

POSTHARVEST TECHNOLOGY, VALUE ADDITION AND MARKETING OF PALMYRA PALM (*BORASSUS FLABELLIFER* L.) – PROGRESS, CONSTRAINTS AND FUTURE PROSPECTS

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ABSTRACT

Palmyra palm (*Borassus flabellifer* L.), the state tree of Tamil Nadu, continues to be an underutilized plantation crop even though it offers wide range of edible and industrial products. This review compiles research (2017-2026) on the postharvest technology, storage, transportation and marketing of palmyra fruit (nungu/ice apple), sap (neera), toddy and value-added products like palm jaggery, sugar, candy and thavun. India holds an estimation of 90-122 million palmyra palms, with Tamil Nadu representing about its half, concentrated in Tuticorin, Virudhunagar, Tirunelveli and Ramanathapuram districts (~9,674 ha; ~14.7/ha). Packaging and refrigeration can prolong the shelf life of tender fruit from hours to 8-14 days, whereas hurdle and thermal treatments can postpone neera fermentation by up to three weeks. Key constraints include the palm's gradual, dioecious growth, a diminishing tapper work force, lack of cold-chain infrastructure, unstandardized processing and regulatory restrictions on toddy. Mechanized tapping tools, cold chain linked bottling, GI labeling and skill-focused entrepreneurship are recommended to redefine palmyra as a climate – resilient commercial crop.

KEYWORDS: Postharvest management; palm jaggery; shelf life; value added products and marketing constraints.

1. INTRODUCTION

Palmyra palm (*Borassus flabellifer* L., family Arecaceae) is a dioecious, slowly growing, long-lived palm indigenous to the Indian subcontinent and South-East Asia recognized as one of the most versatile plantation species known to humankind, with more than 800 documented uses including food, beverage, fibre, fodder, medicine and timber (Rao *et al.*, 2021; Joshi, 2025). It is recognized as the state tree of Tamil Nadu, commonly known as 'karpagatharu' or the tree of life because every part of the tree – crown, trunk, leaf, root and fruit have economic value (Joshi, 2025). Unlike most horticultural crops that are consumed fresh, palmyra-derived products require some degree of postharvest processing before they reach the consumer, placing postharvest technology at the centre of the palmyra value chain.

Three main categories of primary produce are obtained from the palm: (i) the tender and mature fruit, whose jelly like endosperm (nungu, tadgola or ice apple) is consumed as a summer treat while the mature pulp is processed into jam, spread, toffee and pulp powder; (ii) the sweet inflorescence sap (neera or padaneer), which can be consumed fresh as a nutritious beverage or processed into sugar, jaggery, candy and, on natural or induced fermentation, toddy and (iii) a variety of secondary and non-edible products such as fibre, leaf articles, timber and the germinated seedling product thavun (Rao *et al.*, 2021; Vengaiah *et al.*, 2017). All of these commodities are highly perishable: neera ferments within two to three hours after tapping at ambient temperature (Hebbbar *et al.*, 2018) and fresh endosperm spoils within a few hours of extraction due to oxidative browning and microbial fermentation (Ambrose, 2018). The extreme perishability, along with the predominantly unstructured, household processing has historically constrained the commercial utilization of the crop and led to the significant postharvest losses that some estimates indicate above 60% of the annual fruit yield in unmanaged stands.

Over the last decade, however, a growing body has focused on packaging, cold-chain, hurdle preservation, drying and process standardization technologies aimed at prolonging the shelf life of palmyra products and facilitating their entry into organized retail and export markets (Hai *et al.*, 2024; Agritha *et al.*, 2026). Concurrently, socio-economic studies persist in highlighting the constraints facing palmyra farmers, tappers and processors – including regulatory restrictions on toddy, a diminishing tapper workforce and weak market linkages – that hinder the actualization of this potential (Aravind *et al.*, 2025; Downtoearth, 2025). Despite this expanding literature, comprehensive review that integrates postharvest technology, area and production statistics and value chain limitations specific to palmyra in the Indian and particularly the Tamil Nadu, context is lacking. This review

addresses this gap. The goal of the review is to (i) provide an overview of the palmyra production and productivity in Tamil Nadu and India (ii) analyze advancements in postharvest management, packaging, storage and preservation for palmyra and their related products (iii) examine transportation, cold chain and marketing aspects of the palmyra value chain and (iv) identify and consolidate the main constraints faced in the farming, processing and marketing of palmyra products to guide future research priorities and policy interventions.

2. Botany, Distribution and Economic Importance

Borassus flabellifer L. is a robust, solitary stemmed, fan leaved palm that can survive for over 100 years and reach height of 25-30 m. Its is dioecious, possessing distinct male and female trees that can be distinguished only after 12-15 years of growth, a characteristic that directly affects orchard planning and productivity forecasting. The tree endures wide range of edaphic and climatic conditions, thriving on waste lands, field bunds, coastal tracts and drought-prone semi-arid soils where few other tree crops survive, highlighting its historic significance as a durable, low-input component of dryland farming systems in peninsular India (Rao *et al.*, 2021). Botanically, the genus *Borassus* includes multiple species distributed across Asia and Africa, of which *B. flabellifer* is the principal India and South-East Asia, while *B. aethiopum* is more common in Africa (Rao *et al.*, 2021).

The significance of the palm extends beyond its contribution to food and beverage value. It provides significant ecosystem services, including soil-erosion control through its deep taproot system, groundwater recharge, carbon sequestration and pollinator support during flowering and is increasingly mentioned in the context of climate-resilient agroforestry (Joshi, 2025). Every component of palm – crown, leaf, petiole. Trunk, root, tuberous seedling, immature and mature fruit and inflorescence sap- is utilized, leading to an exceptionally extensive array of primary and value-added products that is summarized in Section 6.

3. Area, Production and Productivity of Palmyra in Tamil Nadu and India

Reliable, updated statistics on palmyra remain scarce because the crop is largely cultivated as a non-plantation, wild or semi-wild resource on wastelands, field bunds and home gardens rather than as a structured orchard crop, resulting in inconsistent reporting in regular agricultural census data. Nevertheless, recent assessments and governmental sources align with this broad overview. India is estimated to have between 90 and 122 million palmyra palms, with numbers varying among sources based on the year of the survey and the methodology used (Joshi, 2025; Aravind *et al.*, 2025). Tamil Nadu accounts for nearly half of the nation's total palm population – with estimates ranging from about 51.6 million to 90 million trees – making it the largest repository of the palmyra's genetic and economic resources nationwide (Aravind *et al.*, 2025).

Within Tamil Nadu, palmyra cultivation is largely focused in the southern and southern-eastern districts. Over fifty percent of the palm trees in the state are located in the districts of Virudhunagar, Tuticorin, Tirunelveli and Ramanathapuram, with Tuticorin district alone estimated to have around ten million trees, recognized as the principal hub for value-added palmyra processing and export-oriented production (Aravind *et al.*, 2025). According to district-level crop statistics compiled from the Season and Crop Report of Tamil Nadu, the state records a productive palmyra area of approximately 9,674 hectares with an aggregate annual production of 142,328 tonnes, corresponding to an average productivity of roughly 14.7 t/ha (Aravind *et al.*, 2025). Table 1 compiles data of area, production and productivity statistics of palmyra palm in Tamil Nadu and India.

Table 1: Indicative area, production and productivity statistics of palmyra palm in Tamil Nadu and India, compiled from recent secondary sources (2021-2025)

Parameter	Tamil Nadu	India	Source/year
Estimated number of palmyra trees	51.6-90 million	90-122 million	Aravind <i>et al.</i> (2025); Joshi (2025)
Share of national palm population	~50-60%	100%	Aravind <i>et al.</i> (2025)
Reported productive area (ha)	~9,674	Not consistently reported	Season & Crop Report, TN (2021-22), cited in Aravind <i>et al.</i> (2025)
Reported annual production (t)	~142,328	Not consistently reported	Season & Crop Report, TN (2021-22)
Average productivity (t/ha)	~14.7	Variable by region	Aravind <i>et al.</i> (2025)
Leading districts by area/population	Thoothukudi, Virudhunagar, Tirunelveli, Ramanathapuram	Tamil Nadu, Andhra Pradesh, Odisha, West Bengal, Bihar, Karnataka, Gujarat, Maharashtra	Aravind <i>et al.</i> (2025); World Journal of Advance Pharmaceutical Sciences (2026)
Registered palm-jaggery artisans/tappers (licensed)	9,972 (2020-21)	-	TN Khadi & Village Industries Board records

Source: Compiled by the authors from Aravind *et al.* (2025) and Joshi (2025) and Government of Tamil Nadu Palm Product Development Board/Khadi and Village Industries Board records.

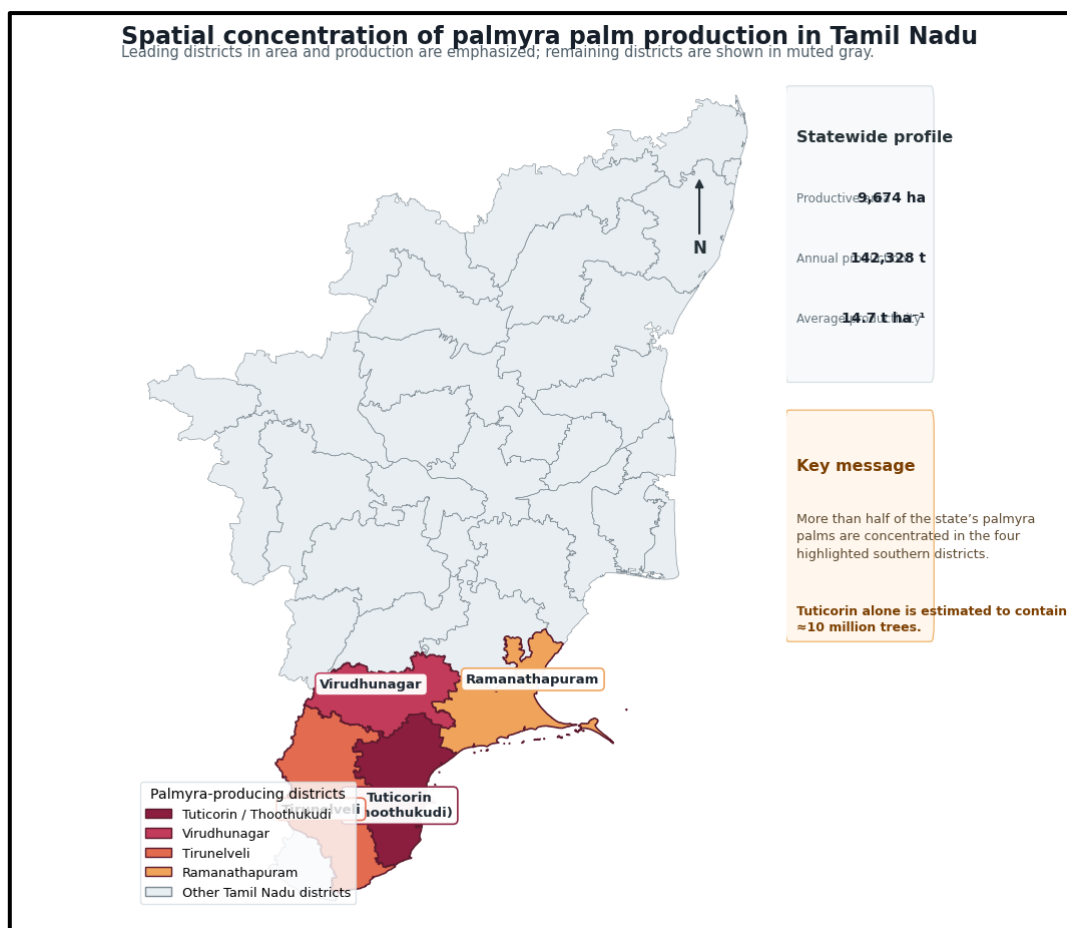


Fig.1: Choropleth map of Tamil Nadu state map compiling palmyra palm area highlighting districts Tuticorin, Virudhunagar, Tirunelveli and Ramanathapuram as the leading production belts.

A recurring observation in recent studies is the gradual decline in the palmyra tree population, despite its ecological and economic significance, attributed to land-use change, logging for timber and construction, intrusion by invasive species like *Prosopis juliflora* (Seemai karuvelam) and the aging of tapping workforce discussed in Section 8 (Aravind *et al.*, 2025). This decline highlights the necessity of postharvest and value-chain interventions that can enhance the economic value from existing plan stands and thus creating an incentive for conservation and replanting.

4. Harvesting and Postharvest Handling of Palmyra Fruit (Nungu/ Ice Apple)

4.1 Maturity indices and harvesting practices

Tender Palmyra fruit, harvested mainly between April and July across southern and eastern India, is cherished for its translucent, jelly-like endosperm known as nungu in Tamil, tadgola in Marathi and Hindi and commonly as 'ice apple' in English (World Journal of Advance Pharmaceutical Sciences, 2026). Harvest maturity is assessed by fruit size, husk color and the sound produced on tapping the bunch, as no standardized instrument-based maturity index exists for the crop – an important research gap since the maturity stage directly influences endosperm firmness, sweetness and post-extraction shelf life. Fruit bunches are generally harvested manually by climbing the palm and the endosperm is then exposed and extracted at the point of sale with a heavy knife or sickle by roadside vendors, a method that provides minimal control over hygiene or post-extraction quality (Ambrose, 2018).

4.2 Postharvest physiology and quality deterioration

Once extracted from its fibrous husk, palmyra endosperm is highly susceptible to spoilage: under warm tropical conditions, it can deteriorate within a few hours due to oxidative browning, moisture loss and microbial fermentation (Ambrose, 2018). The entire (unpeeled) tender fruit is relatively more stable but still experiences gradual weight loss and shrinkage after about two weeks of ambient storage. These physiological characteristics – elevated moisture content, increased respiration and susceptibility to enzymatic browning are similar to those found in other minimally processed tropical fruit tissues (e.g., cut coconut, litchi aril) and have influenced the choice of postharvest interventions discussed below.

4.3 Packaging and storage technologies

A systematic evaluation of retail packaging films has shown that both film type and storage temperature greatly affect the shelf life of tender palmyra endosperm. Ambrose (2018) assessed polypropylene (40 and 80 micron), low-density polyethylene (LDPE, 150 and 450 micron) and high-molecular-density polyethylene (HMPE, 40

micron) pouches at ambient ($32\pm 2^{\circ}\text{C}$) and refrigerated conditions ($5\pm 1^{\circ}\text{C}$). The findings indicated that endosperm packed in 450-micron LDPE stored under ambient conditions retained acceptable sensory quality for two days, whereas endosperm packed in 40-micron HMPE film under refrigerated conditions remained acceptable for up to eight days, a four-fold increase in shelf life achieved simply through appropriate film selection and cold storage. Endosperm packed in thicker LDPE film under refrigerated storage showed consistently lowest weight loss, reflecting its lower water-vapor transmission rate.

Table 2: Effect of packaging film and storage temperature on the shelf life of tender palmyra endosperm

Packaging material	Storage condition	Reported shelf life	Observation
LDPE, 450-micron	Ambient ($32\pm 2^{\circ}\text{C}$)	Up to 2 days	Highest overall acceptability under ambient storage; minimum weight loss
HMPE, 40-micron	Refrigerated ($5\pm 1^{\circ}\text{C}$)	Up to 8 days	Highest overall acceptability under refrigeration
Polypropylene, 40-80 micron	Ambient / refrigerated	Shorter than LDPE/HMPE	Higher permeability; faster browning and off-odor development
Whole unpeeled tender fruit	Ambient	~ 2 weeks before shrinkage	Progressive weight loss and shrinkage; husk offers natural protection

Source: Ambrose, D.C.P. (2018), *Journal of Applied and Natural Science* 10(2): 705-709.

These results indicate a feasible, cost-effective intervention approach for small vendors and small aggregators: pre-packaging endosperm into suitable polymer pouches and using basic ice-box or refrigerated storage can substantially reduce the very high wastage linked to roadside sale. Recent studies on related tropical produce have investigated modified atmosphere packaging (MAP) – by adjusting in-pack O_2 and CO_2 levels to slow respiration and browning – and this approach, well established for climacteric fruit and fresh-cut produce, represents a promising but as yet largely untested avenue for tender palmyra endosperm and merits dedicated study.

5. Postharvest Technology of Neera (Palm sap)

5.1 Tapping and collection technology

Neera is extracted from the unopened flower clusters and conventionally gathered in exposed clay containers, a technique that allows the sap to be exposed to airborne yeasts right from the beginning (Rao *et al.*, 2021). Hygienic options - refrigerated collection vessels and sealed containers - have been advocated to reduce this initial microbial contamination (Sarma *et al.*, 2022a).

5.2 Fermentation chemistry and spoilage

Neera has a high sugar content and a nearly neutral pH, which makes it very susceptible to spontaneous fermentation. At room temperature, it transforms to toddy (~4% alcohol) in 2-3 hours; storing it in the fridge extends this process to approximately three days (Hebbar *et al.*, 2018). Kinetic analyses have illustrated the related variations in pH, sugar and ethanol levels, establishing a foundation for anticipating shelf life (Sarma *et al.*, 2022b).

5.3 Preservation technologies

Thermal processes (pasteurization, tyndallization) and chemical hurdle techniques (lime, bark extracts, either alone or alongside gentle heating) have been employed to postpone fermentation, prolonging refrigerated shelf life to 21-28 days during experiments (Hai *et al.*, 2024). The selection of packaging material – HDPE, PET or glass for cold storage also impacts the preservation of color, flavor and nutrients (Sarma *et al.*, 2022a).

Validated non-thermal approaches for the similar coconut sap – plasma bubbling, pulsed light, frozen storage and protective probiotic cultures- present promising, mostly unexamined options for palmyra neera (Aparajitha and Mahendran, 2019; Vishnu Priya *et al.*, 2024; Sukumaran and Radhakrishnan, 2021; Somashekaraiah *et al.*, 2019).

Table 3: Comparison of principal preservation approaches for palmyra and closely related palm inflorescence saps (neera)

Preservation approach	Typical treatment	Reported shelf-life extension	Key references
Refrigeration alone	Storage at $2-10^{\circ}\text{C}$	Up to 3 days (untreated sap)	Hebbar <i>et al.</i> (2018)
Pasteurization	$60-95^{\circ}\text{C}$, 5-20 min	Up to 1 week (ambient); longer refrigerated	Hai <i>et al.</i> (2024)
Double-stage heat/tyndallization	60°C for 10 min, repeated	Up to 21 days (refrigerated)	Hai <i>et al.</i> (2024)

Chemical hurdle (lime, bark extract)	Ca (OH) ₂ and/or bark extract +/- pasteurization	Up to 28 days (refrigerated)	Hai <i>et al.</i> (2024)
Packaging optimization	HDPE/PET/glass at controlled cold-chain temperature	Variable; improves retention of color, taste and nutrients	Sarma <i>et al.</i> (2022a)
Emerging techniques (plasma, pulsed light)	Non-thermal microbial inactivation	Under active investigation; promising for coconut sap	Aparajhitha and Mahendran (2019); Vishnu Priya <i>et al.</i> (2024)

Source: Compiled from Hebbar *et al.* (2018), Hai *et al.* (2024), Sarma *et al.* (2022a, 2022b), Aparajhitha and Mahendran (2019) and Vishnu Priya *et al.* (2024).

6. Value-added products from Palmyra

6.1 Palm jaggery (karupatti) and palm sugar

Palm jaggery is produced by reducing neera to a solid form through boiling and is the primary commercially significant product derived from palmyra (Agritha *et al.*, 2026). Due to production mostly being at the household level, the quality varies significantly and lime amounts or heating durations are seldom standardized (Bashir *et al.*, 2023). It is significantly higher in iron, zinc and potassium compared to cane sugar and possesses a reduced glycemic index (Agritha *et al.*, 2026). Recent studies have concentrated on furnace design, functional enhancement and spectroscopic techniques (NMR, Raman) for identifying adulteration (Barad *et al.*, 2021; Singh *et al.*, 2024; Biswas *et al.*, 2025).

6.2 Palm candy (panang kalkandu) and palm honey

Palm candy is derived from the gradual crystallization of concentrated neera syrup, which traditionally requires 40-45 days; enhancements in the process have allegedly reduced this timeframe to around 25 days (Government of Tamil Nadu, Palm Products Development Board records; Chauhan *et al.*, 2017). Palm honey, produced through prolonged boiling, is a less commercially available item that exhibits anti-diabetic and antioxidant properties similar to jaggery.

6.3 Fruit-pulp based products: spread, toffee, jam and dehydrated powder

A significant portion of the yearly fruit harvest is wasted due to inadequate pulp utilization. Standardized recipes for palm toffee, spread and cream have demonstrated favorable sensory acceptance. Optimized foam-mat drying and steaming-assisted hot-air drying yield stable, rehydratable pulp powder, where drying temperature influences the balance between antioxidant preservation and functional quality (Madhava *et al.*, 2024; Thanaboonrongkom *et al.*, 2025). Nutraceutical applications have also seen the development of encapsulated pulp powders (Sangeetha *et al.*, 2023).

6.4 Thavun and other under-utilized products

Thavun, the haustorium from sprouted fruit, is rich in nutrients but prone to rapid spoilage, exhibiting documented antioxidant and anti-diabetic effects (Subha and Devi, 2023; Narayanankutty *et al.*, 2023). Mechanical pulp-separation equipment and product testing - jam, pickle, syrup and idli-mix powder - have prolonged its typically brief shelf life. Phytochemical analysis has identified more bioactive substances in dried thavun powder (Pavithra *et al.*, 2023).

6.5 Fibre, wood and other non-edible products

Non-edible use of the palm-leaf fibre for crafts, leaves for thatching and timber for construction supports allied cottage industries and adds to its overall livelihood value (Rao *et al.*, 2021). The value-added products of palmyra are shown in Fig. 2.

Table 4: Overview of major value-added products from palmyra palm, their raw material

Product	Raw material	Principal process	Reported shelf life / outcome
Palm jaggery (karupatti)	Neera	Lime treatment + open-pan concentration/boiling	Weeks to months (solid form); quality variable, adulteration risk
Palm candy (kalkandu)	Concentrated neera syrup	Slow crystallization (25-45 days)	Long shelf life once crystallized
Palm sugar	Neera	Controlled boiling and crystallization	Similar to jaggery; more refined product
Palm honey	Neera	Extended boiling +/- tamarind addition	Several months; viscous, stable
Palm toffee/ spread/ cream	Ripe fruit pulp	Standardized recipe, boiling, moulding	High sensory acceptability; ambient/refrigerated storage studies

Foam-mat / hot-air dried pulp powder	Ripe fruit pulp	Foaming + drying (50-70°C) or steaming + drying	Stable, rehydratable powder; months under dry storage
Thavun-based products (jam, syrup, pickle and idli powder)	Germinated fruit haustorium (thavun)	Standard confectionery/food processing	Extends otherwise very short (1-2 day) natural shelf life
Toddy	Fermented neera	Natural or induced fermentation	Consumed fresh; ~4% alcohol; regulatory restrictions in many states
Fibre/leaf/craft articles	Leaf, petiole, fibre	Mechanical processing, weaving	Non-perishable; cottage-industry products

Source: Compiled from Agritha *et al.* (2026), Chauhan *et al.* (2017), Madhava *et al.* (2024), Thanaboonrongkom *et al.* (2025), Subha and Devi (2023) and Rao *et al.* (2021).

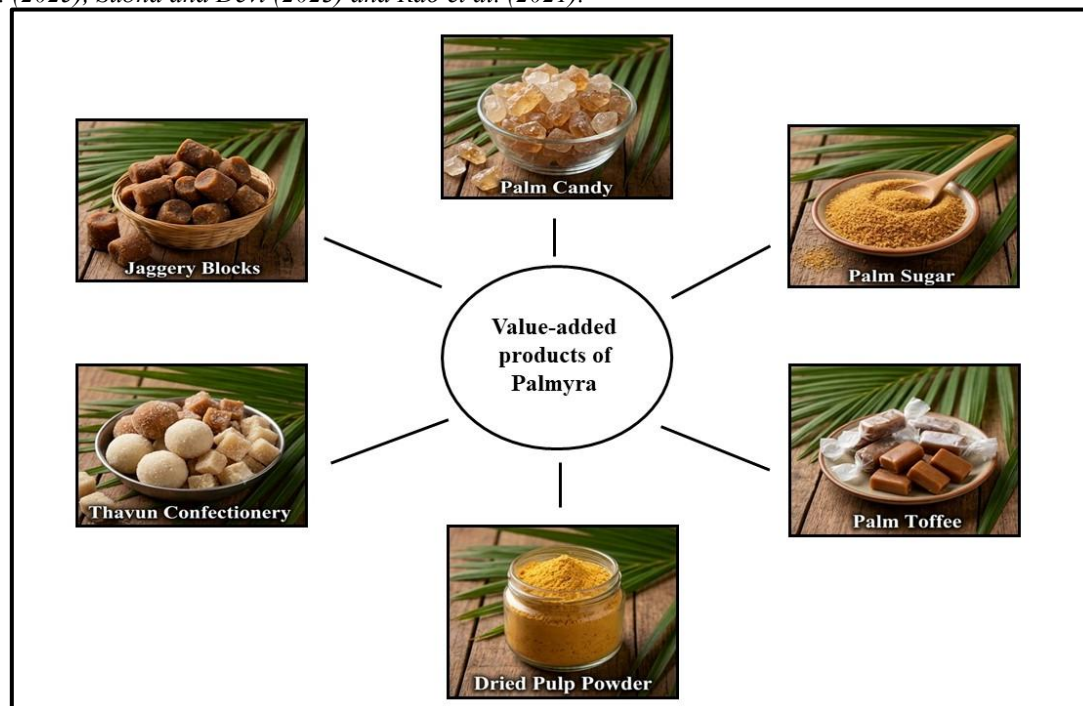


Fig.2: Collage of some finished value-added products of palmyra – jaggery blocks, palm candy, palm sugar, palm toffee, dried pulp powder and thavun confectionery.

7. Storage technologies for Value-added palmyra products

Solid palmyra products like jaggery, candy and dehydrated pulp powder have enhanced storage stability compared to fresh fruit or sap because of reduced water activity, yet they are still susceptible to moisture, microbial degradation, color alterations and contamination. Jaggery studies concentrate on moisture-resistant packaging and verification through NMR and Raman methods, whereas dehydrated pulp powder can ensure safe, stable preservation when moisture is kept under 10% and water activity ranges from 0.52 to 0.55, and is packaged in moisture-proof laminates (Biswas *et al.*, 2025; Bashir *et al.*, 2023; Thanaboonrongkom *et al.*, 2025). Toffee, spreads and creams need shelf-life studies at ambient and refrigerated conditions due to physicochemical and microbial alterations. Nonetheless, dedicated cold storage and controlled-humidity facilities are mainly lacking at the village and cooperative levels, in contrast to structured horticultural chains, which restrict effective storage and quality maintenance; this is elaborated on in Section 9.

8. Transport, Cold-chain Logistics and Marketing Channels

8.1 Transport and cold-chain logistics

Due to the fact that fresh endosperm and unpasteurized neera are only viable for a few hours to a couple of days without intervention, transportation logistics severely restrict the distance that palmyra products can cover. At present, the majority of tender fruit and fresh neera circulate through brief, unregulated supply chains like street vendors and local markets, highlighting the absence of a structured cold chain similar to those for milk and horticultural products. Institutional initiatives have mainly concentrated on packaging innovations, like tetra-pack trials for neera, instead of comprehensive cold-chain development (Arulagam, 2021, project records). Refrigerated-film packaging and hurdle-preserved, cold-chain-compatible neera establish a technical foundation for enhanced distribution; however, broader acceptance necessitates reefer transportation, village-level cooling facilities and aggregation centers. Technologies involving modified and controlled atmospheres, prevalent for various perishable fruits, are still mostly unexamined for palmyra.

8.2 Marketing channels and institutional support

The Tamil Nadu Palm Products Development Board, part of the Tamil Nadu Khadi and Village Industries Board, offers the primary institutional structure for palmyra marketing via 720 Primary Palm Jaggery Manufacturing Cooperative Societies, eight District Palmgur Cooperative Federations and a state marketing federation, overseeing tapping and sales through annual licenses granted to registered artisans (9,972 in 2020–21) (Government of Tamil Nadu, Palm Products Development Board records). It sells food items like neera, palm jaggery, palm sugar, palm candy, preserved nungu, jam and chocolate, as well as non-food palm-leaf and fiber goods, while promoting production goals, training and technology exchange. Farmer Producer Organizations (FPOs), especially in regions like Ramanathapuram, enhance aggregation, market linkages and provide training in value addition, branding and export readiness, while e-commerce is fostering higher-value markets for shelf-stable items like palm jaggery and candy; nonetheless, fresh nungu and neera are limited to short local supply chains due to their perishable nature (agriculturaljournals.com, 2025).

9. Nutritional and nutraceutical significance

Rising interest in palmyra products is backed by additional nutritional and pharmacological research. Neera and fresh fruit pulp are sources of vitamin C, B-complex vitamins, carotenoids, potassium, iron, zinc and phenolic antioxidants, whereas immature fruit, sprouts, roots and thavun contain bioactive substances including alkaloids, flavonoids, tannins, saponins, terpenoids and phenolics, with antioxidant properties evidenced by DPPH, ABTS and similar assays (Sarma *et al.*, 2022a; Agritha *et al.*, 2026; Pavithra *et al.*, 2023; Narayanankutty *et al.*, 2023; Singh and Chellammal, 2022; Thakur, 2023). Research additionally indicates anti-inflammatory, hepatoprotective, antimicrobial, anti-arthritis and antioxidant properties, while studies on animals suggest anti-hyperglycemic and insulinogenic effects of palm jaggery and honey, along with enhanced lipid and renal indicators. Their reduced glycemic index compared to refined cane sugar further reinforces the classification of palm jaggery, sugar and honey as functional foods instead of conventional sweeteners (Agritha *et al.*, 2026). These results bolster the argument for investing in palmyra postharvest management and quality standardization (Da Silveira and Agostini-Costa, 2018).

10. Constraints in farming, production and marketing of palmyra

10.1 Agronomic and biological constraints

- Slow development and extended maturation: Palmyra require 15–30 years to produce fruit and its dioecious characteristic means that identifying seedling sex only occurs after 12–15 years, which hinders organized replanting and cultivation investments (Rao *et al.*, 2021).
- Wild/semi-wild populations: Mainly disorganized populations result in inconsistent spacing, differing genotype quality and challenges in mechanization (Aravind *et al.*, 2025).
- Decreasing palm numbers: Logging, changing land use, invasive species like *Prosopis juliflora*, and insufficient replanting efforts are diminishing tree populations (Aravind *et al.*, 2025).
- Climate and pest/disease threats: Severe weather can influence flowering and fruiting, though drought resilience still offers a significant benefit.

10.2 Processing and infrastructural constraints

- Highly perishable: Fresh endosperm and neera decay rapidly within hours if not subjected to prompt cooling or hurdle treatment and village-level cold storage and pre-cooling facilities are still primarily lacking (Ambrose, 2018; Hebbar *et al.*, 2018).
- Non-standardized processing: Jaggery production at the household level leads to inconsistent quality, variable lime application and risks of contamination due to insufficient scientific knowledge (Bashir *et al.*, 2023).
- Restrained contemporary facilities: Insufficient apparatus for pulp extraction, drying, candy crystallization and packaging compels dependence on low-output, labor- and fuel-intensive traditional techniques (Aravind *et al.*, 2025).
- Fragile cold-chain system: The lack of refrigerated transport and structured cold chains connecting rural production areas with urban and export markets limits distribution to brief local supply chains (Section 8.1).

10.3 Socio-economic and human-resource constraints

- Aging tapping workforce: Harvesting sap from tall palms is strenuous and dangerous, deterring younger laborers and leading to a decrease in workforce in Tamil Nadu and other areas that produce toddy (Downtoearth, 2025; The Federal, 2026).
- Low farm-gate prices: Unstable and inadequate prices for raw neera and unprocessed fruit pose a significant challenge to maintaining palmyra-based livelihoods (ResearchGate, 2023).
- Constrained entrepreneurial abilities: Small and marginal farmers frequently do not possess market insights, branding expertise, value-added processes and skills for export readiness, depending largely on traditional knowledge (agriculturaljournals.com, 2025).

10.4 Regulatory and policy constraints

Since 1 January 1987, Tamil Nadu's comprehensive ban on toddy tapping and sales has reduced illegal liquor production; however, it has also eliminated a significant traditional income source and motivation for preserving palms for sap harvesting, in contrast to adjacent states that allow controlled toddy sales. Ongoing discussions,

particularly remarks from the Madras High Court in 2026, have emphasized the possibility of enhancing rural earnings, job opportunities and palm preservation through regulated, quality-controlled toddy production, provided that suitable safeguards are put in place (IANS/Prokerala, 2026). The licensing requirements for neera tapping and sale aim to prevent diversion into illegal liquor but also impose administrative burdens and might deter new and younger participants (TN Khadi and Village Industries Board records).

11. Emerging technologies and Innovations

Numerous developing technologies, while not yet utilized commercially for palmyra, demonstrate significant promise based on their success with coconut inflorescence sap and various tropical fruits. Non-thermal techniques like cold-plasma bubbling and pulsed-light treatment can manage spoilage microflora in coconut neera while preserving heat-sensitive nutrients and flavor compounds more effectively, presenting possibilities for palmyra sap preservation (Aparajhitha and Mahendran, 2019; Vishnu Priya *et al.*, 2024). Lactic-acid bacteria from naturally fermenting palm nectar may facilitate the controlled functional fermentation of stable probiotic drinks (Somashekaraiah *et al.*, 2019). Foam-mat drying and steam-assisted hot-air drying offer scalable techniques for producing shelf-stable palmyra pulp powders for food and nutraceutical uses, whereas encapsulation helps stabilize bioactive compounds (Madhava *et al.*, 2024; Thanaboonrongkom *et al.*, 2025; Sangeetha *et al.*, 2023). Portable Raman spectroscopy and quantitative NMR sugar profiling provide effective methods for verifying jaggery authenticity, minimizing adulteration and enhancing confidence among consumers and in export markets (Biswas *et al.*, 2025).

12. Future Prospects and Recommendations

Key priorities involve enhancing validated packaging and cold-chain procedures for endosperm and neera via cooperatives and FPOs, backed by extension and micro-financing; creating safer, ergonomic tapping devices to entice younger labor; standardizing processing techniques for jaggery, candy and pulp powder; and seeking GI registration and quality certification for unique products like Tuticorin palm jaggery to foster premium and export markets. A monitored reassessment of toddy policy, combined with studies on modified/controlled-atmosphere packaging and non-thermal preservation methods, could further enhance the industry. Aggregation, branding and e-commerce driven by FPOs should be broadened, aided by insulated transportation and local chilling facilities for fresh goods, while organized replanting and germplasm preservation should encourage high-quality, disease-resistant palms and tackle diminishing tree numbers.

13. CONCLUSION

The Palmyra palm showcases both ecological durability and remarkable product variety, but its potential is limited due to the high perishability of its main products and largely disorganized processing and marketing systems. The postharvest innovations examined in this review - enhanced packaging, refrigerated and hurdle-preserved storage and consistent processing of jaggery, candy and dried pulp - show that shelf life and quality can be significantly elevated with fairly straightforward measures. Tamil Nadu, possessing nearly 50% of India's palmyra resources and robust institutional backing, is ideally positioned to leverage these developments. Tackling workforce decline, cold-chain deficiencies and quality standardization will be crucial for converting palmyra from a diminishing wild resource into a competitive, nutritionally rich commercial crop.

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Conflict of interest

The authors declare no financial or non-financial competing interests relevant to the content of this article.

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