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THE SACRED BAEL TREE: ANCIENT HEALER MEETS MODERN MEDICINE

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ABSTRACT

Aegle marmelos. L (commonly known as Bael or Bilva) is a sacred and multifunctional medicinal tree deeply embedded in the traditional Indian healing systems of Ayurveda, Siddha, and Unani. Widely recognized for its curative potential, *A. marmelos* has been used for centuries to treat gastrointestinal, metabolic, respiratory, and inflammatory conditions. This review presents a comprehensive analysis of its phytochemical composition, therapeutic activities, traditional applications, and modern formulation approaches. Various plant parts leaves, fruits, bark, seeds, and roots, contain bioactive compounds such as flavonoids (rutin, quercetin), alkaloids (aegeline), coumarins (marmelosin), and tannins that contribute to its antidiabetic, antioxidant, antimicrobial, hepatoprotective, and anticancer properties. Novel delivery systems including nanoemulsions, phytosomes, and transdermal gels have been developed to enhance solubility, bioavailability, and therapeutic efficacy. However, despite promising preclinical evidence, clinical validation, pharmacokinetic profiling, and toxicological assessments remain limited. Biotechnological and genomic advancements offer new avenues for metabolite optimization and conservation of elite chemotypes. This review is based on a comprehensive literature search from Scopus, Web of Science, and PubMed databases. It underscores the urgent need for rigorous clinical trials, standardized formulations, and regulatory frameworks to establish *Aegle marmelos* as an evidence-based therapeutic in modern integrative medicine.

1. INTRODUCTION AND BOTANICAL OVERVIEW:

Aegle marmelos L (known as bael or Bilva) is an herb that is held in the highest regard in Ayurveda, Siddha, and Unani, traditional healing systems of India, and is referenced in the primary texts of Ayurveda and Siddha, the Charaka Samhita and Sushruta Samhita, for therapy of gastrointestinal, metabolic, respiratory, and inflammatory conditions [1–3]. The name "Bilva" or "Bael" is Sanskrit/folk, the trifoliate leaves of the tree symbolize Lord Shiva's trident and are used sacredly in Hindu practices [4–6]. Tribal and folk communities in India and Southeast Asia have used A. marmelos leaves, bark, fruit, roots, and seeds for medicine and treatment of diarrhea, fever, dysentery, diabetes, inflammation and even respiratory

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issues [1,3,7].

Botanically, A. marmelos is the sole species in the genus Aegle (in the family Rutaceae) and used to be indigenous to India, Sri Lanka, and Bangladesh but is now cultivated throughout Southeast Asia and some parts of Africa [3,8,9]. It is a small-medium sized deciduous tree of 12-15 m (40-49 ft) having spiny branches, greyish rough bark, and trifoliate aromatic branches used in rituals, [10]. The fruit is hard-shelled and contains sweet, mucilaginous pulp that also has fairly high concentrations of vitamins, minerals, bioactive compounds such as coumarins, alkaloids, and flavonoids [6,11,12]. The roots and seeds have plenty of value in folk pharmaceuticals.The bael tree is found in a range of ecological settings, from arid to semi-humid areas, and is tolerant to drought, high temperature, and variation in soil pH (5-10), thus making it well suited for agroforestry and the reclamation of marginal land [13-15]. The natural range of the tree is the Indian subcontinent, Part of Pakistan, Thailand, Malaysia, Myamnar, Africa, and the Caribbean [8].Despite its long history of being used in traditional systems, modern pharmacological validation, standardization, and regulatory classification of bael is limited [16]. Ethnomedicinal knowledge indicates universal benefit; however, clinical trials and systematic phytochemical standardization are absent. Therefore, this paper aims to link traditional knowledge with the modern scientific categorization and regulatory frameworks for *Aegle marmelos*, a complex multi-target botanicals with strong potential for evidence-based therapeutic use [3,16].

Table 1: Taxonimical of *Aegle marmelos*

Kingdom	**Plantae**
Subkingdom	Tracheobionta
Super division	Spermatophyta
Class	Magnoliopsida
Subclass	Rosidae
Order	Sapindales
Family	Rutaceae
Genus	Aegle
Species	*Aegle marmelos*

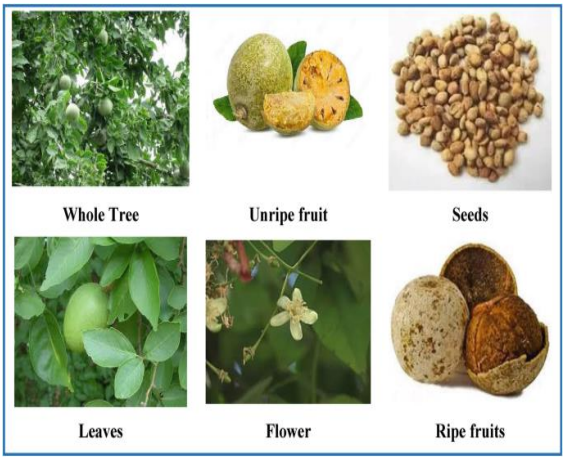

Fig (1): Plant parts of *Aegle marmelos*

2. PHYTOCHEMICAL COMPOSITION AND EXTRACTION APPROACHES

Phytochemical Distribution and Pharmacological Significance

Bael (*Aegle marmelos* (L.) is a pharmacologically important plant widely used in Indian system of traditional medicine (Ayurveda, Siddha and Unani). Its variation in phytochemicals that are

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systemically distributed throughout the different plant parts renders it a pharmacologically active substance. All these phytopharmaceuticals (sterols, alkaloids, flavonoids, coumarins, tannins, essential oil) possess its own medicinal characteristic [17, 18]. Leaves, fruit pulp, bark, roots, and seeds of *Aegle marmelos* have been found to possess specific chemical compositions along with distinct biological activities. The practice of inducing site-specific phytochemical expression is the foundation of targeted usage in traditional formulations and new pharmacological research [19,20].Leaves are rich in alkaloids (aegeline), flavonoids (rutin and quercetin), and they are responsible for the leaves antioxidant, anti-inflammatory and cardioprotective properties [21,22].The fruit pulp containing coumarins (marmelosin, imperatorin), tannins and mucilage have been reported to exhibit significant antidiarrheal, laxative, and antimicrobial activities. It is commonly used in traditional remedies to treat pathological conditions of the gut [23]. The bark and root parts are rich in powerful alkaloids and coumarins that have been proven as analgesic and antimicrobial [24]. Seeds contain drying oils, fatty acids, and a complex mixture of sterols including β-sitosterol, which are used as anti-inflammatory and nutritive agents [25,26]. These ingredients exhibit not only individual but combined effects when used as whole-part or as polyherbal combination which have been previously discussed [27].

Table 2: Phytochemical Profiles and Pharmacological Activities of Plant Parts

Plant Part	Major Phytochemicals	Extraction Methods	Pharmacological Activities
Leaves 	Aegeline (alkaloid), Rutin, Quercetin (flavonoids)	Infusion, methanol/ethanol extraction, UAE	Antioxidant, Anti-inflammatory, Cardioprotective
Fruit 	Marmelosin, Imperatorin (coumarins), Tannins, Mucilage	Decoction, ethanol extraction, Microwave-Assisted Extraction (MAE)	Antimicrobial, Antidiarrheal, Laxative

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Plant Part	Major Phytochemicals	Extraction Methods	Pharmacological Activities
Bark 	Skimmianine (alkaloid), Coumarins	Decoction, hydroalcoholic extraction, UAE	Analgesic, Antimicrobial
Seeds 	Fixed oils, Fatty acids, β-sitosterol	Cold pressing, Supercritical Fluid Extraction (SFE)	Anti-inflammatory, Nutritive

The several phytochemicals present in *Aegle marmelos* explain its wide usage in traditional medicine and modern research for therapeutic field. Its part-specificity of chemical composition has drawn it for personalized usage like gut-health supplements (fruit pulp), cardiac supporting tonics (leaves), painkillers (bark/root), and nutraceuticals (seeds) [28]. Used in combination with suitable extraction approaches, these compounds may become valuable source for the development of evidence-based herbal drugs or standardized phytopharmaceuticals**.**

3. PHARMACOLOGICAL ACTIVITIES

Aegle marmelos, more commonly known as bael, is a multitasking medicinal plant; its broad-spectrum therapeutic effects, including digestive aid, anti-inflammatory properties, and potential antidiabetic activity, have been established, in vitro, laboratory studies, in vivo animal studies, and a few clinical studies [29]. These pharmacological effects are associated with its broad spectrum of flavonoids, coumarins, tannins, and alkaloids, which act in concert to create this medicinal plant's healing ability [30].

Table 3: Phytochemical Activity Mechanism Model Used

Compound	Activity	Mechanism	Model
Rutin	Antioxidant	Free radical scavenging	DPPH, ABTS
Aegeline	Antidiabetic	insulin stimulation	STZ rats
Marmelosin	Antimicrobial	Membrane disruption	MIC, MBC

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3.1 Antidiabetic Activity

Bael (*Aegle marmelos*) has well-documented antidiabetic activity; this class of molecules has activity that is supported by considerable amounts of phytochemicals and investigation through experimental work. The active compounds analyzed, which includes aegeline, rutin, and quercetin, are responsible for diverse actions such as inhibition of α-glucosidase and α-amylase, promoting regeneration of β-cells and insulin secretion of β-cells, and increased glucose uptake by muscle and adipose tissue [31], which has been demonstrated in streptozotocin and alloxan diabetic rats, where researchers used fasting blood glucose, HbA1c, OGTT, and insulin sensitivity as outcome measures for both efficacy in obtaining their outcome, and for consideration of future clinical application [32].

3.2 Antioxidant and Anti-inflammatory Activity

Aegle marmelos (bael) Â demonstrated significant antioxidant and anti-inflammatory effects largely derived from its phytochemicals, including flavonoids such as quercetin and kaempferol and tannins. Like other extracts, bael extracts express effects via free radical scavenging (DPPH and ABTS assays) and reducing lipid peroxidation which produces MDA - a biomarker of oxidative damage. Bael extracts can also reduce pro-inflammatory cytokines (such as TNF-α, IL-6, and IL-1β) and contribute to modulating the cell to molecular inflammatory response. Altogether, these findings were validated by a variety of laboratory approaches in in vitro studies (i.e., LPS induced cytokine assays) and in vivo study design of carrageenan induced paw edema in rodent models. [33, 34]

3.3 Antimicrobial and Antiviral Activity

Aegle marmelos (bael) provide natural multi-target antimicrobial and antiviral properties, making it a strong protective natural agent against various pathogens. The primary bioactive compounds of A. marmelos - like marmelosin, volatile oils and aegeline - possess potent activity against Gram-positive and Gram-negative bacteria, fungi (e.g. Candida), and viruses. Those benefits are likely due to disrupting the cell walls of microbes, inhibiting important microbial enzymes, and virus penetration and replication. Research has established the antimicrobial activity of A. marmelos using methods like disk diffusion, MIC (Minimum Inhibitory Concentration), and MBC (Minimum Bactericidal Concentration) studies. All of which confirmed their actions and provided modern science evidence to support traditional medicinal use to treat infections [35,36].

3.4 Hepatoprotective and Gastroprotective Activity

Aegle marmelos (bael) offers impressive hepatoprotective and gastroprotective benefits and serves as a valuable natural remedy for liver and stomach health. In models of liver injury-such as carbon tetrachloride (CCl_4) and paracetamol-induced toxicity-bael extracts significantly reduce elevated serum markers like ALT, AST, and ALP, and help preserve liver histoarchitecture [37]. In the gastrointestinal system, bael promotes ulcer healing by enhancing mucosal defense and stimulating the release of protective prostaglandins. These effects are largely attributed to its high content of flavonoids and coumarins, which combat oxidative stress and inflammation [38].

3.5 Other Pharmacological Activities

Aegle marmelos (bael) also has a variety of pharmacological properties outside of its role in the traditional context, including anticancer effects and inducing apoptosis

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and cell cycle arrest in a number of cancer lines including colon, breast and liver [39]. Bael also has important roles in heart health, showing cardioprotective effects by exerting a beneficial effect lipid profiles and providing antioxidant protection in ischemia injury models. In relation to neurobiology, bael appears to have neuroprotective effects, with positive effects seen in animal models looking at anticonvulsant activity, anxiolytic activity and learning and memory. Notably, Bael also showed antifertility effects at higher doses, where spermatogenesis was reversibly affected which has sparked interest in bael being used as a natural male contraceptive [40]. These effects outlined above show how diverse bael's actions are, and highlight both the therapeutic potential of bael and its value to traditional medicine and phytopharmacologic research and development.

4. ETHNOMEDICINAL USES AND MODERN FORMULATIONS

Aegle marmelos (bael) has traditionally been given great importance in medicine across the traditional medicinal systems of Ayurveda, Siddha, and folk medicine throughout India and Southeast Asia. Historically, the pulp of the fruit has been used to treat digestive complaints such as diarrhea and dysentery, while the leaves have been used for diabetes and inflammation. The bark and roots are used for fever, respiratory issues, and infections. These traditional uses have really only been used in modern herbal medicines - syrups, capsules, powders, and teas - so bael can reach greater audiences without losing any of the traditional medicinal value. In this way, bael can continue to blend neoteric uses with the ancient uses, thus allowing bael to remain part of holistic health care.

Table 3: Modern Formulations and Delivery Systems

Formulation Type	Description	Advantages	Limitations	Modern Applications
Churna	Coarse powder of dried plant materia	Easy to prepare, cost-effective	Poor taste, low bioavailability	Traditional Ayurvedic use
Tablet	Compressed powdered herbs	Convenient, standardized dose	Slow absorption, may require binders	OTC herbal supplements
Capsule	Powder/liquid in gelatin shell	Mask taste, easy to swallow	Capsule stability in humidity	Modern herbal supplements
Nanoemulsion	Nanometer-sized oil-in-water emulsion	Enhanced solubility & bioavailability	Requires precise formulation technology	Curcumin, cannabinoids
Phytosome	Herbal extract + phospholipid complex	Improved membrane permeability	Complex formulation process	Silymarin, green tea polyphenols

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Transdermal Gel	Topical application with active extract	Avoids GI tract, controlled release	Skin irritation in some cases	Pain relief, anti-inflammatory gels

4.1 Ethnomedicinal and Traditional Uses

Aegle marmelos (bael) has long been esteemed in Ayurveda, Siddha, and folk medicine across South Asia. The unripe fruit is traditionally used for diarrhea and dysentery, while the ripe fruit helps relieve constipation and support digestion. Leaf juice or extracts are commonly employed to help manage diabetes. The bark and leaves are made into poultices to treat wounds, inflammation, and skin infections, and decoctions from the bark or roots are used for fever, respiratory ailments, and internal infections. Bael is consumed as juice, decoction, churna (powder), paste, or infusion, often alone or blended into traditional formulations like *Dashamoola* and *Triphala*. This enduring versatility underlines its importance as a holistic herbal remedy across cultures [41,42].

4.2 Modern Formulations and Drug Delivery Systems

Aegle marmelos has a wide range of commercial forms in current herbal practice-churnas (powders), tablets, capsules, and syrups-many of which are registered in India under AYUSH guidelines [43]. *Aegle marmelos* is often included in polyherbal herbal formulations for its antidiabetic, hepatoprotective and gastroprotective effects. In regards to traditional dosage forms, researchers are even developing innovative delivery systems for *Aegle marmelos* such as nanoemulsions, phytosomes, transdermal gels, and polymeric nanoparticles to enhance efficacy through bioavailability, stability, and targeted delivery of active agents such as aegeline and marmelosin [43]. Many patents are currently recommending both of these compounds for the therapeutic use. Nonetheless, there are still major hurdles to its successful clinical use-namely, standardization of products, stability period (i.e., shelf-life) and needed to conduct pharmacokinetic profiling of products in order to establish desirable characteristics for bael to be acceptable by evidence-based healthcare delivery.

5. RECENT ADVANCES AND FUTURE DIRECTIONS

This review has illuminated recent developments in *Aegle marmelos* research, chiefly in terms of progress in biotechnologically driven methods such as tissue culture and genetic profiling, which will allow the conservation and propagation of elite chemotypes on a large scale. There remains ongoing work at improving bioavailability and efficacy using formulations such as nanoemulsions, phytosomes, and transdermal gels. Biotechnological advances show the practical potential for translational clinical and commercial implementation consistent with AYUSH guidelines and regulatory approval, but there are currently gaps in clinical validation, pharmacokinetics and toxicology. Future research should consist of defined multi-centre trials, advanced delivery systems, and clinical integration such that the maximum benefit of the therapeutic and commercial potential can be realised.

5.1 Biotechnological and Genomic Advances

Advancements in biotechnology and genomics of *Aegle marmelos* are

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contributing to its use in medicine and commercialism. Tissue culture and micropropagation techniques, which are enhanced through combinations of auxins and cytokinins based on MS medium, contribute to the conservation of elite chemotypes and large-scale propagation [44]. Callus and suspension culture systems are being employed as a strong platforms to increase secondary metabolite yields [45]. Elicitors are being utilized to promote increased coumarin and flavonoid production using jasmonic acid and salicylic acid. Previous transcriptomic and genomic research has included gene expression investigations to elucidate genes involved in phytochemical biosynthesis and detection of over 94,000 SSR markers from leaf transcriptomes. During early research phases in the area of DNA barcoding, SSR marker studies, and metabolomic profiling to explore genetic diversity with respect to metabolite variation.

5.2 Clinical Research and Translational Gaps

Despite favorable results from preclinical studies, there has been little clinical research done to develop evidence-based support for *Aegle marmelos* [46]. Due to the lack of human studies on *Aegle marmelos*-one of the few Phase 3 studies enrolled type 2 diabetic patients and showed no significant inflammatory marker reduction of hs-CRP-it is crucial to have more rigorous design and assessment of efficacy. Clinical research needs standardized extracts and systematic dose-finding studies to make the use of *Aegle marmelos* reproducible and safe. Moreover, the absence of multicenter, placebo-controlled, clinically relevant studies continues to halt the clinical acceptance of *Aegle marmelos*. In addition, most of the studies conducted relating to toxicology are either old or not done at all [46]. The outdated toxicology studies will require updated assessments and toxicology evaluations to comply with the current standards and regulations to establish the safe therapeutic use of *Aegle marmelos* .

5.3 Pharmaceutical and Regulatory Progress

Pharmaceutical and regulatory advancements for *Aegle marmelos* are mainly limited to AYUSH-approved formulations in India, with no FDA-approved drugs or standardized phytopharmaceuticals currently available [47]. This highlights the need for developing well-defined pharmacopoeial monographs, robust standardization protocols, and compliance with international benchmarks such as WHO and ISO. Strengthening regulatory frameworks and scientific validation is essential to transition *Aegle marmelos* from traditional use to global acceptance in modern integrative healthcare systems [47].

5.5 Future Research Opportunities

Future research opportunities for *Aegle marmelos* offer a breadth of exciting and practical possibilities [48]. Improved formulations for systemic drug delivery (e.g., buccal, transdermal, or colon specific) will provide better targeted therapeutic action that takes advantage of natural polymers as well as microsphere encapsulation methods, the predictions being made about the existence of synergistic polyherbal blends to treat weight loss during metabolic syndrome, gut health, or cancer prevention appear likely and offer the potential for very interesting combination therapies [48]. In addition, the inclusion of bioenhancers hydrophilic compounds such as piperine is promising for improving the oral bioavailability of important phytoconstituents. Further, in vivo and ex vivo based on AI/ML-based screening based with respect to structure–activity relationships (SAR) could fuel cAgAI results in compound discovery.

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Further, clinical validation of nutraceuticals, functional foods, and complementary health therapies could provide a link between traditional practices with modern day needs [48].

CONCLUSION

The *Aegle marmelos* tree (Bael) has immense medicinal value recognized in traditional medical systems like Ayurveda, Siddha and Unani. There are numerous therapeutic potentials for *Aegle marmelos* that humanity benefits from today, supported by modern scientific evidence. Its rich phytochemistry includes alkaloids (like aegeline), flavonoids (like rutin, quercetin), coumarins (like marmelosin) and tannins, which contribute to its broad pharmacodynamics, including antidiabetic, antioxidant, antimicrobial, hepatoprotective, and anticancer activities. Currently, ethnomedicinal use of *Aegle marmelos* is tremendous, but there is little clinical evidence, pharmacokinetic research, and a lack of regulatory standardization in India and beyond for the meat of the Bael fruit. Therefore, it has yet to be accepted in clinical practices worldwide. In the last several decades, progress in biotechnology, genomics, and new drug delivery methods (i.e., nanoemulsions, phytosomes and transdermal gels) can provide a great opportunity to improve bioavailability and therapeutic efficacy of *Aegle marmelos*. However, lack of clinical trials, standardized extracts, and toxicological testing updates currently creates barriers in the transition from traditional remedies to evidence based- medicine. Moving forward emphasis should be placed on developing the research landscape with multicentered clinical studies, improved formulations, and regulatory requirements in order to unite traditional health care modalities with contemporary medicine. In conclusion, *Aegle marmelos* is a powerful multi-target medicinal product with future value for users of contemporary healthcare and important cultural historical connection. It is by coupling today's science with original natural solutions that reflect multi-faceted spatial perspective on health and health delivery neural networks, we may expect *Aegle marmelos* to become an evidenced-based prima facie example of integrative and complementary medicine.

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