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REVIEW ARTICLE

The therapeutic and preservation potentials of palmyrah (*Borassus flabellifer* L.) in its edible and non-edible forms

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Abstract

The palmyrah tree often called the "tree of life" or the "toddy palm". Thriving in equatorial climates particularly in South and Southeast Asia, it remains essential to the lives of millions, even as modernization and changing lifestyles progress. Palmyra exhibits remarkable resilience to harsh environments and diverse applications make it an invaluable resource for sustainable development and conservation. Leaves, spadix, inflorescence, fruit, seed, haustorium and roots of the palmyrah tree provide unique therapeutic benefits. The leaves relieve arthritis, while the inflorescence helps soothe heartburn. Neera (the sap) is effective in healing ulcers and the fruit reduces fevers. Additionally, the bark decoction serves as an effective mouthwash and the roots are known for treating respiratory illnesses. The haustorium, particularly when harvested in the 12th week, contains beneficial chemicals identified through Gas Chromatography- Mass Spectrometry (GC-MS) analysis, such as Hydroxymethylfurfural (19.45 %) and 4H-Pyran-4-one (1.45 %). These compounds aid in treating anemia and sickle cell disease while also exhibiting antimicrobial, anti-inflammatory and antibacterial properties. Similarly, the tuber contains compounds like Linalool (2.97 %), Terpinen-4-ol (1.0 %) and α-Terpineol (3.8 %), identified through GC-MS analysis, which provide antimicrobial, antifungal and antibacterial effects. Beyond its medicinal value, the palmyrah tree significantly contributes to the production of value-added products, including palm sugar, high fiber tuber flour. Further current work explores various methods for extending the shelf life of palmyrah-derived products, enhancing their availability and promoting sustainable development.

Keywords: bioactive compounds; palmyrah palm; shelf-life extension; therapeutic properties; value-added products

Introduction

Borassus flabellifer L. the palmyrah or "kalpaga tharu" of Tamil lore has served South and Southeast Asian societies as food, medicine, fibre and timber since antiquity. Originating in tropical Africa and now naturalised from West Africa to peninsular India and Indochina, the palm supplies sap (neera and toddy), sugary fruit pulp, starch-rich tubers, protein-dense haustoria and craft-worthy leaves, making it both a livelihood crop for smallholders and an emerging source of nutraceutical ingredients. India alone hosts 102 million trees, half of them in Tamil Nadu, whose farmers already export jaggery, toddy vinegar and fibre handicrafts (2). Yet, despite this prominence three key research gaps persist (i) the post-harvest physiology of neera and fruit pulp remains poorly characterised, limiting shelf-life extension strategies (5); (ii) systematic compositional databases for the under-studied haustorium and tuber flour are fragmentary, hindering evidence-based health-claims (12, 37); and (iii) techno-economic assessments of scalable processing interventions such as edible coatings, spray-drying, or high-pressure processing are scarce, leaving small and medium scale enterprises without decision frameworks (23, 89).

Botanical and cultural overview

The genus name Borassus derives from Greek for the fruit's leathery sheath, while the epithet flabellifer ("fan-bearer") describes its giant, pleated fronds (1) (Table 1 for Botanical classification of palmyrah). Botanically, every organ is utilitarian: inflorescences yield drinkable sap within hours of tapping (5); fruits provide carotenoid-rich pulp and a tender, hydrating endosperm (4); germinating seeds swell into carbohydrate- and protein-rich haustoria (12); subterranean shoots store starch (37); and petioles furnish strong fibres (4). Culturally, the palm is venerated as the State Tree of Tamil Nadu where it is called panai maram and known as tadi in Andhra Pradesh and karimpana in Kerala (3, 4). Although Tamil Nadu remains India's largest producer and exporter, most growers still market unprocessed sap or fruit, which spoils rapidly (5). Addressing the above research gaps through integrated post-harvest biology,

Table 1. Botanical classification of palmyrah

Botanical classification	
Domain	Eukarya
Kingdom	Plantae
Division	Magnoliophyta
Class	Monocots
Order	Arecales
Family	Arecaceae
Genus	*Borassus*
Species	*Borassus flabellifer L.*
Chromosome number	2n=32

comprehensive nutrient profiling and costed preservation trials is essential to unlock palmyrah's full economic and nutritional potential and position it as a high value, climate resilient crop across semi-arid South Asia.

Plant products of the palmyrah

Different plant products of palmyrah, include inflorescence, neera, fruits, tender endosperm, haustorium, tuber and seedlings. Plant products of the palmyrah are represented in Fig. 1.

Edible products of the palmyrah

Palmyrah sap/neera and toddy

Neera (in Tamil) is a transparent and sweet beverage that has become popular in both rural and urban areas. Known for its pleasant flavour and rich nutrient content, neera is versatile. It serves as an ingredient in the preparation of various products, including rab, palm sugar, syrup, palm candy and a variety of sweets and ice creams. In rural regions, Neera is commonly consumed as part of the daily diet (1). For long-distance markets, neera is transported under refrigerated conditions. Refrigeration prolongs the shelf life of neera for several days and also slows down fermentation (2). Tapping is the extraction of sap from the inflorescence of palm trees. The tapping procedure varies based on the inflorescence's age and the palm's sex. Female palms have a longer duration for tapping compared to male palms. The spathe is ready for tapping when the inflorescence blooms or is about to open (3). The process of extracting neera from the palmyrah tree is represented in Fig. 2.

Fruits

The fruits mature from June to August and fall from the tree when fully ripe. Each tree produces 150 to 200 fruits per year (4). The palmyrah fruit is enjoyed fresh but is prone to spoilage. Traditionally, its pulp is preserved as fruit leather, which contains pectin and a notable amount of saponin (5). In Africa, fresh fruit pulp is typically hand-mashed, filtered and consumed either raw or boiled with corn or porridge. It is commonly used to enhance the natural sweetness, aroma and colour of various dishes (6). Although palmyrah fruits are seasonal, they possess outstanding physical and chemical qualities that make them ideal for food and beverage production. However, many current commercial products fall short in quality, despite a growing demand for ready-to-consume palmyrah drinks (7).

Tender endosperm

Tender endosperm is in high demand in the market because of its health benefits. However, it is only available seasonally. The delicate endosperm is extracted from young fruit (60-70 days old) and has a jelly-like consistency with a sweet taste, but it perishes quickly (8).

Haustorium

As palmyrah seed nuts sprout, they produce a tasty and nutritious substance called haustorium, which contains protein, fat, carbohydrates, calcium, iron and phosphorus (9).

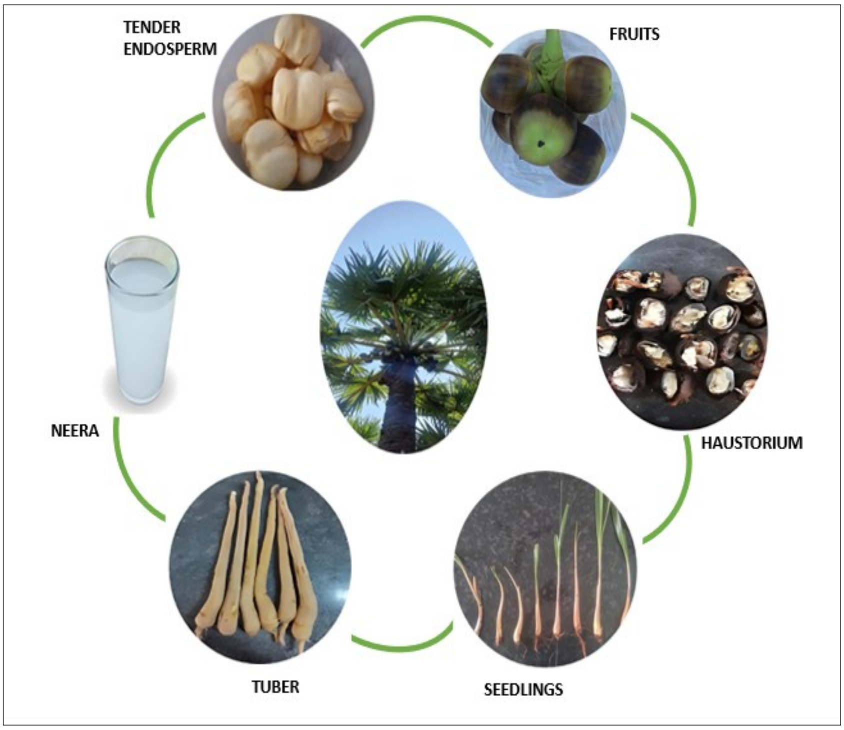

Fig. 1. Plant products of Palmyrah.

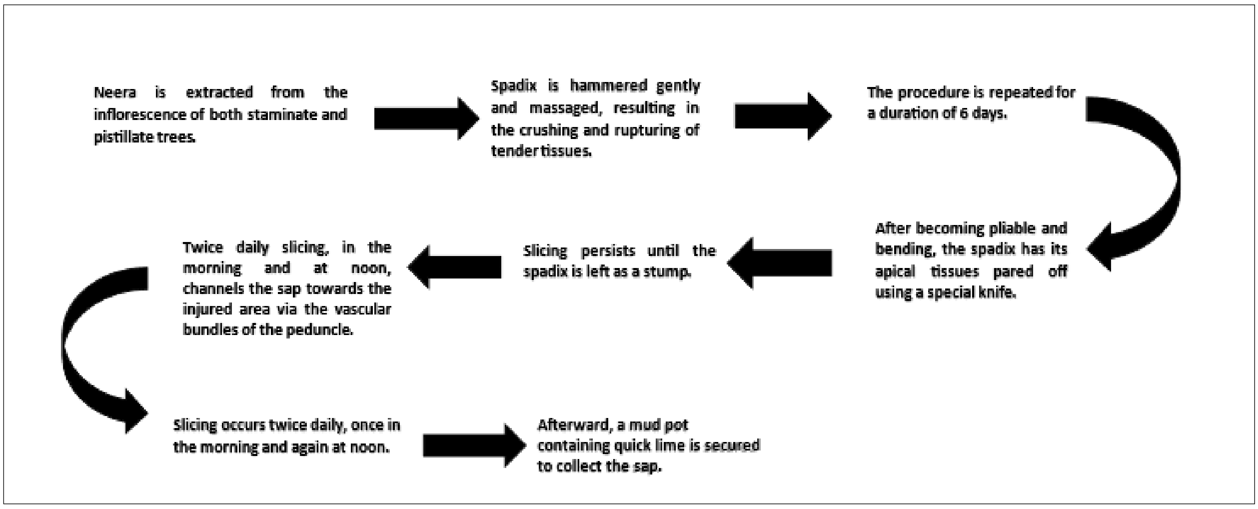

Fig. 2. Process of extracting neera from the palmyrah tree (27).

Tuber

After 120 days, tubers emerge as the primary edible shoot from seeds of a ripe fruit grown in sandy loam soil. Many people consume tubers directly by roasting them over an open flame after peeling off the outer layer (10).

Non-edible products of the palmyrah

Inflorescence

It occurs once every 15 to 20 years and is useful in determining the tree's gender. Staminate flowers have a catkin inflorescence that is less than 1 cm in length. They are characterized by semicircular clusters that have a scaly texture and are located beneath the bracts (11).

Leaves

The midrib resembles a broom and the fan-shaped leaves are used in construction, featuring a fibrous petiole that ranges from 90 to 120 cm long (12).

Seedlings

Palmyra palm seedlings that have been peeled can be eaten raw or cooked and can be dehydrated or fresh. They contain starch, which is combined with rice, fish, herbs, chili peppers and other ingredients to make a gruel (2).

Nutritional and therapeutic properties

The palmyrah tree (*Borassus flabellifer L.*) is a valuable source of traditional and herbal remedies, offering a wide range of therapeutic properties. Nutritionally, its sap, fruit pulp, tuber and haustorium supply meaningful amounts of fibre, protein and key minerals-details summarised in Table 2. Rich in bioactive compounds (Table 3) such as alkaloids, phenolics, flavonoids and vitamins, the palm exhibits antioxidant, antimicrobial, anti-inflammatory and hepatoprotective effects.

Palmyrah products therefore help alleviate respiratory and digestive disorders, skin ailments, inflammation, diabetes, anaemia and other chronic illnesses. With potent antimicrobial activity and broad nutrient coverage (vitamins, proteins, fibres and mineral cofactors), they support heart and liver function while correcting nutritional deficiencies. The breadth of these medicinal and nutritive attributes underscores palmyrah's importance as a sustainable natural remedy.

To deepen insight into its functional chemistry, details the bioactive profile of palmyrah haustorium alone (Table 4), underscoring its especially high concentrations of total phenolics and essential amino acids.

Table 2. Breakdown of the nutritional profile and mineral content found in both edible and processed palmyrah products, including specific values for key nutrients

Component	Neera (per 100 g)	Haustorium	Palm toddy (per 100 ml)	Palm jaggery	Palm sugar (per 100 g)	Palmyrah tuber flour (per 100 g)
Protein	3.12 ± 0.42 mg	5.4 %	1.41 ± 0.01	1.04 %	1.04 g	6.4 g
Fat	0.02 ± 0.01 mg	2.1 %	-	0.19 %	0.19 g	-
Moisture	-	-	-	21.90 %	8.3 g	-
Iron	30 mg	-	10.8 ± 0.1	-	6-10 mg	2 mg
Sodium	15.3 ± 0.14 mg	-	10.85 ± 0.05	-	8-20 mg	50 mg
Potassium	22.6 ± 0.12 mg	-	24.9 ± 0.4	-	102-140 mg	200 mg
Phosphorus	-	290 mg/100 g	0.48 ± 0.06	-	16-27 mg	-
Calcium	-	265 mg/100 g	10.5 ± 0.5	72 mg/100 g	140-233 mg	20 mg
Magnesium	-	-	6.5 ± 0.5	-	5-42 mg	50 mg
Nicotinic acid	4.02 mg	-	-	-	3.30-5.12 mg	-
Ascorbic acid	-	-	3.0 ± 0.01	11.04 mg/100 g	7.3-33.0 mg	-
Carbohydrates	-	70 %	-	73.35 %	-	81.6 g
References	(1, 38)	(9)	(39)	(40)	(41)	(30)

Table 3. Therapeutic properties of the major compounds present in the palmyrah haustorium flour's methanolic extract and palmyrah tuber flour's methanolic extract

Methanolic extract	Compound & area %	Therapeutic properties
Palmyrah haustorium flour	5-Hydroxymethylfurfural (19.45 %)	It has been tested for treating hypoxia, anemia, sickle cell disease and as an antioxidant. Additionally, it is used as a food additive and flavouring agent (42, 43).
	4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6- (1.45 %)	It exhibits antimicrobial, anti-inflammatory and antibacterial properties(44, 45).
	2,6-Octadien-1-ol, 3,7-dimethyl-, (Z)- (1.03 %)	It is a monoterpene used in perfumery and exhibits anticancer activity (46, 47).
	-Glycero-d-galacto-heptose (3.60 %)	It is used as a diet supplement and demonstrates a higher docking score than many commercial COX-2 inhibitors (48, 49).
	d3-(Prop-2-enoyloxy) tridecane (2.12 %)	It is utilized in various industrial applications(50).
	alpha-Terpinyl acetate (8.77 %)	Alpha-terpinyl acetate exhibits antioxidant properties and diverse pharmacological activities, including antiseptic (pulmonary), antispasmodic (neuromuscular), aphrodisiac, expectorant, anthelmintic, antibacterial, cephalic, cardiotonic, diuretic, emmenagogue, sialagogue and stomachic effects. It acts as a nervous system stimulant and serves as a lead compound for developing Multi -Targeted Directed Ligands (MTDL) with potential benefits for Alzheimer's disease (51-53).
	Sucrose (8.88 %)	It is widely used in various food industries, utilizing sucrose as a substrate. Along with hydrolysis activities, it also aids in the production of antioxidant secondary metabolites (54, 55).
	Beta. -D-Glucopyranose, 1,6-anhydro- (3.38 %)	It exhibits anti-HIV and blood coagulant activities (56).
	n-Hexadecanoic acid (10.37 %)	It is used in traditional Indian Ayurvedic medicine to treat rheumatic symptoms and possesses anti-inflammatory, antioxidant and antibacterial properties (57).
	9,12-Octadecadienoic acid (Z, Z)- (7.43 %)	It exhibits hepatoprotective, antihistaminic, hypocholesterolemic, antieczemic activities and functions as a Catechol-O-methyl-transferase inhibitor and Methyl Guanidine inhibitor (58).
Palmyrah tuber flour	Linalool (2.97 %)	It acts as an antidepressant, influencing monoaminergic and neuroendocrine systems, inflammatory processes, oxidative stress and neurotrophic factors (59).
	Terpinen-4-ol (1.0 %)	It has antimicrobial, antifungal and antibacterial properties and helps in preventing gastrointestinal cancers. Additionally, it exhibits antihypertensive effects (60, 61).
	α-Terpineol (3.8 %)	It is an antioxidant, anticancer, anticonvulsant, anti-ulcer, antihypertensive and anti-nociceptive compound. Additionally, it enhances skin penetration and has insecticidal properties (62).
	n-Hexadecanoic acid (3.21 %)	It is used in Ayurvedic medicine to treat rheumatic symptoms and has anti-inflammatory, antioxidant and antibacterial properties (57, 63).
	Dimethyl palmitamine (5.77 %)	It has antioxidant and antifungal properties (64).

Table 4. Bioactive components of *Palmyrah haustorium*

Bioactive compounds	*Palmyra haustorium*	Therapeutic properties	References
Polyphenols	Gallic acid, Ferulic acid, 4-Hydroxycinnamic acid, Quercetin, Myricetin-3-O- glucoside and Quercetin-3- glucoside	Among its many advantages are its antimicrobial, anti -cancer, anti-germ, free radical-scavenging and blood vessel growth-inhibiting qualities.	(65-67)
Phenols	4-Hydroxybenzoic acid, p- coumaric acid, protocatechuic acid, ferulic acid and caffeic acid	It possesses antioxidant, anti-swelling, anti-aging and growth-inhibiting properties.	(68, 69)
Flavonoids	Catechin and quercetin	Virus-inhibiting, anti-allergy, free radical-scavenging and anti-cancer capabilities are only a few of its many medical advantages. It also has neuroprotective benefits and promotes heart health.	(68, 69)
Diarylheptanoid	-	Its benefits include antibacterial, ulcer-healing, anti-laxative, anti-nausea, blood sugar-lowering, bile-stimulating, liver-protecting, lipid-reducing, germ-fighting, antifungal and urine-promoting properties.	(66, 67, 70)
Triazole	-	It has antibacterial, anti-swelling, mood-boosting, virus-fighting, anti-TB, anticancer and free radical-scavenging qualities.	(67, 71)

Therapeutic benefits derived from various parts of the palmyrah tree

Leaves

Palmyrah leaves effectively treat arthritis and exhibit strong antimicrobial and antifungal properties. The methanol extract and acetone fraction show significant activity against various bacterial and fungal strains. Their radical quenching ability, comparable to ascorbic acid, is attributed to natural phenolic antioxidants. Studies highlight a notable increase in fungal inhibition zones, suggesting palmyrah leaves as a potent source of natural antimicrobial agents (13, 14).

Young leaves

When mixed with water, juice extracted from young leaves is traditionally used as an effective remedy for curing dysentery (9).

Spadix

The ash from the spadix is traditionally used to treat acid reflux and hepatosplenomegaly (enlargement of the liver and spleen)(2, 15).

Inflorescence

It is effective as an antacid, antiperiodic and a treatment for conditions such as bilious fever, splenomegaly and heartburn. Additionally, the plant's potential antidiabetic effects have been extensively studied (16).

Staminate flowers

Rats fed sucrose showed increased serum glucose levels, but a methanol-based derivative from the staminate flowers of *Borassus flabellifer* L. prevented this rise, likely due to the presence of a steroid like spirostane. Additionally, it exhibits immunosuppressive properties (48, 49).

Neera

Supports healthy urination, prevents jaundice, aids digestion, regulates body temperature and benefits diabetics due to nicotinic acid (vitamin B3) and riboflavin (Vitamin B2). It acts as a tonic, diuretic, energizer, intestinal regulator, mucus-clearing and amebicidal agent and helps treat ulcers, gastric issues, asthma, anemia and leprosy. Rich in retinol, B vitamins, sugars, micronutrients and minerals (1-3, 17).

Toddy

To cure ulcers (50).

Immature palmyrah fruit pulp

It contains a phenolic content of 104 ± 0.02 µg gallic acid equivalents per 100 mg and a flavonoid content of 98.45 ± 0.03 µg quercetin equivalents per 100 mg (18).

Fruit

This plant alleviates thirst, gastric discomfort, bloating, skin disorders, excessive bleeding, fever and weakness. Rich in alkaloids, terpenes, saponins, tannins, steroids, flavonoids, glycosides, vitamin C, phenols and sterols, it offers antioxidant, anti-inflammatory, antimicrobial and hydrating benefits. These properties support digestion, heart health and applications in herbal medicine and cosmetics. The plant also treats conditions such as liver and spleen enlargement, heartburn and secondary syphilis. Its phytoconstituents include gums, saponins, glycosides, sugars, albuminoids, lipids and vitamins A, B and C. Additionally, the fruit is believed to benefit asthma-related conditions, showcasing its broad medicinal value in traditional and herbal practices (16, 19-22).

Mature fruit pulp

The pulp of the palmyrah fruit contains ten phytochemicals, including 2-furan carboxaldehyde, 5-(hydroxymethyl)-α-D-glucopyranoside, O-α-D-glucopyranosyl-(1→3)-α-D-fructofuranosyl, 5,9,13-pentadecatrien-2-one, 6,10,14-trimethyl -(E,E), n-hexadecanoic acid, oleic acid, 9,12-octadecadienoic acid (z, z)-, estr-1,3,5(10)-trien-17a-ol, erucic acid, 7-methyl-Z-tetradecen-1-ol acetate and squalene. Additionally, the ethanolic extract of this fruit pulp has shown antimicrobial activity against two types of bacteria: *Escherichia coli* which is responsible for urinary tract and enteric infections and *Staphylococcus aureus*, known for causing dermatological infections (23).

Pinnatu (which is prepared by drying the fruit pulp)

Pinnatu has been shown to help lower blood sugar levels in individuals with early stage type II diabetes (4).

Seed and outer layer derivative

The methanol derivatives of the *B. flabellifer* seed coat exhibit bactericidal effects against *S. aureus*, *Bacillus subtilis*, *Klebsiella pneumoniae* and *Serratia marcescens*. Additionally, its cytotoxic properties were evaluated using the MTT assay, revealing effective inhibition of HeLa cell proliferation at concentrations ranging from 32 µg/mL to 750 µg/mL. These findings suggest the potential of *B. flabellifer* seed coat as a source of antimicrobial and cytotoxic agents, warranting further research into its applications(13, 15, 24).

Haustorium

The palmyrah haustorium contains over 50 volatile compounds and secondary metabolites with medicinal properties, including antibacterial, antimicrobial, liver-protective, antiallergic, cardiovascular, diuretic, antioxidant, anti-inflammatory and antineoplastic effects. Notably, 5-Hydroxymethylfurfural treats hypoxia, anemia and sickle cell disease, while also acting as an antioxidant and food additive. Additionally, d-Glycero-d-galactoheptose, a dietary supplement, shows a higher docking score than many COX-2 inhibitors (25).

Young roots

The young roots of the palmyra tree are valued for their medicinal benefits, particularly in treating respiratory illnesses due to their anthelmintic and diuretic properties. To prepare the remedy, the roots are chopped, mixed with twice the amount of water and dried in the sun (Suriya pudam). Applied three times daily, it helps treat alopecia, pterygium, jaundice and urinary tract infections (Pitha vaayu). It enhances kidney function, acts as an anthelmintic, cooling agent and remedy for pulmonary conditions (11, 24).

Roots

The methanol extract of dry palmyrah roots contains 99.34 µg of gallic acid equivalents (GAE) and 98.48 µg of catechin equivalents per 100 mg for phenolic and flavonoid content, respectively. The chloroform extract shows the highest antioxidant activity, with 129.6 µg of butylated hydroxytoluene (BHT) per 100 mg. The roots also contain 1.61 % alkaloids, 0.63 % saponins and various compounds such as aldehydes, diterpenes, phytols, sterols, fatty acids, alkanes, alkenes and ketones. Both the juice and roots help reduce inflammation (15, 16, 19).

Bark

Mouthwash is made from a decoction of bark, combined with salt and charcoal from the same bark, which also serves as a dentifrice (15, 26).

Palm sugar

Palm sugar helps manage chronic illnesses and nutritional deficiencies, with studies showing its analgesic and pain-relieving properties. Palm jaggery, containing 5 to 10 mg of iron per 100 grams, is beneficial for treating anemia and counteracting toxins, aiding in liver disease treatment (1).

Value-added products

Value-added products of palmyrah are represented in Fig. 3.

Culinary value addition: Foods and beverages

Sap-derived products

Freshly tapped *neera* (pH ≈ 6.5; 10-13 °Brix) undergoes spontaneous or pure-culture fermentation. Wild yeasts (≈ 75 strains) and lactic bacteria convert sugars to ethanol (≤ 5 % v/v) to give palm toddy; with controlled inocula, laboratory toddy can reach 7.8 % v/v alcohol while retaining cleaner flavour (5, 16, 17). Immediate chilling (4 °C) or membrane microfiltration can extend toddy shelf life to 48 hr without pasteurisation (6). Partial carbonation of clarified sap plus 250 mL cola essence / 1000 bottles yield palm cola (11 % sugar) after in-line CO_2 injection at 4 bar (5). Prolonged acetous fermentation (≈ 4 wk, 28 °C) in open vats fitted with muslin covers generates palm vinegar containing ≥ 4 g acetic acid 100 mL $^{-1}$ (19).

Thermally concentrated sweets

Boiling sap to 110–115 °C under gentle stirring reduces water activity to < 0.60; rapid cooling in wooden moulds produces palm jaggery (moisture ≤ 6 %). Further concentration to 130 ° C, followed by seed crystallisation at 53 °Brix, forms palm candies a translucent, crystalline sweet rich in vitamin C (7.3-33 mg 100 g^{-1}) and niacin (3.3-5.1 mg 100 g^{-1}) (19, 23). Slow vacuum evaporation (60 °C, 150 mbar) gives a honey-like syrup marketed as palm honey or treacle with prolonged heating to one-sixth original volume (19).

Fruit-based novelties

Ripe pulp (12 °Brix) is hydro-thermally treated (85-90 °C) then concentrated to 32-68 °Brix for fruit bars, pannattu chocobars, spreads and toffees; pectin (0.66-1.5 %) improves sheet formation, whereas citric acid (0.2 %) brightens colour (18, 25, 26). RTS drinks combine 12.5-15 % pulp with xanthan gum, achieving 11.9 % total sugar and 4044 mg L^{-1} antioxidant capacity; products remain micro stable for 10 wk at 4 °C (10). Palmyrah wattlappam, an egg-custard dessert-integrates pulp with coconut milk, tamarind and spices, offsetting inherent bitterness (26, 28).

Tuber & haustorium foods

Oven-dried tuber slices (50-55 °C, 48-72 hr) are milled to < 250 µm tuber flour (32). Substituting 20-48 % of wheat with tuber flour plus *Alternanthera sessilis* stem and red rice flours yields high fibre biscuits (dietary fibre 8.2 g 100 g^{-1}) with best sensory scores at 40:7.5:20 ratios (33). Extruded noodles use 5 % CMC and 0.5 % $NaHCO_3$ to compensate for the absent gluten (34). Germinated-seed haustorium flour (protein 5.4 %, polyphenols 2.8 g kg^{-1}) enriches gulab jamun mixes, boosting iron to 6 mg 100 g^{-1} (32).

Health and nutraceutical potential

Acetic, antioxidant and micronutrient concentrates

Natural acetification of toddy delivers palm vinegar with probiotic *Acetobacter aceti* activity and trace minerals (K 25 mg 100 mL^{-1}, Fe 0.5 mg 100 mL^{-1}), making it a functional condiment (19). Palm candy and jaggery preserve heat-stable vitamin C and niacin, alongside vitamin B_{12} (0.04 µg g^{-1}) and ascorbic acid (11 mg 100 g^{-1}), offering a low-glycaemic sweetener compared with refined cane sugar (5, 23).

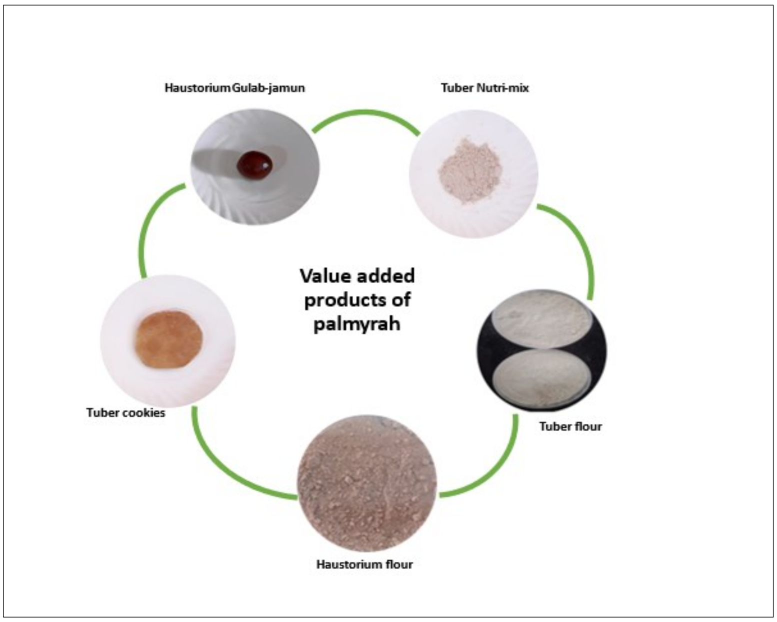

Fig. 3. Value-added products of palmyrah.

Polyphenol-rich flours

GC-MS of tuber and haustorium flours identifies caffeic, ferulic and gentisic acids plus flavan-3-ols in vitro assays show DPPH radical-scavenging up to 65 % at 1 mg mL^{-1} (12, 32). Incorporation into RTS drinks (2.5 % pulp) or dairy matrices (palmyrah yogurt) raises total phenolics and maintains sensory acceptability for 18 d at 4 °C (29, 30).

Emerging claims

Animal studies indicate suppressed post prandial glucose peaks when tuber-flour biscuits replace 30 % of wheat flour (33); clinical validation is pending, underscoring the need for controlled trials. Meanwhile, antioxidant indices (FRAP 4.0 mmol L^{-1}) of pulp-based cordial (31) and spread (25) exceed many tropical fruit products, positioning palmyrah for clean label antioxidant beverages.

Industrial and bio-energy applications

Bioethanol from processing residues

Palmyrah agro waste streams-coir dust (lignocellulosic), molasses (70 % sugars) and fruit-pulp residues (20 % sugars) are acid hydrolysed (3 % H_2SO_4, 121 °C, 45 min) to liberate fermentable sugars (total reducing sugars 42 g L^{-1}) (35). Neutralised hydrolysate inoculated with *Saccharomyces cerevisiae* in PYN medium (pH 5, 30 °C) yields 0.38 g ethanol g^{-1} sugars after 96 hr; productivity from coir dust is lower (0.18 g g^{-1}) because of lignin-bound sugars, but the substrate is abundant and virtually free (35).

Processing in palmyrah

Palm jaggery

Palm jaggery known as palm gur, is prepared by cooking neera at 110 °C in a galvanized iron pan. Neera is converted into a viscous liquid, which is then added to cups (shells) and allowed to solidify. Recovering one kilogram of jaggery requires about eight litres of neera. The texture of palm jaggery is similar to that of jaggery prepared from sugarcane juice. Its flavour is earthy and strong almost like chocolate (27).

After processing palm jaggery has a richer, darker colour. It tastes slightly salty but is far healthier than others. It is highly valued because of its cooling effects on the human body. Palm jaggery results from converting neera into a crystalline mass that is either solid or semisolid and ready for immediate consumption. With a few minor exceptions during production, jaggery is a solidified sweetener blend of reducing sugars and non-reducing sugars and it contains ascorbic acid and vitamin B12 (1). The major problem during the storage of palmyrah is blackening (2).

Processing of palm sugar

Medium sized companies employ membrane technology, vacuum processing and spray drying, whereas small scale enterprises utilize conventional processing methods.

Traditional method

The traditional process of producing palm sugar involves heating filtered palm sap in a large pot and manually stirring it for three to four hours until the water evaporates. This results in a sticky, viscous substance that turns brown due to the Maillard reaction. Once thickened, the sap is poured into bamboo, wood, or coconut mould, where it cools and solidifies in approximately one hr.

However, the drawbacks of this process include the dark brown colour reduced phenolic content and diminished antioxidant properties due to prolonged heating. Additionally, open pan evaporation leads to increased sucrose inversion and the formation of hydroxymethylfurfural, which contributes to a slightly bitter flavour.

Spray drying

A spray dryer, set at specified temperatures (inlet: 220 °C, outlet: 85 °C), is charged with filtered palm sap. Lower input temperatures (140-200 °C) lead to stickiness and lump formation, while higher temperatures result in darker sugar. The sugar formation rate, temperature, particle properties and nutritional content are critical factors in this process. This method produces sugar with reduced moisture while retaining antioxidants. Although it may lead to sticky dryer walls, it offers a higher phenolic content, despite a lower product yield.

Membrane technology

In the sugar industry, membrane technology is utilized for various purposes, including molasses treatment, liquid thickening after evaporation and juice ultrafiltration following lime addition. This technology reduces the need for calcium oxide and aids in the removal of high molecular weight molecules. Ceramic membranes known for their efficiency in concentrating liquids and retaining desirable components are commonly employed. However, fouling can pose a challenge potentially affecting raw materials and leading to reduced sucrose, pectin and sugar content.

Membrane technology typically produces sugar with slightly lower phenolic content compared to traditional methods, which can impact its antioxidant effectiveness. However, it often results in higher antibacterial content than thermal processes, a factor influenced by the total phenolic concentration.

Vacuum drying

Vacuum drying offers significant advantages in preserving phenolic compounds and antioxidant properties in palm sap sugar, with optimal parameters typically set at 40 °C for 3 hrs. However, this method has limitations, including low efficiency, high setup and maintenance costs and the need for skilled labour. Palm sap sugar can be produced using four different approaches. The traditional method, while simple and cost-effective, lacks precision. In contrast, spray drying is notable for its ability to enhance antioxidant and phenolic content and improve storage capacity. However, spray drying also presents challenges such as lump formation and wall stickiness, which require post-processing techniques to resolve (28).

Processing of the palmyrah fruit pulp

The pulp from ripened palmyrah fruit is extracted, cleaned and neutralized using two milligrams of sodium hydroxide (NaOH). Total Soluble Solids (TSS) are combined with chemical additives, including 0.75 % calcium hydrogen orthophosphate, 0.1 % potassium metabisulfite (KMS) and 1 % alginate and then adjusted to 20° Brix before being gelled.

The gel is further stabilized by adding 0.1 % KMS and 0.8 % citric acid, adjusted to 70°Brix and heated for 30 minutes at 65 °C. Once set, the gel is sliced into 1.5 cm cubes using hurdle technology. After packing, the pulp undergoes pasteurization at 100 °C for 15 minutes before being stored (29).

Palmyrah fruit pulp contains 75-80 % moisture, 2.8 g of protein, 1 g of fat, 18.5 g of carbohydrates, 14-16 g of sugars, 1.5 g of crude fibre, 4.3 g of ash and 0.42 g of free amino acids per 100 g of pulp. The free amino acids include lysine, aspartate, glutamate and phenylalanine. Additionally, the pulp contains 3.2 mg of carotenoids per 100 g (30).

Encapsulated fruit pulp powder

Bioactive compound rich spray dried powder from palmyrah fruit pulp offers desirable properties as a functional ingredient in ice cream. The spray drying process, conducted at an inlet temperature of 170 °C utilizes fruit pulp, skim milk and small amounts of C starch and acacia gum. It is recommended to incorporate palmyrah fruit pulp into ice cream at a concentration of 5 % (31).

Spray-dried palmyrah fruit pulp powder

Due to inadequate preservation methods, a significant amount of palmyrah fruit is wasted during the fruiting season. To address this issue, palmyrah fruit pulp is processed into powder using a spray dryer. The SP-500 spray drying machine from Japan is employed for this purpose.

The fruit pulp is spray-dried with gelatine and maltodextrin as carrier agents. A recommended formulation for the fruit pulp powder consists of 55 % fruit pulp, 45 % maltodextrin and 5 % gelatine. The spray-drying process is carried out at 160 °C. The resulting fruit pulp powder is stored in a desiccator room and packed into low-density polyethylene (LDPE) bags (32).

Minimally processed palmyrah kernels

After the fruit is removed, the palmyrah kernels are rinsed for five minutes. They are then packed in standing pouches (100 g per pack) and preservatives, including ascorbic acid, citric acid, sodium benzoate and potassium metabisulfite (KMS), are added in specific quantities. The mixture is pasteurized at 85 °C for 10 minutes (29).

Methodologies to extend the shelf life of edible and value-added products of the palmyrah

Shelf-life extension of neera

The study explored the impact of various covering and storage conditions on the quality of neera. HDPE 50-micron bags, PET bottles and glass bottles were used, with storage temperatures of 2 °C, 4 °C and 8-10 °C. Over the first four weeks, there was an increase in physicochemical traits such as TSS, pH and reducing sugars. Phenols, titratable acidity and alcohol concentration showed a trend toward increasing until the sixth week. Among all packaging materials and storage conditions, HDPE 50 micron bags stored at 2 °C most effectively preserved the shelf life and quality characteristics of neera (33).

Three tests were conducted on delimed palmyrah sap to evaluate the effects of different thermal treatments on its quality, followed by storage at room temperature (30±2 °C). After 60 days, no significant differences were observed among the treatments in terms of physicochemical and microbiological assessments. The sensory evaluation determined that the palmyrah sap treated at 105 °C for 15 minutes yielded the best result (34).

The investigation examined the effects of hurdle preservation strategies on the quality attributes of palmyrah sap to prolong its shelf life. The samples were stored at room temperature (32 ± 2 °C) and in a refrigerator (7 ± 1 °C) for 28 days. Based on physicochemical, microbiological and sensory analyses, the $Ca(OH)_2$ with straw treatment was identified as the most effective method (35).

Shelf-life extension of endosperm

Experiments were conducted to prolong the shelf life of the delicate endosperm of palmyrah palms through delayed processing. The fragile endosperm undergoes heat treatment before being packaged in both transparent and non-transparent retort pouches and stored at room temperature. Evaluations were made regarding the treatments' texture, colour, microbiological attributes and sensory qualities. The overall acceptability of the tender endosperm stored in metal retort pouches was rated at 7.8. This method extends the shelf life by six months without any microbiological growth (8).

Shelf-life extension of palmyrah jaggery

The study aimed to analyze how different packaging materials and storage conditions contribute to the extension of shelf life and the preservation of quality features in palmyrah jaggery. Palmyrah jaggery was packed in aluminum foil, LDPE and HDPE 50-micron pouches and stored at ambient temperature, 2 °C, 4 °C and in refrigerated conditions. The LDPE 50-micron pouch exhibited the highest total soluble solids (9.07°Brix), the lowest phenolic content (0.195 mg) and the lowest reducing sugars (5.72 %) among the packaging options (36).

Shelf-life extension of *palmyrah haustorium*

Young fruit kernels, cooked tubers and palmyrah haustorium are seasonal items prized for their rich nutrients and antioxidants. To ensure year-round availability in the global market, efforts are made to extend their shelf life. Various strengths of preservation solutions, chemical preservatives and pasteurization temperatures were evaluated under room temperature conditions. After 120 days of storage at 90 °C using a 15 % Brix medium of palmyrah haustorium, sucrose media at an isotonic level exhibited improved performance at 80 °C with a 10 % Brix medium for young fruit kernels. However, the boiled tuber sample, stored in a pure 1 % sodium chloride solution and subjected to pasteurization at 80 °C and 100 °C, was found to have superior overall acceptability after 90 days at room temperature (37).

Shelf-life extension of palmyrah kernels

Upon reaching maturity, the kernels are blanched for two minutes at 90 °C in a 70° Brix sugar syrup containing 0.3 % KMS and 0.5 % citric acid. The kernels are soaked in a solution with a 1:2 ratio. After steeping for two hours at 60 °C in the syrup, the kernels are removed and packed. They are then pasteurized for 30 minutes at 85 °C. Additional wrapping is applied to help cool the bottles (29).

Critical synthesis: Palmyrah as a functional food and bioenergy resource

Comparative analysis: Palmyrah vs. other palms and cereal crops

Palmyrah (*Borassus flabellifer*) offers unique nutritional and functional benefits compared to other palms like *Cocos nucifera* (coconut) and *Elaeis guineensis* (oil palm) and cereals like wheat and rice. Unlike coconut, which is primarily used for oil, palmyrah provides a variety of bioactive compounds, including high levels of dietary fiber, antioxidants and minerals, making it a potent functional food (32, 33). Palmyrah flour serves as a gluten-free alternative to wheat flour, supporting gut health and managing glycemic levels better than traditional cereals. In addition, its fruit, sap and residues are not only used for food but also for bioenergy production, giving it a sustainability edge over oil palms, which are linked to environmental concerns (35).

Limitations of current processing technologies

The main challenges with palmyrah's processing include the short shelf life of fresh sap and lack of standardization in production methods, leading to inconsistent product quality. Heat-sensitive bioactive compounds are also degraded during thermal processing, limiting nutrient retention. Additionally, bioethanol production from residues is hindered by low yield due to the lignocellulosic structure of coir, which requires energy-intensive pre-treatment methods like acid hydrolysis (35).

Future directions

To enhance palmyrah's functional food potential, future efforts should focus on:

1. Preservation technologies: Methods like high-pressure processing (HPP) or Pulse Electric Field (PEF) could improve shelf life while retaining nutrients (27, 32).
2. Improved bioethanol production: More efficient enzyme-assisted hydrolysis and genetically engineered yeasts could increase ethanol yields from palmyrah residues (35).
3. Standardization: Developing industry standards and traceability systems would ensure consistent product quality (33).
4. Waste utilization: Converting waste into high-value products like biochar or biodegradable packaging could reduce environmental impact (35).

Functional food development: Further clinical research and innovative product formulations, like palmyrah based dairy and snacks, would expand its market (32, 33).

Industrial application

Adding value to agricultural products improves their usefulness and economic worth. Due to urbanization, industrialization and population growth, India's food security challenges have worsened. Diversifying agriculture with value-added products can help address these issues by reducing dependence on staple crops. The palmyrah palm (*Borassus flabellifer* L.), often underused, has great potential to boost agriculture and combat malnutrition. It can produce nutritious, high value products like palm fruit (nungu) and palm nectar (neera).

Palmyrah palms can be used to create highly nutritious products, have health benefits and offer good commercial potential. With the growing demand for healthier, locally made and sustainable options, innovations based on palmyrah have opportunities for industrial use. Promoting these products effectively can also support small -scale industries while helping to preserve and restore the species. Currently, popular products like palm nectar (neera) and palm jaggery generate only 25 % of the palm's potential income, highlighting the opportunity to boost economic value by expanding their use and improving preservation methods.

Jaggery has a low glycemic index, making it suitable for diabetics and health-conscious people. Popular value-added products like peanut brittles, candies and palm sugar chocolates are highly sought after in both local and international markets. However, better packaging, such as heat and moisture resistant materials, along with cold storage options, are needed to prevent issues like melting and discoloration.

Tender palmyrah endosperm (nungu) is a delicate, highly perishable product that is especially popular in summer for its hydrating and cooling properties. With the right preservation techniques, nungu can be made available year-round despite its seasonal nature. It can be stored in sugar syrup or frozen with natural flavorings like cardamom to meet the global demand for tropical fruits. These products can also be marketed as healthy dessert options. To support global trade and ensure a longer shelf life, exporters can use advanced packaging methods like vacuum packing, aseptic packaging and freezing. Adopting eco-friendly packaging will align with global sustainability trends.

Palmyrah tuber flour can be used in cakes, muffins and pastries in place of some of the all-purpose flour, satisfying the need for wholesome and useful foods. By combining tuber flour, product makers can create creative recipes while maintaining the desired flavor and texture. By marketing these baked goods as "gluten-free" or "high-fiber," they can appeal to dieters, health-conscious people and anyone with dietary requirements.

The haustorium of palmyrah is sweeter and more nutritious than that of coconut. Turning it into confectionery powders can create year-round demand. Techniques like drying, powdering and specialized packaging can help preserve its nutrients, making it suitable for use in products like breakfast cereals and baked goods.

Neera, a naturally nutritious drink, can be made available year-round with proper processing and preservation methods. Techniques like tetra pack packaging, fermentation control and flash pasteurization ensure its quality and versatility as a base for products like vinegar, wine and non-alcoholic beverages. The global demand for natural and functional drinks is rapidly growing and neera-based products have strong potential to succeed, especially in health-focused markets.

The international market for palmyrah products is expanding, with edible items like palm sugar, jaggery, syrup, sugar candy and fruit pulp attracting health-conscious consumers who prioritize natural and organic options. Palm sugar is a natural sweetener gaining popularity due to its health benefits and lower glycemic index compared to refined sugars. In 2023, the global palm sugar market was valued at approximately USD 1.75 billion and is projected to reach USD 2.29 billion by 2032, growing at a compound annual growth rate (CAGR) of 2.99 % during the forecast period. Palmyrah toddy, a fermented beverage tapped from the palmyrah tree, has found niche markets internationally with significant demand from countries like Canada and France. Palmyrah fibers can be used in brushes, ropes and composites, addressing needs in manufacturing sectors. Strengthened collaborations with stakeholders across the supply chain will not only boost economic growth but also preserve cultural heritage and promote environmental stewardship. Integrating palmyrah products into global markets requires a balanced approach emphasizing sustainability, innovation and industry partnerships, ensuring long-term growth and international recognition.

Conclusion

Concrete advances now position *Borassus flabellifer* as an industrial feedstock rather than an under-used palm. Low-glycaemic palm sugar and jaggery already meet Codex non-centrifugal standards and are being incorporated into diabetic snacks and bean-to-bar chocolates; flash-pasteurised/HPP neera holds a 60 day shelf life, enabling functional sodas and tonic vinegars; spray dried tuber and haustorium flours supply gluten free bakery and high-fibre noodle lines; alkali retted palmyrah fibre rivals jute in bio-composite panels; and saccharified coir dust feeds pilot 2-G bioethanol plants. These outcomes demonstrate that palmyrah can simultaneously fuel sweetener, beverage, fibre-composite and biofuel sectors, delivering immediate rural employment and circular-economy benefits.

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Authors' contributions

Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization and writing the original draft were done by JJ. AM performed the conceptualization, data curation, formal analysis, software, supervision, visualization and writing the review & editing and original draft. IVP done the data curation, formal analysis, investigation, methodology, project administration, resources, writing the review and editing. Conceptualization, data curation, formal analysis, methodology, writing the original draft was done by AG. The resources, software, supervision, validation, visualization, writing the original draft by RA.

Compliance with ethical standards

Conflict of interest: The authors declare that the research was conducted without any commercial or financial relationship that could be constructed as a potential conflict of interest.

Ethical issues: None

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