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REVIEW ARTICLE

MADHUCA LONGIFOLIA (MAHUA): A REVIEW OF TRADITIONAL USES, PHYTOCHEMISTRY, PHARMACOLOGICAL ACTIVITIES, TOXICOLOGY, BIOTECHNOLOGY AND THERAPEUTIC POTENTIAL

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Abstract: *Madhuca longifolia* (J.F. Gmel.) J.F. Macbr. (Sapotaceae), commonly known as Mahua or Indian Butter Tree, is a multipurpose indigenous tree widely distributed across the Indian subcontinent. It holds an important place in Ayurveda, Siddha, Unani, and tribal healthcare systems, where its flowers, leaves, bark, fruits, seeds, and seed oil have traditionally been used to treat diabetes, inflammatory disorders, respiratory and gastrointestinal ailments, skin diseases, wounds, ulcers, and rheumatism. Beyond its medicinal importance, Mahua contributes significantly to the livelihood and nutritional security of rural and tribal communities through its edible flowers, seed oil, timber, fermented products, and biodiesel potential. Growing scientific interest has highlighted *M. longifolia* as a valuable source of bioactive compounds with diverse therapeutic properties. This review summarizes together with classical Ayurvedic texts and earlier pharmacognostic studies, covering its taxonomy, botanical characteristics, distribution, ethnomedicinal importance, nutritional composition, phytochemistry, pharmacognosy, pharmacological activities, toxicology, biotechnology, and pharmaceutical applications. Phytochemical studies have identified numerous bioactive constituents, including triterpenoids, saponins, flavonoids, phenolic compounds, phytosterols, fatty acids, tannins, glycosides, and vitamins, which are responsible for its wide range of biological activities. Experimental studies have demonstrated significant antioxidant, anti-inflammatory, antimicrobial, antidiabetic, hepatoprotective, gastroprotective, wound-healing, analgesic, anticancer, and immunomodulatory properties. Recent advances in metabolomics, chromatographic fingerprinting, tissue culture, nanotechnology, and phytopharmaceutical research have further strengthened its medicinal and industrial potential. However, despite encouraging preclinical findings, standardized extracts, pharmacokinetic investigations, long-term safety assessments, and well-designed clinical trials remain limited. Future multidisciplinary research integrating phytochemistry, pharmacology, biotechnology, and clinical sciences is essential to develop safe, standardized, and evidence-based Mahua-derived phytopharmaceuticals for the management of chronic diseases.

Keywords: *Madhuca longifolia*, Mahua, Sapotaceae, Ethnomedicine, Phytochemistry, Medicinal plant

INTRODUCTION

Medicinal plants have served as the cornerstone of traditional healthcare systems for thousands of years and continue to provide valuable therapeutic agents for the prevention and treatment of numerous human diseases (Tomar, 2007; Tomar, 2009; Tomar, 2019; Tomar, 2020; Tomar, 2022, Tomar, 2023 and Sharma *et al.*, 2025). According to the World Health Organization (WHO), nearly 80% of the global population relies, either wholly or partially, on traditional herbal medicines for primary healthcare, particularly in developing countries where medicinal plants remain accessible, affordable, and culturally acceptable (World Health Organization,2013). Increasing concerns regarding antimicrobial resistance, chronic non-communicable diseases, adverse effects of synthetic drugs, and the growing demand for natural therapeutics have renewed worldwide interest in medicinal plants as promising sources of novel bioactive compounds and phytopharmaceuticals.

The family Sapotaceae comprises approximately 65 genera and over 1,250 species distributed predominantly throughout tropical and subtropical regions of Asia, Africa, Australia, and the Americas (Pennington, 1991). Members of this family are well known for their latex-bearing tissues, edible fruits, nutrient-rich seeds, and abundance of biologically active secondary metabolites such as triterpenoids, flavonoids, saponins, phenolic compounds, sterols, and fatty acids. Among them, *Madhuca longifolia* (J.F. Gmel.) J.F. Macbr. is one of the most valuable indigenous tree species of the Indian subcontinent because of its exceptional medicinal, nutritional, ecological, cultural, and economic importance (Khare, 2007).

Commonly known as Mahua, Mowra, Illuppai, or Indian Butter Tree, *M. longifolia* is a medium- to large-sized deciduous tree widely distributed throughout central, western, eastern, and peninsular

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India, extending into Nepal, Sri Lanka, Myanmar, and parts of Southeast Asia. The species thrives in tropical dry deciduous forests and semi-arid ecosystems up to an altitude of approximately 1,200 m above sea level. Owing to its remarkable adaptability to harsh environmental conditions, drought tolerance, and multipurpose utility, Mahua has been regarded as the "Tree of Life" among many indigenous and tribal communities of India. Nearly every component of the tree—including flowers, fruits, seeds, bark, leaves, latex, and wood—is utilized for food, traditional medicine, livestock feed, fuel, timber, biodiesel production, cosmetics, soap manufacturing, and numerous household applications (Orwa *et al.*, 2009).

In the Ayurvedic system of medicine, Mahua is known as Madhuka and is described as possessing Madhura (sweet) and Kashaya (astringent) rasa, Guru (heavy) and Snigdha (unctuous) guna, Sheeta (cooling) virya, and Madhura vipaka. It is traditionally prescribed as a Rasayana, Balya, Vrishya, Brimhana, Raktapittahara, and Vranahara drug for promoting vitality, improving reproductive health, relieving thirst and burning sensations, healing wounds, and managing respiratory and gastrointestinal disorders. Flowers are used as nutritive tonics and expectorants; bark is valued for its astringent and anti-inflammatory properties; leaves are applied to skin diseases and wounds; while seed oil is widely employed for rheumatism, eczema, chronic ulcers, and other dermatological conditions (Nadkarni, 1954; Khare, 2007).

Beyond its medicinal significance, Mahua has substantial nutritional and industrial importance. The carbohydrate-rich flowers are consumed fresh or dried and are widely utilized in the preparation of traditional fermented beverages, syrups, confectionery products, vinegar, and livestock feed. Seeds contain 35–50% edible oil rich in oleic, stearic, palmitic, and linoleic acids, which is extensively used in food processing, biodiesel production, cosmetics, soap manufacture, lubricants, and pharmaceutical formulations. The residual seed cake serves as an organic manure, biofertilizer, and botanical pesticide, thereby contributing to sustainable agriculture and circular bioeconomy.

Phytochemical investigations carried out during the past several decades have revealed an extraordinary diversity of secondary metabolites, including triterpenoids (α-amyrin, β-amyrin, lupeol, betulinic acid, oleanolic acid), triterpenoid saponins, flavonoids (quercetin, myricetin, dihydroquercetin), phenolic acids, phytosterols, glycosides, tannins, carbohydrates, amino acids, vitamins, carotenoids, and fatty acids. These compounds have been associated with a broad range of pharmacological activities including antioxidant, anti-inflammatory, antimicrobial, antidiabetic, hepatoprotective, nephroprotective, gastroprotective, analgesic, wound-healing, immunomodulatory, cardioprotective, neuroprotective, anticancer, antiulcer, spermicidal, insecticidal, and antiviral properties (Patel & Naik, 2010; Grover *et al.*, 2022).

Recent advances in analytical chemistry, metabolomics, high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC–MS), liquid chromatography-mass spectrometry (LC–MS/MS), nuclear magnetic resonance (NMR), molecular docking, DNA barcoding, tissue culture, and nanotechnology have considerably expanded scientific understanding of *M. longifolia*. These modern approaches have facilitated the identification of novel bioactive molecules, quality-control markers, and potential therapeutic targets while supporting the development of standardized herbal formulations and phytopharmaceutical products.

Despite its extensive traditional use and increasing scientific recognition, information concerning the taxonomy, ethnomedicine, phytochemistry, pharmacognosy, pharmacological properties, toxicology, biotechnology, and pharmaceutical applications of *M. longifolia* remains fragmented across ethnobotanical reports, pharmacological investigations, phytochemical studies, and review articles. Furthermore, substantial research published during the last decade has not been comprehensively integrated with classical knowledge.

Therefore, the present review critically compiles and evaluates the available literature published between 2000 and 2025 together with historical reports to provide an updated overview of the botanical characteristics, geographical distribution, traditional uses, nutritional composition, phytochemical profile, pharmacognostic standards, pharmacological activities, toxicological aspects, biotechnology, and therapeutic potential of *Madhuca longifolia*. The review also highlights current research gaps, future perspectives, and opportunities for developing standardized, safe, and evidence-based phytopharmaceuticals from this culturally and economically important medicinal tree.

Botanical Description and Taxonomy

Madhuca longifolia (J.F. Gmel.) J.F. Macbr. is a large multipurpose deciduous tree belonging to the family Sapotaceae, valued for its nutritional, medicinal, ecological, and socioeconomic importance (Tomar, 2024). The species has been recognized in Ayurvedic literature since ancient times under the Sanskrit name Madhuka, where it is described as a rejuvenating (Rasayana) plant possessing cooling, nutritive, tonic, and wound-healing properties (Nadkarni, 1954). Historically, the species has also been reported under the synonyms *Bassia longifolia* Koenig ex L., *Bassia latifolia* Roxb., *Madhuca indica* J.F. Gmel., and *Madhuca latifolia* (Roxb.) A. Chev., reflecting changes in botanical nomenclature over time (Pennington, 1991; Plants of the World Online [POWO], 2025).

Modern taxonomic treatments recognize two botanical varieties, namely *Madhuca longifolia* var. *longifolia*, predominantly distributed in southern India, and *Madhuca longifolia* var. *latifolia* (Roxb.) A. Chev., which occurs mainly in central and northern India (POWO, 2025).

Taxonomic Classification (According to the Linnaean System)

Taxonomic Rank	Classification
Kingdom	Plantae
Division	Magnoliophyta (Angiosperms)
Class	Magnoliopsida (Dicotyledons)
Subclass	Dilleniidae
Order	Ebenales *(currently placed in Ericales under APG IV)*
Family	Sapotaceae
Genus	*Madhuca* J.F. Gmel.
Species	*Madhuca longifolia* (J.F. Gmel.) J.F. Macbr.

Accepted scientific name: *Madhuca longifolia* (J.F. Gmel.) J.F. Macbr.

Important synonyms: *Bassia longifolia* Koenig ex L.; *Bassia latifolia* Roxb.; *Madhuca indica* J.F. Gmel.; *Madhuca latifolia* (Roxb.) A. Chev (Pennington, 1991; Khare, 2007; POWO, 2025).

Vernacular Names

Madhuca longifolia (J.F. Gmel.) J.F. Macbr. is widely recognized throughout the Indian subcontinent under numerous vernacular names, reflecting its extensive geographical distribution and profound cultural, medicinal, and socioeconomic importance. In the Ayurvedic system of medicine, the species is known as Madhuka, with several Sanskrit synonyms including Gudapushpa, Madhudruma, Madhushrava, and Deerghapatra, each describing its distinctive botanical characteristics or therapeutic properties (Nadkarni, 1954; Khare, 2007). In English, it is commonly referred to as Mahua, Indian Butter Tree, or Butter Tree, owing to the edible fat extracted from its seeds. Across different regions of India, the tree is known by various local names, including Mahua or Mohwa in Hindi, Moha or Mohwa in Marathi, Mahudo in Gujarati, Mahua in Bengali, Illuppai in Tamil, Ippa or Ippachettu in Telugu, Hippe in Kannada, and Irippa in Malayalam. The diversity of vernacular names highlights the widespread utilization of *M. longifolia* in traditional medicine, food, religious practices, and rural livelihoods throughout India, emphasizing its significance as one of the country's most valuable indigenous multipurpose tree species (Orwa *et al.,* 2009; Patel & Naik, 2010).

Botanical Description

Madhuca longifolia is a medium- to large-sized deciduous tree attaining a height of 15–20 m, occasionally reaching 25 m under favourable environmental conditions (Tomar,2024). Historical botanical descriptions characterize the tree as possessing a short stout bole with a broad, dense, rounded crown and thick spreading branches (Nadkarni, 1954). The bark is dark grey to brown, rough, longitudinally fissured, and exudes milky latex upon injury. The inner bark is reddish-brown and rich in tannins, explaining its traditional use as an astringent in Ayurveda (Raj & Patel, 1978).

Leaves are simple, alternate, coriaceous, elliptic-oblong to obovate, measuring approximately 10–25 cm long and 5–12 cm wide. Young foliage is reddish-copper in colour before gradually becoming glossy dark green at maturity. Leaves are clustered near the terminal portions of branches and remain persistent for most of the year (Orwa *et al.*, 2009).

Flowering generally occurs between February and April, coinciding with seasonal leaf fall. Flowers are fleshy, cream to pale yellow, fragrant, bisexual, and borne in dense fascicles on leafless branches. They possess a persistent calyx and a tubular corolla with numerous stamens. Flowers are exceptionally rich in fermentable sugars, carbohydrates, vitamins, amino acids, and minerals, making them valuable both nutritionally and medicinally (Patel & Naik, 2010). Traditional literature describes the flowers as cooling, demulcent, tonic, expectorant, nutritive, stimulant, and useful in piles and respiratory ailments (Nadkarni, 1954; Ahluwalia, 1968).

The fruit is an ovoid to ellipsoid fleshy berry measuring 2–6 cm in length, containing one to four smooth, shiny brown seeds embedded in sweet pulp. Seeds contain approximately 35–50% fixed oil, rich in oleic, stearic, palmitic, and linoleic acids, widely utilized in food industries, cosmetics, soap manufacture, pharmaceuticals, and biodiesel production (Ramadan *et al.*, 2006).

The tree develops a deep taproot system with extensive lateral roots that confer remarkable drought tolerance and adaptability to marginal soils, making it highly suitable for agroforestry and ecological restoration programmes (Orwa *et al.*, 2009).

DISTRIBUTION AND HABITAT

Madhuca longifolia is indigenous to the Indian subcontinent and is naturally distributed throughout India, Nepal, Bangladesh, Sri Lanka, and Myanmar, with limited cultivation in several tropical countries because of its nutritional and economic value (Orwa *et al.*, 2009; POWO, 2025).

Historical botanical literature describes Mahua as a medium- to large-sized deciduous tree occurring throughout the greater parts of India up to an altitude of about 1,200 m, especially in dry deciduous forests (Nadkarni, 1954). The species is particularly abundant in Madhya Pradesh, Maharashtra, Chhattisgarh, Jharkhand, Odisha, Gujarat, Rajasthan, Uttar Pradesh, Bihar, Telangana, Andhra Pradesh, Karnataka, Tamil Nadu, and West Bengal, where it constitutes an important component of tribal ecosystems and rural livelihoods (Patel & Naik, 2010).

The two botanical varieties exhibit distinct geographical distributions. *Madhuca longifolia* var. *latifolia* predominates in central and northern India, whereas *M. longifolia* var. *longifolia* is mainly confined to peninsular India, particularly Karnataka, Tamil Nadu, Kerala, Telangana, and Andhra Pradesh (POWO, 2025).

The species grows naturally from sea level to approximately 1,200 m elevation under tropical and subtropical climates with annual rainfall ranging between 500 and 1,500 mm and temperatures from 5°C to 46°C. Mature trees exhibit exceptional drought tolerance because of their extensive root system and ability to withstand prolonged moisture stress (Orwa *et al.*, 2009).

Madhuca longifolia thrives on deep, well-drained loamy, sandy-loam, lateritic, and black cotton soils, although it can also establish successfully on degraded lands and gravelly substrates. The species tolerates soil pH ranging from 5.5 to 8.5 and is frequently encountered in dry deciduous forests, village commons, sacred groves, agricultural field boundaries, and agroforestry systems.

Ecologically, Mahua functions as a keystone species supporting pollinating insects, honeybees, birds, bats, and mammals through its nectar-rich flowers and nutritious fruits. The annual leaf litter contributes significantly to nutrient cycling and soil fertility, while its extensive canopy enhances carbon sequestration and biodiversity conservation. Because of its outstanding ecological adaptability and socioeconomic importance, Mahua is often referred to as the "Tree of Life" or "Kalpavriksha of Tribal India", providing food, medicine, fodder, fuel, timber, and sustainable income to millions of forest-dependent communities (Patel & Naik, 2010).

TRADITIONAL AND ETHNOMEDICINAL USES

Madhuca longifolia (J.F. Gmel.) J.F. Macbr. has occupied a prominent position in the traditional healthcare systems of India for centuries and is extensively documented in Ayurveda, Siddha, Unani, and various indigenous tribal medicinal practices. In Ayurveda, the plant is known as Madhuka and is described as possessing Madhura (sweet) and Kashaya (astringent) rasa, Guru (heavy) and Snigdha (unctuous) guna, Sheeta (cooling) virya, and Madhura vipaka. It is traditionally classified as Balya (strength promoting), Brimhana (body nourishing), Rasayana (rejuvenative), Vrishya (aphrodisiac), Shukrakara, Raktapittahara, Trishnashamana, Vranahara, and Kshatakshayahara, indicating its usefulness in improving vitality, wound healing, reproductive health, and chronic debilitating disorders (Nadkarni, 1954; Khare, 2007).

Almost every part of the plant, including flowers, bark, leaves, fruits, seeds, seed oil, and latex, is utilized therapeutically. The flowers are considered cooling, demulcent, nutritive, tonic, expectorant, stimulant, and appetizer. They are traditionally prescribed for cough, bronchitis, asthma, thirst, burning sensation, emaciation, general debility, bleeding disorders, piles, and chronic constipation. Dried flowers are widely consumed as a restorative food and are fermented to prepare traditional beverages among tribal communities of central and southern India (Nadkarni, 1954; Patel & Naik, 2010; Dhale & Patil, 2024).

The bark possesses pronounced astringent, anti-inflammatory, and antimicrobial properties. Bark decoctions are traditionally administered for diabetes mellitus, diarrhoea, dysentery, bleeding gums, rheumatism, itching, skin diseases, ulcers, and chronic wounds. Tribal healers also prescribe bark preparations for fever and inflammatory conditions (Raj & Patel, 1978; Khare, 2007).

Leaves are extensively employed as topical remedies. Fresh leaves are applied over wounds, burns, eczema, boils, fractures, sprains, and inflammatory swellings. Warm leaf poultices are used to relieve joint pain, rheumatism, and muscular inflammation, whereas leaf decoctions are administered internally for respiratory ailments and skin disorders. The latex is occasionally applied to cracked skin and chronic ulcers because of its wound-healing properties (Nadkarni, 1954).

The seeds yield Mahua butter, a fixed oil that has been used traditionally as a laxative, emollient, analgesic, and anti-inflammatory agent. Seed oil is externally applied for eczema, psoriasis, scabies, rheumatism, arthritis, chronic ulcers, cracked heels, and various dermatological disorders. Internally, it has been used in small quantities for constipation and as a nutritive fat in rural communities (Raj & Patel, 1978; Khare, 2007).

Ethnobotanical investigations conducted across Maharashtra, Madhya Pradesh, Chhattisgarh, Jharkhand, Odisha, Gujarat, Rajasthan, and Telangana have documented the continued dependence of tribal communities such as the Gond, Baiga, Bhil, Kol, Santhal, Oraon, and Koya tribes on *M. longifolia* for primary healthcare, nutrition, and livelihood. Flowers are consumed fresh or dried as food, seeds are processed for edible and medicinal oil, while bark and leaves remain important components of traditional herbal formulations for gastrointestinal disorders, diabetes, respiratory diseases, reproductive ailments, and skin infections (Jain, 1991; Orwa *et al.*, 2009; Singh *et al.*, 2021).

Recent pharmacological investigations strongly support many of these traditional claims by demonstrating antioxidant, anti-inflammatory, antimicrobial, hepatoprotective, antidiabetic, analgesic, wound-healing, gastroprotective, and immunomodulatory activities, thereby validating the ethnomedicinal importance of *Madhuca longifolia* (Grover *et al.*, 2022; Singh *et al.*, 2023).

NUTRITIONAL COMPOSITION

Madhuca longifolia is regarded as one of the most nutritionally valuable forest tree species of India. Its flowers, fruits, and seeds constitute important dietary resources for rural and tribal populations, particularly during periods of food scarcity. The flowers are highly nutritious because of their high carbohydrate content, making them an excellent source of dietary energy. Fresh flowers contain approximately 60–70% fermentable sugars, mainly glucose, fructose, and sucrose, together with proteins, amino acids, vitamins, minerals, dietary fibre, and natural antioxidants (Gopalan *et al.*, 2019; Patel & Naik, 2010).

The flowers are rich in essential minerals such as calcium, phosphorus, potassium, magnesium, iron, zinc, and copper. Earlier nutritional analyses reported approximately 45 mg calcium, 22 mg phosphorus, 40 mg iron, 1.1 mg vitamin C, and 307 µg carotene per 100 g of edible flowers (Gopalan *et al.*, 1984). In addition, they contain B-complex vitamins, amino acids, and phenolic compounds that contribute to their nutritional and antioxidant value.

The seeds contain 35–50% fixed oil, commonly referred to as Mahua butter. The oil is composed predominantly of oleic acid (40–50%), stearic acid (20–25%), palmitic acid (20–25%), linoleic acid (8–14%), and smaller quantities of arachidic, behenic, and myristic acids. This fatty acid profile imparts excellent nutritional as well as industrial value to the seed oil, making it suitable for edible applications after refining, pharmaceutical preparations, cosmetics, soap manufacture, and biodiesel production (Ramadan *et al.*, 2006; Patel & Naik, 2010).

The flowers also contain appreciable quantities of reducing sugars, proteins, dietary fibre, organic acids, flavonoids, and phenolic compounds, which collectively contribute to their antioxidant capacity and health-promoting properties. Recent metabolomic studies have further identified several bioactive phytochemicals that enhance the nutraceutical potential of Mahua flowers, supporting their use in functional foods, fermented beverages, syrups, confectionery products, bakery formulations, and herbal health supplements (Grover *et al.*, 2022).

Mahua seed cake, obtained after oil extraction, is rich in proteins, carbohydrates, and minerals. Although the presence of saponins limits its direct human consumption, detoxified seed cake is increasingly being explored as a protein-rich livestock feed, organic fertilizer, biofertilizer, and botanical pesticide. The flowers are also processed into value-added products including jaggery, vinegar, wine, ethanol, nectar, squash, candies, and fermented beverages, significantly contributing to the rural bioeconomy and food security (Patel & Naik, 2010; Singh *et al.*, 2023).

The remarkable nutritional composition of *Madhuca longifolia*, combined with its abundance of phytochemicals and traditional medicinal value, has attracted increasing attention toward its development as a functional food, nutraceutical ingredient, and phytopharmaceutical resource for improving human health and nutrition.

PHYTOCHEMISTRY

Madhuca longifolia (J.F. Gmel.) J.F. Macbr. is a rich source of structurally diverse phytochemicals distributed throughout its flowers, leaves, bark, fruits, seeds, and seed oil. Since the early phytochemical investigations of the 1950s and 1960s, numerous studies have demonstrated that the medicinal properties of the plant are attributed to the presence of triterpenoids, triterpenoid saponins, flavonoids, phenolic compounds, phytosterols, glycosides, fatty acids, tannins, carbohydrates, amino acids, vitamins, and volatile constituents (Mitra & Awasthi, 1962; Awasthi & Mitra, 1967, 1968). Recent investigations employing HPLC, GC–MS, LC–MS/MS, NMR spectroscopy, and metabolomics have further expanded the phytochemical profile of the species and identified several pharmacologically active metabolites (Grover *et al.*, 2022; Singh *et al.*, 2023).

The flowers are rich in reducing sugars (glucose, fructose, and sucrose), proteins, amino acids, vitamins, carotenoids, minerals, flavonoids, and phenolic acids, making them nutritionally valuable and responsible for their antioxidant activity (Patel & Naik, 2010). Phytochemical screening has revealed the presence of quercetin derivatives, myricetin, gallic acid, chlorogenic acid, caffeic acid, catechin, and rutin, which contribute to the antioxidant, anti-inflammatory, and hepatoprotective activities of the flowers (Grover *et al.*, 2022).

Leaves contain abundant flavonoids, including myricetin, quercetin, myricitrin, quercitrin, myricetin-3-*O*-L-rhamnoside, myricetin-3-arabinoside, and quercetin-3-galactoside, together with tannins, saponins, phenolic compounds, and xanthophyll pigments (Subramanian & Nair, 1972, 1973). Triterpenoids such as oleanolic acid palmitate, 3-β-caproxy-olea-12-en-28-ol, and β-sitosterol glucoside have also been isolated from leaf extracts (Bhatnagar *et al.*, 1972).

The bark is particularly rich in triterpenoids and phytosterols. Phytochemical investigations have identified lupeol acetate, β-amyrin acetate, α-spinasterol, erythrodiol monocaprylate, betulinic acid, oleanolic acid caprylate, and β-sitosterol glucoside. The aqueous fraction additionally contains monosaccharides such as D-glucose, D-galactose, D-xylose, and L-rhamnose, which may contribute to its biological activities (Awasthi & Mitra, 1968). These constituents are largely responsible for the anti-inflammatory, antimicrobial, hepatoprotective, and wound-healing properties of the bark.

Seeds are chemically characterized by a high content of triterpenoid saponins, fixed oil, phytosterols, and glycosides. Two major saponins, designated Saponin A and Saponin B, were isolated and structurally characterized from defatted seeds. These compounds possess bassic acid as the principal sapogenin and have demonstrated spermicidal and antimicrobial activities (Hariharan *et al.*, 1972; Banerji *et al.*, 1979). The seed oil contains approximately 35–50% lipids, consisting mainly of oleic acid, stearic acid, palmitic acid, linoleic acid, and smaller amounts of arachidic and behenic acids, making it suitable for pharmaceutical, cosmetic, and nutraceutical applications (Ramadan *et al.*, 2006).

The fruits contain sugars, phenolic compounds, flavonoids, vitamins, and carotenoids, whereas latex contains proteins, terpenoids, and other bioactive metabolites involved in wound healing and plant defense.

Recent metabolomic analyses have identified numerous volatile compounds, sterols, tocopherols, and polyphenolic constituents that further strengthen the antioxidant, anti-inflammatory, antidiabetic, antimicrobial, and anticancer potential of *Madhuca longifolia*. Advances in chromatographic fingerprinting and metabolomic profiling have also facilitated the establishment of quality-control parameters for herbal formulations prepared from Mahua (Grover *et al.*, 2022; Singh *et al.*, 2023).

Overall, the remarkable diversity of phytochemicals present in *M. longifolia* provides the scientific basis for its broad spectrum of traditional medicinal uses and experimentally validated pharmacological activities.

PHARMACOGNOSY

Pharmacognostic evaluation plays a crucial role in the authentication, quality control, and standardization of medicinal plants. *Madhuca longifolia* has been extensively investigated for its macroscopic, microscopic, physicochemical, and phytochemical characteristics, which serve as reliable diagnostic parameters for identification of crude drugs and herbal formulations (Anonymous, 2001; Khare, 2007).

Macroscopically, *M. longifolia* is a medium- to large-sized deciduous tree with a short, stout trunk and a broad, spreading crown. The bark is dark grey to brown, rough, longitudinally fissured, and exudes milky latex upon injury. Leaves are simple, alternate, coriaceous, elliptic-oblong to obovate, measuring approximately 10–25 cm in length, with entire margins and acute to obtuse apices. Flowers are fleshy, cream to pale yellow, fragrant, bisexual, and borne in dense fascicles on leafless branches. Fruits are fleshy berries containing one to four smooth brown seeds rich in fixed oil (Nadkarni, 1954; Orwa *et al.*, 2009).

Microscopic examination of the bark reveals a multilayered cork composed of rectangular suberized cells followed by a broad cortex containing parenchymatous tissues with abundant tannin cells, stone cells, and laticiferous canals. Calcium oxalate crystals, starch grains, and sclerenchymatous fibres are frequently observed. Secondary phloem is well developed with medullary rays and numerous secretory cells containing phenolic substances (Anonymous, 2001).

Leaf microscopy shows a dorsiventral lamina with a single-layered epidermis covered by a thick cuticle. The mesophyll is differentiated into one to two layers of palisade cells and several layers of spongy parenchyma. Numerous collateral vascular bundles, laticifers, calcium oxalate crystals, and unicellular covering trichomes are present. Stomata are predominantly paracytic and occur mainly on the lower epidermis, indicating a hypostomatic leaf (Khare, 2007).

Powder microscopy of bark and leaves exhibits characteristic fragments of cork cells, lignified fibres, sclereids, spiral and pitted vessels, starch grains, tannin-containing cells, oil globules, calcium oxalate crystals, and pollen grains, which provide important diagnostic markers for authentication and detection of adulteration.

Physicochemical evaluation has reported acceptable ranges for total ash, acid-insoluble ash, water-soluble ash, moisture content, alcohol-soluble extractive, and water-soluble extractive values according to pharmacopoeial standards. Fluorescence analysis under visible and ultraviolet light following treatment with different chemical reagents has also been employed for quality assessment (Anonymous, 2001).

Preliminary phytochemical screening of different plant parts consistently demonstrates the presence of alkaloids (trace), flavonoids, triterpenoids, saponins, tannins, glycosides, steroids, carbohydrates, proteins, amino acids, fixed oils, and phenolic compounds, supporting the therapeutic potential of the species (Khare, 2007; Grover *et al.*, 2022).

Modern pharmacognostic approaches involving High-Performance Thin-Layer Chromatography (HPTLC), High-Performance Liquid Chromatography (HPLC), Gas Chromatography–Mass Spectrometry (GC–MS), Liquid Chromatography–Mass Spectrometry (LC–MS/MS), Fourier Transform Infrared Spectroscopy (FTIR), DNA barcoding, and metabolomic fingerprinting have significantly improved authentication and standardization of *Madhuca longifolia*. These analytical tools facilitate identification of marker compounds such as β-sitosterol, lupeol, betulinic acid, oleanolic acid, quercetin, myricetin, and triterpenoid saponins, ensuring the quality, efficacy, and safety of herbal preparations intended for pharmaceutical applications (Grover *et al.*, 2022; Singh *et al.*, 2023).

PHARMACOLOGICAL ACTIVITIES

The diverse ethnomedicinal applications of *Madhuca longifolia* (J.F. Gmel.) J.F. Macbr. have stimulated extensive pharmacological investigations over the past several decades. Experimental studies using crude extracts, solvent fractions, purified phytochemicals, and isolated compounds have demonstrated a broad spectrum of biological activities that largely validate its traditional medicinal uses. These pharmacological effects are primarily attributed to the synergistic action of triterpenoids, triterpenoid saponins, flavonoids, phenolic compounds, phytosterols, fatty acids, glycosides, and tannins present in different parts of the plant (Khare, 2007; Grover *et al.*, 2022).

Antioxidant Activity

Several in vitro and in vivo studies have demonstrated that flower, leaf, bark, and seed extracts possess potent antioxidant activity by scavenging reactive oxygen species (ROS), inhibiting lipid peroxidation, and enhancing endogenous antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase. The antioxidant potential is mainly attributed to flavonoids, phenolic acids, quercetin, myricetin, and tannins (Patel & Naik, 2010; Grover *et al.*, 2022).

Anti-inflammatory and Analgesic Activity

Traditional use of Mahua in rheumatism and inflammatory disorders has been supported by experimental studies demonstrating significant inhibition of carrageenan-induced paw edema, cotton pellet granuloma, and inflammatory mediators including cyclooxygenase (COX) and nitric oxide. Triterpenoids such as lupeol, β-amyrin, oleanolic acid, and betulinic acid contribute significantly to these effects. Extracts also exhibit peripheral analgesic activity in animal models, supporting their traditional use in pain management (Khare, 2007; Singh *et al.*, 2023).

Antidiabetic Activity

Methanolic and aqueous extracts of bark, leaves, flowers, and seeds have demonstrated significant hypoglycemic effects in streptozotocin- and alloxan-induced diabetic experimental models. Treatment resulted in reduced blood glucose, improved insulin sensitivity, restoration of pancreatic β-cell function, and decreased oxidative stress. These effects have been attributed to flavonoids, phenolic compounds, triterpenoids, and saponins (Raj & Patel, 1978; Grover *et al.*, 2022).

Antimicrobial Activity

Extracts prepared from flowers, leaves, stem bark, and roots exhibit broad-spectrum antibacterial activity against both Gram-positive and Gram-negative bacteria including *Bacillus subtilis*, *Bacillus anthracis*, *Staphylococcus aureus*, *Salmonella paratyphi*, *Vibrio cholerae*, and *Xanthomonas campestris*. Antifungal activity against several pathogenic fungi has also been reported. Earlier investigations demonstrated antibacterial activity of methanolic extracts against medically important microorganisms (Trivedi *et al.*, 1980), while recent studies have confirmed these findings using modern microbiological techniques (Grover *et al.*, 2022).

Hepatoprotective Activity

Experimental studies have demonstrated that flower and bark extracts protect hepatic tissues against carbon tetrachloride-, paracetamol-, and alcohol-induced liver damage by reducing lipid peroxidation, restoring hepatic antioxidant enzymes, and improving serum biochemical markers including AST, ALT, and ALP. Hepatoprotective activity is mainly associated with flavonoids, phenolic compounds, and triterpenoids (Singh *et al.*, 2023).

Gastroprotective and Antiulcer Activity

Traditional use of Mahua flowers for gastrointestinal disorders has been supported by experimental evidence demonstrating significant reduction in gastric ulcer index, gastric acidity, and mucosal damage in ethanol- and indomethacin-induced ulcer models. The mucosal protective effects are attributed to flavonoids, mucilage, tannins, and antioxidant constituents that enhance gastric mucus secretion and reduce oxidative injury (Khare, 2007; Grover *et al.*, 2022).

Wound-Healing Activity

Leaf, bark, and seed oil preparations have been traditionally applied to wounds, burns, ulcers, and skin infections. Scientific investigations have shown accelerated wound contraction, increased collagen synthesis, enhanced epithelialization, and improved tensile strength in excision and incision wound models. These effects are associated with antimicrobial, antioxidant, and anti-inflammatory phytochemicals (Nadkarni, 1954; Singh *et al.*, 2023).

Anticancer Activity

Recent in vitro investigations indicate that extracts of *M. longifolia* possess cytotoxic activity against selected human cancer cell lines by inducing apoptosis, inhibiting cell proliferation, and modulating oxidative stress pathways. Betulinic acid, oleanolic acid, lupeol, and phenolic compounds are considered the principal anticancer constituents. Nevertheless, further mechanistic studies and clinical investigations are required before therapeutic application (Grover *et al.*, 2022).

Spermicidal and Contraceptive Activity

One of the most extensively investigated pharmacological properties of *M. longifolia* is its spermicidal activity. Triterpenoid saponins isolated from seeds demonstrated remarkable spermicidal activity against human semen at low concentrations. Saponin A and Saponin B, possessing bassic acid as the principal sapogenin, exhibited significant contraceptive potential without marked cardiovascular effects (Setty *et al.*, 1976; Banerji *et al.*, 1979, 1981).

Other Pharmacological Activities

Various investigations have also reported hypotensive, antiviral, immunomodulatory, cardioprotective, nephroprotective, neuroprotective, antihelmintic, insecticidal, and nematicidal activities. Earlier pharmacological screening demonstrated hypotensive effects of stem bark extracts in cats and dogs (Bhakuni *et al.*, 1969), antiviral activity against Potato virus X (Singh & Singh, 1972), and insecticidal properties against houseflies (Atal *et al.*, 1978). Furthermore, Mahua seed cake exhibits nematicidal activity against important agricultural nematodes, suggesting potential applications in sustainable agriculture (Alam *et al.*, 1982).

Overall, accumulating pharmacological evidence strongly supports the traditional therapeutic claims associated with *M. longifolia*. However, most investigations remain preclinical, emphasizing the need for standardized formulations, pharmacokinetic studies, and well-designed clinical trials to establish therapeutic efficacy and safety in humans.

TOXICOLOGY AND SAFETY

Although *Madhuca longifolia* has been consumed safely for centuries as food and traditional medicine, toxicological evaluation remains essential for ensuring its safe therapeutic application. Available evidence indicates that edible flowers, properly processed seed oil, and traditionally prescribed doses of herbal preparations are generally considered safe. Nevertheless, certain plant constituents, particularly triterpenoid saponins present in seeds and seed cake, exhibit dose-dependent toxicity and therefore require appropriate processing before medicinal or dietary use (Mulky & Gandhi, 1977; Banerji *et al.*, 1981).

Acute toxicity studies on 50% alcoholic stem bark extract demonstrated an intraperitoneal LD_{50} of approximately 1000 mg/kg in albino mice, indicating relatively low acute toxicity under experimental conditions (Bhakuni *et al.*, 1969). Similarly, ethanolic extracts of aerial parts exhibited LD_{50} values greater than 1000 mg/kg, suggesting a wide margin of safety for crude extracts when administered in recommended doses (Dhar *et al.*, 1974).

Triterpenoid saponins isolated from Mahua seeds have received considerable toxicological attention because of their spermicidal activity. Experimental investigations revealed that these saponins possess minimal cardiovascular and haemolytic activity at pharmacologically effective concentrations but become highly toxic when administered parenterally at high doses. Mulky and Gandhi (1977) reported that the acute toxicity of seed saponins following intravenous or intraperitoneal administration was substantially greater than after oral administration, indicating poor gastrointestinal absorption. Banerji *et al.* (1981) further demonstrated that purified seed saponins did not produce significant cardiovascular effects in dogs or haemolysis of human erythrocytes at therapeutic concentrations.

Traditional literature indicates that excessive consumption of fermented Mahua liquor may produce gastric irritation, nausea, and intoxication because of ethanol formation during fermentation (Nadkarni, 1954). Consequently, fermented flower products should be consumed responsibly and under appropriate regulatory guidelines.

Mahua seed cake contains substantial quantities of saponins that limit its direct use as animal feed. However, detoxification significantly reduces toxicity, and studies involving lactating buffaloes demonstrated no adverse effects on erythrocyte count, haemoglobin concentration, serum proteins, or general health following incorporation of detoxified Mahua seed cake into the diet (Pyne *et al.*, 1981). Similarly, detoxified seed cake is increasingly utilized as an organic fertilizer and biofertilizer without significant environmental hazards.

Recent investigations have also evaluated the genotoxicity and cytotoxicity of Mahua extracts and generally report low toxicity at therapeutic concentrations. Nevertheless, comprehensive chronic toxicity, reproductive toxicity, mutagenicity, carcinogenicity, pharmacokinetic, and human clinical safety studies remain insufficient. Future investigations should establish standardized dosage regimens, herb–drug interactions, and long-term safety profiles to facilitate regulatory approval of Mahua-derived phytopharmaceuticals.

Overall, current evidence suggests that *M. longifolia* is relatively safe when consumed traditionally or administered within recommended therapeutic doses. However, standardized processing, quality control, and rigorous toxicological evaluation are essential before its widespread pharmaceutical application.

BIOTECHNOLOGICAL APPLICATIONS

The increasing demand for sustainable natural products has stimulated considerable interest in the biotechnological utilization of *Madhuca longifolia* (J.F. Gmel.) J.F. Macbr. Advances in plant biotechnology, tissue culture, metabolomics, genetic improvement, and industrial biotechnology have expanded the commercial and pharmaceutical value of this multipurpose tree. Modern research focuses not only on conservation of elite germplasm but also on enhancing the production of bioactive compounds, improving propagation efficiency, and developing value-added products for food, pharmaceutical, cosmetic, and bioenergy industries (Patel & Naik, 2010; Grover *et al.*, 2022).

Micropropagation and In Vitro Regeneration

Conventional propagation of *M. longifolia* through seeds is limited by prolonged juvenile periods, irregular germination, and considerable genetic variability. Consequently, micropropagation techniques have been developed for rapid multiplication of elite genotypes. Successful regeneration has been achieved using nodal segments, shoot tips, cotyledonary nodes, and immature embryos cultured on Murashige and Skoog (MS) medium supplemented with cytokinins such as benzylaminopurine (BAP), kinetin (Kn), and thidiazuron (TDZ). These protocols facilitate large-scale clonal propagation of disease-free planting material for afforestation, agroforestry, and commercial plantations (Rai *et al.*, 2016; Singh *et al.*, 2023).

Germplasm Conservation

Rapid deforestation, habitat degradation, and unsustainable harvesting have increased the need for conservation of *M. longifolia* genetic resources. Ex situ conservation through seed banks, field gene banks, cryopreservation, and in vitro repositories has become an important strategy for preserving elite germplasm. Tissue culture techniques further support long-term conservation and facilitate the exchange of disease-free planting material among research institutions (FAO, 2014; Grover *et al.*, 2022).

Metabolic Engineering and Secondary Metabolite Production

Recent advances in plant biotechnology have enabled investigations into the biosynthetic pathways responsible for the production of triterpenoids, flavonoids, phenolic compounds, and saponins in *M. longifolia*. Cell suspension cultures, callus cultures, hairy root cultures, and elicitor-based approaches are being explored to enhance the production of pharmacologically important secondary metabolites. Omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, are expected to accelerate metabolic engineering for large-scale production of valuable phytochemicals (Grover *et al.*, 2022; Singh *et al.*, 2023).

Biodiesel and Bioenergy Production

Mahua seed oil has emerged as one of the most promising non-edible feedstocks for biodiesel production because of its high oil content (35–50%), favorable fatty acid composition, and widespread availability. Transesterification of Mahua oil yields biodiesel with physicochemical properties comparable to conventional diesel, making it a sustainable renewable energy source. Mahua-based biodiesel exhibits good cetane number, oxidative stability, biodegradability, and reduced greenhouse gas emissions, thereby contributing to rural energy security and environmental sustainability (Patel & Naik, 2010; Atabani *et al.*, 2013).

Fermentation and Industrial Biotechnology

The carbohydrate-rich flowers of *M. longifolia* are extensively utilized as substrates for microbial fermentation to produce ethanol, bioethanol, vinegar, wine, organic acids, enzymes, and probiotics. Owing to their high fermentable sugar content, Mahua flowers are increasingly recognized as valuable renewable biomass for biofuel industries and sustainable biorefineries. Modern fermentation technologies have significantly improved ethanol yield and product quality while minimizing waste generation (Patel & Naik, 2010; Singh *et al.*, 2023).

Nanobiotechnology

Recent studies have demonstrated the potential of Mahua extracts in green synthesis of metallic nanoparticles such as silver and zinc oxide nanoparticles. These phytosynthesized nanoparticles exhibit enhanced antimicrobial, antioxidant, wound-healing, and anticancer activities, opening new opportunities for biomedical applications. Green nanotechnology offers an eco-friendly alternative to conventional chemical synthesis and aligns with sustainable pharmaceutical development (Grover *et al.*, 2022).

Overall, biotechnology provides powerful tools for conservation, genetic improvement, metabolite enhancement, and industrial utilization of *Madhuca longifolia*, thereby supporting its sustainable commercialization and long-term utilization.

Pharmaceutical Applications

Madhuca longifolia has attracted considerable attention as a valuable source of bioactive phytochemicals with significant pharmaceutical potential. The presence of triterpenoids, flavonoids, phenolic acids, saponins, phytosterols, glycosides, and fatty acids has encouraged extensive investigations into the development of herbal medicines, phytopharmaceuticals, nutraceuticals, cosmeceuticals, and novel drug-delivery systems (Khare, 2007; Grover *et al.*, 2022).

Herbal Medicines

Extracts obtained from flowers, bark, leaves, and seeds are incorporated into traditional herbal formulations used for treating diabetes, inflammation, arthritis, skin diseases, respiratory disorders, gastrointestinal ailments, wounds, ulcers, and liver diseases. Modern pharmacological evidence validating antioxidant, antimicrobial, anti-inflammatory, antidiabetic, hepatoprotective, gastroprotective, and wound-healing properties supports the continued development of standardized herbal medicines derived from *M. longifolia* (Singh *et al.*, 2023).

Nutraceuticals and Functional Foods

The flowers are rich in carbohydrates, minerals, vitamins, amino acids, flavonoids, and phenolic antioxidants, making them excellent candidates for functional foods and nutraceutical products. Mahua flowers are increasingly utilized in the preparation of herbal beverages, syrups, jams, candies, bakery products, dietary supplements, fermented health drinks, and antioxidant-rich food formulations that promote nutritional security and preventive healthcare (Patel & Naik, 2010).

Cosmeceutical Applications

Mahua seed oil, commonly known as Mahua butter, possesses excellent emollient, moisturizing, anti-inflammatory, and skin-conditioning properties. Consequently, it is extensively used in soaps, creams, lotions, lip balms, massage oils, shampoos, conditioners, sunscreens, and anti-aging formulations. The presence of essential fatty acids and natural antioxidants improves skin hydration, enhances wound healing, and protects against oxidative skin damage (Ramadan *et al.*, 2006; Singh *et al.*, 2023).

Drug Delivery Systems

Natural polysaccharides, seed oil, and mucilaginous components obtained from *M. longifolia* are being investigated as pharmaceutical excipients for controlled-release tablets, topical ointments, nanoemulsions, microemulsions, lipid nanoparticles, and transdermal drug-delivery systems. Mahua oil has shown promise as a biodegradable carrier for lipophilic drugs because of its biocompatibility and stability (Grover *et al.*, 2022).

Antimicrobial and Wound-Healing Formulations

Because of their broad-spectrum antimicrobial and wound-healing properties, Mahua extracts are increasingly incorporated into herbal antiseptic creams, gels, hydrogel dressings, ointments, and wound-care products. Their ability to reduce microbial growth, accelerate collagen synthesis, and promote tissue regeneration makes them attractive candidates for pharmaceutical wound management (Singh *et al.*, 2023).

Reproductive Health and Spermicidal Products

Triterpenoid saponins isolated from Mahua seeds have demonstrated potent spermicidal activity and have been investigated as potential plant-based contraceptive agents. These naturally occurring compounds offer prospects for developing safer, biodegradable, and affordable spermicidal formulations after further toxicological and clinical evaluation (Setty *et al.*, 1976; Banerji *et al.*, 1979).

Future Pharmaceutical Prospects

Recent advances in phytochemistry, molecular pharmacology, metabolomics, artificial intelligence-assisted drug discovery, and nanotechnology have accelerated the identification of novel therapeutic leads from *M. longifolia*. Bioactive constituents such as betulinic acid, lupeol, oleanolic acid, myricetin, quercetin, and triterpenoid saponins exhibit promising activities against chronic inflammatory diseases, diabetes, microbial infections, neurodegenerative disorders, cardiovascular diseases, and cancer. Future multidisciplinary studies involving pharmacokinetics, molecular docking, clinical trials, and regulatory standardization are expected to facilitate the development of evidence-based phytopharmaceuticals from this important medicinal tree (Grover *et al.*, 2022; Singh *et al.*, 2023).

Collectively, the available evidence indicates that *Madhuca longifolia* possesses enormous potential for the development of modern pharmaceuticals, nutraceuticals, cosmeceuticals, and sustainable bioproducts. Continued research integrating traditional knowledge with advanced biotechnology and pharmaceutical sciences will significantly enhance its commercial and therapeutic utilization.

CLINICAL STUDIES

Despite the extensive traditional use and encouraging pharmacological evidence, clinical investigations on *Madhuca longifolia* remain limited. Most available data originate from in vitro experiments, animal models, and ethnopharmacological observations. Well-designed randomized controlled clinical trials evaluating standardized Mahua preparations are still scarce. Consequently, current therapeutic applications are largely supported by traditional knowledge and preclinical evidence rather than high-quality clinical validation (Grover *et al.*, 2022; Singh *et al.*, 2023).

Traditional Clinical Use

For centuries, Mahua has been used by Ayurvedic physicians, Siddha practitioners, and tribal healers for managing diabetes, bronchitis, cough, asthma, skin diseases, rheumatism, wounds, ulcers, gastrointestinal disorders, malnutrition, reproductive disorders, and general weakness. Although these uses have been continuously practiced in Indian traditional medicine, systematic clinical documentation remains limited (Nadkarni, 1954; Khare, 2007).

Clinical Evidence in Diabetes

Experimental studies have demonstrated significant hypoglycemic and antioxidant activities of bark, flower, and leaf extracts in diabetic animal models. However, only a few preliminary observational studies and small pilot investigations have evaluated Mahua-based herbal formulations in patients with type 2 diabetes. These studies suggest improvements in fasting blood glucose and oxidative stress markers when Mahua is administered as part of polyherbal Ayurvedic formulations. Nevertheless, the individual therapeutic contribution of *M. longifolia* cannot yet be conclusively established because of limited sample sizes and lack of placebo-controlled clinical trials (Grover *et al.*, 2022).

Clinical Applications in Wound Healing and Dermatology

Traditional topical preparations containing Mahua seed oil, bark, and leaf extracts are widely used in rural India for treating chronic wounds, burns, eczema, cracked skin, ulcers, and inflammatory skin disorders. Clinical observations indicate accelerated wound healing and improved tissue regeneration, although these reports are largely anecdotal or derived from traditional medical practice. Controlled clinical trials evaluating standardized topical formulations are still lacking (Khare, 2007; Singh *et al.*, 2023).

Nutritional and Functional Food Applications

Mahua flowers have long been consumed as nutrient-rich traditional foods and beverages by tribal communities. Their high carbohydrate, mineral, vitamin, and antioxidant contents have encouraged their development as functional foods and nutraceuticals. Community-based nutritional studies suggest that Mahua flowers contribute to food security and provide supplementary dietary energy during periods of seasonal food scarcity. However, rigorous human intervention studies evaluating their effects on nutritional status, antioxidant capacity, metabolic syndrome, or chronic diseases remain unavailable (Patel & Naik, 2010).

Reproductive Health

Among the various pharmacological properties of *M. longifolia*, the spermicidal activity of seed saponins has received considerable scientific attention. Laboratory investigations have demonstrated effective spermicidal action in human semen in vitro, suggesting the possibility of developing plant-derived contraceptive formulations (Setty *et al.*, 1976; Banerji *et al.*, 1979). However, no approved clinical contraceptive products based on Mahua saponins are currently available, and comprehensive human clinical trials evaluating efficacy and safety have not yet been completed.

Safety in Humans

Traditional dietary consumption of Mahua flowers and refined seed oil indicates a generally favorable safety profile. Available toxicological evidence suggests that properly processed plant materials are safe when consumed in recommended quantities. Nevertheless, excessive intake of fermented Mahua liquor may result in ethanol-related adverse effects, while raw seed saponins require detoxification before use because of their potential toxicity. To date, no comprehensive Phase I–III clinical trials have established standardized therapeutic doses, long-term safety, pharmacokinetics, or herb–drug interactions of Mahua-derived preparations (Mulky & Gandhi, 1977; Banerji *et al.*, 1981).

Future Clinical Perspectives

Given the promising pharmacological profile of *Madhuca longifolia* (J.F. Gmel.) J.F. Macbr., there is an urgent need to translate the growing body of preclinical evidence into well-designed human clinical studies. Future research should prioritize randomized, double-blind, placebo-controlled clinical trials to establish the efficacy, optimal dosage, and therapeutic safety of standardized Mahua formulations. Standardization of plant extracts using validated phytochemical markers and advanced analytical techniques such as HPLC, LC–MS/MS, and metabolomic fingerprinting is essential to ensure batch-to-batch consistency and reproducibility. Comprehensive pharmacokinetic, pharmacodynamic, and bioavailability studies are required to elucidate the absorption, distribution, metabolism, excretion, and mechanisms of action of its bioactive constituents. In addition, long-term toxicological investigations, including chronic toxicity, reproductive toxicity, genotoxicity, carcinogenicity, and herb–drug interaction studies, are necessary to establish an evidence-based safety profile. Clinical evaluations should focus on diseases for which substantial preclinical evidence exists, including type 2 diabetes mellitus, inflammatory and autoimmune disorders, wound healing, liver diseases, metabolic syndrome, cardiovascular diseases, microbial infections, dermatological disorders, and selected cancers. Furthermore, Mahua-derived nutraceuticals, phytopharmaceuticals, cosmeceuticals, and botanical drug formulations should be developed and evaluated according to internationally accepted regulatory frameworks, including WHO, ICMR, AYUSH, USFDA, and EMA guidelines. The integration of omics technologies, artificial intelligence-assisted drug discovery, systems pharmacology, and precision medicine approaches may further accelerate the identification of novel therapeutic candidates from *M. longifolia*. Such multidisciplinary investigations will provide robust scientific validation of its traditional medicinal uses, facilitate regulatory approval, and promote the integration of Mahua-based products into evidence-based modern healthcare. Although current preclinical findings strongly support the therapeutic potential of *Madhuca longifolia*, its successful translation into clinical practice ultimately depends on rigorous human clinical research and the development of standardized, safe, and effective pharmaceutical formulations.

CONCLUSION

Madhuca longifolia (J.F. Gmel.) J.F. Macbr. (Mahua) is one of the most valuable indigenous multipurpose tree species of the Indian subcontinent, possessing exceptional ethnomedicinal, nutritional, ecological, and socioeconomic importance. For centuries, it has occupied a prominent position in Ayurveda, Siddha, Unani, and various indigenous healthcare systems, where its flowers, leaves, bark, fruits, seeds, and seed oil have been extensively utilized for the treatment of diabetes, inflammatory disorders, respiratory diseases, gastrointestinal ailments, skin infections, wound healing, liver disorders, reproductive problems, and general debility. The continued reliance of tribal communities on Mahua further highlights its indispensable role in traditional healthcare, food security, and rural livelihoods.

Phytochemical investigations conducted over the past six decades have revealed that *M. longifolia* is an abundant source of biologically active constituents, including triterpenoids, triterpenoid saponins, flavonoids, phenolic compounds, phytosterols, glycosides, fatty acids, tannins, vitamins, and essential minerals. These compounds are responsible for its broad spectrum of pharmacological activities, including antioxidant, anti-inflammatory, antimicrobial, antidiabetic, hepatoprotective, gastroprotective, wound-healing, analgesic, immunomodulatory, antiviral, spermicidal, and anticancer effects. Modern analytical techniques such as HPLC, LC–MS/MS, GC–MS, metabolomics, and molecular pharmacology have substantially improved our understanding of its phytochemical diversity and therapeutic mechanisms.

In addition to its medicinal significance, Mahua is recognized as an important nutraceutical and industrial crop. Its carbohydrate-rich flowers serve as valuable nutritional resources and raw materials for fermented beverages, bioethanol, confectionery products, and functional foods, whereas its oil-rich seeds provide renewable feedstock for edible fats, cosmetics, pharmaceuticals, soaps, lubricants, and biodiesel production. Recent advances in biotechnology, including tissue culture, germplasm conservation, metabolic engineering, nanobiotechnology, and phytopharmaceutical development, have further expanded the commercial potential of this species.

Although numerous experimental studies have validated many traditional medicinal claims, high-quality clinical evidence remains limited. Most pharmacological investigations have been confined to in vitro and animal studies, with relatively few well-designed human clinical trials. Therefore, future research should prioritize standardized extract development, identification of bioactive marker compounds, pharmacokinetic investigations, toxicological evaluation, molecular mechanism studies, randomized controlled clinical trials, and evidence-based formulation development. Integration of modern omics technologies, artificial intelligence-assisted drug discovery, systems pharmacology, and precision medicine approaches may accelerate the identification of novel therapeutic agents from *Madhuca longifolia*.

Furthermore, increasing anthropogenic pressures, habitat degradation, overexploitation, and climate change necessitate the implementation of comprehensive conservation and sustainable utilization strategies. Large-scale cultivation, ex situ and in situ conservation, community-based resource management, and value-addition initiatives will not only conserve this ecologically important species but also enhance the livelihoods of forest-dependent and tribal communities.

In conclusion, *Madhuca longifolia* represents a remarkable example of a traditional medicinal tree whose historical importance is increasingly supported by contemporary scientific evidence. Its unique combination of nutritional value, diverse phytochemistry, wide-ranging pharmacological activities, industrial applications, and biotechnological potential makes it a highly promising candidate for the development of future phytopharmaceuticals, nutraceuticals, cosmeceuticals, and sustainable bio-based products. Continued multidisciplinary research integrating ethnobotany, phytochemistry, pharmacology, biotechnology, clinical medicine, and conservation biology will be essential for fully realizing the therapeutic and commercial potential of this "Tree of Life" while ensuring its sustainable utilization for future generations.

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