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The Value Chain Transformation of *Madhuca longifolia* Deoiled Cake: A Critical Assessment of Saponin Valorization and Its Implications in Different Industries

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Abstract
Madhuca longifolia (Mahua), a multipurpose tree of the Sapotaceae family, produces large amounts of deoiled seed cake as a byproduct of oil extraction. This cake contains 4-8% saponins along with proteins, fibres, and minerals. This review examines how it can be transformed into a valuable resource through saponin valorization, covering extraction methods, industrial uses, and sustainability. We discuss conventional and biotechnological methods, including solvent, supercritical fluid, ultrasound-assisted, microwave-assisted, and enzyme-assisted extraction. Saponins find applications in pharmaceutical, nutraceutical, cosmetic, detergent, biopesticide, and food sectors. The review also considers technical challenges in extraction and purification, economic concerns around processing costs versus market value, and the environmental benefits of waste valorization and circular economy integration. Special attention is given to Chhattisgarh, where Mahua is an important minor forest produce supporting tribal livelihoods, with a single tree capable of earning Rs. 40,000-50,000 a year. The review identifies gaps in biorefinery integration, standardized protocols, life cycle assessments, and region-specific value chains, and offers a roadmap for turning Mahua deoiled cake from an underused waste stream into a high-value bioactive resource supporting sustainable rural development and the circular bioeconomy.

Keywords: Madhuca longifolia, saponin valorization, deoiled cake, value chain transformation, biorefinery, circular economy, Chhattisgarh, sustainable development

Introduction
The push for sustainable resource use and circular economy thinking has increased interest in valorizing agricultural and industrial byproducts. Oilseed cakes are one such resource, often underused even though they contain valuable bioactive compounds [1]. *Madhuca longifolia* (J. Koenig ex L.) J.F. Macbr., known as Mahua or butter nut tree, is an economically and culturally important species native to the Indian subcontinent and especially common in central India [2, 3]. The tree provides edible flowers, seed oil (Mahua butter), and large amounts of deoiled seed cake left over from oil extraction. This cake, long treated as waste or low-value cattle feed after detoxification, holds 4-8% saponins together with proteins (20-25%), fibres, and minerals [1, 4]. Saponins are amphipathic glycosides made of a water-repelling aglycone (sapogenin) joined to water-loving sugar units, and they show antimicrobial, anticancer, anti-inflammatory, immunomodulatory, and surfactant activities [2, 3]. These properties make Mahua saponins useful for pharmaceutical, nutraceutical, cosmetic, detergent, and agricultural products [5, 6]. Despite this potential, systematic use of the cake for saponin recovery is still limited, especially in major producing regions like Chhattisgarh, which has a large tribal population and extensive Mahua cultivation [7, 8]. The state's forest communities use Mahua flowers for food and drinks and process seeds for oil, leaving the cake largely unused [9]. This review examines how the cake can be transformed through saponin valorization, covering extraction technologies, industrial applications, and the technical, economic, and environmental sides of the process, with particular focus on Chhattisgarh [10, 11].

Madhuca longifolia and the Chhattisgarh Context

Madhuca longifolia (syn. *Madhuca indica*, *Bassia longifolia*) of the family Sapotaceae is a large deciduous tree reaching 16-20 m with thick dark grey bark, elliptic-oblong leaves, and fragrant cream-coloured flowers appearing from February to April [3,6,12]. The fruits are fleshy berries holding 1-4 seeds made up of about 50-70% kernel and 30-50% seed coat [13]. The species grows across the subtropical Indian subcontinent and extends to Sri Lanka, Myanmar, and Nepal [2, 14]. In India it is common in Madhya Pradesh, Chhattisgarh, Jharkhand, Odisha, Maharashtra, Gujarat, Andhra Pradesh, and Tamil Nadu, growing in dry deciduous forests up to 1200 m and tolerating poor soils and moderate drought, which suits it to agroforestry on marginal land [3, 6, 15]. The plant is rich in secondary metabolites such as sapogenins, triterpenoids, steroids, saponins, flavonoids, glycosides, tannins, and phenolics [2, 3, 12]. Seeds contain 33-43% oil (Mahua butter), a semi-solid yellowish fat made mainly of oleic, stearic, palmitic, and linoleic acids [7, 13]. The remaining deoiled cake keeps much of the protein, saponins, and other actives, a valuable but underused resource [1, 4]. Chhattisgarh in central India is one of the most important regions for Mahua, where the tree is a key minor forest produce supporting rural and tribal livelihoods [7, 8]. About 32% of the state's people are tribal, and many live in forest areas where Mahua is abundant; the tree has deep cultural, spiritual, and economic value, and communities hold traditional knowledge for harvesting and processing it [7–9]. In the Central Bastar region, a single tree can give a farmer Rs. 40,000-50,000 a year through flower and seed sales. Flowers, gathered in March-April, are eaten fresh or dried and fermented into Mahua liquor; found 10-15 households per village brewing a beverage with 7-9% alcohol. Seeds are pressed for oil used in cooking and in soap and detergent making, and while the Chhattisgarh Minor Forest Produce Federation handles some processing and trade, value addition stays limited [6,7,9].The cake is mostly used as cattle feed after detoxification, or for biogas, compost, and fertilizer, while its saponin value remains untapped [4].

Composition of the Deoiled Cake

Mahua deoiled cake is the solid residue left after oil is removed from the seeds. Its composition depends on the extraction method, seed variety, and processing conditions, but it generally holds 20-25% crude protein, 8-12% residual oil, 10-15% crude fibre, 5-8% ash, and 8-10% moisture. The protein fraction is notable: showed the cake flour and its protein isolate have real potential for food use. The cake also supplies calcium, phosphorus, potassium, magnesium, iron, and trace elements, plus dietary fibre, though anti-nutritional saponins have traditionally limited its direct use [1, 4, 16]. Saponins are the most important bioactive part of the cake, present at 4-8% by dry weight. These amphipathic glycosides have a triterpenoid or steroid aglycone (sapogenin) linked to one or more sugar chains. Identified sapogenins include oleanolic and ursolic acid and related structures, while the sugars include glucose, galactose, rhamnose, arabinose, and xylose [2, 3, 12]. This variety gives the saponins their surfactant behaviour, membrane-permeabilizing effects, and interactions with cholesterol and other sterols. Their amphipathic nature lets them form stable foams, explaining the traditional use of the cake for washing, but also causes bitterness and toxicity requiring detoxification before feeding [5]. Besides saponins, the cake contains flavonoids such as quercetin and kaempferol with antioxidant and anti-inflammatory action, plus phenolics and tannins. Phytosterols like β-sitosterol, stigmasterol, and campesterol in the residual oil add cholesterol-lowering and immunomodulatory effects, and the protein fraction shows useful emulsifying, foaming, and gelling properties [16].

Extraction and Purification Technologies

Conventional solvent extraction is still the most common way to recover saponins, using polar solvents such as methanol, ethanol, or aqueous ethanol, with yield depending on solvent, temperature, solid-to-solvent ratio, time, and pH. Ethanol-water mixtures of 50-80% ethanol are preferred because they extract saponins well, pull in fewer unwanted compounds, and are less toxic than methanol. The process involves grinding, solid-liquid extraction, filtration, concentration, and purification by maceration, percolation, or Soxhlet extraction [10]. Aqueous extraction is cheap and safe but co-extracts more impurities. Aqueous Mahua flower extracts had stronger antibacterial activity than methanolic ones, showing solvent choice affects both yield and activity [17]. The main drawbacks of conventional methods are long times, high solvent use, possible thermal damage, and poor selectivity [18]. These limits have driven green technologies. Supercritical CO_2 extraction works at mild conditions (31.1°C, 7.38 MPa), is non-toxic and non-flammable, and leaves no solvent residue; for polar saponins the CO_2 is usually modified with ethanol, and it is fast and selective but costly, limiting use in developing regions [19]. Ultrasound-assisted extraction uses sound waves (20-100 kHz) whose cavitation breaks cell walls and cuts extraction time from hours to minutes while keeping yields high; it is simple, low-cost, and scalable, suiting regions like Chhattisgarh [10,18]. Microwave-assisted extraction heats solvent and matrix quickly, finishing in 5-30 minutes with less solvent and good yields, though heat-sensitive compounds need care [10]. Enzyme-assisted extraction uses cellulases, pectinases, and proteases to break down cell walls under mild conditions, suiting the lignocellulosic cake matrix; enzyme cost and pH sensitivity are challenges, but cheaper enzymes and combination with ultrasound or microwave are improving its viability [11]. Crude extracts then need purification. Options include liquid-liquid extraction with n-butanol or ethyl acetate, precipitation, chromatography, and membrane separation [10]. Macroporous resin adsorption is effective and scalable, shown for soapnut saponins [20], and foam separation uses the saponins' own surfactant nature. HPLC and preparative HPLC give high-resolution separation for pharmaceutical-grade material, while ultrafiltration and nanofiltration concentrate extracts by molecular weight. Characterization relies on UV-visible spectrophotometry for total saponins, HPLC for composition, and NMR and mass spectrometry for structure. Optimization uses response surface methodology, and scale-up needs attention to heat and mass transfer, continuous processing, and techno-economic and life cycle analysis [10, 18].

Industrial Applications of Mahua Saponins

Mahua saponins possess diverse industrial applications owing to their biological and surface-active properties. In the pharmaceutical sector, they exhibit antimicrobial, antioxidant, anti-inflammatory, antiulcer, cardioprotective, anticancer, immunomodulatory, and hypoglycemic activities, acting against Gram-positive and Gram-negative bacteria and inducing anticancer effects through apoptosis, cell cycle arrest, and angiogenesis inhibition. Their natural origin and health-promoting properties also make them attractive nutraceutical ingredients with potential cholesterol-lowering, immune-boosting, antioxidant, and adaptogenic benefits, although issues related to bioavailability, dosage, safety, and standardization require further investigation [2, 3, 21]. In cosmetics and personal care products, Mahua saponins function as mild natural surfactants, providing stable foam along with antimicrobial, antioxidant, anti-inflammatory, and wound-healing benefits. Their biodegradability, cleaning efficiency, foaming capacity, and antimicrobial properties also support their use as eco-friendly alternatives to synthetic surfactants in detergents and cleaning formulations [5–7, 15]. In agriculture, Mahua saponins exhibit insecticidal, fungicidal, molluscicidal, and mosquito-repellent activities, while residual cake can be utilized as organic fertilizer, compost, or biogas substrate. Although direct food applications of saponins are limited by bitterness and toxicity, they can serve as natural emulsifiers, foaming agents, and preservatives, whereas protein-rich cake remaining after saponin removal has potential applications in bakery, meat, and beverage products. Furthermore, emerging applications such as nanoparticle-based drug delivery, biodiesel production, animal feed, aquaculture, wastewater treatment, soil remediation, and biogas generation highlight the potential of Mahua-based biorefineries and circular bioeconomy approaches [4, 12, 16, 17].

Critical Assessment

Conventional extraction is slow, solvent-heavy, and poorly selective, and the complex cake matrix of protein, fibre, and residual oil makes clean saponin recovery hard; green technologies help but are not yet optimized for Mahua. Crude extracts need extensive purification, and the lack of standard protocols leads to variable quality. The saponins' structural diversity complicates characterization and demands NMR and MS that may not be available locally [2]. Saponins also have poor oral bioavailability and need delivery systems, while their hemolytic activity and toxicity at high doses make safety studies essential.

The cake is currently a low-value byproduct, so raw material is cheap, but reliable collection, transport, and storage need investment, especially given seasonal seed availability [8]. Conventional extraction has low capital but high running costs, while green methods cost more upfront; ultrasound and enzyme methods may offer the best balance for small and medium operations [11, 19].Saponin prices range from a few dollars per kilogram for crude extract to hundreds for pharmaceutical grade, and the low 4-8% content means large volumes must be processed, so viability depends on high efficiency and access to high-value markets. An integrated biorefinery that also recovers protein, fibre, and energy spreads costs across products, and value addition can raise the Rs. 40,000-50,000 per tree income provided benefits reach tribal communities fairly [1, 16, 22].

Turning the cake into saponins and then recovering protein and energy embodies circular economy principles and reduces waste. Conventional solvents raise emission and footprint concerns, while green methods cut solvent and energy use [19]. Saponins are biodegradable and low-persistence, better than synthetic surfactants, though toxic to fish and needing careful use. Mahua trees aid carbon sequestration, soil conservation, and biodiversity, so sustainable harvesting matters, and full life cycle assessment is needed to confirm benefits [15].

Major saponin sources include soapnut, quinoa, yucca, quillaja, ginseng, and legumes; soapnut is common in detergents, quillaja is an approved food additive, and ginseng saponins fetch premium prices [20] Mahua's advantages are abundant Indian supply, existing oil infrastructure, diverse activities, cultural acceptance, and biorefinery potential, while its disadvantages are lower saponin content than soapnut, limited research, no standard protocols, few regulatory approvals, and underdeveloped markets.

Value Chain Transformation and Circular Economy

The current Mahua value chain is simple and traditional. Trees grow naturally with little management, and communities collect flowers in March-April and seeds in May-July, mostly for home use and local sale, with poor storage causing losses [23]. Flowers are eaten, dried, fermented, or made into local foods, while seeds are pressed for oil used in cooking, soap, and biodiesel, and the cake goes to feed, biogas, or fertilizer [4, 24]. An integrated biorefinery offers a way forward by extracting value in sequence: oil first, then saponins from the cake, then protein from the residue, and finally fibre and biomass for biogas or agriculture [25]. This cascade needs careful process integration, since the oil extraction method affects the cake and the saponin solvent affects protein recovery.

In Chhattisgarh, Mahua use follows traditional patterns with little modern value addition identified as a promising minor forest produce. Post-harvest practices in the Narayanpur forest area, where liquor is a common product handled by the MFP Federation. As noted, current uses centre on flowers for food and brewing, seeds for oil, and cake for feed, biogas, and fertilizer. Systematic saponin extraction is essentially absent, a major missed opportunity, though existing oil infrastructure and traditional knowledge provide a foundation for upgrading. Mahua is central to tribal and rural livelihoods, providing income, seasonal employment, women's participation, and cultural value. But current chains capture little potential value, with intermediaries taking the larger share and collectors getting low prices; community-owned or cooperative processing could improve income retention and equitable benefit sharing. The policy framework helps in parts but has gaps. Mahua is a minor forest produce with collection rights vested in communities under the Forest Rights Act, 2006, and PESA, 1996, but unclear tenure and weak support hinder community management, and the MFP Federation has limited capacity for value addition. State-specific saponin research is scarce, quality standards and certification are absent, and credit access is limited.

Future opportunities are strong. A network of small to medium biorefineries across Mahua districts such as Bastar, Kanker, Narayanpur, and Sukma could boost value capture and rural development. Branded saponin products for pharmaceutical, cosmetic, detergent, and biopesticide markets, sold with a sustainability and tribal-heritage story and possibly aided by geographic indication status, could earn premium prices. Capacity building through training centres and women's self-help groups, sustainable resource management including enrichment planting and certification, and stronger policy and institutional support would all help realize this potential [15].

Future Perspectives and Research Gaps

On technology, systematic comparison and optimization of extraction methods for Mahua saponins is needed, along with techno-economic and environmental assessment and hybrid methods that exploit synergies. Scalable purification using macroporous resin, foam separation, membrane, and chromatographic methods should be developed for Mahua, and full structural characterization by HPLC-MS and NMR is needed for quality control and structure-activity links. Formulations that improve stability and bioavailability, and process engineering for an integrated biorefinery with pilot-scale demonstration, would prove feasibility and inform scale-up [5].

On markets and society, specific products for pharmaceutical, cosmetic, detergent, and biopesticide uses need formulation work, efficacy testing, and regulatory approval from bodies such as FSSAI and CDSCO, supported by market research, complete value chains with fair benefit sharing, and strong branding around natural origin, sustainability, and tribal livelihoods. Comprehensive life cycle and socioeconomic assessment, sustainable harvesting and cultivation research, documentation of traditional knowledge, and supportive policy research are also needed. Together these priorities call for collaboration among scientists, industry, government, and communities.

Conclusion

Madhuca longifolia deoiled cake, traditionally regarded as a low-value byproduct of oil extraction, represents a promising and underutilized source of bioactive saponins with applications across pharmaceutical, nutraceutical, cosmetic, detergent, agricultural, and environmental sectors. The presence of 4–8% saponins, together with valuable proteins, fibres, and minerals, provides significant opportunities for value addition and sustainable resource utilization. Advances in extraction and purification technologies, including ultrasound-assisted, microwave-assisted, enzyme-assisted, supercritical fluid extraction, and membrane-based separation, offer potential routes for efficient saponin recovery, although standardized protocols and large-scale validation for Mahua remain limited.

The valorization of Mahua deoiled cake aligns strongly with circular economy and biorefinery concepts by enabling the sequential recovery of oil, saponins, proteins, and energy-rich residues, thereby minimizing waste generation and maximizing resource efficiency. Such an approach can improve the economic value of Mahua-based supply chains while creating opportunities for rural entrepreneurship and livelihood enhancement. This is particularly relevant in Chhattisgarh and other Mahua-growing regions, where the species plays an important socio-economic role in tribal communities but currently generates limited value beyond conventional uses. Despite its considerable potential, several challenges remain, including low extraction efficiency, variability in raw material composition, lack of standardized quality parameters, limited toxicological and bioavailability data, insufficient techno-economic assessments, and the absence of well-established commercial value chains. Future research should focus on optimized extraction and purification processes, detailed structural characterization of Mahua saponins, product development, life-cycle assessment, and pilot-scale biorefinery demonstrations. With appropriate scientific, industrial, and policy support, Mahua deoiled cake can be transformed from an underexploited agroforestry byproduct into a high-value bioresource that contributes to sustainable industrial development, rural prosperity, and the advancement of a circular bioeconomy.

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