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A Review on the Medicinal and Therapeutic Potential of Bael (Aegle Marmelos)

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Abstract: *Because of its qualities, Aegle marmelos, a plant of the Rutaceae family, is among the most important in the medical sector. Bilwa is used to cure a wide range of illnesses. This plant has existed since the dinosaur era. Numerous pharmacological properties of the plant include wound healing, diuretic action, antipyretic potential, antidiarrheal activity, ulcer healing, and more. Radioprotective effect, contractile action, antiarthritis activity, analgesic activity, immunomodulatory activity, antifungal activity, antimicrobial activity, antioxidant activity, cytoprotective effect, and constipating effect. With a number of advantageous pharmacological qualities, Aegle marmelos (L.) is arguably one of the most revered medicinal plants in the Indian subcontinent. Over the past few decades, significant advancements have also been made advancements have also been made in the research of the biological activities and therapeutic uses of Bael plan, independent of the chemistry of the compounds. Similar to this, it has already been demonstrated that different plant parts— such as leaves, fruits, seeds, etc. Provide nutrients and health benefits to human diets. Another Indian plant that has been used for centuries to treat a wide range of Illnesses is the bael (Aegle Marmelos) (L.) Corr. The goal of the current review is to gather the medicinal values of Aegle Marmelos that were discovered during the research process utilizing cutting-edge scientific methods and instruments*

Keywords: Aegle Marmelos, Pharmacological Activities, Medicinal Values

I. INTRODUCTION

Aegle marmelos, commonly known as bael, is a perennial tree belonging to the Rutaceae family, widely distributed across South and Southeast Asia [1]. Traditionally, various parts of the plant—including leaves, fruit, bark, and root—have been employed in folk medicine for the management of digestive disorders, fever, and respiratory ailments [2]. The plant is rich in diverse phytochemicals such as alkaloids, flavonoids, tannins, coumarins, and terpenoids, which contribute to its broad spectrum of biological activities [3].

In addition to its traditional applications, Aegle marmelos has attracted scientific attention for its therapeutic and nutritional potential, being investigated for roles in antioxidant, antiinflammatory, antimicrobial, and antidiabetic interventions [6].

• General Background of Aegle marmelos (Botany, Distribution, Traditional Use) Aegle marmelos (L.) Corr., commonly known as Bael or Bilva, is a sacred and medicinally important plant belonging to the family Rutaceae. It is a moderate-sized, deciduous tree that grows up to 10–12 meters in height, characterized by trifoliate aromatic leaves, pale greenish-white flowers, and hard-shelled globose fruits. The plant thrives in tropical and subtropical climates and is widely distributed across India, Sri Lanka, Bangladesh, Nepal, Myanmar, and Southeast Asia. In India, it grows naturally in dry forests and is also cultivated in temple gardens due to its cultural and religious significance. Bael holds a special place in Hindu mythology, where it is regarded as sacred to Lord Shiva, and its leaves are traditionally offered during worship rituals [1,2].

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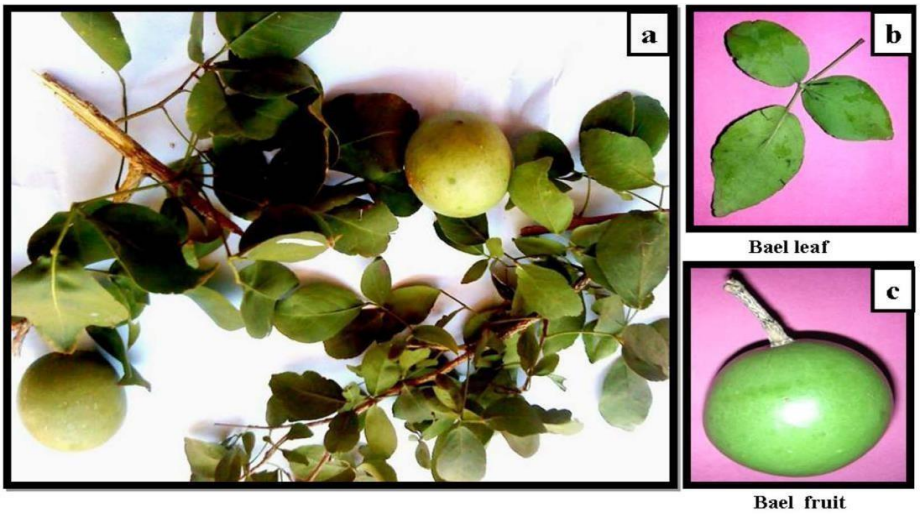

Fig 1.: Photographs of (a) Bael plant with the fruits, (b) leaf, and (c) fruit [7].

From a botanical perspective, Aegle marmelos shows remarkable adaptability to various soil types and climatic conditions. It can withstand both drought and high temperatures, making it suitable for semi-arid regions. The tree propagates through seeds and root cuttings, and its flowering season usually occurs from April to June, while fruits mature during October to March. The fruit shell is woody and hard, enclosing a sweet, aromatic pulp filled with numerous seeds embedded in a mucilaginous substance. The fruit pulp and leaves are known for their distinctive aroma and therapeutic taste, which has been traditionally associated with medicinal properties [3].

Traditionally, Bael has been one of the most valued plants in Ayurveda, Unani, and Siddha systems of medicine. Almost every part of the plant—leaves, fruits, roots, bark, and seeds— is used for therapeutic purposes. The unripe fruit is used as astringent and digestive tonic, effective in diarrhea, dysentery, and gastrointestinal disorders, while the ripe fruit is considered a mild laxative and cooling agent. Leaf extracts are utilized in treating diabetes, jaundice, and inflammation, whereas root and bark decoctions are prescribed for cardiac and respiratory ailments. The plant is also believed to possess antipyretic, antiinflammatory, and antioxidant properties, contributing to its use in various traditional formulations [4,5].

• Importance of Aegle marmelos in Medicine and Nutrition

Aegle marmelos (commonly known as Bael) holds immense medicinal and nutritional value, making it one of the most versatile plants in traditional and modern healthcare systems. For centuries, different parts of the plant — including fruits, leaves, bark, and roots — have been used in various traditional medicinal formulations to manage digestive disorders, diabetes, inflammation, and infections. In recent years, extensive phytochemical and pharmacological research have scientifically validated many of these traditional uses, demonstrating that the plant possesses a wide range of bioactive compounds responsible for its therapeutic effects [8].

The plant is a rich source of phytochemicals such as coumarins, alkaloids, phenolic acids, flavonoids, tannins, and terpenoids. These compounds contribute to several biological functions, including antioxidant, anti-inflammatory, hepatoprotective, and antidiabetic activities. Its high antioxidant potential helps neutralize free radicals and protect the body from oxidative stress-related diseases, while its anti-inflammatory and antidiabetic actions support metabolic balance and improve insulin sensitivity [8,9]. The pharmacological benefits of Aegle marmelos thus extend beyond symptomatic relief, contributing to longterm disease prevention and health maintenance [8,9].

In addition to its therapeutic role, Aegle marmelos also offers significant nutritional value. The fruit is abundant in dietary fiber, vitamins such as vitamin C and beta-carotene, and essential minerals like potassium, calcium, and iron. These nutrients make it a functional food capable of improving digestion, boosting immunity, and maintaining

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electrolyte balance. Modern formulations such as effervescent tablets and health supplements derived from Bael fruit have shown excellent stability of bioactive compounds and high consumer acceptability, indicating its suitability for nutraceutical and food applications [10].

From a nutritional perspective, the incorporation of Bael-derived ingredients in food systems provides a dual benefit: enhancing taste and texture while delivering essential health-promoting compounds. The plant's fruit pulp is utilized in beverages, jams, candies, and herbal tonics, which not only contribute to improved digestion but also offer protection against microbial infections and oxidative damage. As a result, Aegle marmelos is increasingly being explored as a functional ingredient in the development of nutraceutical formulations and fortified foods, integrating its therapeutic and nutritional significance into modern health management practices [10,11].

• Phytochemical Richness and Bioactivity

Aegle marmelos (L.) Corr., commonly known as Bael, is a reservoir of diverse bioactive phytochemicals that contribute to its broad spectrum of pharmacological activities. The plant contains alkaloids, coumarins, terpenoids, flavonoids, tannins, and phenolic compounds, each associated with specific therapeutic functions ranging from antioxidant to antimicrobial properties. The phytochemical profile varies among different parts of the plant — leaves, fruits, bark, and roots — reflecting its multifunctional role in traditional and modern medicine. The leaves are particularly rich in marmelosin, aegeline, and lupeol, which exhibit potent anti-inflammatory and hepatoprotective effects, while the fruit pulp contains coumarins and flavonoids responsible for antioxidant and gastrointestinal benefits
[4,5].

The antioxidant potential of Aegle marmelos has been attributed to its high phenolic and flavonoid content, which effectively scavenges free radicals and protects cellular components from oxidative damage. This activity contributes to the management of chronic diseases such as diabetes, cardiovascular disorders, and neurodegenerative conditions by reducing oxidative stress and lipid peroxidation [1,5]. Moreover, the synergistic interaction of multiple phytoconstituents enhances its efficacy, as these compounds simultaneously target oxidative, inflammatory, and metabolic pathways. Such bioactivity provides a molecular basis for its long-standing use in traditional medicine as both a curative and preventive agent [2,4].

The antimicrobial and antidiabetic potential of Aegle marmelos further reinforces its pharmacological significance. The presence of compounds like skimmianine, aegelin, and marmin has demonstrated inhibitory effects against bacterial pathogens and improved glucose metabolism in experimental models [12,13].

• Therapeutic Relevance

Aegle marmelos (Bael) has been extensively studied for its therapeutic potential across multiple disease models, demonstrating both preventive and curative effects. The plant exhibits antidiabetic properties, primarily through its bioactive compounds that modulate carbohydrate metabolism, enhance insulin sensitivity, and reduce blood glucose levels [4]. In addition, Aegle marmelos possesses significant antioxidant activity, which protects cells from oxidative stress and reduces the risk of chronic diseases such as cardiovascular disorders and neurodegeneration [5].

The anti-inflammatory and hepatoprotective activities of the plant are mediated by triterpenoids, limonoids, and flavonoids, which inhibit pro-inflammatory mediators and protect liver function [1]. Such effects underscore its importance in managing inflammatory conditions, metabolic syndrome, and hepatic disorders [1].

Phytochemical Composition of Aegle marmelos

Aegle marmelos (L.) Corr. Serr., a member of the family Rutaceae, is recognized for its wide range of secondary metabolites that confer significant therapeutic potential. The plant synthesizes a rich array of phytochemicals including alkaloids, coumarins, flavonoids, tannins, phenolics, terpenoids, and limonoids, each contributing to distinct pharmacological effects [1].

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Studies have revealed that these compounds are unevenly distributed across different plant parts—leaves, bark, roots, fruits, and seeds—reflecting a complex metabolic network that supports both defense and physiological processes [2].

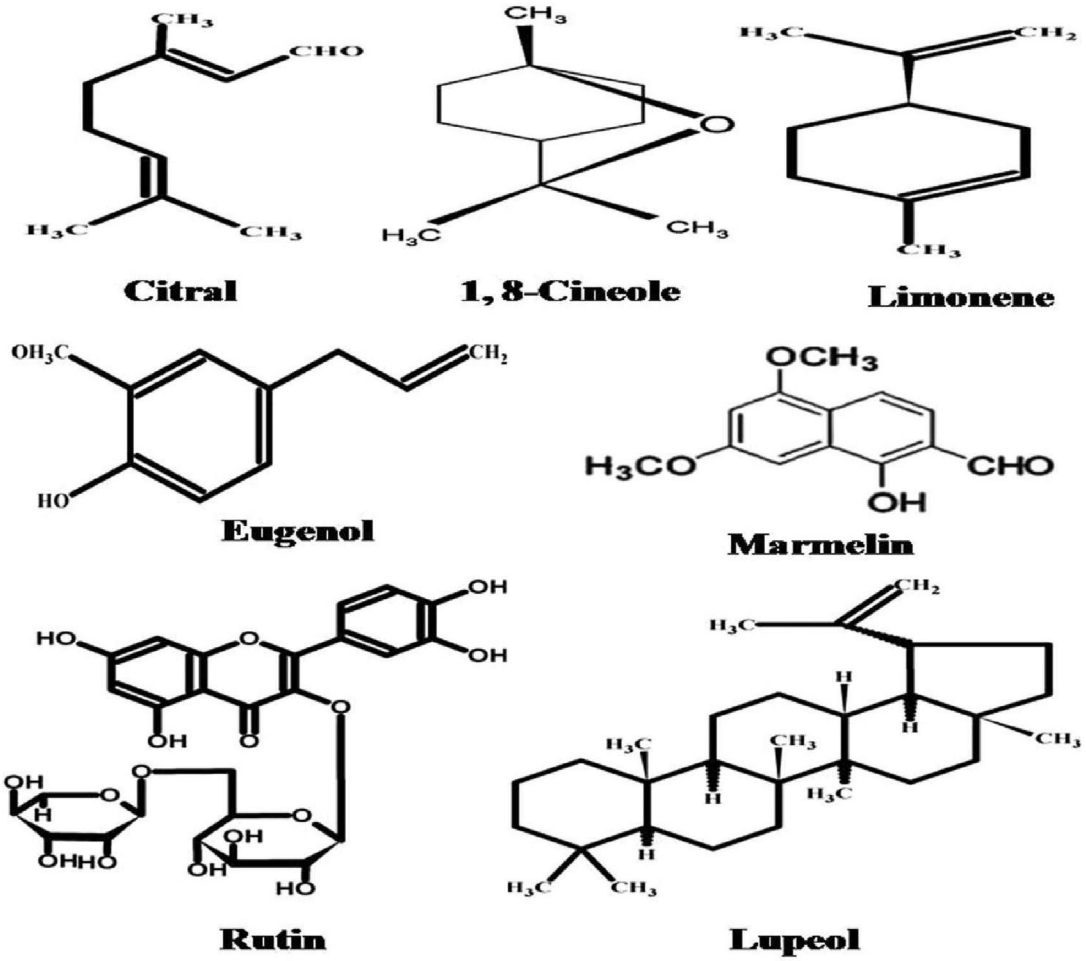

Fig 2: Phytochemicals of Aegle marmelos [7].

The biochemical diversity of A. marmelos forms the foundation for its traditional use in Ayurveda and modern phytotherapeutics, bridging ancient and contemporary medicinal practices [3].

1. Alkaloids

Alkaloids are among the most pharmacologically active constituents in A. marmelos. The plant contains aegeline, skimmianine, and marmesiline, which exhibit antidiabetic, antimicrobial, and anti-inflammatory activities [6].

Aegeline, an amide alkaloid primarily found in the leaves and young stems, enhances insulin sensitivity and regulates lipid metabolism, explaining its traditional use in managing diabetes. Skimmianine, isolated from the root bark, possesses strong antimicrobial and vasorelaxant properties due to its furoquinoline backbone, which interacts with smooth muscle receptors [13].

These alkaloids act through multiple biochemical pathways, often serving as enzyme modulators or neurotransmitter analogs, underscoring their therapeutic versatility [1].

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2. Flavonoids

Flavonoids form another major class of phytochemicals in Aegle marmelos, contributing significantly to its antioxidant and anti-inflammatory activities. The key flavonoids include rutin, quercetin, isorhamnetin, and kaempferol, predominantly localized in the leaves and fruit pulp [2].

These compounds act as free radical scavengers and metal chelators, protecting cellular components from oxidative damage. Rutin and quercetin, in particular, are known to stabilize cell membranes and enhance capillary resistance, thereby supporting cardiovascular health [6].

3. Tannins and Phenolic Compounds

Tannins and phenolic compounds are abundant in A. marmelos, particularly within the unripe fruit and bark. These molecules are primarily responsible for the plant's astringent, antimicrobial, and antioxidant properties [23]. Hydrolyzable tannins such as ellagic acid and gallic acid derivatives have been identified as major constituents, contributing to free radical neutralization and enzyme inhibition. The phenolic profile of A. marmelos also includes ferulic acid, syringic acid, and vanillic acid, all of which play roles in protecting tissues from oxidative stress and inflammation [12].

4. Coumarins

Coumarins are a distinctive group of phytochemicals abundant in Aegle marmelos, characterized by their benzopyrone structure that provides diverse pharmacological effects. Major coumarins include marmelosin, marmesin, umbelliferone, and scopoletin, found mainly in the fruit pulp and leaves [1]. Marmelosin, a furanocoumarin, exhibits notable antimicrobial and anticancer activity by inducing apoptosis and inhibiting microbial cell wall synthesis [19].

Umbelliferone and scopoletin, on the other hand, act as anti-inflammatory agents, inhibiting cyclooxygenase and nitric oxide synthase pathways [13]. The structural variation among coumarins contributes to their multi-targeted pharmacological actions, which explain their importance in modern drug discovery and traditional medicine formulations [23].

Plant Part	Major Phytochemicals	Approx. Percentage Constituents (%)	Pharmacological Roles
Leaves	Alkaloids (Aegeline), Flavonoids (Quercetin, Rutin)	1.5–2.8% alkaloids, 0.8–1.2% flavonoids	Antidiabetic, Antioxidant, Anti-inflammatory
Fruit Pulp	Coumarins (Marmelosin, Scopoletin), Phenolics	2–3% coumarins, 3–4% phenolics	Antimicrobial, Anticancer, Antioxidant
Bark	Tannins, Saponins, Alkaloids	5–8% tannins, 2–3% saponins	Astringent, Antimicrobial, Hepatoprotective
Roots	Skimmianine, Terpenoids, Sterols	1–2% alkaloids, 2–3% terpenoids	Analgesic, Vasorelaxant, Anti-inflammatory
Seeds	Limonoids, Fatty acids	3–5% limonoids, 15–18% fatty acids	Cytotoxic, Insecticidal, Nutritional

Table 1: Major Phytochemicals and Pharmacological Roles of Different Parts of Aegle marmelos

5. Terpenoids and Limonoids

Terpenoids and limonoids represent another vital group of metabolites in Aegle marmelos, mainly found in the fruit rind, roots, and leaves. The plant's terpenoid profile includes lupeol, β-sitosterol, and α-amyrin, all known for their anti-inflammatory, hepatoprotective, and hypolipidemic effects [19].

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Limonoids such as limonin, nomilin, and auraptene exhibit cytotoxic and insecticidal activities, making them potential leads for natural pesticide development [13]. These compounds act by modulating signal transduction pathways and enzyme activity, especially in the detoxification of reactive oxygen species. Additionally, terpenoids contribute to the distinct aroma of A. marmelos fruits, linking phytochemistry to sensory and nutritional attributes [12].

6. Saponins, Sterols, and Other Secondary Metabolites

In addition to alkaloids and flavonoids, Aegle marmelos contains significant amounts of saponins, steroids, and glycosides. Sterols such as β-sitosterol play a key role in cholesterol metabolism and membrane stabilization, while saponins exhibit anti-inflammatory and immunomodulatory activities [6].

These compounds are mainly found in the roots and bark, contributing to the plant's tonic and rejuvenating effects traditionally valued in Ayurveda [3].

Recent chromatographic profiling has also identified trace amounts of volatile oils and essential terpenes, which provide aroma and contribute to antimicrobial activity [19].

Pharmacological Activities of Aegle marmelos

Aegle marmelos exhibits a wide range of pharmacological properties due to its diverse phytochemical profile, including alkaloids, flavonoids, tannins, and coumarins. These bioactive compounds contribute synergistically to various therapeutic effects such as antioxidant, antimicrobial, antidiabetic, anti-inflammatory, hepatoprotective, and anticancer activities. The following sections summarize the pharmacological activities of A. marmelos as supported by recent literature [12].

1. Antioxidant Activity

Aegle marmelos exhibits remarkable antioxidant potential, primarily attributed to its rich phytochemical composition, including flavonoids, phenolic acids, tannins, and coumarins. These compounds scavenge reactive oxygen species (ROS) and prevent oxidative stressinduced cellular damage, which is implicated in the pathogenesis of chronic diseases. The methanolic and aqueous extracts of the leaves have been shown to inhibit lipid peroxidation and enhance endogenous antioxidant enzymes such as superoxide dismutase, catalase, and glutathione peroxidase [4]. Such effects highlight the plant's capacity to restore oxidative balance and protect tissues against free radical damage. The antioxidant mechanisms of Aegle marmelos extend beyond direct scavenging activity. Polyphenolic compounds modulate the expression of oxidative stress-related genes, enhancing cellular defence pathways and preventing protein and DNA oxidation. The leaf extract has also been reported to maintain stability of antioxidant compounds during storage, which supports its application in functional foods and nutraceutical formulations [6].

2. Antimicrobial and Antifungal Activity

The antimicrobial efficacy of Aegle marmelos spans a wide range of bacterial and fungal strains, confirming its traditional use for treating infections. The ethanol and methanol extracts demonstrate inhibitory action against Escherichia coli, Staphylococcus aureus, and Bacillus subtilis, largely due to the presence of alkaloids and tannins that disrupt microbial cell membranes [5]. The extracts also interfere with bacterial quorum sensing mechanisms, preventing biofilm formation and thereby enhancing their therapeutic relevance.

In addition, the essential oils and furanocoumarin-rich fractions show significant antifungal properties against Candida albicans and Aspergillus niger. The antifungal effect is linked to inhibition of spore germination and ergosterol biosynthesis, which compromises fungal cell membrane integrity [13]. These findings suggest that Aegle marmelos can serve as a natural antimicrobial agent for the formulation of herbal antiseptics and preservative systems [5,13].

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3. Antidiabetic and Hypoglycemic Effect

Extracts of Aegle marmelos have demonstrated significant hypoglycaemic activity through multiple mechanisms, including modulation of insulin secretion, enhancement of glucose uptake, and inhibition of carbohydrate-hydrolysing enzymes. The aqueous leaf extract has been reported to reduce fasting blood glucose and improve glycogen content in diabetic animal models, indicating its potential as a natural antidiabetic agent [4]. The bioactive compounds such as aegeline and marmelosin influence pancreatic β-cell activity and improve glucose tolerance [4,15].

Moreover, coumarin-enriched fractions derived from the fruit pulp exhibit potent αamylase and α-glucosidase inhibitory activity, reducing postprandial hyperglycaemia [15]. This enzyme-targeted approach aligns with modern strategies for diabetes management, where plant-based inhibitors are preferred for their safety and multi-targeted action [15,17].

4. Anti-inflammatory and Analgesic Activity

The anti-inflammatory activity of Aegle marmelos is largely attributed to the presence of phenolic compounds and terpenoids, which modulate the expression of pro-inflammatory mediators such as TNF-α, IL-6, and COX-2. The ethanolic leaf extract has shown to reduce paw oedema and inflammatory lesions in experimental models, demonstrating dosedependent analgesic effects [13]. These actions occur through the inhibition of prostaglandin synthesis and suppression of nitric oxide production [19].

Activity	Active Compounds / Extracts	Mechanism / Effect
Antioxidant	Flavonoids, Phenolics	Free radical scavenging, lipid peroxidation inhibition
Antimicrobial / Antifungal	Coumarins, Alkaloids	Cell wall disruption, enzyme inhibition
Antidiabetic	Aegeline, Coumarins	α-amylase inhibition, improved glucose uptake
Anti-inflammatory / Analgesic	Scopoletin, Rutin, Marmelosin	Cytokine inhibition, COX pathway modulation
Hepatoprotective / Cardioprotective	Flavonoids, Terpenoids	Antioxidant enzyme restoration, lipid regulation
Anticancer	Coumarins, Limonoids, Phenolics	Apoptosis induction, DNA protection

Table 2: Pharmacological Activities of Aegle marmelos.

Furthermore, phytoconstituents like marmelosin and lupeol have been reported to stabilise lysosomal membranes, thereby preventing the release of inflammatory enzymes at the site of injury [19]. This dual mechanism — suppression of inflammatory mediators and membrane stabilisation — contributes to the plant's overall anti-inflammatory efficacy [15].

5. Hepatoprotective and Cardioprotective Properties

Aegle marmelos plays a vital role in protecting hepatic and cardiac tissues from chemical- or oxidative-induced injury. The methanolic leaf extract has been shown to normalise serum enzyme markers such as AST, ALT, and ALP, indicating effective hepatoprotection against toxicants [6].

Cardioprotective activity has also been demonstrated through the regulation of lipid profiles, reduction of low-density lipoprotein (LDL), and elevation of high-density lipoprotein (HDL) levels. These effects are mainly attributed to the presence of limonoids and flavonoids, which enhance endothelial function and prevent oxidative damage to cardiac tissues [19].

6. Anticancer Potential

The anticancer potential of Aegle marmelos has been widely explored, with evidence supporting its cytotoxic effects against various cancer cell lines, including those of breast, colon, and lung origin. The ethanolic extract induces

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apoptosis through activation of caspase pathways and downregulation of anti-apoptotic proteins, leading to controlled cell death [7].

Further studies have highlighted the role of coumarins and alkaloids in suppressing angiogenesis and metastasis, essential processes in cancer development. The presence of limonin and marmelosin enhances the plant's cytotoxic potential by targeting reactive oxygen species generation and mitochondrial dysfunction [20].

Nutritional and Functional Properties of Aegle marmelos

Aegle marmelos is valued not only for its therapeutic potential but also for its rich nutritional profile. The fruit and leaves contain essential vitamins, minerals, and dietary fibre, which contribute to overall health and support metabolic and digestive functions [8]. In addition to these primary nutrients, the plant is a source of bioactive compounds such as polyphenols and flavonoids, which exhibit antioxidant and protective effects, enhancing its functional food value [12]. Traditional use as fresh fruit, juice, or dried powder highlights its role in promoting wellbeing, while modern investigations have demonstrated its suitability for nutraceutical formulations and fortified food products [10]. This combination of nutrients and bioactive compounds positions Aegle marmelos as a valuable ingredient for both dietary supplementation and the development of functional food applications [11].

1. Nutritional Composition

Aegle marmelos is recognised not only for its medicinal value but also for its rich nutritional profile. The fruit pulp is a notable source of essential vitamins, including vitamin C, vitamin A, and several B-complex vitamins, which contribute to its antioxidant and immunesupportive properties [8]. Minerals such as potassium, calcium, magnesium, and iron are present in appreciable amounts, supporting cardiovascular health, bone strength, and enzymatic processes within the body [10]. The fruit is also high in dietary fibre, which aids in gastrointestinal motility, enhances satiety, and contributes to the regulation of blood glucose levels [8].

Polyphenols and flavonoids in the pulp and leaves provide additional health benefits by mitigating oxidative stress and enhancing overall metabolic function [12].

2. Functional and Nutraceutical Applications

The consumption of Aegle marmelos in traditional diets includes fresh fruit, juice, and dried powder, which have been historically used to support digestion, immune function, and general well-being [8]. Modern nutraceutical applications have expanded to include capsules, powders, and tablets, allowing for standardised dosing and enhanced shelf life [10].

The juice and pulp powders are increasingly utilised in functional foods, offering antioxidant, digestive, and anti-inflammatory benefits while providing natural flavour and colour [12]. Additionally, the incorporation of Aegle marmelos extracts into beverages and health bars has demonstrated improved nutritional density and consumer acceptability [17]. These applications underscore the potential of Aegle marmelos as a versatile ingredient in both traditional and contemporary dietary regimes [8].

3. Modern Formulations and Delivery Systems

Recent research has focused on the development of innovative delivery systems to maximise the bioavailability and stability of Aegle marmelos phytochemicals. Effervescent tablets derived from the fruit pulp exhibit rapid solubilisation, enhanced taste, and prolonged shelf life, making them suitable for daily supplementation [10]. Ultrasonicationassisted extraction of nano-polysaccharides from fruit shells has enabled the creation of edible coatings for fresh-cut fruits, combining preservation with functional benefits [11].

Such advanced formulations not only protect the bioactive compounds from degradation but also provide convenient dosage forms for therapeutic and nutraceutical purposes [11,17]. Furthermore, these products are aligned with current

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trends in health-conscious and environmentally sustainable food systems, offering alternatives to synthetic additives and preservatives [11].

Industrial and Pharmaceutical Applications of Aegle marmelos

The multifaceted properties of Aegle marmelos extend beyond its traditional medicinal and nutritional applications, establishing its importance in industrial and pharmaceutical sectors. Its rich phytochemical profile, comprising flavonoids, coumarins, alkaloids, and polyphenols, has been exploited in the development of herbal formulations, cosmetics, and functional food products [8,10]. Advances in nanotechnology have further enabled the creation of nano-extracts and nano-polysaccharides, improving the stability, bioavailability, and targeted delivery of bioactive compounds for both therapeutic and nutraceutical applications [11]. Moreover, these applications align with contemporary trends in healthconscious and environmentally sustainable industries, offering natural alternatives to synthetic preservatives and additives [10,11]. Collectively, the industrial and pharmaceutical utilisation of Aegle marmelos highlights its economic potential and reinforces its significance as a versatile plant resource suitable for modern commercial exploitation [8,11].

1. Cosmetics and Herbal Formulations

The bioactive constituents of Aegle marmelos, including flavonoids, polyphenols, and essential oils, have been increasingly incorporated into cosmetics and herbal formulations. These compounds provide antioxidant, antimicrobial, and antiinflammatory properties, making them effective in skin creams, face masks, hair oils, and soaps [8]. The antimicrobial action of marmelosin and aegeline enhances the shelf life of cosmetic
formulations and protects the skin against microbial infections [5]. Additionally, polyphenolic compounds contribute to photoprotective effects, reducing oxidative stress induced by ultraviolet radiation, which is critical for anti-ageing and skin repair formulations [12].

2. Nanotechnology Applications and Sustainable Industry Potential

Recent research has demonstrated the potential of Aegle marmelos in nanotechnologybased formulations. Nano-extracts and nanoparticles derived from its fruit, leaves, and bark improve bioavailability and stability of bioactive compounds, making them suitable for targeted drug delivery and functional food fortification [11]. For instance, ultrasonicationassisted nano-polysaccharides derived from fruit shells have shown efficacy in edible coatings and controlled-release systems for perishable foods, aligning with eco- friendly and sustainable industrial practices [11]. Additionally, the green synthesis of silver nanoparticles using Aegle marmelos extracts provides a sustainable approach to antimicrobial coatings and biomedical applications [9]. These advances highlight the dual role of Aegle marmelos as a source of bioactive compounds and a sustainable industrial raw material, contributing to environmentally conscious manufacturing processes [11].

3. Commercial and Economic Significance

The commercial and economic potential of Aegle marmelos is substantial, given its multifaceted applications in pharmaceuticals, nutraceuticals, cosmetics, and food industries. The cultivation of bael contributes to rural economies, and the processing of its fruit and leaves into juices, powders, effervescent tablets, and other value-added products generates significant revenue [10,17]. Functional food products enriched with Aegle marmelos bioactives are gaining popularity due to consumer demand for health-promoting ingredients. Additionally, the global herbal market recognises Aegle marmelos for its natural therapeutic compounds, positioning it as a key crop for export-oriented cultivation and industrial development [8,11]. Its integration into modern herbal formulations, nutraceuticals, and sustainable food packaging illustrates a convergence of economic value with environmental and health-conscious innovation [10,11].

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Toxicological and Safety Profile

The toxicological evaluation of Aegle marmelos is essential to validate its traditional use and ensure safety in modern therapeutic, nutraceutical, and industrial applications. Historically, various parts of the plant, including leaves, fruit, bark, and roots, have been widely consumed without reported severe adverse effects, reflecting a generally safe profile at conventional doses [6].

1. Acute Toxicity

Acute toxicity studies in rodent models have shown that leaf and fruit extracts of Aegle marmelos exhibit low toxicity, with no mortality observed at doses up to 2000 mg/kg body weight. Mild gastrointestinal disturbances such as diarrhoea and reduced food intake were reported only at very high doses, suggesting a high therapeutic index for conventional medicinal applications [6,10].

2. Sub-Chronic and Chronic Toxicity

Sub-chronic toxicity evaluations over 28–90 days have revealed dose-dependent physiological and biochemical changes, primarily affecting liver enzymes and renal markers at supratherapeutic doses. Histopathological examinations indicated that regular consumption within therapeutic limits did not cause significant tissue damage, whereas high-dose administration occasionally resulted in mild hepatocellular alterations [10,12].

3. Dosage Considerations

Optimal dosing of Aegle marmelos extracts varies depending on the plant part, extraction method, and intended application. Fruit pulp and leaf extracts are most commonly used, with doses ranging from 250–500 mg/day in human studies, while bark and root extracts are generally administered in lower quantities due to higher concentrations of secondary metabolites [12,13].

4. Adverse Reactions and Contraindications

Although adverse reactions are generally mild, reports include gastrointestinal discomfort, transient hypotension, and allergic responses in sensitive individuals [10]. No severe systemic toxicity has been observed in human clinical settings at recommended doses. Nonetheless, caution is advised for pregnant or lactating women, patients with hepatic or renal impairment, and individuals on concurrent pharmacotherapy, as the bioactive compounds may interact with conventional drugs [6].

Research Gaps and Future Prospects

Despite extensive studies on the phytochemistry and pharmacological properties of Aegle marmelos, several critical gaps remain in the existing literature. Variations in extraction methods, plant maturity, and environmental conditions result in inconsistencies in the concentration and efficacy of bioactive compounds, making it difficult to standardise dosages for therapeutic and nutraceutical applications [15]. Furthermore, while in vitro and in vivo studies highlight a broad spectrum of biological activities, the number of welldesigned clinical trials remains limited, restricting the translation of laboratory findings into evidence-based clinical practice [12].

At a molecular level, there is a paucity of studies investigating the precise mechanisms of action of individual phytochemicals and their synergistic interactions. A deeper understanding of how compounds such as marmelosin, aegeline, flavonoids, and limonoids influence specific biochemical pathways could pave the way for targeted drug development and more effective nutraceutical formulations [15].

1. Lack of Standardised Extraction and Dosage Consistency

Despite the extensive pharmacological and phytochemical studies on Aegle marmelos, there is notable inconsistency in extraction methods across studies. Different solvents, extraction times, and plant parts result in considerable variation in the concentration of active compounds, such as marmelosin, aegeline, and limonoids [15]. Such variability limits the reproducibility of results and challenges the development of standardised formulations for therapeutic or nutraceutical use. Future research should prioritise the optimisation and validation of extraction protocols to ensure uniformity and consistent pharmacological
efficacy [15].

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2. Limited Clinical Trials

While numerous in vitro and animal studies demonstrate antioxidant, anti-inflammatory, antimicrobial, and anticancer properties of Aegle marmelos, human clinical trials remain scarce [12]. Most studies are confined to laboratory settings, leaving a gap in understanding the efficacy and safety profile in human populations. The lack of rigorous, placebocontrolled clinical studies hinders the translation of preclinical findings into clinical recommendations and evidence-based formulations. Expanding clinical research would provide essential data on optimal dosages, treatment duration, and long-term effects in diverse populations [10].

3. Need for Mechanistic and Molecular-Level Studies

The multi-targeted actions of Aegle marmelos phytochemicals are often described qualitatively, without detailed molecular elucidation. While compounds like marmelosin, flavonoids, and limonoids exhibit antioxidant and anti-inflammatory effects, the precise cellular pathways and molecular targets remain underexplored [15]. Understanding enzyme modulation, signal transduction pathways, and gene expression changes induced by these bioactives could inform the rational design of novel drugs and functional foods. Further mechanistic studies at the molecular level would also clarify synergistic interactions among phytochemicals, enabling the development of more potent, multi-targeted therapeutics [15].

4. Long-Term Safety and Toxicity Evaluation

Although short-term studies support the relative safety of Aegle marmelos for dietary and therapeutic use, comprehensive long-term toxicological assessments are limited [12]. Chronic exposure studies are required to evaluate cumulative effects, potential organspecific toxicity, and inter-individual variability. Particular attention is needed for vulnerable populations, including pregnant or lactating women, patients with hepatic or renal impairment, and individuals taking concurrent pharmacotherapy [6].

5. Potential in Drug Discovery

Aegle marmelos* possesses multiple bioactive constituents that exhibit cytotoxic, antiinflammatory, and metabolic modulatory effects [15]. However, their full potential in drug discovery remains underutilised. Systematic screening, isolation of active compounds, and pharmacokinetic profiling can enable the identification of lead molecules for novel therapeutics. Integrating computational modelling, molecular docking, and in vitro validation could accelerate the discovery of plant-derived compounds suitable for clinical translation [15].

6. Innovation in Nutraceutical and Functional Food Development

The bioactive profile of Aegle marmelos makes it an ideal candidate for inclusion in functional foods and nutraceutical products [10]. However, research on optimal formulation strategies, bioavailability enhancement, and stability under industrial processing conditions is limited. Future studies should focus on nanoencapsulation, effervescent tablets, and edible coatings to maximise the bioefficacy of the active compounds while maintaining consumer acceptability [10]. Such innovation would allow Aegle marmelos to play a larger role in preventive healthcare and dietary supplementation [8].

II. CONCLUSION

Aegle marmelos, commonly known as bael, emerges as a plant of remarkable therapeutic and nutritional potential. Across multiple studies, it has been established that the plant harbours a diverse array of bioactive phytochemicals, including alkaloids, flavonoids, tannins, coumarins, phenolics, terpenoids, and limonoids, which are distributed throughout its leaves, fruits, bark, and roots. These compounds confer a wide spectrum of pharmacological activities, ranging from potent antioxidant, anti-inflammatory, and hepatoprotective effects to antidiabetic, antimicrobial, and anticancer activities. The mechanisms underlying these effects often involve modulation of key enzymatic pathways,

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inhibition of oxidative stress, and suppression of inflammatory mediators, demonstrating the plant's multi-targeted therapeutic efficacy.

In addition to its pharmacological profile, Aegle marmelos holds significant nutritional and functional value. The fruit and leaves contain essential vitamins, minerals, dietary fibres, and bioactive compounds, making them suitable for incorporation into various nutraceutical formulations, functional foods, and beverages. Modern applications, including effervescent tablets, nano-polysaccharide coatings, and other processed derivatives, not only enhance the stability and bioavailability of active constituents but also align with contemporary consumer preferences for health-conscious and environmentally sustainable products. Furthermore, the industrial and pharmaceutical utilisation of Aegle marmelos highlights its economic relevance, showcasing its potential in cosmetics, herbal formulations, food preservation systems, and green manufacturing processes.

Safety assessments indicate that the plant is relatively non-toxic at recommended dosages, supporting its inclusion in therapeutic, nutraceutical, and functional food preparations. Nonetheless, standardisation of active compounds such as aegeline, marmelosin, and limonoids is crucial to ensure consistent efficacy and to mitigate the risk of adverse interactions, particularly in vulnerable populations such as pregnant women or patients on concurrent medication. Limited long-term clinical data underscore the need for extended toxicological evaluation and rigorous preclinical studies to confirm the safety of chronic consumption and high-dose exposure.

Despite substantial progress, research gaps remain. Variability in extraction methods, plant age, and environmental conditions affects phytochemical composition and biological activity, complicating dosage standardisation. Moreover, comprehensive mechanistic studies at the molecular level are limited, and large-scale clinical trials evaluating multitargeted effects remain scarce. Addressing these gaps will facilitate the development of well-characterised herbal formulations and nutraceutical products, enabling Aegle marmelos to play a more significant role in preventive healthcare and functional dietary applications.

In summary, Aegle marmelos represents a valuable botanical resource with a unique combination of medicinal, nutritional, and industrial properties. Its bioactive compounds offer multi-faceted therapeutic potential, while its functional attributes support innovative applications in nutraceuticals, food systems, and sustainable industry. Future research focusing on standardisation, mechanistic elucidation, clinical validation, and industrial scalability is essential to fully exploit this plant's capabilities, ensuring its safe and effective integration into modern healthcare, dietary, and commercial frameworks.

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