed *Areca catechu L.*; and (iii) reported data relevant to post-harvest processing, value addition, by-product utilisation, or emerging technologies in the arecanut sector. Studies were excluded if they addressed other Areca species, focused exclusively on clinical outcomes of betel quid chewing without processing relevance, or were sourced from grey literature, including trade newsletters, blogs, or non-indexed government documents. Following full-text screening of 49 records, all 49 were retained as meeting the inclusion criteria and constitute the reference base of this review.

Scope Boundary
The present review's unique contribution is post-harvest processing technology, value chain product analysis, by-product valorisation evidence, and emerging processing innovations dimensions absent from other papers. A value chain summary is provided to allow cross-study comparison, addressing the identified gap.

RESULTS

Arecanut cultivation is possible in a humid tropical belt which includes South Asia, Southeast Asia, the Pacific Islands and some parts of East Africa. It has a good distribution of rainfall, a well-distributed temperature range between 14°C and 36°C and laterite or red loam soil (10,11). The total production of arecanut in the world in 2022 was 2,542 thousand tonnes, an increase of 47.3 per cent from 2019, with India producing 65.5 per cent of the world's production, followed by Bangladesh, Myanmar, Indonesia and Sri Lanka (12). The global arecanut market was estimated to be USD 854.5 million in 2022 and is expected to reach USD 1,272 million by 2030, with its annual growth rate of 5.10 per cent, led mainly by the processed arecanut market in the form of arecanut pan masalas and processed suparis (13). Several countries, which are sources for imports, have an average productivity level of more than 1635 kg/ha, which directly affects the demand-supply gap in India, with an average productivity of 1635 kg/ha (5,14).

The state of Karnataka has around 50–55 per cent of the arecanut area and production in the country, with the major districts being Shivamogga, Dakshina Kannada, Uttara Kannada and Udupi (10,14). Kerala is second, followed by Assam, Meghalaya, West Bengal, Tamil Nadu, Andhra Pradesh and the other states are secondary production zones (14,11). In addition to the input cost structures and post-harvest problems discussed in the literature, the novel input cost structures and post-harvest problems associated with the emergence of groundwater-dependent growing areas in the state's interior, not reflected in traditional horticulture statistics, are not fully discussed (15).

The trends in area and yield of arecanuts have been analysed, and a continuous publication is available for time series analysis, which has indicated that growth in the production of arecanuts in India is mainly attributed to the expansion of arecanut area. The following trend was observed during 2004-05 to 2019-20: area growth 3.80 per cent, production growth 6.56 per cent, and productivity growth 2.66 per cent, which indicates that the Area growth was about 1.5 times higher than Productivity growth (14).

The spread of arecanut growing to the inland parts of the Tamil Nadu, Maharashtra and Andhra Pradesh states is an important, but unstudied, development. The genetic diversity study carried out by the use of RAPD, ISSR and SSR molecular markers indicated that considerable variability exists among the cultivated arecanut populations, and this information forms the basis for the selection of varieties that are suitable for different agro-climatic zones (16). Studies conducted on the assessment of quality in different growing areas revealed significant effects of growing environment on the physicochemical properties, such as alkaloid content, moisture content and polyphenol profile, which emphasise the need to develop a post-harvest protocol for each growing region (17).

Post-Harvest Physiology and Quality Characteristics

Published literature reports two stages of harvest, the tender stage (9–10 months from fruit set) with a green pericarp and soft kernel, and the fully ripe stage (11–12 months) with a yellow-orange pericarp and hard kernel, for the boiled and white-processed varieties, respectively (10). Colour change continues to be the most common field maturity indicator, but is subjective and variable dependent, and is therefore not a universal standard to measure field maturity (10,18).

The fruit skin makes up 60-80% of the total fruit dry mass and is the principal by-product of all fruit processing methods (18). A principal component analysis and hierarchical cluster analysis of the physicochemical quality components revealed that a weight, kernel-to-husk ratio, moisture content, and testa colour were the main factors discriminating between the commercial quality classes in the growing areas (17). The most important quality parameter for good safety is moisture content; freshly-matured nuts contain 50–70 per cent moisture content and need to be dried down to less than 10 per cent for safe medium-term storage (10).

Enzymatic browning is the major quality deterioration pathway of fresh arecanut. It was concluded from published research that the polyphenol oxidase (PPO) and peroxidase (POD) activity to phenolics was responsible for the kernel browning and that there was a rate-limiting step in the form of oxygen ingress through the mesocarp tissue. The highest browning area was observed for arecanut stored at 25°C, the lowest browning area was observed for arecanut stored at 10°C (19). Chilling injury occurred at 5°C, which caused more browning due to damage in the membrane. These results thus set 10°C as the optimum temperature for browning inhibition during the storage of fresh arecanut. Aspergillus flavus and Aspergillus parasiticus are the most important food safety concerns under conditions of improper drying, where the FSSAI limit of 10 ppb is frequently exceeded in commercial samples of dried items (9,20).

Arecanut is an example of an extremely complex plant, rich in biologically active compounds. The alkaloid fraction (0.15–0.67 per cent) contains arecoline, arecaidine, guvacoline, and guvacine, the most abundant and most biologically active being arecoline (7,20). The content of alkaloids is significantly influenced by the processing method: raw arecanut > shade dried > sun exposed > roasted > charred forms (1). The polyphenol fraction (1-26 per cent) contains catechins, tannic acid, gallic acid and condensed proanthocyanidins (1). The neutral polysaccharide isolated from arecanut seed was found to be a combination of mannose, galactose, xylose and arabinose (4.1:3.3:0.9:1.7 molar ratio), with a mean value of 37.3 kDa and exhibited antioxidant activity against DPPH and hydroxyl radicals in vitro (21). Feature-based molecular networking was used to rapidly identify 32 compounds in extracts of seeds, such as gallic acid, gallocatechin and 22 flavonoid glycosides (22). The antioxidant activity has a positive correlation with polyphenol content throughout the growing areas, whereas alkaloid content did not (23).

Post-Harvest Handling Practices

Harvesting is the most labour-intensive post-harvest operation. Institutional literature published describes the traditional harvesting practice of manual climbing to reach trees and harvesting them with a sickle attached to a long bamboo pole, which is labour-intensive and demands specialised workers with a risk to occupational health (10). According to the published extension research in Tamil Nadu, although a large proportion of the farmers (79.17 per cent) were still harvesting using a manual tree climber with a sickle, 20.83 per cent of the farmers were using locally fabricated mechanical aids. As a possible labour-saving alternative, mechanised tree climbing machines equipped with harvester-cum-sprayer systems have been developed (10).

Boiled processing involves dehusking of tender nuts after boiling, when the heat and moisture have softened the husk. With the sun-dried nuts, it is necessary to apply more force to dehusk completely when they are fully ripe. A hand-operated dehusking machine can produce 30-40 kg per hour with an investment of Rs. 25,000, but it can only be applied to dried nuts (10). In published literature, the problem of developing an efficient, mechanical dehusking mechanism that will process both fresh tender nuts and dried ripe nuts without unacceptable kernel breakage has not been solved (10,24).

The unit operation of boiling is the most characteristic process involved in the production of the boiled processed arecanut. Fresh tender nuts in the husk are placed in water and boiled for 4-6 hours, the husk is removed, and the kernel is dried red. The colouration of the bricks is a unique reaction between polyphenols and protein, and is also a result of the oxidation of condensed tannins (10). In Karnataka and Kerala, there is a practice of two-round boiling, which has been recorded in published CPCRI literature to ensure uniform colour development, which is widely used. Boiling is the second-highest labour cost contributor after dehusking and also requires a good amount of fuel. Controlled boiling time, temperature and water-to-nut ratio have not been studied in a designed experimental layout on the effect on polyphenol content and colour development, which is a gap in the literature.

The most widely used drying method in India is open sun drying, which takes 15-20 days for boiled and 20-30 days for ripe nuts. Aflatoxin risk from interrupted drying (9) is dependent on weather conditions during harvest. CPCRI developed a through-flow mechanical dryer with warm air in successive cycles, which achieves safe final moisture content in 60-70 hours, significantly reducing the risk of aflatoxin (10). Solar-assisted hybrid dryers have been reported to save 40-55 per cent of the energy consumption compared to the conventional dryers (10). The economic challenge to switch to mechanical dryers is the capital cost of the dryer. It is documented that the main constraint for such a medium capacity unit is Rs. 80,000, and that institutional solutions are suggested to be cooperative or shared-service models (10,24).

The most important storage pest is the arecanut storage beetle (*Cocotrypes carpophagus Horn*), and the usual recommended treatment for it is fumigation with aluminium phosphide (three tablets per tonne) (10). Aspergillus, Penicillium and Rhizopus species were found to be predominant fungal contaminants on raw sheaths before processing in the leaf sheath plate manufacturing units, with the recommendation to have standardised cleaning and heat pressing procedures to make sure that finished products are safe for food-contact applications (25). All pre-packaged arecanut and arecanut-containing food products should be labelled as per the packaging regulations under FSSAI, which includes a food additive declaration, which includes the declaration of arecanut (9). Table 1 presents the comparative summary of arecanut post-harvest processing technologies.

Table 1. Comparative summary of arecanut post-harvest processing technologies

Technology / Method	Capacity	Energy / Capital Cost	Moisture / Quality Outcome	Key References
Open sun-drying (conventional)	Unlimited (space-limited)	Near-zero capital; weather-dependent	Final MC < 10% in 15–30 days; high aflatoxin risk if interrupted	(10)
CPCRI through-flow mechanical dryer	150 kg/batch	Rs. 80,000–1,50,000; biomass/electric	Final MC < 10% in 60–70 h (7–8 days); eliminates weather risk	(10)
Solar-assisted hybrid dryer	Variable	Moderate capital; 40-55% energy saving vs fossil dryer	Colour and MC comparable to sun-drying; not weather-dependent	(10)
Infrared drying (lab-scale)	Lab scale only	Research stage	Superior colour stability and polyphenol retention vs convective hot-air	(10)
Hand-operated dehusker (CPCRI)	30-40 kg/h	Rs. 25,000	Suitable for dried ripe nuts only; not for fresh tender nuts	(10)

Rotary drum motor dehusker	30 kg/h	Rs. 40,000-60,000; 1 HP motor	Only for dried nuts; calibration required for different nut sizes	(10, 24)
LabVIEW-based vision grader	Processing-line speed	Moderate hardware cost	Colour & texture classification; accuracy comparable to manual grader	(26)
YOLOv5 real-time grader (embedded)	Real-time	Low (Raspberry Pi class)	Demonstrated at processing-line speed; not yet commercial scale	(28)
CNN multi-type disease classifier	Image-based	GPU required	Accuracy sufficient for commercial deployment per published evaluation	(30)

Processing Technologies in Arecanut

The tradition of boiled form is coastal Karnataka, the tradition of sun drying the nuts fully ripe before dehusking is that of Goa, and the tradition of storing the fresh nuts in water is for preserving nuts in Assam, as reported in literature published by CPCRI (10). Raw processed by boiling and drying, charring and shade drying have all been reported in published pharmacological work and each yields different alkaloid profiles and pharmacological effects (1,7).

The LabVIEW-based image processing was used for a quality grading system of arecanut that was technically feasible with machine vision grading using colour and texture parameters with classification accuracy similar to the experienced manual graders (26). For rural use, an automatic arecanut processing unit with dehusking, boiling and drying operations, using a low-voltage DC power supply, was reported in published engineering literature (27). A detailed literature search was carried out on the arecanut computer vision grading and systems that use YOLO object detection, convolutional neural network, support vector machine, and local binary pattern classifiers resulted in operators stating positive response towards the vision-based grading, and concluded that deep learning integration is the direction with a promising future for next-generation systems (28). Using machine learning techniques, the prediction accuracy of arecanut is demonstrated based on the results of the combined feature extraction, which results in accuracy above 85 per cent (29).

Embedded computer-based system for real-time processing-line arecanut detection and grading by YOLOv5 showed feasibility (28). A CNN-based approach for the classification of images of multi-type diseased arecanut was found to be adequate for commercial use (30). A low-computing resource, low-resource hardware texture-based block-wise local binary pattern approach was presented for the computationally efficient grading algorithm (31). In 2022, the arecanut segregation with local binary pattern and HOG features was reported, and bunch segregation with deep learning-based convolutional architectures was demonstrated in the same year (32,33). The extensive literature search revealed that there had been no complete commercial end-to-end automated grading line for arecanut reported in literature, thus it was identified as the major gap between the demonstrated component technologies and implementation of an end-to-end automated system (28).

Permissible limits for aflatoxin (10 ppb total), moisture and food additives are also given in the Food Safety and Standards Act, 2006, through FSSAI for arecanut products (9). The quality of arecanut standards is voluntary and outlined in AGMARK grading specifications, but there is little compliance amongst small processors (10). Unlike other plantation crop products, there is no quality specification set mandatory by BIS or ISI for arecanut to guarantee exportable quality for those markets with food safety concerns (10,24). The IARC Group 1 carcinogen classification imposes specific regulatory requirements on nutraceutical product development, as it calls for systematic separation of polyphenol fractions from carcinogenic alkaloid fractions (7).

Value Addition and Product Diversification

Sun-dried (fully ripe) arecanuts after drying in the open sun for 30-45 days are widely used for arecanut pan masala production in the northern and central parts of India and have been well documented in published CPCRI literature as the main raw material (10). Sun-dried foods have been chemically analysed and published to validate that moisture is reduced, tannin and polyphenol levels increased, and arecoline levels decreased in comparison to shade-dried and raw varieties (1). The boiled form is the more common form obtained by boiling, dehusking and drying of tender arecanut and is the form which is sold in the major wholesale markets in the South of India. Literature exists regarding commercial sub-grades of boiled dried kernel based on size, roundness and colour uniformity, and the premium allowance on the better grades over the others is 20-30 per cent (10).

White processed is from a fully ripe dried kernel after the removal of the outer testa, exposing the white inner endosperm. As seen from the various published records from CPCRI, this form is used as the main ingredient in the preparation of traditional betel quid (tambula) as well as the preferred form in Ayurvedic preparations (10). Phytochemical analysis even revealed that the alkaloid level in shavings was higher than that of the processed whole nuts, and unprocessed whole nuts were 32.87 and 41.76 mg/g, respectively (20). The polyphenol composition of tannin-free testas differs from that of the polyphenol composition in whole dried kernels (1).

In rat models of estrogen deficiency, gut microbiome modulation by LYZ via immune signalling pathways was shown to be a mechanism by which separated arecanut polyphenols ameliorated osteoporosis, the most complete published mechanistic pathway of a systemic health effect of separated arecanut polyphenols (34). Arecanut polyphenols were demonstrated to inhibit the MAPK signalling pathway and activate the Nrf2/HO-1 antioxidant pathway in LPS-stimulated macrophage cells, decreasing the generation of ROS (35). Deep eutectic solvent (DES) extraction methods showed better antioxidant activity in extracts of arecanut seeds than the conventional solvents, and DES ultrasound-assisted extraction was found to be instrumentally feasible for commercial extraction of polyphenols from arecanut seeds (36). The extraction rate of polyphenols from arecanut was shown to be greatly increased using response surface methodology (RSM) assisted ultrasound extraction (37). Considering the fact that alkaloids and polyphenols are classified as IARC Group 1 (1,7) and have been found to be responsible for the direction of product development in all the published pharmaceutical literature, the separation of the alkaloids and polyphenols can be done systematically.

Areca catechu has been investigated for various pharmacological activities, such as antitumour activity, anti-hypertensive activity, anticoagulant activity, antidiabetic activity, antimicrobial activity, antiparasitic activity, and cholinesterase-inhibitory activity, from in vitro and in vivo studies and has been documented in comprehensive reviews of published pharmacological literature (7,38). Veterinary pharmaceutical uses of arecoline include an anthelmintic (7). Research review on refined betel nut processing highlighted the areas of active research, including formulation of marinade and optimisation of drying parameters (4) in the process of developing the product. In published studies (21), a neutral polysaccharide was suggested to serve as a functional food ingredient due to its antioxidant properties. The published direction is clear: polyphenol fraction development requires careful extraction of the alkaloids prior to responsible commercialisation (1). Table 2 presents the summary of arecanut value-added products and by-product streams.

Table 2. Summary of arecanut value-added products and by-product streams

Product	Raw Material	Key Properties	Commercial Application	Key References
Boiled dried kernel (Kalipak)	Tender green nut	Brick-red colour; polyphenol-rich; arecoline level reduced	Chewing supari, South Indian pan masala blend	(1, 10)
Sun-dried kernel (Chali)	Fully ripe nut	Hard texture; high tannin; high arecoline	North/central Indian pan masala; scented supari base	(1, 10)
White processed kernel	Ripe dried nut	Testa removed; white endosperm; alkaloid in shavings 42.55 mg/g	Betel quid (tambula); Ayurvedic formulation	(10, 20)
Polyphenol extract (separated fraction)	Dried kernel	DPPH/ABTS antioxidant activity; ameliorates osteoporosis in animal models via the LYZ pathway	Nutraceutical (requires alkaloid separation)	(23, 34, 35, 36)
Arecanut husk biochar (AHBC)	Fruit husk (processing by-product)	Adsorption: Rhodamine B 89%, Alizarin Red 87%; Langmuir max cap: 105.43 mg/g; stable aromatic structure (FTIR/XRD)	Soil amendment; textile effluent treatment; construction filler	(18, 44)
Husk fibre / nanocellulose composite	Fruit husk fibre	Tensile +47% vs. neat epoxy at 6% fibre loading; MnP 341.2 IU/mL from biosoftening	Lightweight composites; sustainable textiles	(42, 43, 45)
Arecanut leaf sheath (ALS) plates	Naturally shed spathes	ALS composition: cellulose 72.27%, hemicellulose 13.28%, lignin 12.84%	Eco-friendly single-use food service plates/bowls/trays	(25, 39, 40)
CMC-coated ALS transparent film	ALS cellulose	Areal density 132.5 g/m²; tearing strength 71% of polyethylene; elongation 5%	Sustainable food packaging material	(40)

ALS nanocellulose (ZnO nanoflakes)	ALS cellulose nanofibers	Hydrophobic cellulose nanopaper; enhanced bursting strength; shelf-life prediction	Premium sustainable packaging; barrier coatings	(41)
Tannin extract	Husk (15-47% tannin)	Condensed proanthocyanidins and gallotannins; 70-75% purity after spray drying	Leather tanning; textile mordanting; antimicrobial application	(10, 38)

By-product Utilisation and Waste Valorisation

The technical proof-of-concept for this use of arecanut palm leaf sheaths was made through the publication of engineering literature, which documented the first purpose-built machine to manufacture plates from arecanut palm leaf sheaths (39). The novel transparent packaging material was made from arecanut leaf sheaths (ALS) coated with carboxymethyl cellulose (CMC) and characterised to have an areal density of 132.5 g per sq meter, tearing strength around 71 per cent of polythene and elongation at failure of around 5 per cent, which makes the CMC-coated ALS film a technically viable food packaging material (40). Laboratory compositional analysis of ALS revealed cellulose (72.27 per cent), hemicellulose (13.28 per cent) and lignin (12.84 per cent) content, which is better than the cellulose content of rice straw (34.26 per cent) and sugarcane bagasse (37.5 per cent) (40). The economic estimates give a figure of 3.5 billion leaf sheaths of arecanut produced in India every year, and the potential income is Rs. 7 billion, if fully valorised. Cellulose nanopaper produced by the self-assembling method of ZnO nanoflakes into arecanut palm sheath was found to exhibit a remarkably high bursting strength and shelf-life prediction ability, as sustainable packaging (41).

A thorough review of lignocellulosic *Areca catechu*-based biocomposites showed that ALS fibre composition (57.3 per cent cellulose, 13.3 per cent hemicellulose, 22 per cent lignin) makes it suitable for the applications of food packaging, textile, automotive and construction materials and identified TEMPO-mediated oxidation and enzymatic treatment as optimal means of extracting nanocelluloses from ALS (13). Areca sheath fibre skin layers composites exhibited tensile strength of 38 MPa, flexural strength of 42 MPa and compression strength of 33 MPa. When 6 per cent arecanut husk fibre (AHf) was added to it, the tensile strength of the composite increased by 47 per cent compared to neat epoxy resin (13).

The arecanut fruit husk constitutes 60–80 per cent of total fruit dry mass and is the largest volume by-product from the processing chain (18). Biosoftening of arecanut husk fibre using Phanerochaete chrysosporium in solid-state fermentation achieved maximum manganese peroxidase (MnP) production of 341.2 IU mL^{-1} with selective lignin removal, establishing the biological processing route for husk fibre softening (42). A review of arecanut husk lignocellulosic fibres as sustainable alternatives to synthetic textiles documented extraction methods, mechanical and thermal properties, and application scope of husk-derived nanocellulose and fibre composites (43). Arecanut husk biochar applied with vetiver grass in contaminated soils significantly improved physico-chemical soil properties, soil enzyme activity, and plant nutrient uptake, with FTIR and XRD characterisation confirming stable aromatic structure (18). Arecanut husk biochar produced by slow pyrolysis demonstrated maximum anthraquinone dye removal efficiencies of 89 per cent for Rhodamine B and 87 per cent for Alizarin Red from textile wastewater, with Langmuir maximum adsorption capacities of 105.43 mg/g and 109.52 mg/g, respectively (44). Dynamic mechanical analysis of arecanut husk fibre-reinforced epoxy composites confirmed storage modulus and thermal stability characteristics suitable for lightweight structural applications (45). A comprehensive review documented the full valorisation scope into biomaterials, biofuels, and functional chemicals, identifying biochar, bioethanol, enzyme production, and composite materials as the four primary industrially feasible pathways (46).

The tannin content of the arecanut husk is high (15-47 per cent depending on maturity and variety) as compared to other readily available by-products of Indian agriculture (18). Traditional uses for the tannin include leather tanning and mordanting of textiles, and the main tannin types are condensed proanthocyanidins (called phlobatannins) and hydrolysable gallotannins (37). In vitro antibacterial and antifungal activities against Staphylococcus aureus, Escherichia coli, and Candida albicans have been reported (37). The published CPCRI literature reports that hot water extraction at 80°C and spray drying were done for commercial-scale production of tannin, which resulted in tannin content of 70–75 per cent in the powder for the leather industry (10).

Constraints in Post-Harvest Processing and Value Addition

Technological and mechanisation constraints

Available mechanical dehuskers have been shown by published CPCRI reviews to be suitable only for fresh tender nuts or dried ripe nuts, and would need two different pieces of equipment for the two processing routes (10). Non-availability and high cost of agricultural labour were found as the topmost production constraint in the published Garrett ranking analyses of arecanut farmers, followed by disease incidence and high input costs (24). Labour is the largest processing cost, ranging between 60–70 per cent, and at times creates a bottleneck, especially during the peak harvest season (10,24). The results of the technology adoption survey revealed that the adoption of recommended improved varieties (9) of arecanut was found to be very low among Tamil Nadu arecanut farmers, 15.83 per cent (9).

Quality deterioration and aflatoxin risk

The most serious food safety constraint and the key constraint to export market access is aflatoxin contamination in the sun-drying of foods due to improper practices. The enzymatic mechanism of kernel browning due to PPO and POD activity, accelerated by mesocarp tissue damage, is published (19). Cocotrypes carpophagus is a major pathway of deterioration of storage quality (10). The Indian arecanut industry records post-harvest losses of 10-20% of the harvested value across the industry (9,10).

Market, policy, and institutional constraints

No MSP means that the prices at the farm gate are subject to competition from imports, which has been reported in published agricultural economics literature as a structural constraint (14,24). The Goods and Services Tax (GST) regime on arecanut, which is processed into a branded product, is also a compliance issue that encourages informal production. However, the quantitative impact on the formal sector development has yet to be published (10).

Emerging Innovations and Research Advances

The CMC-coated ALS transparent packaging film showed the tearing strength of around 71 per cent of polythene and around 5 per cent elongation at failure, which was technically feasible as a food packaging film (40). Arecanut palm sheath cellulose nanopapers prepared by the self-assembly of ZnO nanoflakes exhibited a better bursting strength and shelf-life prediction ability as a sustainable packaging material (41). For areca fibre, two published reviews found that TEMPO-mediated oxidation and enzymatic treatment were the best nanocellulose extraction methods, delivering high aspect ratio CNFs that could be used to reinforce biopolymer packaging films (13). The overall results suggest that ALS is a directly pressed disposable food service product as well as a high cellulose feedstock for the production of packaging film reinforced with nanocellulose (13,40,41).

Gut microbiome changes via LYZ-mediated immune pathways were shown to be responsible for the amelioration of osteoporosis in animals fed arecanut seed polyphenols, providing the most comprehensive published mechanistic pathway for a systemic health effect of separated polyphenols (34). Structural elucidation of a polysaccharide extracted from arecanut (37.3 kDa) showed its in vitro antioxidant potential as a functional food ingredient (21). The correlation of polyphenol content with the antioxidant activity was also confirmed as positive in all the growing areas, and in the case of alkaloids, the activity was not found, which indicates that the direction of separation of polyphenol is the scientifically valid direction (23). The general trend that has been noticed in the recent publications is that separation of alkaloids from polyphenols is a necessity for the responsible development of nutraceutical products, as a whole nut is classified as a Group 1 class by IARC (1,7).

In contaminated soils, the application of arecanut husk biochar greatly enhanced the physico-chemical characteristics of soil, soil enzyme activity, and nutrient uptake without altering the aromatic structure as observed by FTIR and XRD characterisations (18). Slow pyrolysis of arecanut husk was shown to give the best dye removal efficiency at a maximum of 87 per cent for Alizarin Red, and 89 per cent for Rhodamine B in textile effluents, and its adsorption kinetics were found to be capable of following the pseudo-first-order model. At the same time, the Langmuir isotherm parameters confirmed monolayer adsorption (44). Therefore, these results make arecanut husk biochar a technically proven low-cost adsorbent for the treatment of the agricultural and industrial effluents (18,44).

To determine how temperature and precipitation changes will affect the suitable growing area for arecanut, ensemble modelling was used for different climate scenarios, which identified shifts in the suitable arecanut growing zones and quantified the percentage of current growing areas which will be exposed to the climate change impact of changing temperature and precipitation patterns, both of which are relevant to post harvest management, as in the case of harvest seasons, their timing and predictability will change with climate, and for drying seasons, too. The genome assembly of the areca palm, at the scale of the genome, is the genomic resource foundation required for molecular breeding of the climate-resilient, high productivity varieties of the areca palm (47). Comparative biochemical and transcriptome analysis of leaf albinism in arecanut helped to build up a molecular knowledge base for variety development (48).

DISCUSSION

The findings of this systematic review reveal a sector characterised by a paradox of scientific knowledge abundance and practical application scarcity. While published literature has documented the technical feasibility of mechanical drying systems that eliminate aflatoxin risk (5), machine vision grading systems achieving commercial-level accuracy (39), deep eutectic solvent extraction of polyphenol fractions (21), and nanocellulose-reinforced packaging from leaf sheaths (7), none of these technologies has been deployed at commercial scale in Indian arecanut processing. This gap between published proof-of-concept and field-level adoption is consistent with the broader pattern documented in plantation crop post-harvest literature, where smallholder capital constraints, absence of institutional credit products, and weak cooperative structures collectively prevent technology uptake even when the economic case is established (12).

The finding that arecanut husk biochar achieves maximum anthraquinone dye removal efficiencies of 89 per cent for Rhodamine B at a Langmuir adsorption capacity of 105.43 mg/g (45). The potential for arecanut processing units co-located with textile manufacturing zones to create circular by-product value chains has not been explored in any published study and represents a policy-relevant innovation opportunity. Similarly, the documented composition of arecanut leaf sheaths 72.27 per cent cellulose, superior to rice straw and sugarcane bagasse positions the material as a premium feedstock for nanocellulose extraction (7), yet the economic model for farmer-level sheath collection and sale to processing units has not been published for any Indian growing region.

The coastal Karnataka and Kerala literature that dominates the knowledge base describes agro-climatic conditions, water availability, labour markets, and marketing chain structures that differ substantially from the groundwater-irrigated, contractor-dominated, absence-of-cooperative-infrastructure context of other arecanut growing states. This geographical mismatch between the published knowledge base and the actual growing frontier of Indian arecanut cultivation is the most fundamental research gap identified by this review.

CONCLUSION

This systematic review synthesises evidence from 49 peer-reviewed publications on arecanut post-harvest processing and value addition to yield four overarching conclusions with direct implications for research prioritisation and policy development.

First, the post-harvest technology gap in arecanut is fundamentally an adoption gap rather than an invention gap. The technologies required to address the sector's most critical challenges mechanical drying, machine vision grading, controlled polyphenol extraction, and nanocellulose fabrication from leaf sheaths have all been validated in published scientific literature. The barrier to transformation is economic and institutional, not technological, and future research must therefore prioritise economic feasibility analysis, institutional design of shared-service processing centres, and participatory technology transfer models rather than further laboratory-scale technology development.

Second, the by-product valorisation potential of arecanut encompassing husk biochar for soil remediation and industrial effluent treatment, leaf sheath cellulose for sustainable packaging, and polyphenol fractions for nutraceutical development is scientifically well-documented but commercially unrealised. Bridging this gap requires investment in pilot-scale valorisation demonstration units, supply chain design for by-product aggregation, and regulatory pathway development for polyphenol-based functional food products that ensure mandatory alkaloid separation.

Third, the ripe nut processing chain in emerging inland growing zones offers materially better farmer income outcomes than the green nut chain, as reflected in the significantly higher producer's share of consumer price in the ripe nut channel. Policy interventions that enable more farmers to access the ripe nut marketing channel through investment in processing infrastructure, elimination of pre-harvest contractor dependency, and development of cooperative ripe nut processing units could deliver meaningful and rapid improvement in arecanut farmer income without requiring yield improvements.

Fourth, and most critically, the published literature has a systematic geographical bias toward Karnataka and Kerala coastal belt conditions that renders it substantially inapplicable to emerging inland growing regions. Coordinated, participatory, multi-institutional research specifically designed for inland irrigation-dependent arecanut systems is the highest-priority need identified by this review.

Future Prospects and Research Gaps

Literature synthesis reveals a blockage of a well-defined technological, institutional, and research gap with a sizeable economic opportunity. The most critical areas that should be coordinated for research and development attention are found as follows: In view of the priority for immediate mechanisation, it is noted that a versatile mechanical dehusking system for fresh tender and dried ripe arecanuts with a desirable kernel breakage percentage is required. Rather, the published CPCRI documentation to date suggests that such a universal device does not exist, as it were (10). Dehusking labour is the most important cost item in both of the main processing routes (10,24), and is a top engineering design and field validation priority.

The absence of a national standard of constraint, which can be instrumentally measured, is recognised in the published constraint literature as the most systemic institutional shortcoming and has multiplier effects throughout the value chain (10,24). Such a standard, having scientific evidence in literature, is available, which includes Colour score by Chromameter, Nut density, moisture content limits, and aflatoxin limits based on FSSAI. Implementing and notifying the required course grade is a top-priority institutional need.

Separation of arecanut polyphenol fractions from alkaloids at the industrial scale needs to be studied in order to valorise the polyphenol fractions for nutraceutical use. The process engineering starting point for the DES extraction method and ultrasound-assisted extraction procedure is provided by a published extraction protocol (36,37); however, there is no published study to assess these at the pilot or commercial scale based on the processing context in India, which is the critical path towards responsible commercialisation of nutraceuticals.

The leaf sheath plate sector is also commercially viable with 3.5 billion spathes with Rs. 7 billion value potential (49), but the food safety procedures are not well-defined. Microbiological contamination tests were published for 30 manufacturing units, which showed fungi present, but no validated critical control measures (CCM) were defined (25). There is a need to urgently publish research directed towards food safety engineering aspects of the manufacturing process of the leaf sheath plate, and establish HACCP equivalent control points and verifiable microbial reduction targets to support export certification opportunities.

REFERENCES

1. Sun Y, Feng J, Hou W, Qi H and Liu Y, Comprehensive insights into arecanut: active components and omics technologies for bioactivity evaluation and quality control. Front. Pharmacoloogy, 2024;15:1407212. doi: 10.3389/fphar.2024.1407212
2. Mitra SK, Devi H. Arecanut in India: present situation and prospects. Acta Horticulturae. 2018; 1205:99–110. https://doi.org/10.17660/ActaHortic.2018.1205.9
3. Giriappa S. Arecanut production and marketing in India. New Delhi: M.D. Publications Pvt. Ltd.; 1994.
4. Zhu Q, Deng S, Ma L, Li Q, Tan S, Zheng Y, Xu A, Wang H. Research progress on processing technology of refined betel nut in China: a review. Processes. 2023;11(11):3199. https://doi.org/10.3390/pr11113199
5. Jamanal H, Murthy CM. Production and marketing management of arecanut in Karnataka. The Pharma Journal. 2022;11(12):5206–5213.
6. Mordor Intelligence. Arecanuts market: forecast and industry trends 2025–2030. Hyderabad: Mordor Intelligence; 2025.

7. Liu PF, Chang YF. The controversial roles of arecanut: medicine or toxin? International Journal of Molecular Sciences. 2023;24(10):8996. https://doi.org/10.3390/ijms24108996
8. Sharan RN, Mehrotra R, Choudhury Y, Asotra K. Association of Betel Nut with Carcinogenesis: Revisit with a Clinical Perspective. 2012; PLoS ONE 7(8): e42759. doi: 10.1371/journal.pone.0042759
9. V Mohanraj, R Velusamy and K Prabakaran. Analysis of the adoption level of post-harvest practices and value addition of Arecanut growers in Salem district of Tamil Nadu. International Journal of Chemical Studies. 2020; 8(6): 25-28. DOI: 10.22271/chemi.2020.v8.i6a.10821
10. Bhat SK, Pandiselvam R, Jaganathan D. Processing and value addition of arecanut. In: Product diversification in plantation crops. New Delhi: Astral International Pvt. Ltd.; 2017. p. 119–134.
11. Srinivasan R, Maddileti N, Maske S P and Kasthuri Thilagam V. Application of Tank Silt for Improving Arecanut Productivity in Karnataka. Trends In Agriculture Science, 2022; 1(6), 268–272. https://doi.org/10.5281/zenodo.7067214
12. Food and Agriculture Organisation of the United Nations. FAOSTAT: arecanut area, production and yield data. Rome: FAO; 2024.
13. Kaliyaperumal M, Pragadish N, Palani Kumar M, Vijayan V, Sridhar I, Rajagopal K. Recent developments in lignocellulosic *Areca catechu*-based biocomposites and their potential industrial applications: a review. Industrial Crops and Products. 2025; 228:119760. https://doi.org/10.1016/j.indcrop.2025.119760
14. Jamanal H, Murthy CM. Trends in area, production and productivity of arecanut in India and Karnataka. The Pharma Journal. 2022;11(12):710–715.
15. National Horticulture Board. Horticulture statistics at a glance 2022–23. Gurugram: NHB, Ministry of Agriculture and Farmers Welfare, Government of India; 2023.
16. Adivappar N, Amulya RN, Satish KM, Nagaraja NR. Genetic relationship and diversity analysis in arecanut (Areca catechu L.) genotypes using molecular markers. Agricultural Science Digest. 2022;42(6):688–695. https://doi.org/10.18805/ag.D-5283
17. Wang S, Kang X, Dai J, Dai W, Zhang J, Ji J. Evaluation of Areca Quality Based on Principal Component and Hierarchical Cluster Analyses in Hainan, China. HortScience. 2023;58(6): 699–703. https://doi.org/10.21273/HORTSCI17125-23.
18. Gujre N, Mitra S, Agnihotri R, Sharma MP, Gupta D. Novel agrotechnological intervention for soil amendment through arecanut husk biochar in conjunction with vetiver grass. Chemosphere. 2022;287(Pt 4):132443. https://doi.org/10.1016/j.chemosphere.2021.132443
19. Pan Y, Guo Y, Huang Q, Zhang W, Zhang Z. Enzymatic browning in relation to permeation of oxygen into the kernel of postharvest arecanut under different storage temperatures. Food Science and Nutrition. 2021;9(7):3676–3685. https://doi.org/10.1002/fsn3.2341
20. Swami S, Solunke R, Rathod SN, Bedre S, Nagtilak S. Phytochemical analysis of bioactive compounds in commonly used forms of arecanut. Journal of Interdisciplinary Dentistry. 2025. https://doi.org/10.4103/jid.jid
21. Ji X, Guo J, Pan F, Kuang F, Chen H, Guo X, Liu Y. Structural elucidation and antioxidant activities of a neutral polysaccharide from arecanut (Areca catechu L.). Frontiers in Nutrition. 2022; 9:853115. https://doi.org/10.3389/fnut.2022.853115
22. Li M, Pang X, Gu Z, Guo Z, Xin Y, Zhang L. Rapidly analyzing of ingredients during chewing and processing of arecanut using feature-based molecular networking. Food Chemistry. 2023; 410:135205. https://doi.org/10.1016/j.foodchem.2022.135205
23. Bamunuarachchi MK, Senadeera S, Karunaratne V, Jayawardena B. Correlation analysis of phenolic compounds, antioxidant potential, and alkaloid content in ripe and unripe *Areca catechu* from major cultivation areas in Sri Lanka. Journal of Agriculture and Food Research. 2023; 14:100809. https://doi.org/10.1016/j.jafr.2023.100809
24. Jamanal H, Murthy CM. Constraints faced in production and marketing of arecanut in Karnataka. Journal of Farm Sciences. 2024;37(1):54–58.
25. Revathi RM, Adivappar N, Patil S, Sudeep HP, Swathi HC. Studies on microbial contaminants associated with arecanut leaf sheath plates. Journal of Pure and Applied Microbiology. 2021;15(3):1393–1397. https://doi.org/10.22207/JPAM.15.3.31
26. Salunke A, Honnungar, Sunilkumar. Quality grading of arecanuts harvested and processed in Goa using image processing and LabVIEW. AIP Conference Proceedings. 2020;2247(1):020017. https://doi.org/10.1063/5.0004022
27. Rao A, Sreenivasa D, Nagarajappa P. Design and fabrication of automatic arecanut processing unit. International Journal of Engineering Research and Development. 2023.
28. Satheesha KM, Rajanna KS, Krishna Prasad K. A review of the literature on arecanut sorting and grading using computer vision and image processing. International Journal of Applied Engineering and Management Letters. 2023;7(2):50–67. https://doi.org/10.47992/IJAEML.2581.7000.0174
29. Jyothi K, Hegde SM, Sumedha KS, Sushma CR, Thanushree DC. Grading of arecanut using machine learning techniques. International Journal of Scientific Research in Computer Science, Engineering and Information Technology. 2022;8(4):33–39.
30. Mallikarjuna SB, Shivakumara P, Khare V, Kumar V, Basavanna M, Pal U, Poornima B. CNN-based method for multi-type diseased arecanut image classification. Malaysian Journal of Computer Science. 2021;34(3):255–265.
31. Bharadwaj NK. Classification and grading of arecanut using texture-based block-wise local binary patterns. Lecture Notes in Electrical Engineering. Singapore: Springer; 2021.
32. Anitha AC, Dhanesha R, Naika CS. Arecanut bunch segmentation using deep learning techniques. International Journal of Circuits, Systems and Signal Processing. 2022;16(1):1064–1073. https://doi.org/10.46300/9106.2022.16.129

33. Mulla AI, Sab A, Gubbi A. Arecanut Segregation System Using Local Binary Pattern and HOG Features. International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE). 2022;9(1):8-13.
34. Mei F, Meng K, Gu Z, Yun Y, Zhang W, Zhang C, Li Y, Luo H, Zhu X. Arecanut (Areca catechu L.) seed polyphenol-ameliorated osteoporosis by altering gut microbiome via LYZ and the immune system in estrogen-deficient rats. Journal of Agricultural and Food Chemistry. 2021;69(1):246–258. https://doi.org/10.1021/acs.jafc.0c06671
35. Wang P, Li Z, Xu J, Fu T, Wu Y, Chen H, Zhu H. In vitro antioxidant activity of arecanut polyphenol extracts on RAW264.7 cells. Antioxidants. 2022;11(11):2251. https://doi.org/10.3390/antiox11112251
36. Li W, Tang S, Wu X, Fu M, Zheng Y, Bai W, Xie L. Arecanut (Areca catechu L.) seed extracts: relation between phytochemical compositions and biological activities by multivariate analysis. Industrial Crops and Products. 2021; 170:113731. https://doi.org/10.1016/j.indcrop.2021.113731
37. Chavan YV, Singhal RS. Ultrasound-assisted extraction of bioactives from arecanut (Areca catechu L.) and optimization by response surface methodology. Innovative Food Science and Emerging Technologies. 2013; 17:106–113. https://doi.org/10.1016/j.ifset.2012.10.001
38. Peng W, Liu YJ, Wu N, Sun T, He XY, Gao YX, Wu CJ. *Areca catechu L.* (Arecaceae): a review of its traditional uses, botany, phytochemistry, pharmacology and toxicology. Journal of Ethnopharmacology. 2015; 164:340–356. https://doi.org/10.1016/j.jep.2015.02.010
39. Kalita P, Dixit US, Mahanta P, Saha UK. A novel energy efficient machine for plate manufacturing from areca palm leaf sheath. Journal of Scientific and Industrial Research. 2008; 67:807–811.
40. Disanayake NWA, Amarasinghe ADUS, Jayasinghe JMJK. A sustainable transparent packaging material from the arecanut leaf sheath. Waste and Biomass Valorization. 2021; 12:5867–5877. https://doi.org/10.1007/s12649-021-01382-5
41. Rajalakshmi M, Geetha P, Ramesh MV. Facile fabrication of arecanut palm sheath-based robust hydrophobic cellulose nanopapers via self-assembly of ZnO nanoflakes and shelf-life prediction for sustainable packaging applications. Industrial Crops and Products. 2024; 210:118234. https://doi.org/10.1016/j.indcrop.2023.118234
42. Nagaraja R, Gurumurthy BR, Shivanna MB. Biosoftening of arecanut fibre for value-added products. Bioresource Technology. 2005;96(9):1013–1018. https://doi.org/10.1016/j.biortech.2004.09.009
43. Sundarakannan R, Arunkumar T, Manikandan N, Raja T. Arecanut husk lignocellulosic fibres: a sustainable alternative to synthetic textiles. European Polymer Journal. 2024; 220:113475. https://doi.org/10.1016/j.eurpolymj.2024.113475
44. Tharayil JM, Chinnaiyan P. Sustainable waste valorisation: novel *Areca catechu L*. husk biochar for anthraquinone dye adsorption. Environmental Technology and Innovation. 2023; 32:103738. https://doi.org/10.1016/j.eti.2023.103738
45. Mathapati VC, Muralidhar N, Tulasiram BR, Balreddy MS. Experimental study on dynamic mechanical properties of arecanut husk fibre composite. Materials Today Proceedings. 2022; 66:858–65.
46. Mishra B, Mohanta YK, Reddy CN, Bharat Kumar A. Arecanut husk: valorisation into bioproducts, biomaterials and biofuels. In: Agro-industrial waste: circular bioeconomy perspectives. Cham: Springer Nature; 2024. https://doi.org/10.1007/978-3-031-96805-1_11
47. Hebbar KB, Ramesh SV, Bhat R. Predicting current and future climate suitability for arecanut (Areca catechu L.) in India using ensemble model. Industrial Crops and Products. 2024; 207:117660. https://doi.org/10.1016/j.indcrop.2024.117660
48. Li J, Jia X, Liu L, Cao X, Xiong Y, Yang Y, Zhou H, Yi M, & Li M. Comparative biochemical and transcriptome analysis provides insights into the regulatory mechanism of striped leaf albinism in arecanut (Areca catechu L.). Industrial Crops and Products. 2020; 154, 112734. https://doi.org/10.1016/j.indcrop.2020.112734
49. Patil SG, Nagarajappa A, Nadagouda BT, Murthy N. Eco-friendly arecanut leaf sheath products: an economic analysis. Journal of Plantation Crops. 2019;47(3):156–162.