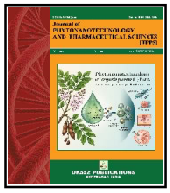
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Aegle marmelos (L.) Correa: Ethnomedicinal significance, phytochemical profile, pharmacological activities, and therapeutic prospects

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Abstract

Aegle marmelos (L.) Correa, commonly known as bael, Bengal quince, or the sacred fruit tree, is a thorny deciduous tree of the family Rutaceae that occupies a central place in Indian traditional medicine, religious practice, and cuisine. Native to the Indian subcontinent and now naturalized across South and Southeast Asia, every part of the tree; root, bark, leaf, flower, fruit, and seed have a documented place in Ayurvedic, Siddha, Unani, and folk medicine systems. The plant is chemically distinguished by coumarins (marmelosin, marmin, imperatorin), alkaloids (aegeline, marmeline), flavonoids, tannins, terpenoids, and essential oils that together underlie its wide pharmacological repertoire, including antidiabetic, antidiarrheal, antimicrobial, hepatoprotective, cardioprotective, radioprotective, anti-inflammatory, antioxidant, immunomodulatory, and anticancer effects. Preclinical work in rodent models consistently supports these traditional claims, and acute and subacute toxicity studies indicate a wide margin of safety, with reported notoxiceffect doses in the multigram per kilogram range. Human studies remain comparatively few and are dominated by small, shortduration, and often unblinded trials of leaf or fruit-pulp preparations in type 2 diabetes, which show modest and inconsistent glycemic benefit. Emerging work has also explored bael mediated green synthesis of silver, gold, zinc oxide, and selenium nanoparticles as a route to enhanced antimicrobial and delivery applications. This review consolidates the ethnobotanical background, phytochemistry, pharmacology, clinical evidence, novel delivery approaches, and safety profile of *A. marmelos*, and outlines the research needed standardized extracts, mechanistic studies, and adequately powered clinical trialsto move this long-used botanical toward validated modern therapeutic use.

1. Introduction

Plants have supplied the foundation of human therapeutics since antiquity, and traditional systems built on plant derived remedies continue to serve a large share of the world's population, particularly in developing regions where herbal medicine remains the first and most accessible line of care. India, home to one of the richest floristic and ethnomedicinal traditions in the world, has documented several hundred plant species within Ayurveda, Siddha, and Unani texts, many of which retain contemporary relevance as subjects of pharmacological validation. Among these, *A. marmelos* occupies an unusually prominent cultural and medicinal position. Known widely as bael, Bengal quince, golden apple, stone apple, or wood apple, and revered in Hindu tradition as the bilva tree sacred to Lord Shiva, *A. marmelos* is the sole species of the monotypic genus *Aegle* within the citrus family Rutaceae (Manandhar *et al*., 2018; Bhar *et al*., 2019).

A. marmelos is indigenous to the Indian subcontinent and is now found growing wild or cultivated across Pakistan, Bangladesh, Sri Lanka, Nepal, Myanmar, Thailand, and parts of Indo-China, having also been introduced to East Africa and tropical America (Manandhar *et al*., 2018). Unlike many medicinal plants whose use is confined to a single plant part, virtually every organ of the bael tree; root, stem bark, leaves, flowers, unripe and ripe fruit, seeds, and even the gummy exudate has a distinct place in traditional pharmacopoeias (Baliga *et al*., 2011; Mahato and Kumar, 2021). The unripe fruit has long been prized for managing diarrhea and dysentery (Vrushabendra Swamy *et al*., 2007), the leaves are chewed or taken as a decoction for glycemic control and general debility (Nigam and Nambiar, 2019), and the aromatic ripe fruit pulp is consumed as a refreshing drink (bael sharbat) and functional food across the Indian summer season (Baliga *et al*., 2011). This dual identity as food and medicine mirrors that of other Indian ethnobotanicals and reflects a long history of empirical use that modern phytochemistry and pharmacology are now beginning to substantiate mechanistically.

Despite this depth of traditional use, *A. marmelos* remains comparatively under-capitalized as a standardized nutraceutical or phytopharmaceutical when set against its scientific promise. Existing literature on the plant is fragmented across phytochemical surveys, isolated pharmacological assays, and a handful of small clinical trials, without a single accepted standardized extract or dosing regimen (Manandhar *et al*., 2018). This review brings together the ethnobotanical background, botanical description, phytochemical composition, pharmacological evidence, clinical findings, emerging nanotechnological applications, and toxicological profile of

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A. marmelos, with the aim of clarifying both what is well established and what remains to be investigated before the plant's traditional reputation can be more fully translated into validated modern therapeutics.

1.1 Botanical description

A. marmelos is a slow growing, deciduous shrub or small to medium sized tree reaching 8-15 m in height, with a short trunk, thick flaking bark, and a spreading, often irregular crown of drooping branches (Bhar *et al*., 2019). The bark is pale brown to grayish and finely fissured, and the branches as well as young suckers bear stiff, straight axillary spines up to 1-2.5 cm long, occurring singly or in pairs. Wounded stems exude a clear, gum-arabic-like sap that hardens into long, sweet-tasting strands with a mildly irritating aftertaste.

The leaves are alternate and trifoliate, composed of three (occasionally five) ovate, pointed leaflets, 4-14 cm long, that are toothed or shallowly crenate at the margin; the terminal leaflet bears a distinctly longer petiole than the lateral pair. New foliage emerges glossy and pinkishmaroon before maturing to a smooth dark green, and crushed leaves release a characteristic citruslike, somewhat disagreeable odour owing to their glandular oil content an anatomical hallmark of the Rutaceae (Karki, 2022). Fragrant, greenishwhite to pale yellow flowers, each with four to five fleshy recurved petals and numerous stamens, arise in small axillary clusters on young branchlets, generally appearing together with new leaf flush.

The fruit is a large, globose to slightly pear-shaped berry, 5-20 cm in diameter, encased in a thick, hard, woody shell that is gray-green while unripe and turns yellow on maturation. Internally, the fruit is divided into 8-20 wedge-shaped segments containing an aromatic, paleorange, sweet and resinous pulp in which numerous woollies, mucilage-coated seeds are embedded (Baliga *et al*., 2011). This combination of a hard protective rind and a soft, fragrant interior give the fruit both a long shelf-life and strong culinary appeal, features that likely contributed to its early adoption as both food and medicine.

1.2 Geographical distribution

A. marmelos is native to the dry deciduous forests and scrublands of the Indian subcontinent, occurring naturally from the sub-Himalayan tracts and northern plains down through peninsular India, and ascending to elevations of roughly 1,200 m in the western Himalaya (Manandhar *et al*., 2018). It has become naturalized across Pakistan, Bangladesh, Sri Lanka, and Nepal, and is cultivated or found semi-wild in Myanmar, Thailand, and other parts of Indo-China (Manandhar *et al*., 2018; Karki, 2022). Beyond its native range, the species has been introduced into East Africa, the Caribbean, and other tropical regions largely for its fruit and ornamental or religious value. The tree tolerates a wide range of soils, drought, and heat, which made it much like other resilient dryzone medicinal plants of India; a dependable and widely accessible resource for rural and tribal communities. In many parts of India, it is grown in home gardens, temple compounds, and as a roadside or boundary tree, reflecting both its religious significance and its everyday utility as a food-yielding, hardy species (Bhar *et al*., 2019).

1.3 Ethnomedicinal and traditional uses

A. marmelos has been used in the Indian subcontinent for well over two millennia, and virtually every part of the plant appears in classical Ayurvedic formularies as well as in folk and tribal medicine (Baliga *et al*., 2011; Mahato and Kumar, 2021).

1.3.1 Gastrointestinal and antidiarrheal use

The unripe fruit is the most celebrated part of the plant in traditional practice, prepared as a decoction, powder, or marmaladelike preserve and administered for acute and chronic diarrhoea, dysentery, and other digestive complaints (Baliga *et al*., 2011; Vrushabendra Swamy *et al*., 2007). This use is attributed to its tannin and mucilage content, believed to exert an astringent, mucosal-protective, and mild antimicrobial action on the gut lining.

1.3.2 Antidiabetic and metabolic use

Leaf decoctions and chewed fresh leaves have long been used by rural and tribal communities to help control blood sugar (Nigam and Nambiar, 2019), and the plant is frequently listed alongside other Indian antidiabetic botanicalsin ethnobotanical surveys of hypoglycemic plants.

1.3.3 Culinary and nutritional uses

The ripe fruit pulp is consumed fresh, dried, or made into a popular cooling beverage (bael sharbat), jam, or squash, particularly in the hot summer months in India, where it is valued for its digestive and rehydrating properties (Baliga *et al*., 2011). Young leaves are occasionally used in regional cuisines of Southeast Asia as a flavouring in dipping sauces.

1.3.4 Other traditional applications

Root, bark, and leaf preparations have been used traditionally for fever, respiratory ailments, inflammation, pain, jaundice, peptic ulcer, and as a general tonic (Manandhar *et al*., 2018), while the tree itself holds deep religious significance in Hinduism and Buddhism, with its trifoliate leaves offered in the worship of Lord Shiva. Ethnopharmacological surveys additionally record antifertility, woundhealing, and anthelmintic uses in various regional folk traditions (Mahato and Kumar, 2021).

2. Phytochemical profile of *A. marmelos*

The therapeutic versatility of *A. marmelos* is underpinned by a chemically diverse profile that varies meaningfully between plant parts. The leaves, unripe fruit, bark, and seeds each show distinct concentrations of the plant's principal constituent classes: coumarins, alkaloids, flavonoids, tannins, terpenoids, and essential oils (Manandhar *et al*., 2018).

Coumarins are the most pharmacologically prominent class isolated from bael, with marmelosin (also called aegelinol or imperatorinrelated furanocoumarins depending on nomenclature), marmin, marmesinin, and related furanocoumarin derivatives concentrated mainly in the fruit and root (Baliga *et al*., 2011). These compounds have been linked to the plant's antidiabetic, anti-inflammatory, and antimicrobial actions. The alkaloid aegeline, together with related imidazole alkaloids such as marmeline, is a defining constituent of the leaves and has been repeatedly implicated in the plant's hypoglycemic and hypolipidemic effects (Manandhar *et al*., 2018; Mujeeb *et al*., 2014), although aegeline containing weightloss supplements have separately drawn regulatory scrutiny in some markets for hepatotoxicity concerns unrelated to the whole plant traditional use, underscoring the importance of using well characterized, standardized extracts rather than isolated high dose alkaloid concentrates.

Flavonoids (including rutin and quercetin type glycosides), tannins, phenolic acids, and terpenoids are broadly distributed across leaf,

bark, and fruit tissue and are principally responsible for the plant's antioxidant and radical scavenging capacity (Dheeba *et al*., 2010; Mujeeb *et al*., 2014). The seeds and fruit pulp additionally yield fixed oils, mucilage, and pectinlike polysaccharides that likely contribute to the demulcent, mucosal protective action traditionally exploited in antidiarrheal preparations. Essential oil analyses of the leaves have identified monoterpenes and sesquiterpenes such as limonene, α-pinene, and caryophyllene as major volatile constituents, consistent with the characteristic citrus-like scent of crushed foliage (Karki, 2022).

Table 1: Extraction, identification, and principal phytoconstituents of key parts of *A. marmelos*

Plant part	Extraction technique	Identification/ characterization	Major phytoconstituents	Illustrative activities	References
Leaves	Methanol/ethanol/ aqueous extraction; Soxhlet extraction	GC-MS, HPLC, FTIR, phytochemical screening	Aegeline, marmeline, flavonoids, tannins, essential oil (limonene, caryophyllene)	Antidiabetic, antioxidant, anti-inflammatory, antimicrobial	Mujeeb *et al*., 2014; Karki, 2022; Ahmad *et al*., 2021
Unripe fruit	Aqueous decoction, hydroalcoholic extraction	Colorimetric assays, HPLC, GC-MS	Marmelosin, tannins, mucilage/pectin, phenolics	Antidiarrheal, antiulcer, anti-inflammatory	Baliga *et al*., 2011; Vrushabendra Swamy *et al*., 2007
Ripe fruit pulp	Aqueous/hydroalcoholic extraction	Spectrophotometric antioxidant assays	Carotenoids, sugars, vitamin C, phenolics	Antioxidant, nutritional/functional food use	Baliga *et al*., 2011
Root/ stem bark	Methanolic/ethanolic Soxhlet extraction	TLC, HPLC, spectroscopic elucidation	Marmin, coumarins, alkaloids	Antidiarrheal, antipyretic, anti-inflammatory	Dheeba *et al*., 2010; Vrushabendra Swamy *et al*., 2007
Seeds	Solvent (petroleum ether, ethanol) extraction	GC-MS, fattyacid profiling	Fixed oils, fatty acids, tannins	Wound healing, anthelmintic	Mahato and Kumar, 2021

3. Pharmacological potential of *A. marmelos*: Experimental evidence and bioactive constituents

Extracts of *A. marmelos*, prepared from different plant parts and solvents, have been evaluated across a wide range of *in vitro* and *in vivo* models, with consistent support for antidiabetic, antidiarrheal, antimicrobial, hepatoprotective, cardioprotective, radioprotective, anti-inflammatory, antioxidant, immunomodulatory, and anticancer activity (Manandhar *et al*., 2018). As with many polyherbalgrade botanicals, most of this evidence derives from rodent models and cell-based assays rather than confirmatory human trials, but the consistency of effect across independent laboratories and extraction methods lends reasonable weight to the traditional indications.

Table 2: Summary of pharmacological activities of *A. marmelos*

Pharmacological activity	Experimental models/assays	Key findings	Putative bioactive constituents	References
Antidiabetic activity	Alloxan/streptozotocin -induced diabetic rats and mice; leaf decoction in human T2DM patients	Leaf extracts reduced fasting and postprandial blood glucose in rodents over 4-8 weeks; a decoction of 5 g leaf powder/day lowered postprandial glucose in a small human cohort over 16 weeks	Aegeline, marmeline, flavonoids	Birudu *et al*., 2020; Ahmad *et al*., 2021; Nigam and Nambiar, 2019
Antidiarrheal activity	Castoroiland magnesium-sulfateinduced diarrhea, PGE, induced enteropooling, charcoalmeal gastrointestinal transit in mice /rats	Leaf, fruit, and rootbark extracts significantly reduced diarrhoeal frequency and intestinal motility, with efficacy comparable to loperamide/atropine at higher doses	Tannins, mucilage, marmelosin	Vrushabendra Swamy *et al*., 2007; Baliga *et al*., 2011
Antioxidant activity	DPPH, FRAP, ABTS radicalscavenging assays; HepG2 and kidney fibr oblast cell models	Leaf and fruit extracts showed dose-dependent free-radical scavenging and reduced high-glucose-induced reactive oxygen species generation in cell culture	Flavonoids, phenolic acids, tannins	Ahmad *et al*., 2021; Dheeba *et al*., 2010; Venkatesan *et al*., 2024
Anti-inflammatory activity	Albumin denaturation assay; RT-qPCR of iNOS /TNF-α in high-glucose-stressed kidney fibroblasts	Reduced protein denaturation and downregulated inflammatory gene expression under hyperglycemic stress	Coumarins, flavonoids	Venkatesan *et al*., 2024

Hepatoprotective activity	CCl_4 and paracetamol-induced hepatotoxicity models in rats	Restoration of liver enzyme levels (ALT, AST, ALP) and histological improvement of hepatic architecture	Flavonoids, phenolics	Manandhar *et al*., 2018
Radioprotective activity	Mice exposed to graded doses of γ-radiation, pre-treated orally with fruit extract	Pretreatment increased LD50/30 from 8.1-8.2 Gy to 8.8-9.7 Gy, delayed radiation sickness and mortality, and reduced lipid peroxidation with elevated hepatic glutathione	Flavonoids, tannins, coumarins	Jagetia and Venkatesh, 2005; Jagetia *et al*., 2004
Anticancer/antiproliferative activity	Ehrlich ascites carcinoma-bearing mice; DMBA induced breast cancer in rats	Dose-dependent tumor remission and prolonged survival at optimal extract doses; reduced tumor volume with improved TNF and glucose biomarkers in a breast-cancer model	Coumarins, alkaloids	Jagetia *et al*., 2005
Immunomodulatory activity	Neutrophil adhesion test, carbon clearance assay, haemagglutination assay in rats/mice	Methanolic fruit extract enhanced both cellular and humoral immune parameters at 100-500 mg/kg	Flavonoids, alkaloids	Patel and Asdaq, 2010
Antimicrobial activity	Agar well/disc diffusion against Gram-positive and Gram-negative bacteria	Leaf and fruit extracts, and their green-synthesized nanoparticle derivatives, inhibited *S. aureus*, *E. coli*, *B. cereus*, and *P. aeruginosa*	Coumarins, tannins, essential oil constituents	Mujeeb *et al*., 2014; Devi *et al*., 2020; Patil *et al*., 2012
Cardioprotective activity	Isoproterenol induced myocardial injury models in rats	Reduced markers of cardiac oxidative stress and improved histopathological indices of myocardial damage	Flavonoids, phenolics	Manandhar *et al*., 2018

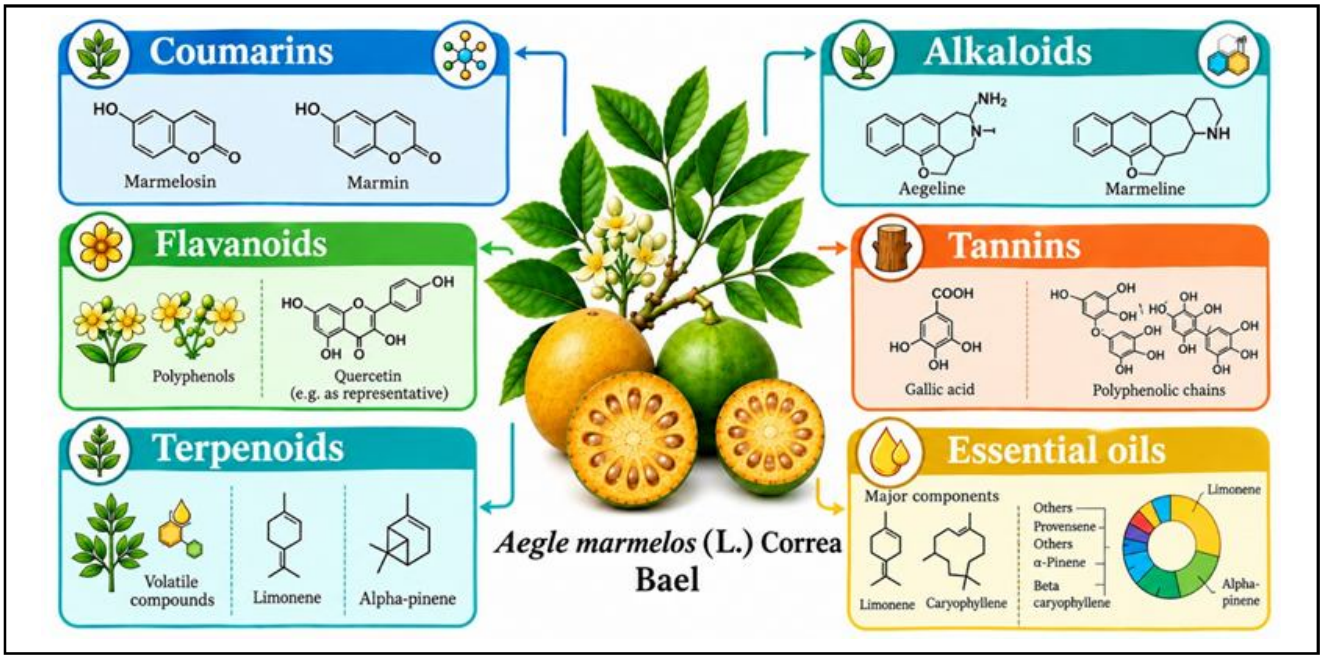


Figure 1: Phytochemical profile of *A. marmelos*.

4. Clinical evidence on *A. marmelos*

Human data on *A. marmelos* are limited in number, generally small in sample size, and concentrated on glycemic and gastrointestinal outcomes in type 2 diabetes mellitus (T2DM), with mixed results. In one small unblinded study, twenty T2DM patients given a daily decoction of 5 g dried leaf powder showed a significant reduction in postprandial blood glucose after 16 weeks (Ismail and Yaheya, 2009); a related short trial similarly found that a one-month leaf decoction potentiated the glucose-lowering effect of standard oral antidiabetic

drugs (Ismail and Yaheya, 2009). A separate randomized controlled trial in Gujarat, India, examined bael leaf juice as a complementary therapy in T2DM management, reporting improvements in glycemic parameters when the juice was added to conventional care (Nigam and Nambiar, 2019).

Crossover studies using the unripe fruit pulp of *A. marmelos* in T2DM patients at BIRDEM (Dhaka, Bangladesh) produced more equivocal results: fasting blood glucose did not differ significantly between intervention and control periods (Aziz *et al*., 2021), and a companion trial examining chronic subclinical inflammation (*via* high sensitivity C-reactive protein) likewise found no significant change relative to control (Aziz *et al*., 2021). A registered crossover trial in Sri Lanka evaluated a water extract of dried bael flowers for its hypoglycaemic effect over two weeks of continuous consumption, reflecting continued clinical interest in flower-based preparations though flower derived data remain sparse in the peer reviewed literature.

Taken together, the clinical picture for *A. marmelos* mirrors that seen with many traditionally used antidiabetic botanicals: while several small studies of leaf-based preparations suggest a modest glucose-lowering or adjunctive benefit (Nigam and Nambiar, 2019; Ismail and Yaheya, 2009), fruit-pulp preparations have not consistently reproduced this effect (Aziz *et al*., 2021), and no adequately powered, doubleblind, placebo-controlled trial has yet established a reliable dose-response relationship or defined which plant part and extraction method deliver the most consistent clinical benefit. Larger, standardized, and blinded trials ideally using well characterized extracts with quantified marker compound contents are needed before firm clinical recommendations can be made.

5. Novel drug delivery systems (NDDS) of *A. marmelos*

As with many phytochemically rich medicinal plants, *A. marmelos* extracts have increasingly been explored as reducing and capping agents in the green synthesis of metallic and metaloxide nanoparticles, offering an ecofriendly alternative to chemical synthesis routes while potentially enhancing the antimicrobial and therapeutic reach of the plant's bioactive constituents.

5.1 Silver nanoparticles (AgNPs)

Methanolic fruit extract (Devi *et al*., 2020) and aqueous leaf extract (Patil *et al*., 2012) of *A. marmelos* have both been used to biosynthesize silver nanoparticles, characterized by UV-Vis spectroscopy, FTIR, SEM, XRD, and zeta-potential analysis. Leaf extract derived AgNPs (average particle size approximately 15-30 nm) showed strong inhibitory activity against *Streptococcus pyogenes*, *Escherichia coli*, and *Pseudomonas aeruginosa* (Patil *et al*., 2012), while fruit extract derived AgNPs were most active against *B. cereus*, *P. aeruginosa*, and *E. coli*, generally out performing the corresponding crude solvent extracts (Devi *et al*., 2020). Microwave assisted synthesis combining *A. marmelos* with other plant extracts has also been reported as a rapid, energy efficient route to antibacterially active AgNPs (Kala *et al*., 2025).

5.2 Gold nanoparticles (AuNPs)

Optimized biosynthesis of gold nanoparticles from methanolic leaf extract, confirmed by UV-Vis spectroscopy, zeta-sizing, XRD, TEM, and FTIR, produced particles roughly 38 nm in size that showed a synergistic antibacterial effect against *E. faecalis*, *K. pneumoniae*, and *K. oxytoca* when combined with standard antibiotics (Anuradha and Manimekalai, 2019).

5.3 Selenium nanoparticles (SeNPs)

Aqueous fruit extract has also been used to co-synthesize selenium and gold nanoparticles in parallel, with both nanoparticle types showing strong antibacterial activity against *Micrococcus luteus*, *K. pneumoniae*, *S. epidermidis*, *P. aeruginosa*, and *S. aureus*, with the strongest effect observed against *S. epidermidis* (Sarkar *et al*., 2023).

5.4 Combination and photocatalytic applications

More recent work has synthesized AgNPs from *A. marmelos* leaf extract in combination with other botanicals (*e.g*., *Cissus quadrangularis*) to evaluate combined anti-inflammatory and antioxidant effects (Kovoor *et al*., 2024), broadening the plant's potential applications beyond direct oral or topical use into materials science and combination therapy nanomedicine.

6. Safety and toxicity profile of *A. marmelos*

A. marmelos extracts are generally regarded as safe within traditionally used and experimentally tested dose ranges, with a consistently favourable margin between effective and toxic doses across preclinical studies.

6.1 Acute and subacute toxicity in animal studies

Acute and subacute toxicity testing of *A. marmelos* extracts in rodents has not identified significant adverse effects at doses well above those used for pharmacological testing (Veerappan *et al*., 2007). Toxicity assessments of leaf and fruit extracts conducted alongside antidiarrheal, antidiabetic, and radioprotective studies have similarly reported no visible signs of toxicity in rats or mice at single oral doses of up to 2,000 mg/kg body weight (Birudu *et al*., 2020), and hydroalcoholic fruit extract used in radioprotection studies was found to be non-toxic up to the highest testable dose of 6,000 mg/kg body weight, the practical ceiling for oral administration in those experiments (Jagetia and Venkatesh, 2005).

6.2 Reported effects in human use

Direct clinical toxicity data in humans remain limited, but the extensive and long-standing dietary and medicinal use of bael fruit and leaf preparations across South Asia, without a documented pattern of serious adverse events, supports a favourable general safety impression. Clinical trials of leaf decoctions and fruit pulp over periods of several weeks have not reported significant hepatic, renal, or haematological abnormalities (Nigam and Nambiar, 2019; Aziz *et al*., 2021), although mild gastrointestinal effects cannot be ruled out with more concentrated or higher-dose preparations. It is worth noting that concerns regarding aegeline related hepatotoxicity have arisen specifically in the context of concentrated, highdose weightloss supplements combining isolated aegeline with other stimulant ingredients, rather than from traditional whole leaf or whole fruit preparations of *A. marmelos* (Manandhar *et al*., 2018), reinforcing the importance of distinguishing standardized whole extract use from isolated highdose alkaloid supplementation when assessing safety.

Table 3: Summary of toxicological studies on *A. marmelos* extracts

Study type	Extract/plant part	Dose range tested	Key findings	References
Acute oral toxicity (rats)	Ethanolic leaf extract	2,000 mg/kg	No mortality or overt toxicity signs	Veerappan *et al*., 2007
Acute oral toxicity (mice)	Ethanolic unripe-fruit extract	500-2,000 mg/kg	No visible toxicity at any dose tested	Birudu *et al*., 2020
Acute toxicity (mice, radioprotection study)	Hydroalcoholic fruit extract	Up to 6,000 mg/kg	Non-toxic at highest testable dose	Jagetia and Venkatesh, 2005
Subacute/repeated-dose studies	Methanolic leaf extract	100-250 mg/kg (28 days)	No significant adverse biochemical changes; supported antidiabetic efficacy findings	Jagetia *et al*., 2004
Human use (small clinical trials)	Leaf decoction, fruit pulp	5 g leaf powder/day; fruit pulp preparations (weeks)	No serious adverse events reported; mild gastrointestinal effects possible at higher doses	Nigam and Nambiar, 2019; Aziz *et al*., 2021

7. Future prospects

Despite its long ethnomedicinal history and broad preclinical pharmacological support, *A. marmelos* remains under-characterized relative to its therapeutic potential. Future research should prioritize: (i) standardization of extracts to defined marker compounds (*e.g*., marmelosin, aegeline content) to enable reproducible dosing across studies; (ii) mechanism based investigations clarifying the molecular targets underlying its antidiabetic, anti-inflammatory, and anticancer effects; (iii) adequately powered, randomized, double-blind, placebo-controlled clinical trials in metabolic and gastrointestinal indications, given the current reliance on small and often unblinded human studies; (iv) long-term toxicological and safety evaluation of standardized extracts, with particular attention to any alkaloid related hepatic risk at high or concentrated doses; and (v) continued exploration of nanoparticle-based and other novel delivery systems to improve bioavailability, targeting, and antimicrobial efficacy. Sustainable cultivation and post-harvest standardization will also be important to support any move toward commercial nutraceutical or phytopharmaceutical development.

8. Conclusion

A. marmelos is a botanically distinctive and ethnomedicinally significant tree whose fruit, leaves, bark, and roots have supported digestive, metabolic, and general health needs across the Indian subcontinent for millennia. Its phytochemical profilerich in coumarins, alkaloids, flavonoids, and tannins provide plausible mechanistic grounding for its traditionally claimed antidiarrheal, antidiabetic, antimicrobial, hepatoprotective, cardioprotective, radioprotective, and anti-inflammatory properties, and these effects are broadly reproduced across preclinical rodent and cell-based studies. Toxicological data indicate a wide safety margin in animal models, consistent with the plant's extensive dietary and medicinal use without a substantial record of serious harm, although isolated highdose alkaloid supplementation (as opposed to traditional whole extract use) warrants caution. Clinical evidence; however, remains sparse, small in scale, and inconsistent, particularly regarding fruit-based preparations, underscoring the need for larger and better controlled human trials before *A. marmelos* can be confidently positioned as a validated modern therapeutic agent. With continued phytochemical standardization, mechanistic research, and rigorous clinical evaluation, bael has clear potential to bridge its deep traditional heritage with an evidence-based role in contemporary integrative medicine, particularly in metabolic and gastrointestinal health.

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Availability of data and material

All data are provided within the manuscript.

Authorship contribution statement

H. B. Roghan: Conceptualization, academic oversight, critical review and validation of scientific content; **S. Vennila**: Writing, software handling and data curation.

Consent for publication

All authors gave full consent for publication and submission to this journal.

Ethical approval

Not applicable.

Conflict of interest

The authors declare no conflict of interest relevant to this article.

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