



Received on 25 June 2026; received in revised form, 14 July 2026; accepted, 23 July 2026; published 01 August 2026

PHYTOCHEMICALS OF *AEGLE MARMELLOS* FRUIT AND THEIR POTENTIAL ROLE IN HEALTH REGULATION: A REVIEW

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Keywords:

Aegle marmelos fruit, Bael fruit, Aegeline, Health regulation, Functional foods

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ABSTRACT: *Aegle marmelos* or bael fruit is an important source of traditional medicine and attracts much attention because of the different phytochemistry in its composition as well as many health benefits. This review focuses on phytochemicals in bael fruits and their potential effects on health management. Different bioactive compounds are present in the fruit including tannins, coumarins, alkaloids, flavonoids, phenols, as well as unique chemicals such as marmelosin, aegeline, umbelliferon, skimmianine, and rutin. Phytochemical composition of the fruit varies according to fruit maturity: young fruits are rich in tannins and ripe fruits contain elevated levels of sugars and flavonoids. Antioxidant effect of bael fruit occurs owing to radical-scavenging capacity as well as stimulation of body's defence mechanisms. Anti-inflammatory effect relates to pro-inflammatory mediator inhibition and reduction in cellular damage. Antidiabetic properties of the plant are characterized by a reduction in blood glucose level as well as insulin sensitivity. Moreover, the fruit demonstrates gastroprotective activity that confirms its long-term application for stomach disease treatment. Due to the presence of numerous phytochemicals in *Aegle marmelos*, its possible benefits as an herbal medicine can be exploited to promote good health as well as prevent the development of chronic diseases. The plant exhibits considerable prospects in terms of production of functional foods and nutraceuticals.

INTRODUCTION:

General Overview: Secondary metabolites called phytochemicals, which are derived from fruits, are highly regarded for their ability to improve human health.

Phenolics, flavonoids, alkaloids, tannins, terpenoids, and coumarins are some examples of such compounds that increase the therapeutic potential of fruits through their various biological effects resulting from interference in oxidative stress and cell signalling processes, including antioxidant, anti-inflammatory, antibacterial, hepatoprotective, and antidiabetic activities^{1,2}.

An excessive accumulation of ROS causes oxidative stress, which is considered one of the factors responsible for the onset of chronic diseases

QUICK RESPONSE CODE 	DOI: 10.13040/IJPSR.0975-8232.IJP.13(8).768-77 Article can be accessed online on: www.ijournal.com DOI link: https://doi.org/10.13040/IJPSR.0975-8232.IJP.13(8).768-77
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like diabetes, cancer, neurological disorders, and cardiovascular ailments. Fruit phytochemicals can reduce oxidative stress by neutralizing such ROS and thus prevent the development of any physiological imbalance within the body^{3,4}.

For many years, the traditional medicine systems such as Ayurveda have been exploiting the fruit of *Aegle marmelos* as an important medicinal fruit. This is due to its efficiency in curing digestive disorders. Since the fruit is rich in tannins and astringency, the unripe fruit pulp is exploited in treating diarrhoea and dysentery, while the ripe one is used for digestion purposes, and even as a laxative and nutrient⁵.

A variety of phytochemicals such as flavonoids, phenols, alkaloids, coumarins, and terpenoids have been identified in the bael fruit in contemporary scientific studies. The extensive pharmacological activities of the fruit that include antioxidant activity, antibacterial action, hepatoprotection, cardio protection, anti-inflammatory activity, and antidiabetic are due to key ingredients like marmelosin, aegeline, umbelliferon, and skimmianine^{6,7}.

This is further enhanced by recent research which points at its possible use in nutraceuticals and functional foods⁸.

Taxonomy and Classification: The bael fruit (*Aegle marmelos* (L.) Correa) belongs to the family Rutaceae. The bael fruit tree is a very slow-growing deciduous tree renowned for its nutritious

and medicinal properties. Due to the presence of phytochemicals in abundance, this particular plant species, the sole representative of the genus *Aegle*, is used in many traditional healing systems^{2,5}.

TABLE 1: TAXONOMICAL CLASSIFICATION OF *AEGLE MARMELOS*

Rank	Classification
Kingdom	Plantae
Subkingdom	Tracheobianta
Division	Mangnoliopsida
Super division	Spermatophyta
Class	Mangnoliopsida
Order	Sapindales
Family	Rutaceae
Subfamily	Aurantioideae
Genus	<i>Aegle</i>
Species	<i>Aegle marmelos</i>

The Flavonoids, coumarins, alkaloids, tannins, and phenolic acids are examples of bioactive compounds that are responsible for some of the pharmacological properties of the plant species³.

Fruit Morphology: *Aegle marmelos* makes a giant, tough-skinned fruit containing pulp, seeds, and rind. The hard woody rind changes colour from yellow when it matures to green when immature. The pulp is edible and accounts for most of the pharmacologically active compounds. The pulp is slimy and has an aromatic nature. It is made up of many embedded seeds.

The health benefits of the pulp arise from its high levels of important phytochemicals such as phenolic acids, flavonoids, tannins, and coumarins^{4,2}.



FIG. 1: AEGLE MARMELOS TREE AND FRUIT

Stages of Fruit Maturity (Unripe vs Ripe): The phytochemical composition of the fruit varies significantly with maturity.



FIG. 2: STAGES OF FRUITS MATURITY

Feature	Unripe Fruit	Ripe Fruit
Taste	Astringent	Sweet aromatic
Tannins	High	Low
Sugar	Low	High
Pectin	Very high	Moderate
Main use	Anti-diarrheal	Digestive tonic
Activity	Antimicrobial	Antioxidant

Since unripe fruit contains high tannin content, unripe fruits are used as an antidote for treating problems related to the stomach, while ripe fruits are used for digestion ⁵.

Functional Role of Fruit Parts: Different parts of the fruit show distinct phytochemical and pharmacological properties.

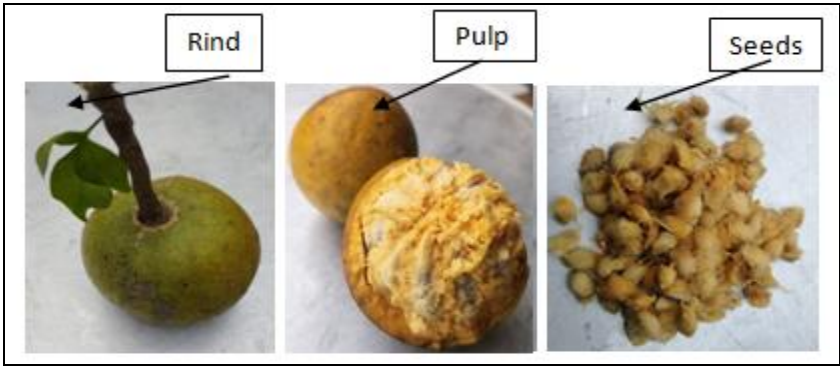


FIG. 3: FRUIT PARTS

Part	Major compounds	Biological Role
Rind	Fibers, phenolic	Protective, mild medicinal activity
Pulp	Flavonoids, tannins, coumarins	Antioxidant, antidiabetic, gastroprotective
Seeds	Alkaloids, Oils	Hypoglycaemic, lipid-lowering effects

The most pharmacologically important part of *Aegle marmelos* fruit is pulp, consist of compounds such as marmelosin, aegeline, and umbelliferon ^{2, 6}.

Geographic Distribution and Cultivation: Indigenous to the Indian sub-continent, *Aegle*

marmelos is distributed in South and Southeast Asia. Countries like India, Bangladesh, Sri Lanka, Myanmar, Thailand, as well as parts of Indo-China are some places where the plant is quite common ^{8, 6}. The plant adapts to various environmental

situations and thrives in tropical as well as subtropical climates⁸.

Due to the exceptional tolerance towards extreme temperatures and drought-like environmental conditions, it makes an ideal candidate for cultivation in semi-arid areas^{6, 10}. The plant is capable of withstanding tough weather conditions that result in the failure of other fruits harvests¹⁰.

Recent studies have shown that the bael varieties adapt themselves very well in various agro-climatic regions, especially in arid and marginal zones¹⁰. Due to the above reason, it becomes an important underexploited fruit crop in dryland agriculture^{11, 12}.

Vernacular Names:

TABLE 4: DIFFERENT NAMES ACROSS REGIONS AND LANGUAGES

Language	Country/region	Local names
English	Global	Bael, Wood apple
Hindi	India	Bael, Bilva
Sanskrit	India	Bilva
Tamil	South India	Vilvam
Bengali	Eastern India	Bel
Telugu	Andra Pradesh	Maredu
Thai	Thailand	Ma-tum

These regional names reflect its wide cultural and medicinal importance across Asia^{6, 13}.

Nutritional Composition of *Aegle marmelos* Fruit:

Macronutrients (Carbohydrates, Proteins, Fats): *Aegle marmelos* is an important fruit source of energy due to its high percentage of

carbohydrate content in its pulp. The percentage of carbohydrate content ranges from 30% to 40%, depending upon the maturity stage. The carbohydrates in pulp consist of both sugars and polysaccharides such as cellulose and pectin^{14, 19}.

Though it contains a fairly small number of proteins ranging between 1.5% and 3.6%, it still offers essential amino acids for metabolic reactions. Due to its low lipid content (1%), it can be included in dietary plans with low-fat sources¹⁵.

Micronutrients (Vitamins and Minerals): The main vitamins that are present in the fruit include Vitamin C, vitamin A (carotenoids), and B complex vitamins (thiamine, riboflavin, and niacin). They are responsible for immunity, energy, and antioxidant protection¹⁶.

Other components include minerals such as potassium, calcium, magnesium, iron, phosphorus, and copper. Potassium is the main mineral, which helps to preserve electrolyte balance and heart functions^{6, 18}.

Fiber and Pectin Content: Fiber components such as cellulose, hemicellulose, lignin, and pectin are plentiful in the fruits of *Aegle marmelos*. These fibres are crucial for regulating blood sugar levels, controlling bowel movements, and maintaining overall gut health¹⁷.

Pectin, a water-soluble dietary fibre, plays an important role due to its ability to reduce cholesterol levels and enhance gut microflora balance through prebiotic effects^{14, 19}.

TABLE 5: NUTRITIONAL COMPOSITION OF AEGLE MARMELOS FRUIT

Nutritional Category	Component	Functional Role
Macronutrients	Carbohydrates	Primary energy source
	Protein	Metabolic & enzymatic function
	Fats	Minimal lipid contribution
Micronutrients	Vitamin (A, B-complex, C)	Antioxidant activity, metabolic regulation
	Minerals (K, Ca, Fe, Mg, P)	Electrolyte balance, haematopoiesis, bone health
Dietary Fiber	Pectin (soluble Fiber)	Cholesterol reduction, glycaemic control
	Cellulose (insoluble Fiber)	Improves bowel movement & gut regulation
	Lignin (insoluble Fiber)	Supports digestive health & intestinal function

Phytopharmacological Profile of *Aegle marmelos* Fruit: Phytochemicals with diverse structures are present in fruits of *Aegle marmelos* (L.) Correa, making them more useful in terms of medicinal applications. They exist in the pulp, rind, and seed, among other parts of the fruits. Some of the most

common phytochemicals present include alkaloids, flavonoids, phenolics, coumarins, tannins, terpenes, glycosides, carotenoids, and polysaccharides. It is their responsibility to ensure many biological functions are performed, and health maintenance occurs.

Major Phytochemical Constituents:

Alkaloids: Some of the essential alkaloids such as dictamine, skimmianine, and aegeline can be found in the fruit pulp and seed of *Aegle marmelos*. These include aegeline which is a very essential bioactive component that has been found to have lipid-lowering and anti-diabetic effects due to its ability to regulate glucose metabolism and insulin sensitivity. Dictamine and skimmianine are some of the alkaloids that possess neuroprotective and antibacterial effects useful for regulating the central nervous system and infections^{20,21}.

Coumarins: The major bioactive constituents of the fruit of *Aegle marmelos* are coumarins, which are present in the form of imperatorin, psoralen, umbelliferon, scopoletin, marmelosin, and marmesin. The latter compounds can be found in the fruit's pulp, rind, and seed. Through their ability to inhibit tumour and inflammatory mediator development, both imperatorin and marmelosin demonstrate their antitumor and anti-inflammatory effects. Furthermore, umbelliferon possesses hepatoprotective activity, whereas scopoletin displays antihyperglycemic and antioxidant properties. For the treatment of skin diseases through photochemotherapy, psoralen is used^{22,23}.

Phenolic Compounds: The fruit pulp and peel contain various phenolic acids such as gallic acid, chlorogenic acid, protocatechuic acid, and ferulic acid. These components act as excellent antioxidants by eliminating free radicals and lowering oxidative stress. Gallic acid helps in reducing inflammation and preventing cancer, while chlorogenic acid assists in regulating glucose metabolism and controlling diabetes. By changing oxidative pathways, these phenols contribute to preventing chronic disorders such as cancer, diabetes, and heart disease^{24,25}.

Flavonoids: The pulp from the fruit is rich in flavonoids including catechin, kaempferol, rutin,

and quercetin, which have strong cardioprotective, anticarcinogenic, and antioxidant activity. Rutin improves vascular health and reduces oxidation, while quercetin manages inflammation and apoptosis. These flavonoids have an important part to play in reducing the likelihood of having heart diseases or metabolic syndromes^{25,6}.

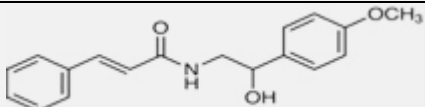
Tannins: Use of this fruit in treating diarrhoea and dysentery has been common for a long time because of high content of tannins in both green fruits and the skins. This property helps in reducing inflammation while creating protective coatings within the intestines thanks to their anti-inflammatory and anti-ulcer properties. Tannins are therefore vital for protection of the digestive system²⁵.

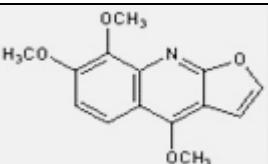
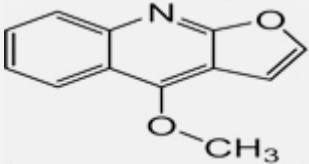
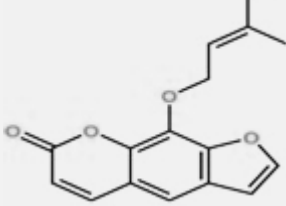
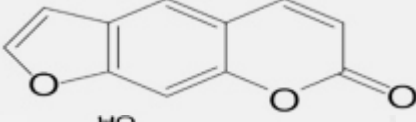
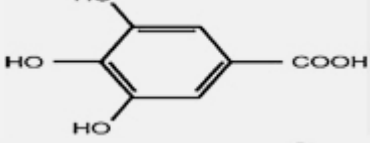
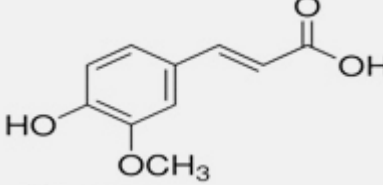
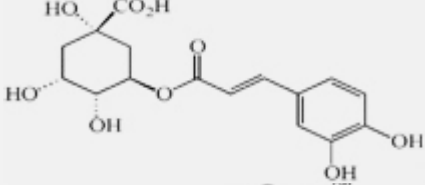
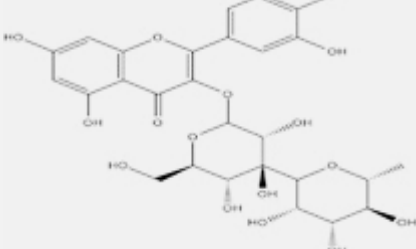
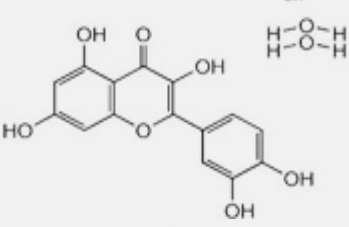
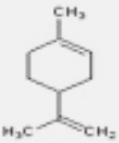
Terpenoids and Volatile Compounds: Antibiotic, anti-inflammatory, and analgesic terpenoids such as limonene, β -caryophyllene, cineole, and linalool are present in the rind. Although β -caryophyllene can help reduce pain, limonene possesses anti-tumour effects. They have roles in protecting against infections and inflammation^{25,27}.

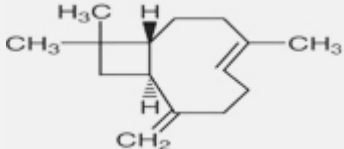
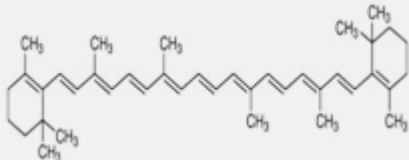
Carotenoids and Vitamins: Beta-carotene, which serves as a pre-cursor for vitamin A and is an effective antioxidant and immune system regulator, can be obtained from fruit pulp. This nutrient helps maintain overall well-being through enhanced vision, improved immune system, and protection against oxidation²⁸.

Polysaccharides (Pectin): Fruit pulp is composed of polysaccharides such as pectin which has prebiotic and gastroprotective activities. This helps in maintaining healthy microflora, regulating digestion, and improving overall gut health. Being biocompatible, they can be employed as delivery agents for drugs^{24,28}.

TABLE: 6 SOME BIOACTIVE COMPOUNDS OF AEGLE MARMELOS FRUIT AND THEIR PHARMACOLOGICAL ACTIVITY

Sr. no.	Phytochemical class	Bioactive compound	Molecular structure	Pharmacological activity
1.	Alkaloid	Aegeline		Antidiabetic anti-inflammatory, lipid-lowering ²⁰

2.	Coumarin	Skimmianine		Antimicrobial, antioxidant ^{20, 21}
		Dictamine		Antimicrobial, anti-inflammatory ²¹
3.	Phenolic	Marmelosin		Anti-ulcer, antioxidant ²²
		Psoralen		Antimicrobial, phototoxic activity ²³
		Gallic acid		Antioxidant, Anti-inflammatory ²⁴
		Ferulic acid		Anti-inflammatory, anticancer ²⁵
4.	Flavonoid	Chlorogenic acid		Antidiabetic, Cardioprotective ²⁵
		Rutin		Antioxidant, cardioprotective ²⁶
		Quercetin		Anti-inflammatory, anticancer ^{25, 26}
5.	Terpenoid	Limonene		Anti-inflammatory, antimicrobial ^{25, 27}

		β -Caryophyllene		Anti-inflammatory, analgesic ²⁵
6.	Carotenoid	β -Carotene		Antioxidant, Immune regulation ²⁸

Importance of Phytochemicals: The pharmacological and therapeutic properties of the fruit of *Aegle marmelos* can largely be associated with phytochemical compounds, such as:

- Antioxidants (carotenoids, phenolics, and flavonoids)
- Anti-diabetic activity due to alkaloids and flavonoids.
- Anti-inflammatory due to terpenoids and coumarins.
- Effects on stomach by tannins and coumarins.
- Effects on the heart by phenolics and flavonoids.
- Effects on immunity due to polysaccharides and saponins.
- This synergy in the interactions between these substances improves their efficacy biologically

Pharmacological Profiling of *Aegle marmelos*

Fruit in Health Regulation: By way of various biological functions, the phytochemicals present in the fruits of *Aegle marmelos* are vital for maintaining physiological balance. These include alkaloids, flavonoids, phenolics, coumarins, tannins, and polysaccharides, to name a few of such components that play an important role in regulating metabolic activities, reducing oxidative stress, modifying immune response, and preventing certain diseases

Antioxidant Activity: The antioxidants present in fruits such as *Aegle marmelos* include gallic acid, chlorogenic acid, and quercetin, which are some phenolic compounds and flavonoids. Their ability to combat free radicals protects against oxidative damage in cells and thus reduces the probability of

developing chronic diseases by eliminating reactive oxygen species (ROS), preventing lipids oxidation, and inducing endogenous enzymes^{29, 30}.

Antidiabetic Activity: The active components found in the fruit, such as aegeline and chlorogenic acid, possess significant antidiabetic properties.

These chemicals play a crucial role in managing the condition by enhancing insulin resistance, regulating blood sugar levels, and blocking enzymes like α -amylase and α -glucosidase^{29, 32}.

Antimicrobial Activity: Fruit exhibits antibacterial activity in cases involving several bacteria and fungi infections. The use of fruit in the treatment of infections is due to the presence of such compounds as coumarins, alkaloids, and terpenoids, which act by damaging microorganisms' membrane enzymes^{29, 30}.

Anti-inflammatory Activity: Since the fruit inhibits pro-inflammatory mediators such as cytokines, prostaglandins, and nitric oxide, it is known to have anti-inflammatory properties. Quercetin and scopoletin control inflammatory pathways such as NF-kB and others³⁰.

Anticancer (Potential) Activity: Phytochemicals including marmelosin, quercetin, and imperatorin have shown potential anticancer activity in experimental studies. These compounds induce apoptosis, inhibit tumour cell proliferation, and modulate cancer-related signalling pathways^{30, 32}.

Cardioprotective Activity: In addition to reducing oxidative stress, improving endothelial function, and ensuring a proper lipid profile, the fruit is effective in promoting cardiovascular well-being. Consequently, it helps prevent heart ailments and protects against atherosclerosis^{29, 32}.

Gastroprotective and Antidiarrheal Activity:

With the formation of the protective mucus layer and reduction of intestinal inflammation, the fruit's tannins and pectin exhibit gastroprotective action. This fruit is beneficial in the treatment of diarrhoea and dysentery as the compounds reduce intestinal motility and secretion^{31, 34}.

Neuroprotective Activity: This is because it reduces oxidative stress in neurons and modulates neurotransmission, giving it neuroprotective characteristics. Diseases such as Alzheimer's disease and other neurological disorders can be prevented through its consumption³⁵.

Immunomodulatory Activity: Polysaccharides and phenolics play an important role in enhancing the immune system activity due to stimulation of immune cells and regulation of inflammatory mediators³⁰.

Hepatoprotective Activity: The protective effect of *Aegle marmelos* on the liver is achieved through a reduction in oxidative stress and an increase in liver enzyme activity, which helps in protecting the liver against toxin-induced damage²⁹.

Antiulcer Activity: The fruit is effective in treating ulcers through reduced stomach acid, increased mucus production, and protection of the stomach lining. This is mainly attributed to tannins and flavonoids³³.

Antihyperlipidemic Activity: By increasing HDL levels and reducing LDL, triglyceride, and total cholesterol levels, the fruit enhances metabolism through control of lipid metabolism³⁷.

Antipyretic and Analgesic Activity: By affecting inflammatory mediators and reducing pain and fever sensations, some of the components of the fruit exhibit weak antipyretic and analgesic effects³⁰.

Overall Health Regulation: Overall, the phytochemical compounds present in the fruit of *Aegle marmelos* interact synergistically to regulate several physiological systems, including the immune system, metabolism, heart, and gut physiology. This fruit is therefore an effective dietary and medicinal supplement that ensures overall well-being and the prevention of chronic

diseases due to its various pharmacological functions.

Integrated Role in Health Regulation: The phytochemicals act collectively to generate a multipoint mechanism of action for health control and include:

- Metabolic disease control (obesity and diabetes).
- Reduction in cell damage and oxidative stress.
- Maintenance of gastrointestinal health
- Inflammation management.
- Enhancement of immunity.
- Protection from virus and heart diseases.

The application of *Aegle marmelos* fruits as functional foods and herbal remedies is justified by the above synergic effect of phytochemicals, thereby maximizing their overall therapeutic potency.

CONCLUSION: The fruits of the important medicinal herb *Aegle marmelos* contain high levels of bioactive chemicals, such as flavonoids, alkaloids, tannins, coumarins, and phenols. Many biological activities like antioxidant, antidiabetic, antibacterial, anti-inflammatory, and gastroprotective effects occur due to these natural chemicals. The presence of these bioactive properties increases the utility of the herbal medicine in traditional medicine systems and underscores their importance in maintaining good health and preventing various diseases.

The fruit of *Aegle marmelos* has also been considered as a potential functional food and a natural source of medicinal agents. The formulation of *Aegle marmelos* is available in market in various form such as tablets, capsules, syrup etc. Some formulation such as Himalaya wellness pure Herbs tablets and Ayurleaf Bael capsules are used in the digestive health. This has become an ideal candidate in the development of herbal drugs owing to its diverse phytochemical composition. In this review cover all the information related to the fruit because are in other literatures contain overall information on all parts of the *Aegle marmelos*.

Therefore, this review helps in the focus on the fruits concern information. In summary, there seems to be great potential in *Aegle marmelos* modern medical applications and nutraceuticals.

ACKNOWLEDGEMENT: The authors are grateful to Nagpur College of Pharmacy, Nagpur, Principal Dr. Vinod M. Thakare, Guide Dr. Lalchand D. Devhare and faculty for their constant support and valuable guidance throughout this work.

CONFLICT OF INTEREST: Nil

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How to cite this article:

Lanjewar KT, Devhare LD, Raut MR, Thote P, Bawankar I, Kaikade A, Hiradeve SM, Uplanchiwar VP and Thakare VM: Phytochemicals of *Aegle marmelos* fruit and their potential role in health regulation: a review. *Int J Pharmacognosy* 2026; 13(8): 768-77. doi link: [http://dx.doi.org/10.13040/IJPSR.0975-8232.IJP.13\(8\).768-77](http://dx.doi.org/10.13040/IJPSR.0975-8232.IJP.13(8).768-77).

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