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REVIEW ARTICLE

A Comprehensive Review on Traditional Uses, Phytochemistry, and Pharmacological Activities of *Aegle marmelos*

Ramakrishna S [*1], Vidyashree.G.N [2]

[1]*Associate Professor and HOD, Department of Pharmacognosy, Varadaraja Institute Of Pharmaceutical Education And Research, Tumkur, Karnataka, India.*
[2]*UG Scholar, Varadaraja Institute Of Pharmaceutical Education And Research, Tumkur, Karnataka, India.*

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Abstract: *Aegle marmelos*, commonly known as bael or Indian quince, is a revered plant in Ayurvedic medicine and Hindu culture. This review aims to provide a comprehensive understanding of the traditional uses, phytochemistry, and pharmacological activities of *A. marmelos*. The plant has been traditionally used for various ailments, including diarrhea, dysentery, fever, respiratory disorders, and hemorrhoids, due to its cooling, gastroprotective, antimicrobial, and anti-inflammatory properties. The phytochemical analysis of *A. marmelos* has revealed the presence of terpenoids, coumarins, alkaloids, fatty acids, and amino acids in various parts of the plant. These compounds contribute to the pharmacological activities of the plant, including antidiabetic, antioxidant, cardioprotective, hepatoprotective, anticancer, antiulcer, and antimalarial activities. The fruit of *A. marmelos*has been reported to possess antidiabetic and antioxidant properties, while the leaf extract exhibits hepatoprotective and antimalarial activities. The unripe fruit has shown cardioprotective effects, and the fruit pulp has been used to treat chronic diarrhea and dysentery. Additionally, the plant extracts have demonstrated anticancer potential against various human tumor cell lines. This review provides a comprehensive overview of the traditional uses, phytochemistry, and pharmacological activities of *A. marmelos*, highlighting its potential as a valuable medicinal plant for further research and drug development.

Keywords: *Aegle marmelos*; Bael, Phytochemistry, Ethnomedicine, Traditional uses.

1. Introduction

Aegle marmelos, belonging to the Rutaceae family, is a revered plant in traditional medicine systems, particularly in Ayurveda. Known as "Bael" or "Indian Quince," this plant holds a sacred status in Hindu culture. *A. marmelos* is a medium-sized, slow-growing tree that can reach a height of 12 to 15 meters. It is a hardy plant, capable of thriving in well-drained soils, even in arid and desert conditions. The tree is adorned with small spines along its branches, and its fruits are prized for their therapeutic and nutritional qualities. These fruits are large, round, or oval-shaped, with a hard, woody shell enclosing a fibrous, golden pulp that has a marmalade-like taste and floral aroma.

In Ayurvedic medicine, various parts of *A. marmelos* have been utilized for centuries to treat a wide range of ailments, including boils, diarrhea, earaches, fever, and cold. The bark, roots, leaves, flowers, and fruits of this plant have been incorporated into numerous formulations due to their potent medicinal properties. The plant has a long-standing history of use in traditional medicine, with its various parts being employed for their unique therapeutic benefits. *A. marmelos* is not only valued for its therapeutic potential but also for its remarkable nutritional composition. The fruit is a rich source of proteins, fats, minerals, fibers, carbohydrates, calcium, phosphorus, and potassium, making it a valuable addition to a healthy diet. Its nutrient-dense profile contributes to its overall medicinal value, as many of these essential nutrients play crucial roles in maintaining optimal health and well-being.

Furthermore, the plant is believed to possess minimal side effects compared to synthetic drugs, making it an attractive candidate for further exploration. This attribute, coupled with its long-standing traditional use and potential for therapeutic applications, has garnered significant interest from researchers and healthcare professionals alike. The objective of this review is to provide a comprehensive understanding of the traditional uses, phytochemistry, and pharmacological activities of *A. marmelos*, highlighting its potential applications in modern healthcare and drug development. By delving into the plant's rich history, chemical composition, and biological activities, this review aims to shed light on the vast potential of this remarkable plant and pave the way for future research and therapeutic advancements.

* Corresponding author: Ramakrishna S and Vidyashree.G.N

2. Nutritional Value of Bael

Aegle marmelos, or Bael, is a nutrient-dense fruit that offers an array of essential vitamins, minerals, and other beneficial compounds. The nutritional value of Bael is remarkable, making it a valuable addition to a healthy diet. The fruit is rich in proteins, fats, minerals, fibers, carbohydrates, calcium, phosphorus, and potassium. The protein content in Bael is around 1.8%, which can contribute to meeting the daily protein requirements. The fat content, although low at 0.3%, contains essential fatty acids that are beneficial for overall health. Bael is an excellent source of dietary fiber, with a content of 2.9%, which aids in maintaining a healthy digestive system and regulating blood sugar levels. One of the notable features of Bael is its rich mineral composition. It contains significant amounts of calcium (0.085%), phosphorus (0.050%), and potassium (0.60%). These minerals play crucial roles in various bodily functions, such as bone health, muscle contractions, and maintaining fluid balance. In addition to its impressive nutrient profile, Bael is also a good source of various organic acids, amino acids, and other phytochemicals that contribute to its medicinal properties. These compounds are believed to possess antioxidant, anti-inflammatory, and other therapeutic effects, making Bael a valuable addition to traditional medicine systems.

3. Plant Profile (Botanical Description)

3.1. Botanical Classification

Kingdom: Plantae

Order: Sapindales

Family: Rutaceae

Subfamily: Aurantioideae

Genus: Aegle

Species: *Aegle marmelos*

Botanical Name: *Aegle marmelos*

A. marmelos is a semi-tropical plant that can grow up to an altitude of around 1200 meters above sea level. It is a medium-sized, slow-growing tree that can reach a height of 12 to 15 meters. The tree is hardy and can thrive in well-drained soils, even in arid and desert conditions. The morphological features of *A. marmelos* are distinctive. The tree is adorned with small, straight spines that measure 1.2 to 2.5 cm in length, either individually or in pairs along the branches. The bark is smooth, finely fissured, and flaky, with shades of pale brown or grayish color. It is common to observe sticky sap oozing from the cut portions of the bark, which eventually solidifies and resembles gum arabic. The leaves of *A. marmelos* are trifoliate, with each leaflet being oval-shaped, untoothed or with shallow, rounded teeth, and tapering or pointed at the tip and rounded base. The mature leaves are dark green and smooth, while the young leaves have a pinkish-green hue and are coarsely hairy.

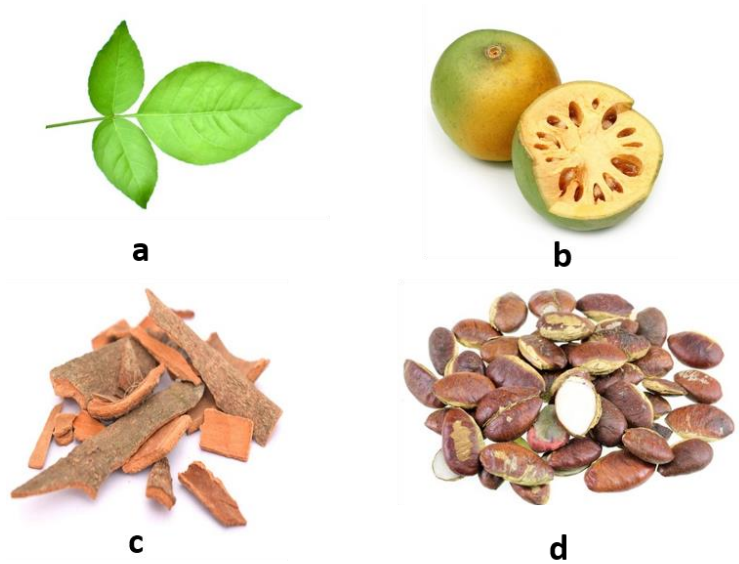


Figure 1. Various parts of *A. marmelos* a. Leaves b. Fruit c. Bark d. Ripe seeds

4. Geographical Distribution

Aegle marmelos is widely distributed across various regions, including India, Sri Lanka, Bangladesh, Nepal, Myanmar, Thailand, Vietnam, and parts of the Philippine Islands. In India, it can be found in almost every state, such as West Bengal, Kerala, Madhya Pradesh, Himachal Pradesh, Andhra Pradesh, and Jammu & Kashmir. The plant is well-adapted to semi-tropical and tropical climates, thriving in dry woodlands and hilly areas. Its ability to withstand arid conditions makes it suitable for cultivation in regions with limited water resources.

It is important to note that while *A. marmelos* is native to the Indian subcontinent, it has also been introduced and cultivated in other regions with similar climatic conditions, such as parts of Africa, the Caribbean, and certain regions of South America. The wide distribution of *A. marmelos* can be attributed to its versatility, hardiness, and the valuable medicinal and nutritional properties it offers. As a result, the plant has gained significant importance in traditional medicine systems and has been incorporated into various cultural and religious practices across different regions

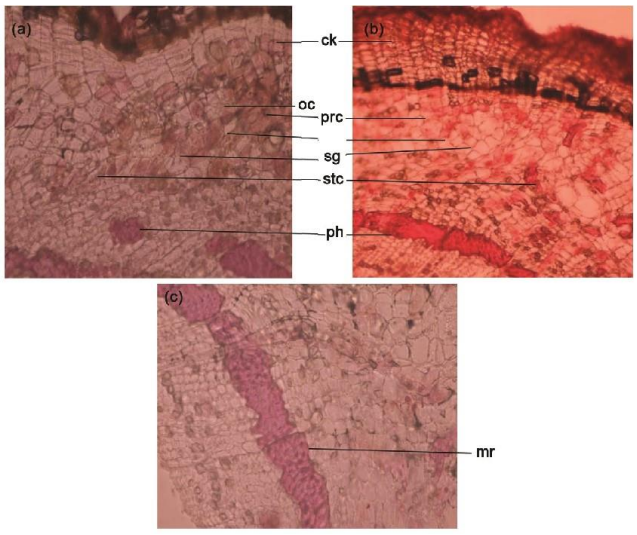
5. Morphology and Microscopy

5.1. Morphology

Aegle marmelos is a hardy, medium-sized tree with a slow growth rate. It is the sole species in the Aegle genus and is classified as a large subtropical tree. The tree bears fruit once a year during the Indian summer, which spans from March to June. The fruits of *A. marmelos* have a dual purpose, serving both medicinal and nutritional needs, and can be round, pyriform (pear-shaped), oval, or oblong in shape. One of the remarkable features of *A. marmelos* is its ability to produce fruit over an extended period. The fruits take approximately 11 months to ripen on the tree, during which time they can grow to the size of a large pomelo or grapefruit, or even larger in some cases. The shell of the fruit is extremely hard, often requiring a hammer or machete to break it open.

5.2. Microscopy

The microscopic examination of *A. marmelos* reveals intricate details about its internal structure. The transverse section of the plant shows a well-defined arrangement of various tissues and cells. The outermost layer is the epidermis, which is followed by the cortex region. The cortex is composed of parenchymatous cells and may contain specialized structures like oil glands or resin ducts, depending on the plant part examined. Moving inwards, the vascular bundles are arranged in a distinct pattern, consisting of phloem (responsible for transporting nutrients) and xylem (responsible for transporting water and minerals) tissues. The phloem and xylem elements are typically arranged in a collateral manner, with the phloem towards the outer side and the xylem towards the inner side. The central region of the transverse section is occupied by the pith, which is composed of parenchymatous cells. The pith plays a role in storage and can also contribute to the overall mechanical strength of the plant. Detailed microscopic studies of different plant parts, such as leaves, stems, roots, and fruits, can provide valuable information about the distribution and localization of various phytochemicals and active compounds responsible for the medicinal properties of *A. marmelos*. The microscopic image of transverse section of *A. marmelos* is shown in Figure 2.



(Key: ck-cork, ct- cortex, mr-medullary rays, oc- oil cell, scsclereids, stc-stone cells, ph-phloem, phf-phloem fibres, sg- starch grains)

Figure 2. TS of *Aegle marmelos* root bark

6. Traditional Uses

The traditional uses of *A. marmelos* encompass a wide range of ailments, including diabetes, scurvy, respiratory issues, hemorrhoids, flatulence, and inflammatory conditions. The plant's various parts have been integral to traditional medicine systems for centuries, highlighting its significant role in maintaining human health and well-being. Following are the traditional uses of various parts of Bael.

6.1. Fruit

The bael fruit is one of the most prized parts of the *A. marmelos* plant due to its various traditional uses and medicinal properties. The fruit has a green or yellow peel on a smooth, woody shell, and its diameter typically ranges from 5 to 12 centimeters. The fibrous golden pulp inside the fruit is known for its marmalade-like taste and floral aroma. Traditionally, the bael fruit has been consumed after diarrhea to aid in the recovery process. Its pulp is believed to possess antiprotozoal properties, making it effective in treating chronic diarrhea accompanied by loose stools or, occasionally, constipation. The fruit powder has been used to stop bleeding and restore normal bowel movements.

6.2. Bark

The bark of *A. marmelos* has been widely used in traditional medicine for various ailments. Local communities often prepare a bark decoction to treat their ailments. The bark is smooth, finely fissured, and flaky, with shades of pale brown or grayish color. It is equipped with long, straight spines measuring 1.2 to 2.5 cm, either individually or in pairs. The bark is also known to exude a sticky sap from cut portions, which eventually solidifies and resembles gum arabic. This sap is initially sweet-tasting but can become irritating to the throat upon prolonged exposure.

6.3. Flower

The delicately fragrant, light green or yellowish flowers of *A. marmelos* are borne in short, drooping, unbranched clusters at the tips of branches and leaf axils. Measuring 1.5 to 2 cm in size, these bisexual flowers contain constituents known as flavonoids, coumarins, and tannins, which are believed to aid in reducing inflammation and edema. Traditionally, the flowers have been used to treat asthma, diarrhea, and other conditions, as some of their constituents are thought to help lower blood sugar levels.

6.4. Root

The roots of *A. marmelos* have been traditionally used to treat fevers, prevent heart palpitations, and address urinary issues. It is also believed that the roots can provide relief from stomach aches.

6.5. Seeds

Each tiny, hard, flattened-oblong seed of *A. marmelos* is covered in woolly hairs and surrounded by an adhesive sac. The seeds are lodged within the pulp and are white, rectangular, and compressed, with a creamy yellowish surface covering the sacs. In traditional medicine, seed extracts of *A. marmelos* have been used to exhibit hypolipidemic (lipid-lowering) and antidiabetic properties in rats.

6.6. Leaf

The trifoliate leaves of *A. marmelos* have a pointed tip and a rounded base. Each leaflet is oval-shaped, measuring 5-14 × 2-6 cm, with an untoothed or shallow, rounded teeth margin. Mature leaves are dark green and perfectly smooth, while young leaves have a pinkish-green hue and are coarsely hairy. Leaf extracts have been traditionally applied to affected areas to reduce inflammation. The leaf juice, combined with honey, has been used to effectively treat fever. Additionally, *A. marmelos* leaves have been employed as a potential treatment for tuberculosis, owing to their high antioxidant content and ability to promote insulin production, thereby lowering blood sugar levels.

7. Active Constituents

Aegle marmelos is reported to have a diverse chemical composition comprising various phytochemicals, including terpenoids, coumarins, alkaloids, fatty acids, and amino acids. These active constituents contribute to the plant's numerous pharmacological activities and medicinal properties.

7.1. Terpenoids

Several terpenoid compounds have been identified in *A. marmelos*, such as cineol, caryophyllene, and various other monoterpenes and sesquiterpenes. These terpenoids are known for their antimicrobial, anti-inflammatory, and antioxidant properties.

7.2. Coumarins

A. marmelos is a rich source of coumarins, including marmin, marmelide, psoralen, and imperatorin. Coumarins are known for their diverse biological activities, such as anti-inflammatory, antioxidant, antimicrobial, and anticancer properties.

7.3. Alkaloids

Alkaloids present in *A. marmelos* include aegeline, fragrine, and aegelenine. These alkaloids have been studied for their potential therapeutic effects, including anticancer, antidiabetic, and antimicrobial activities.

7.4. Fatty acids

A. marmelos contains various fatty acids, including palmitic acid, stearic acid, oleic acid, and linoleic acid. These fatty acids contribute to the plant's nutritional value and may also possess pharmacological activities.

7.5. Amino acids

Several amino acids, such as glutamic acid, aspartic acid, and glycine, have been isolated from *A. marmelos*. Amino acids are essential building blocks of proteins and play crucial roles in various biological processes.

8. Phytochemistry

The phytochemical diversity of *A. marmelos* has attracted significant research interest, as these compounds may hold the key to unlocking the plant's medicinal potential and developing new therapeutic agents. Ongoing research efforts continue to explore the isolation, characterization, and pharmacological evaluation of these phytochemicals, aiming to harness their full potential for human health and well-being. Extensive research has been conducted on the phytochemistry of *A. marmelos*, with many Indian scientists contributing significantly to the isolation and characterization of its chemical constituents. The various parts of the plant, including the fruit, leaves, bark, seeds, and roots, have been studied for their phytochemical composition.

The fruit of *A. marmelos* is particularly rich in phytochemicals, such as marmelosin, lupeol, and auraptene. These compounds have been associated with various pharmacological activities, including antioxidant, anti-inflammatory, and anticancer properties. The leaves of *A. marmelos* contain flavonoids, such as rutin and quercetin, which are known for their antioxidant and anti-inflammatory effects. Additionally, the leaves are a source of essential oils and terpenoids, contributing to their medicinal properties.

The bark of *A. marmelos* is a rich source of coumarins, including marmin and marmelide, which have been studied for their potential anticancer and anti-inflammatory activities. The bark also contains alkaloids, such as aegeline and aegelenine, which have shown promise in the treatment of diabetes and cancer. The seeds of *A. marmelos* are a valuable source of fatty acids and amino acids, as well as compounds like skimmianine and aegeline, which exhibit antidiabetic and hypolipidemic activities. The roots of *A. marmelos* are known to contain various phytochemicals, including terpenoids, coumarins, and alkaloids, with potential therapeutic applications in traditional medicine. Table 1 provides the list of major phytoconstituents in each part of the *A. marmelos*.

Table 1. Phytochemical Constituents of *Aegle marmelos*

Plant Part	Major Phytochemical Constituents
Fruit	Terpenoids (marmelosin, lupeol, auraptene), Coumarins (marmin, marmelide), Alkaloids (aegeline, aegelenine)
Leaves	Flavonoids (rutin, quercetin), Essential oils, Terpenoids
Bark	Coumarins (marmin, marmelide), Alkaloids (aegeline, aegelenine)
Seeds	Fatty acids, Amino acids, Skimmianine, Aegeline
Roots	Terpenoids, Coumarins, Alkaloids

9. Pharmacological Activities

Aegle marmelos possesses a wide range of pharmacological activities, owing to its diverse phytochemical composition. The following are some of the notable pharmacological activities reported for this plant:

9.1. Antidiabetic activity

Extracts from *A. marmelos* fruits have been found to be effective in managing streptozotocin-induced diabetes in rats by positively impacting pancreatic histology and regulating blood glucose levels. The presence of compounds like aegeline and skimmianine in the seeds is believed to contribute to the plant's antidiabetic properties.

9.2. Antioxidant activity

Both ripe and unripe fruits of *A. marmelos* have demonstrated potent antioxidant and free radical-scavenging properties. The ripe fruit extracts have been found to contain higher levels of enzymatic antioxidants compared to unripe fruit extracts, except for glutathione peroxidase. The antioxidant activity of *A. marmelos* is attributed to the presence of flavonoids, coumarins, and other phytochemicals.

9.3. Cardioprotective effect

The alcoholic extract from unripe *A. marmelos* fruits has been reported to offer cardioprotective effects in myocardial infarction induced by isoproterenol. This activity is attributed to the presence of auraptene, a potent compound found in the plant.

9.4. Antidiarrheal and antidysenteric activities

The unripe or half-ripe fruit of *A. marmelos* has been traditionally used as an effective treatment for persistent diarrhea and dysentery without fever. The fruit pulp exhibits antiprotozoal properties, making it beneficial in the management of chronic diarrhea.

9.5. Hepatoprotective activity

Bael leaf extract has been found to be effective in inhibiting doxorubicin-induced hepatotoxicity at a dose of 25 mg/kg. Similarly, eugenol isolated from bael leaves has demonstrated hepatoprotective action.

9.6. Anticancer activity

Extracts from *A. marmelos* fruit have been shown to strengthen the immune system, thereby enhancing the body's anticancer activity. Additionally, extracts from various parts of the plant have exhibited growth-inhibitory effects on several human tumor cell lines, including MDAMB-231, erythroleukemic HEL, melanoma colo38, and MCF7.

9.7. Antiulcer activity

The leaf infusion of *A. marmelos* has been traditionally used to treat peptic ulcers. The fruit, when consumed as a beverage, has been found to possess significant antiulcer potential due to the presence of mucilage, which coats the stomach mucosa and aids in ulcer healing.

9.8. Antimalarial activity

The leaf extract of *A. marmelos* has exhibited promising antimalarial activity against Plasmodium falciparum in vitro, with an IC50 of 75 µg/mL. This activity, coupled with low cytotoxicity, highlights the plant's potential as an antimalarial agent. The pharmacological activities, and key compounds involved are summarized in Table 2.

Table 2. Pharmacological activities of *A. marmelos*

Pharmacological Activity	Plant Part(s) Involved	Key Compounds/Mechanisms
Antidiabetic	Fruits, Seeds	Aegeline, Skimmianine
Antioxidant	Ripe and Unripe Fruits	Enzymatic antioxidants, Flavonoids, Coumarins
Cardioprotective	Unripe Fruits	Auraptene
Antidiarrheal/Antidysenteric	Unripe/Half-ripe Fruits, Pulp	Antiprotozoal activity
Hepatoprotective	Leaves	Eugenol
Anticancer	Various Parts	Immune system modulation, Growth inhibition of tumor cells
Antiulcer	Leaves, Fruits	Mucilage, Luvagetin
Antimalarial	Leaves	In vitro activity against Plasmodium falciparum

10. Conclusion

Aegle marmelos, a revered plant in traditional medicine systems, particularly Ayurveda, has garnered significant attention for its diverse pharmacological activities and potential therapeutic applications. This review has provided a comprehensive overview of the plant's traditional uses, phytochemistry, and pharmacological activities, highlighting its value as a medicinal resource. The various parts of *A. marmelos*, including the fruit, leaves, bark, seeds, and roots, have been extensively studied for their chemical constituents and biological activities. The plant's phytochemical diversity, comprising terpenoids, coumarins, alkaloids, fatty acids, and amino acids, contributes to its wide range of pharmacological properties. However, it is crucial to conduct further rigorous studies to fully elucidate the safety, efficacy, and pharmacokinetic properties of *A. marmelos* extracts and isolated compounds. Such research endeavors will not only validate the plant's traditional uses but may also uncover new applications in modern healthcare. In

conclusion, *Aegle marmelos* stands as a promising candidate for future drug discovery and development, with its rich phytochemical profile and diverse pharmacological activities offering a vast repertoire of therapeutic potential. Continued research efforts in this area will undoubtedly contribute to the advancement of human health and well-being

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