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Review

Golden Apple of Healthcare: Exploring the Synergy Between *Aegle marmelos* Secondary Metabolites and Global Commercial Wellness Products

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Abstract

Aegle marmelos (L.) Correa, commonly known as bael, is an important medicinal plant of the family Rutaceae that has been extensively used in traditional systems of medicine across the Indian subcontinent and Southeast Asia. The present review comprehensively summarizes the bioactive phytochemistry, pharmacognosy, therapeutic potential, toxicity profile, extraction methods, and commercial applications of *Aegle marmelos*. Various parts of the plant, including leaves, fruits, bark, roots, and seeds, are rich sources of diverse phytoconstituents such as alkaloids, flavonoids, tannins, coumarins, terpenoids, saponins, glycosides, and essential oils, many of which exhibit significant biological activities. Experimental and preclinical studies have demonstrated a wide range of pharmacological properties, including antidiarrhoeal, antimicrobial, antiviral, anticancer, antipyretic, anti-inflammatory, antidiabetic, and diuretic activities. Notably, compounds such as marmelin, lupeol, aegeline, eugenol, and citral have shown promising mechanisms of action involving antioxidant defense, enzyme inhibition, modulation of inflammatory mediators, and induction of apoptosis in cancer cells. Toxicological evaluations indicate that *Aegle marmelos* extracts are relatively safe at therapeutic doses. In addition to medicinal uses, the plant has considerable commercial value in food products, essential oils, and traditional formulations. Advances in extraction techniques such as maceration and Soxhlet extraction have further facilitated the isolation of bioactive compounds. Overall, this review highlights the immense therapeutic potential of *Aegle marmelos* and supports its role as a valuable natural resource for the development of novel phytopharmaceuticals and functional foods, while emphasizing the need for further clinical and mechanistic studies to validate its traditional claims.

Keywords: *Aegle marmelos,* Antidiabetic activity, Anticancer activity, Extraction methods, Pharmacological activities, Phytochemistry, Rutaceae, Secondary metabolites, Therapeutic potential.

1.INTRODUCTION:

Aegle marmelos (L.) Correa, commonly known as Bael, is an indigenous medicinal plant of India belonging to the family Rutaceae and is widely cultivated throughout the Indian subcontinent. The plant is a medium- to large-sized deciduous tree and has been extensively utilized in traditional and ethnomedicinal practices for centuries. Various parts of *Aegle marmelos*, including the leaves, fruits, stem, and roots, possess significant therapeutic value and have been traditionally used for a wide range of medicinal purposes. These include astringent, antidiarrhoeal, antidysenteric, demulcent, antipyretic, antiscorbutic, hemostatic, aphrodisiac, and anti-venomous activities, particularly as an antidote for snake envenomation. In addition, *Aegle marmelos* has been reported to be effective in the management of diabetes mellitus and its associated complications. The plant is also traditionally employed in the treatment of pain, fever, and inflammatory conditions.

Nature serves as a vast reservoir of therapeutic agents for the treatment of human diseases. It is estimated that nearly 80% of the global population relies wholly or partially on traditional systems of medicine for primary

Figure 2: Bael leaves with Fruit

healthcare. According to a World Health Organization (WHO) survey conducted in 1993, approximately 80% of patients in India, 85% in Myanmar, and 90% in Bangladesh are treated by practitioners of traditional medicine. Herbal medicines, which form the backbone of these traditional medical systems, have been used for thousands of years and have significantly contributed to the maintenance of human health. Medicinal plants are rich sources of secondary metabolites and essential oils with proven therapeutic potential, many of which serve as valuable leads for drug development. The widespread use of herbal medicines can be attributed to their safety, cost-effectiveness, therapeutic efficacy, and easy availability, making them suitable for the management of various ailments.

Natural products have also played a crucial role in the prevention and management of human diseases over centuries. Advances in modern techniques for isolation, characterization, structural elucidation, and combinatorial synthesis have further enhanced their potential in pharmaceutical research. In this context, the World Health Organization (WHO) has established guidelines for the standardization of medicinal plants, emphasizing macroscopic and microscopic evaluation. Several studies indicate that pharmacognostic parameters are essential for the proper identification, authentication, and quality control of plant-derived drugs. Owing to its extensive traditional usage, *Aegle marmelos* has gained considerable scientific interest.

All parts of the plant are known to contain biologically active phytoconstituents, with the leaves and fruits being most commonly used in medicinal formulations. Consequently,

the present study focuses on evaluating the phytochemical composition of *Aegle marmelos* and investigating its pharmacological activities, including antioxidant, anti-inflammatory, and antidiabetic effects. [1,2,3]

Figure 1: The Bael Tree

2.TAXONOMY:

Table 1[4]:

KINGDOM	PLANTAE
Subkingdom	Sapindales
Division	Magnoliophyta
Class	Magnoliopsida
Subclass	Rosidae
Order	Sapindales
Family	Rutaceae
Sub-Family	Aurantioidae
Genus	*Aegle*
Species	*marmelos*

3.BOTANICAL DESCRIPTION:

Table 2[5]:

Plant Part	Morphological characteristics
Bark	The bark is grey or brownish in colour, and it bears a number of long, straight spines. It includes gums, which form from wounded branches and harden over time. The easiest way to describe these gums is as a transparent, sticky sap. It tastes good at first, but it quickly gets irritating to the throat.
Leaf	It has trifoliate leaves with a circular base and a pointed apex. The adult leaves are dark green, whilst the young leaves are pale green.
Flower	The flowers are bisexual and greenish or yellowish in colour. It is usually evident with fresh leaves.
Fruit	The bael fruit has a tough outer jacket with a diameter of around 5 to 12 cm. It is green while unripe and turns yellowish brown when ripe. Its interior includes up to 20 orange pulp.

Figure 3: Bael leaves

Figure 4: Bael Fruit

4.ECOLOGY AND GEOGRAPHICAL DESCRIPTION:

Bael (*Aegle marmelos*) is native to India and is widely distributed in Bangladesh, Myanmar, Pakistan, Sri Lanka, Thailand, Egypt, and Malaysia. The tree occurs naturally in dry woodlands, hill slopes, and plains of central and southern India, as well as in regions of Burma, Pakistan, and Bangladesh. It is commonly found in mixed deciduous forests and dry dipterocarp forests. *Aegle marmelos* is a subtropical species that exhibits high environmental tolerance. In the Punjab region, it grows at elevations of up to 1,200 m and withstands extreme climatic conditions, with summer temperatures reaching up to 48.89 °C in the shade and winter temperatures falling to −6.67 °C, along with prolonged periods of drought. However, the species requires a distinct dry season for fruiting and does not bear fruit in areas lacking prolonged dry periods, such as southern Malaysia[6].

5. PHYTOCHEMISTRY:

Studies have shown that bael fruit pulp is abundant in bioactive constituents, including carotenoids, phenolic compounds, alkaloids, pectin, tannins, coumarins, flavonoids, and terpenoids. Among the solvents evaluated, methanol and water are the most effective for extracting these metabolites, with ethanol showing slightly lower efficiency The phytochemical profile of *Aegle marmelos* has been widely investigated, revealing the presence of numerous biologically active compounds

Some of the key phytochemicals found in *Aegle marmelos* include:

Alkaloids are nitrogen-bearing compounds widely distributed in plants and are well recognized for their pharmacological properties. In *Aegle marmelos*, several alkaloids have been reported

from the leaves and roots, notably marmesin, marmelosin, and aegeline.

Tannins are widely occurring plant compounds recognized for their astringent and antioxidant characteristics. The fruit of *Aegle marmelos* is particularly rich in tannins, which have demonstrated potent antioxidant and anti-inflammatory effects. Similarly, flavonoids are broadly distributed phytochemicals known for their significant antioxidant, anti-inflammatory, and anticancer activities.

Flavonoids have been reported in the leaves and roots of *Aegle marmelos*, and several of these compounds have demonstrated notable antinociceptive (pain-relieving) and antipyretic (fever-reducing) effects.

Terpenoids are a diverse class of phytochemicals widely distributed throughout the plant kingdom and are well known for their medicinal potential. In *Aegle marmelos,* various terpenoids have been identified, several of which exhibit significant antifungal and antibacterial activities.

Saponins are widely occurring plant compounds characterized by their foaming and emulsifying properties. In *Aegle marmelos*, saponins have been reported in both the fruits and leaves, and several of these constituents have demonstrated antinociceptive and anti-inflammatory activities.

Glycosides are widely distributed phytochemicals recognized for their therapeutic potential. In *Aegle marmelos*, glycosides have been detected in both the fruits and leaves, with several of these compounds exhibiting antinociceptive and anti-inflammatory activities.[4]

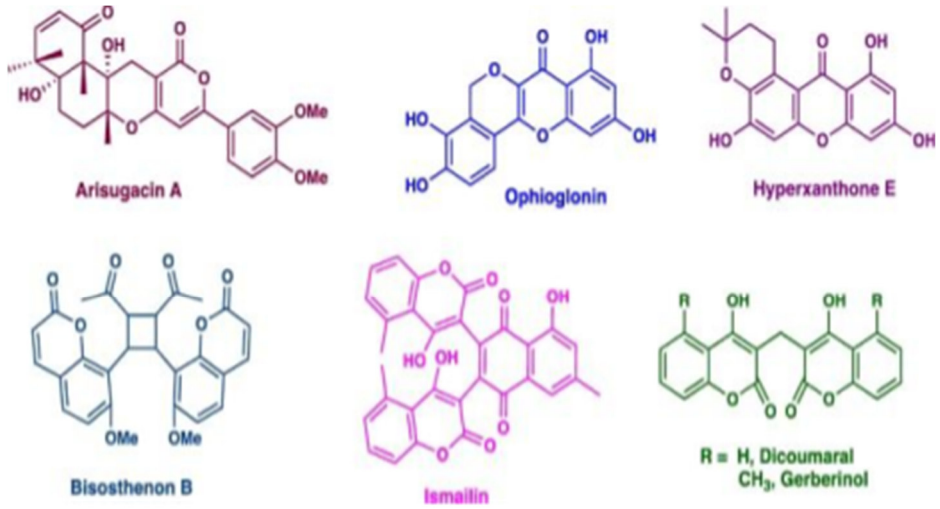

Figure 5: Structures

Table 3[5]: PLANT PART CHEMICAL CONSTITUTENTS:

Plant part	Chemical Constituents
Leaf	Skimmianine, Aeglin, Rutin, α -sitosterole, β -sitosterol, Flavone, Lupeol, Cineol, Citral, Glycoside, O-isopentenyl, Hallordiol, Mameline, Citronellal, Cumin aldehydephenylethyle cinnamamides, Euginol.
Fruit	Psoralen, Marmelide, Tannin, Phenol, Marmelosin, Luvangetin, Aurapten.
Bark	Alkaloids, Fagarine, Marmin, Furoquinoline
Seed	D-limonene, A-D-phellandrene, Cineol, Citronellal, Citral, P-cyrnene, Cumin aldehyde are essential oils.
Root	Terpines, Halopine, Coumarins, and Alkaloid

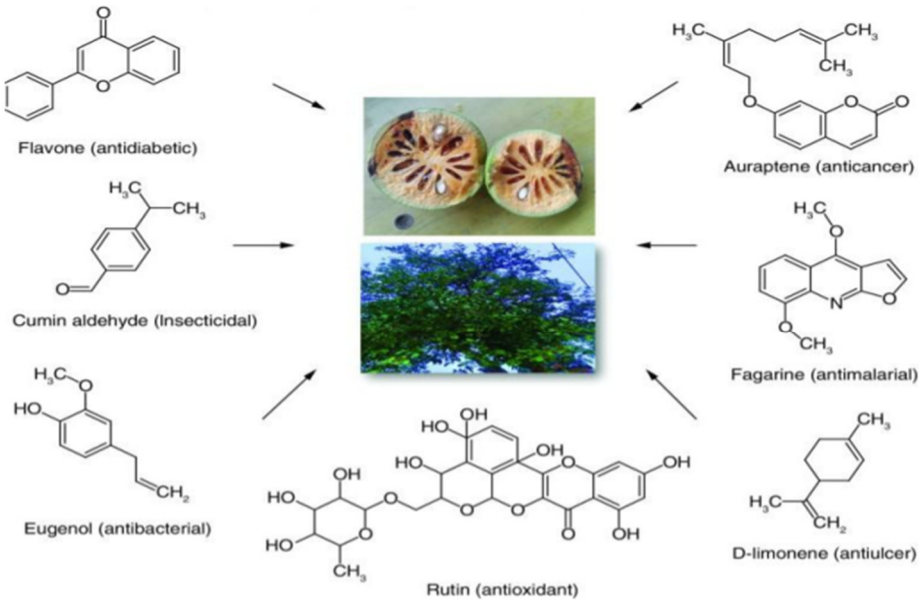

Figure 6: Structures with pharmacological Activities

6. PHARMACOLOGICAL ACTIVITIES:

6.1 Anti diarrheal activity

Mazumder et al. evaluated the in vitro and in vivo antidiarrhoeal activity of the chloroform extract obtained from the roots of *Aegle marmelos*. The in vitro findings revealed that the extract exhibited activity comparable to that of ciprofloxacin and showed maximum effectiveness against Vibrio cholerae, followed by Escherichia coli (E. coli) and Shigella species. In addition, studies demonstrated that the methanolic extract of *Aegle marmelos* fruits significantly reduced intestinal propulsion in rats. Furthermore, the unripe fruit pulp of *Aegle marmelos* was found to influence bacterial colonization of the gut epithelium and interfere with the production as well as the action of specific enterotoxins. These observations indicate multiple possible mechanisms through which *Aegle marmelos* exerts its therapeutic effects in infectious diarrhoea. Collectively, these findings support its traditional use as documented in ancient Indian texts and its continued application by local communities in the management of diarrhoeal disorders.[2]

6.2 Anti microbial and Anti viral activity

The essential oil extracted from the leaves of *Aegle marmelos* has demonstrated significant antifungal activity against a wide range of animal and human pathogenic fungi, including Trichophyton mentagrophytes, Trichophyton rubrum, *Microsporum gypseum, Microsporum audounii, Microsporum cookie*, *Epidermophyton floccosum, Aspergillus niger, Aspergillus flavus*, and *Histoplasma capsulatum.* Balakumar et al. reported that leaf extracts and fractions of *Aegle marmelos* exhibited fungicidal activity against various clinical isolates of dermatophytic fungi. Among the tested extracts, the minimum inhibitory concentration (MIC) and minimum fungicidal concentration (MFC) were relatively higher for water and ethyl alcohol extracts, as well as methanolic fractions, showing effective activity at a concentration of 200 µg/mL against the dermatophytes studied.

The antifungal mechanism of *Aegle marmelos* leaf essential oil is believed to involve interference with the Ca^{2+}dipicolinic acid metabolic pathway, potentially leading to inhibition of spore germination. Calcium ion uptake and utilization by fungal spores are critical determinants of whether spores germinate or remain dormant. By disrupting this process, *Aegle marmelos* may reduce the development of the vegetative fungal body within the host or in solid media, thereby providing protection against fungal infections. This mechanism explains the antifungal efficacy of *Aegle marmelos* leaf oil. In addition to antifungal properties, various extracts obtained from the leaves, roots, and fruits of *Aegle marmelos* have been reported to possess antibacterial

activity against several bacterial strains. Numerous studies have documented the antimicrobial potential of crude plant extracts. In 2009, Venkatesan et al. demonstrated that both aqueous and ethanolic extracts of *Aegle marmelos* were active against Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus, and Bacillus subtilis, with the ethanolic extract exhibiting markedly higher antibacterial activity than the aqueous extract. The strongest inhibitory effect was observed against Bacillus subtilis, followed by Staphylococcus aureus, E. coli, and Pseudomonas aeruginosa.

Similarly, Jyothi and Rao reported that hexane, cold methanolic, and hot methanolic extracts inhibited the in vitro growth of Klebsiella pneumoniae, Micrococcus luteus, Enterococcus faecalis, and Streptococcus faecalis. However, these extracts did not show any inhibitory effect against E. coli and Proteus vulgaris.

The antimalarial potential of alcoholic extracts derived from *Aegle marmelos* seeds and leaves has also been investigated using both in vivo and in vitro models against the NK65 strain of *Plasmodium berghei.* The seed extracts exhibited schizontocidal activity in both experimental systems, whereas the leaf extracts showed activity only under in vitro conditions.

Furthermore, the in vitro antiviral activity of different parts of the *Aegle marmelos* tree has been assessed against human Coxsackie viruses B1–B6. The IC_{50} values for extracts from leaves; stem and stem bark; fruit; root and root bark; and the isolated compound marmelide were found to be 1,000; 500–1,000; 250–500; and 62.5 µg/mL, respectively. In comparison, ribavirin, a standard antiviral drug, exhibited an IC_{50} value of 2,000 µg/mL against the same viruses under identical experimental conditions. Additionally, Balasubramanian et al. reported that *Aegle marmelos* extracts were effective against white spot syndrome virus in shrimp when administered at a dose of 150 mg/kg body weight.

Overall, *Aegle marmelos* appears to exert antiviral activity predominantly during the early stages of viral replication with minimal cytotoxic effects on the host. This contrasts with conventional virucidal chemotherapeutic agents such as ribavirin, which generally act at later stages of viral replication and are often associated with significant adverse effects.[2]

6.3 Anti cancer activity

Cancer represents a major global public health challenge and is the second leading cause of mortality among both men and women in developed and developing nations. In 2008, an estimated 12.7 million new cancer cases were reported worldwide, with nearly 56% occurring in developing regions, and approximately 7.6 million cancer-related deaths were recorded, of which 63% occurred in less developed countries. Projections indicate that by 2020, the global incidence of cancer may increase nearly threefold, with a disproportionately higher burden of cases and mortality in resource-limited developing countries.

Preclinical investigations have demonstrated that *Aegle marmelos* leaf extracts exhibit significant inhibitory effects on the proliferation of several cancer cell lines, including leukemic K562, T-lymphoid Jurkat, B-lymphoid Raji, erythroleukemic HEL, melanoma Colo38, and breast cancer cell lines MCF-7 and MDA-MB-231. Additionally, *Aegle marmelos* extracts were found to enhance estrogen receptor alpha (ERα) gene expression in ERα-negative MDA-MB-231 breast cancer cells, leading to suppressed cellular proliferation. The leaf extract also displayed notable antineoplastic activity against Ehrlich ascites carcinoma in Swiss albino mice, while ethanolic fruit extracts showed cytotoxic effects against SKBR3 cells in vitro.

Several bioactive phytochemicals present in *Aegle marmelos*, including lupeol, eugenol, citral, cineole, and d-limonene, have been identified as contributors to its antineoplastic properties. Marmelin (1-hydroxy-5,7-dimethoxy-2-naphthalene carboxaldehyde), a key compound isolated from *Aegle marmelos*, selectively inhibited the growth of epithelial cancer cell lines such as HCT-116 colon carcinoma and HEp-2 alveolar epithelial carcinoma, while sparing normal mouse embryo fibroblasts.

Marmelin induced apoptosis through activation of tumor necrosis factor-α (TNF-α), TNF receptor 1 (TNFR1), and TNF receptor-associated death domain (TRADD), leading to G1 phase cell cycle arrest and caspase-3-mediated apoptosis. This effect was reversed upon

pretreatment with caspase-3 inhibitors. Furthermore, marmelin activated caspase-8 and Bid, promoting cytochrome c release, thereby indicating cross-talk between death receptor-mediated and mitochondrial apoptotic pathways. Marmelin also suppressed phosphorylation of AKT and extracellular signal-regulated kinase (ERK) in both cultured cells and tumor xenograft models. Since AKT plays a crucial role in cancer cell survival, proliferation, and invasiveness, its inhibition by marmelin significantly reduces tumor cell viability and aggressiveness.

Lupeol, another prominent constituent of *my Aegle marmelos*, has demonstrated potent anticancer activity against various human malignancies, including melanoma (451Lu, WM35, B162F2), pancreatic adenocarcinoma (AsPC-1), epidermoid carcinoma (A431), hepatocellular carcinoma (SMMC7721), and prostate cancer cell lines (LNCaP, CWR22Rγ1, and PC-3). Lupeol induced G1–S phase cell cycle arrest by downregulating cyclin D1, cyclin D2 and CDK2, while upregulating the cyclin-dependent kinase inhibitor p21 in PC-3 cells, thereby inhibiting cell cycle progression. Additionally lupeol modulated the expression of several genes involved in apoptosis and metastasis, including Bax, ErbB2, tissue inhibitor of metalloproteinases-3, FADD, MMP-2, and 14-3-3σ. It also suppressed the PI3K/Akt and MAPK signaling pathways, reduced phosphorylation of IκBα and NF-κB/p65, and inhibited the expression of cell cycle regulatory proteins such as cyclin B, cdc25C, and polo-like kinase 1 (plk1). Apoptosis induction by lupeol involved downregulation of the anti-apoptotic protein Bcl-2, upregulation of pro-apoptotic Bax, activation of caspase-3 and caspase-9, increased apaf-1 expression, and cleavage of poly(ADP-ribose) polymerase in prostate cancer cells. Lupeol treatment also increased reactive oxygen species generation, disrupted mitochondrial membrane potential, and caused DNA fragmentation in PC-3 cells.

Other phytoconstituents of *Aegle marmelos*, such as eugenol and citral, also exhibit notable antiproliferative effects. Eugenol demonstrated cytotoxic activity against salivary gland tumor cells (HSG), normal human gingival fibroblasts, HepG2 hepatoma cells, Caco-2 colon carcinoma cells, melanoma cell lines (WM1205Lu and B16), and non-malignant human VH10 fibroblasts. Citral (3,7-dimethyl-2,6-octadien-1-al) has been reported to induce apoptosis in various hematopoietic cancer cell lines. Recent studies indicate that citral exerts antiproliferative effects by inducing G2/M phase cell cycle arrest, promoting apoptosis in MCF-7 breast cancer cells, and inhibiting prostaglandin E_2 synthesis.[2]

6.4 Anti pyretic activity

Shukla et al. investigated the antipyretic activity of *Aegle marmelos* using Brewer's yeast-induced pyrexia in albino rats. Their findings demonstrated that the ethanolic extract, administered at doses of 200 mg/kg and 400 mg/kg body weight, produced a significant and dose-dependent reduction in elevated body temperature. The antipyretic efficacy of the extract was found to be comparable to that of the standard drug paracetamol administered at a dose of 100 mg/kg body weight.[2]

6.5 Diuretic activity

Singh et al. evaluated the diuretic potential of different organic extracts and their fractions obtained from *Aegle marmelos* fruit using experimental animal models. The extracts were administered intraperitoneally to rats at doses of 300, 400, and 500 mg/kg body weight. Diuretic activity was assessed by measuring urine output and urinary sodium concentration. The results indicated that the ethanolic extract significantly enhanced sodium excretion at the highest tested dose (500 mg/kg). Additionally, petroleum ether, chloroform, and ethyl acetate fractions also demonstrated notable diuretic effects.[2]

6.6 Anti - inflammatory activity

Various organic extracts of *Aegle marmelos* leaves have been reported to exhibit highly significant acute and subacute anti-inflammatory activity. Studies using both acute and chronic inflammatory animal models demonstrated that *Aegle marmelos* possesses marked anti-inflammatory potential, indicating its promise as a therapeutic anti-inflammatory agent. These effects are likely attributed to the presence of bioactive constituents such as lupeol and skimmianine in the leaves, as both compounds have independently shown comparable anti-inflammatory activity in their purified forms.

Histamine receptor activation plays a crucial role in

allergic and asthmatic responses. The alcoholic extract of *Aegle marmelos* leaves was found to antagonize histamine-induced contractions and produced a significant relaxant effect in isolated guinea pig ileum and tracheal chain preparations. These findings suggest that inhibition of H_1 receptor activity may contribute to the observed pharmacological effects of the extract.[2]

6.7 Anti diabetic activity:

The aqueous extract of *Aegle marmelos* fruits have been shown to significantly reduce blood glucose levels in streptozotocin (STZ)-induced diabetic rat models. This antihyperglycemic effect is attributed to enhanced insulin secretion resulting from partial regeneration of pancreatic β-cells. Notably, the fruit extract produced superior effects compared with the standard antidiabetic drug Glibenclamide. In vitro studies further demonstrated strong antidiabetic activity of the fruit lectin extract, assessed through glucose uptake in yeast cells. The lectin extract exhibited an IC_{50} value of 3.36 µg/mL and was more effective than the commonly used drug metformin in promoting glucose uptake. These findings suggest that the hypoglycemic activity of *Aegle marmelos* fruit extract may be related to its antioxidant potential and high concentration of bioactive constituents. Consequently, different parts of the *Aegle marmelos* plants may serve as functional food components and as promising sources for the development of antidiabetic agents.

Further studies indicate that active compounds present in the leaves and callus tissues significantly lower blood glucose levels in STZ-induced diabetic rabbits. The methanolic extract of *Aegle marmelos* callus powder was found to be as effective as the leaf extract in managing diabetes, Additionally, aqueous seed extracts of *Aegle marmelos* markedly reduced blood glucose levels in both normal and severely diabetic rats and improved glucose tolerance in mild and sub-diabetic animals, with effects comparable to the standard drug tolbutamide. Moreover, the alcoholic extract of *Aegle marmelos* leaves exhibited significant inhibitory activity against α-amylase and α-glycosidase enzymes, with IC_{50} values of 46.21 and 42.07 µg/mL, respectively. The extract also reduced elevated reactive oxygen species (ROS) levels induced by high glucose and significantly enhanced glucose utilization in HepG2 cells.[4]

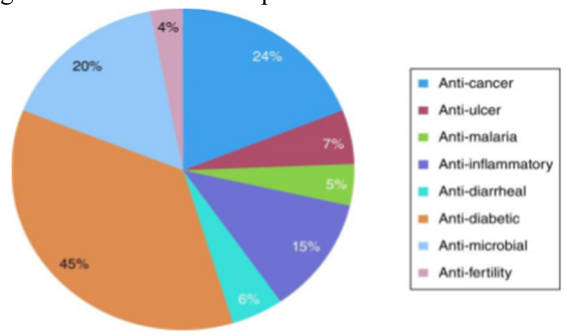

Figure 7: pie-chart of pharmacological Activities of Bael

7. TOXICITY:

Aegle marmelos dried fruit pulp is examined for its topical characteristics. Swiss albino mice were tested for acute oral toxicity with an ethanol extract of the dried fruit pulp from
Aegle marmelos at 550 and 1250 mg/kg. Test results. Should indicate that the extract is not hazardous at these doses. Mice's behavior and physiological activity remained Unchanged (14 days) throughout the trial [43]. The findings showed that the test extract's LD50 is highly significant. The oral acute toxicity study did not show any toxic symptoms, changes in behavior, or mortality at 1250 mg/kg. Doses. Thus, the ethanolic extract of *Aegle marmelos* dried fruit pulp extract has no discernable biologically significant. Toxic effect on the mice below LD50.[4]

8. COMMERCIAL PRODUCTS:

1 Food:

The fruits of *Aegle marmelos* are commonly consumed in various forms. They may be halved or, in the case of soft fruits, broken open, and the pulp mixed with palm sugar and eaten as a breakfast food, a practice widely followed in Indonesia. The pulp is also processed into nectar. In India, the seeded pulp is blended with milk and sugar to prepare a popular beverage known as sherbet. Another refreshing drink is made by combining bael fruit pulp with tamarind pulp. Mature but unripe fruits are processed into jam with the addition of citric acid. A confection known as bael fruit toffee is prepared by mixing the pulp with sugar, glucose, skim milk powder, and hydrogenated fat. Indian food technologists consider bael fruit to have strong potential for expanded commercial processing.[6]

2. Essential oil:

The essential oil obtained from the leaves contains d-limonene, α-d-phellandrene (56%), cineole, citronellal, citral, p-cymene (17%), and cumin aldehyde (5%). An oil rich in limonene is also distilled from the fruit rind and is used for perfuming hair oils.[6]

3. Medicine:

A decoction prepared from the unripe fruit along with fennel and ginger is prescribed for the treatment of hemorrhoids. For medicinal purposes, young and tender fruits are typically sliced horizontally, sun-dried, and sold in local markets. These dried fruits are widely exported to Malaysia and Europe. Due to their pronounced astringency, particularly in wild varieties, unripe bael fruits are highly valued for treating diarrhea and dysentery, especially during the summer season in India.[6]

4. Bael powder

Figure 8: Bael Fruit Powder

Bael fruit powder is prepared by different techniques. They are stored for a long period and also maintain their medicinal value. The powder is prepared from dehydrated unripe or unripe fruit[7]

5. Bael Toffee

Toffee is a brittle confection prepared by combining melted butter and syrup along with suitable flavoring agents and colorants. In general, fruit-based toffees possess higher nutritional value compared to conventional toffees. Since bael fruit pulp is rich in both nutritive and therapeutic properties, its incorporation results in toffees of superior nutritional and functional quality.[7]

6. Other products:

The fruit pulp exhibits detergent properties and has traditionally been used for washing clothes. The hard shell of mature fruits is fashioned into pill and snuff boxes, often ornamented with gold or silver. A fragrant cologne is obtained by distillation of the flowers. In Hindu tradition, the leaves of *Aegle marmelos* hold great

Figure 9: Bael Candy

religious significance and are essential offerings to Lord Shiva.[6]

- **EXTRACTION:**

Extraction is a crucial preliminary step in the isolation of bioactive compounds from plant materials. Various extraction techniques are employed, each possessing specific advantages and limitations depending on the nature of the target compounds and the desired outcomes.

1. Maceration:

It is one of the oldest and simplest extraction techniques, which involves soaking plant material in a suitable solvent at room temperature. This method is easy to perform and requires minimal equipment, making it widely accessible.

Procedure of Maceration:

- The plant material is first dried and finely powdered to increase the surface area for extraction.
- The powdered material is then completely immersed in a suitable solvent.
- The solvent is allowed to remain in contact with the plant material for an extended period, usually ranging from a few hours to several days, depending on the nature of the plant material, the solvent used, and the target compounds.
- Intermittent stirring or occasional shaking is carried out to enhance solvent penetration and improve extraction efficiency.

- After completion of the maceration period, the solvent containing the dissolved constituents is separated from the plant residue by filtration or decantation.
- The solvent is then evaporated to obtain a concentrated extract, which can be further processed or used for subsequent applications.[8]

2. Soxhlet extraction:

It is a continuous solvent extraction technique in which plant material is repeatedly washed with an appropriate solvent under reflux conditions. The procedure was carried out as follows:

- Five grams of the crushed plant material were placed in a thimble, which was then inserted into the Soxhlet extractor.
- A total of 300 mL of methanol was used as the organic solvent for extraction.
- The side arm of the apparatus was packed with glass wool. The solvent was heated using a heating mantle, causing it to evaporate and pass through the apparatus to the condenser.
- The condensed solvent dripped into the extraction chamber containing the thimble. When the solvent level reached the siphon arm, it was automatically drained back into the round-bottom flask, initiating a new extraction cycle.
- The extraction process continued for 8 hours.
- After completion of seven extraction cycles, the plant extract was collected, air-dried, and transferred to an extraction collector for further analysis.

This method provides high extraction efficiency and is particularly effective for isolating secondary metabolites such as alkaloids, flavonoids, tannins, and saponins.[9]

Results and Discussion

Phytochemical Composition

This review consolidates extensive scientific evidence confirming the rich phytochemical profile and diverse therapeutic potential of *Aegle marmelos*. A comprehensive analysis of the literature reveals that the plant's leaves, fruits, bark, roots, and seeds house a broad spectrum of bioactive constituents, notably alkaloids, flavonoids, tannins, coumarins, terpenoids, saponins, glycosides, and essential oils.

Specific compounds—including marmelosin, marmelin, aegeline, lupeol, eugenol, citral, and skimmianine—emerge as the primary drivers of the plant's pharmacological profile. Furthermore, the efficacy of methanolic, ethanolic, and aqueous extraction methods underscores the polarity-dependent solubility of these secondary metabolites, providing a roadmap for future drug standardization.

Pharmacological Evaluation

The reviewed data demonstrate that *A. marmelos* possesses significant antidiarrhoeal, antimicrobial, anticancer, and antidiabetic activities, among others. Key findings include:

Gastrointestinal Health: The plant's antidiarrhoeal efficacy is dual-action, combining direct antimicrobial effects against enteric pathogens with the modulation of intestinal motility and toxin neutralization.

Antimicrobial & Antiviral Potential: Extracts have demonstrated broad-spectrum activity, often performing comparably to standard pharmaceutical agents while maintaining low cytotoxicity in host cells.

Oncology: The anticancer potential is particularly significant. Bioactive constituents inhibit proliferation by inducing apoptosis, triggering cell cycle arrest, and suppressing critical signaling pathways such as PI3K/Akt and MAPK.

Metabolic Regulation: Strong antidiabetic effects were observed, characterized by enhanced insulin secretion, improved glucose utilization, and the inhibition of carbohydrate-hydrolyzing enzymes.

Safety and Future Directions

Toxicological assessments indicate that *A. marmelos* extracts are relatively safe at therapeutic doses, supporting its viability as a phytotherapeutic agent. The collective evidence suggests that its efficacy stems from the synergistic action of its complex chemical matrix

rather than isolated compounds.

Conclusion for Development: While preclinical evidence is robust, the transition to clinical application requires rigorous human trials and mechanistic studies. Establishing standardized formulations and precise dosing regimens is essential for integrating *Aegle marmelos* into the modern phytopharmaceutical landscape.

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