



Significance, pharmacological properties, and industrial applications of bael (*Aegle marmelos*): A review of current knowledge

Farina Mujeeb^a, Ahamad Faiz Khan^b, Vinay Kumar Pandey^{c,*}, Ashapurna Sinha^a, Mukul Machhindra Barwant^d, Sarvesh Rustagi^e, Béla Kovács^f, Ayaz Mukarram Shaikh^{f,**}

^a Department of Biosciences, Integral University, Lucknow, 226026, Uttar Pradesh, India

^b Department of Bioengineering, Integral University, Lucknow, 226026, Uttar Pradesh, India

^c Research & Development Cell, Biotechnology Department, Manav Rachna International Institute of Research and Studies (Deemed to Be University), Faridabad, 121004, Haryana, India

^d Department of Botany, Sanjivani Arts Commerce and Science College, Kopergaon, Maharashtra, India

^e Department of Food Technology, School of Applied and Life Sciences, Uttarakhand University, Dehradun, Uttarakhand, India

^f Faculty of Agriculture, Food Science and Environmental Management, Institute of Food Science, University of Debrecen, Debrecen, 4032, Hungary

ARTICLE INFO

Keywords:

Aegle marmelos
Natural medicine
Bioactive compounds
Pharmacological properties
Food industry

ABSTRACT

The well-known traditional medicinal plant bael (*Aegle marmelos*) is used in many traditional medical systems, including Ayurveda, and may contain valuable compounds for industrial usage. The numerous health benefits of bael, including hepatoprotective, anti-inflammatory, antibacterial, and coumarin capabilities, are attributed to its bioactive constituents, including alkaloids, coumarins, and essential oils. One way to replicate the therapeutic capabilities of Bael across a wide range of illnesses in the pharmaceutical industry is to formulate bioactive compounds derived from Bael extracts and compounds into medicines for the treatment of diabetes, gastrointestinal problems, or skin ailments. Moreover, the food sector uses bael antioxidants and preservatives to enhance the nutritional value and shelf life of functional foods and drinks. To support green energy practices, plant byproducts have also been investigated for reclamation and biodegradable resources. Bael's integration into several businesses demonstrates the fruit's significant economic impact and highlights its significance in maintaining good health and leading a sustainable lifestyle. This study provides a thorough overview of Bael, focusing particularly on its potential commercial applications and biological uses.

1. Introduction

Bael (*Aegle marmelos*), or Bengal quince, is a deciduous tree in the Indian subcontinent (where it is known as bili or bhel) and Southeast Asia. It has a long history of use in various classical medicinal systems (Ayurveda, Unani, and Siddha) for the treatment of various diseases and occupies a significant position in traditional systems of medicine. Such extensive activity may be attributable to its diverse range of phytoconstituents such as alkaloids, coumarins, flavonoids, and essential oils [1]. Bael contains several bioactive constituents that exhibit various pharmacological properties, making it suitable for a wide range of therapeutic and industrial applications. Bael has been reported to possess a greater scope of pharmacological activities, with ancient texts being known for its use in digestive disorders, respiratory disorders, diabetes,

and cardiovascular diseases. These ancient medicinal uses have now been confirmed by modern scientific studies, along with an explanation of the complex biochemical mechanisms through which the plant acts. Different studies have proposed the antiinflammatory, antimicrobial, antidiabetic, hepatoprotective, and anticancer potential of Bael. The isolation and identification of certain bioactive constituents from Bael have attracted interest in potential prospects for the synthesis of new pharmacological agents related to these compounds [2] (see Fig. 3).

The present review on Bael provides multidisciplinary insights into the field with respect to its nature of explorations, such as pharmacology and molecular biology. Molecular docking and in silico studies can predict the interactions of these compounds with biological targets, thus helping to understand their prospective application as therapeutic agents. Preclinical data, including in vitro and in vivo studies, provide

* Corresponding author.

** Corresponding author.

E-mail addresses: v.k.pandey30@gmail.com (V.K. Pandey), ayaz.shaikh@agr.unideb.hu (A.M. Shaikh).

<https://doi.org/10.1016/j.jafr.2025.101631>

Received 27 February 2024; Received in revised form 24 December 2024; Accepted 2 January 2025

Available online 10 January 2025

2666-1543/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

insight into the pharmacokinetics and pharmacodynamics of Bael extracts and/or isolated compounds with the ultimate goal of performing clinical trials and developing potential drugs [3]. Apart from its significance in medicine, the industrial role of Bael has been acknowledged. In the drug business, Bael extracts are made into health items and traditional solutions for an extensive variety of persistent infections, including diabetes and gastrointestinal issues. The nutritional and antioxidant abilities of Bael offer a rich choice for the food industry to use its extracts in health foods and diets. Bael also imparts its natural antiseptic action, which enhances the shelf life of these food items, thereby increasing their nutritional value of such products [4]. The progression of keywords throughout various time periods from 2010 to 2018 is shown in Fig. 1 Research on novel *Aegle marmelos* pharmacological qualities and industrial uses may fall under this cluster (see Fig. 2).

Bael fruit has been beneficial not only in the medical field, but also in the food and drink, pharmaceutical, and cosmetic industries among other areas. Formally and functionally, its versatility stands out with its practice in traditional and modern styles. It is primarily employed in sweetening confitures, marmalades, and refreshing drinks. Bael is widely respected within the culinary industry because of its unique taste and health advantages. The fruit is enriched in essential minerals, such as calcium, potassium, iron, and vitamins A,C, and B, making it a significant part of the diet [5]. Pharmaceutical companies use it for its antibacterial, anti-inflammatory, antioxidant, and antidiabetic therapeutic effectiveness. Its pulp is extensively administered for disorders of the gastrointestinal tract, such as diarrhea, dysentery, and irritable bowel syndrome [2] whereas its leaves are particularly important in controlling diabetes. Recent studies have focused on evaluating the potential of bael for pharmaceutical purposes, natural products, and drug applications. Because bael extracts are believed to provide anti-aging properties that keep the skin framed, they are also beginning to become a conventional element in skincare formulations. Bael might be able to cure oxidative stress, which leads to early aging, due to its antioxidant properties. Owing to its antibacterial properties, bael may also be used to treat skin infections and help maintain healthy skin. Although the bael fruit has been extensively researched, these studies have often been limited to particular sections of the plant and where their properties are relevant to those sections (e.g., antibacterial and antidiabetic) as opposed to being evaluated in relation to the whole [6]. These studies provide relevant information; however, they are not fully illustrative of the pharmacological activities of bael. Recent studies (does not yet exist in the case of bael) have traced the augmentative

interactions of individual bioactive compounds found in herbal plants, pointing towards a greater sum of action effects compared to their singular usage. A similar situation exists with bael, which signifies the necessity of a holistic approach that takes into consideration the interactions between the various phytochemicals and their health effects to fully appreciate bael's therapeutic potential. This review elucidates several pharmaceutical properties and industrial applications of the bioactive compounds in Bael (*Aegle marmelos*).Fig. 4

2. Biological significance of bael

Bael fruit is a widely used traditional Indian medicinal plant owing to its immense phytotherapeutic capacity [2]. *Aegle marmelos* (Linn.) is a member of the Rutaceae family, generally cultivated in tropical and subtropical countries, particularly India, and is also called Bael. Thus, this species has profound significance in our mythologies as well as ancient medical systems and has been preserved within sacred groves by tribal communities over generations. It has been used for centuries as a food and a cure for various diseases. Owing to the edible, therapeutic, and welfare-improving efficacies of this plant, research has been focused [7]. In the last few years, researchers have mainly focused on identifying and validating compounds from plants that are used for curing various ailments and decreasing toxicity. As mentioned before, different bioactive substances that can potentially be important for human nutrition and health are present in plant parts, such as leaves, fruits, and seeds. Bael has been shown to accumulate a high diversity of nutritional compounds, including a broad class of phytochemicals, such as phenolic acids, flavonoids, tannins, alkaloids, and coumarins. Bales are also said to be full of minerals, carbohydrates, vitamins, fatty acids, amino acids, and fiber, and thus have great nutritional value and other health benefits. The fruit may help to treat diseases related to diabetes, cardiovascular disease, gastrointestinal issues, and inflammatory illnesses [8]. The pharmacological characteristics of the bael and their effects on human health are presented in Table 1.

"No drug has been longer and better known, nor more appreciated by the inhabitants of India than the Bael fruit," according to Chopra [19]. Based on its therapeutic properties, including antidiabetic, antiulcer, antioxidant, antimalarial, anti-inflammatory, anticancer, radioprotective, antihyperlipidemic, antifungal, antibacterial, and antiviral effects, bael is regarded as a valuable reservoir for bioactive compounds [20]. Several components of this plant have been separated, and their pharmacological effects have been assessed. To create pharmaceuticals, chemicals must be developed and focused on. Numerous bioactive

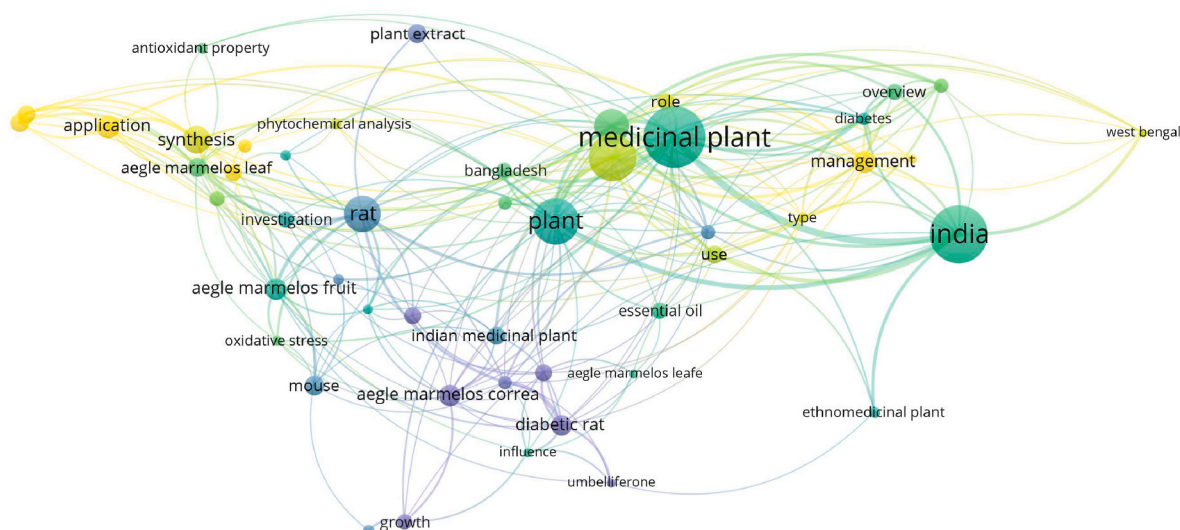


Fig. 1. Research network visualization in context with pharmaceutical properties and industrial applications of bael from the data accessed by Web of Science.

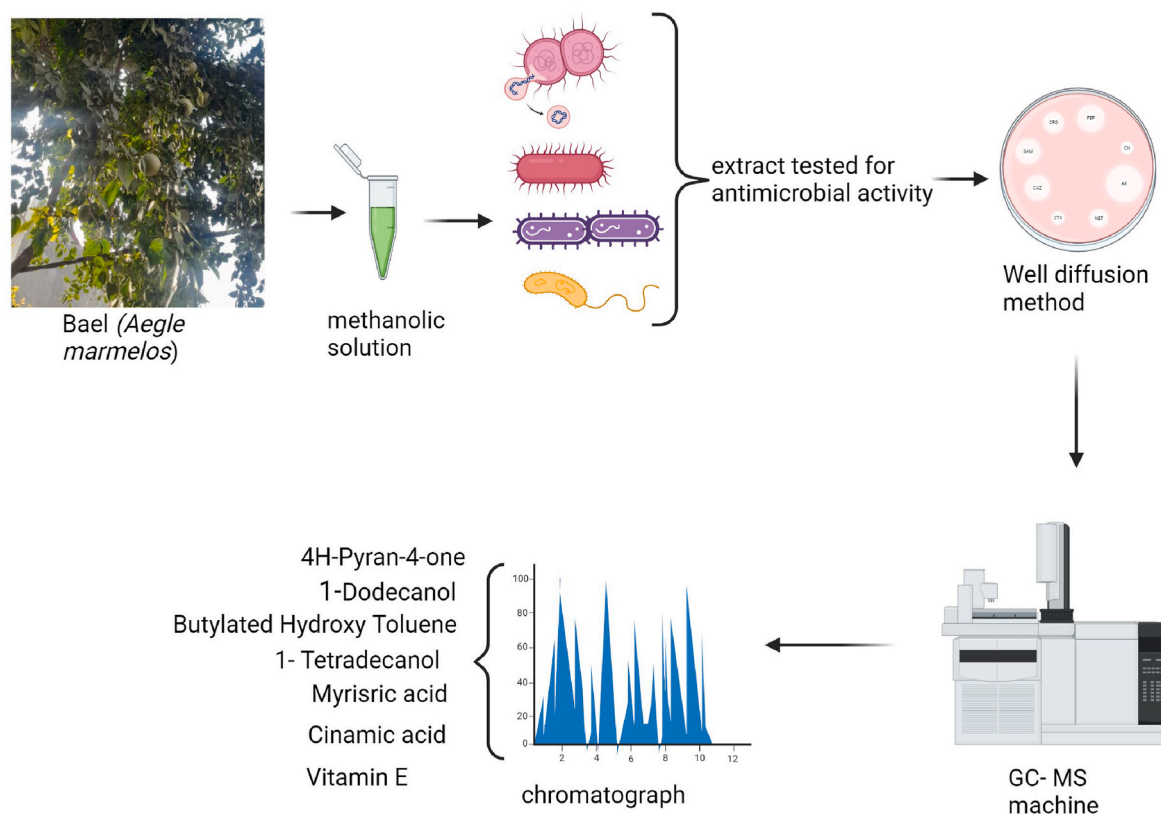


Fig. 2. Antimicrobial activity of *Aegle marmelos*

chemical entities, including γ -sitosterol, aegelin, lupeol, rutin, marmesinin, β -sitosterol, flavone, glycoside, O-isopentenyl halfordiol, marmeline, and phenylethyl cinnamamides have been suggested by various studies on the phytochemistry of plants. As more people are aware that natural products are non-toxic, have fewer negative effects, and are more reasonably priced, there is a growing demand for plant-based medications, health products, phytopharmaceuticals, health supplements, cosmetics, etc. in both developed and developing nations [21].

2.1. Biological characteristics of bael (*Aegle marmelos*)

Every portion of the bael plant, including the stem, bark, leaves, fruits, and roots, has a variety of uses at every stage of growth and pesticidal, nutritional, and medicinal properties. The fruit also occupies a significant place in Ayurvedic medicine and has several therapeutic benefits. Known as the "panacea of stomach ailments" [3], memelosin ($C_{13}H_{12}O_3$) is a significant component extracted from this fruit and is used as a diuretic and laxative. Similarly, tannin is abundant in bael, with approximately 20% of the components found in the rind and 9% in the fruit pulp. Ripe fruit is used as a mild astringent for conditions including dysentery and diarrhea, whereas pectin and mucilage are the main components of unripe fruit. Various parts of the plant have yielded alkaloids, coumarins, and steroids. Fresh ripe pulp is used because of its moderate digestive, tonic, and laxative properties. Psoralen is also present in pulp and is used to treat leukoderma (Bhattacharjee et al., 2018). Leaves have been used to treat a variety of inflammatory conditions, acute bronchitis, and eye conditions. In India, the roots are used as anti-inflammatory and anti-venomous snake remedies.

2.2. Nutritional value of bael

According to the ancient Indian medical system, the roots, bark, leaf, flower, seed, and latex of the plant are used for many purposes in

traditional medical systems [22]. Abstract Fruit is one of the most indispensable foods with important nutritional value that has been proven by physicochemical studies. Pulp is a very good source of carbohydrates, sugar (when used as an energy drink), and fiber, which makes it very beneficial. Bael contains the vitamins like vitamin A, B₁, C; macro-elements such as protein (8.32–27.09 g/100), fat (0.48) and minerals contents fibres 3.03 g/100 or increased/and calcium (14 g/kg of air-dry fruit), phosphate, potassium sulfide iron and others [23]. Bael pulp is rich in dietary fiber, protein, carbohydrates, vitamins (A, B₁, B₂ and B₃), and minerals (calcium, phosphorus, and iron), and contains a number of physiologically active substances (coumarins, carotenoid flavonoids, and terpenoids). Many biological and phytochemical studies on the importance of bael have been reported in scientific literature. Therefore, its antidiabetic, hypolipidemic, and antioxidant properties have been exploited in ethnomedicine [22]. Numerous studies have revealed that bael contains various phytochemicals with nutritional components such as phenolic acids, flavonoids, alkaloids, tannins, and coumarins. Bael is a nutrient-dense fruit containing a comprehensive blend of amino acids, fatty acids, minerals, carbs, vitamins, and fibers, and offers high health benefits. The fruit may also provide relief from diabetes, cardiovascular problems, inflammatory diseases, and gastrointestinal problems. Moreover, Bael has exhibited protective effects against depression [24], radiation [25], microbes, wounds and trauma (Kaushik and Bhatia, 2017), oxidative stress (Sathyaprabha et al., 2023) and trauma [2].

2.3. Bio-chemical properties of bael

Numerous phytochemicals, including coumarins, alkaloids, steroids, and essential oils, have been identified in this plant. The contents of palmitic acid, 8.3% stearic acid, 28.7% linoleic acid, and linolenic acid were 15.6%, 8.3%, 28.7%, and 7.6%, respectively. The leaves contain rutacine, α -sitosterol, aegeline, and aegeline, which are neutral

Aegle marmelos



Brine Shrimp Lethality Assay And Methyl Thiazolyl Tetrazolium (MTT)

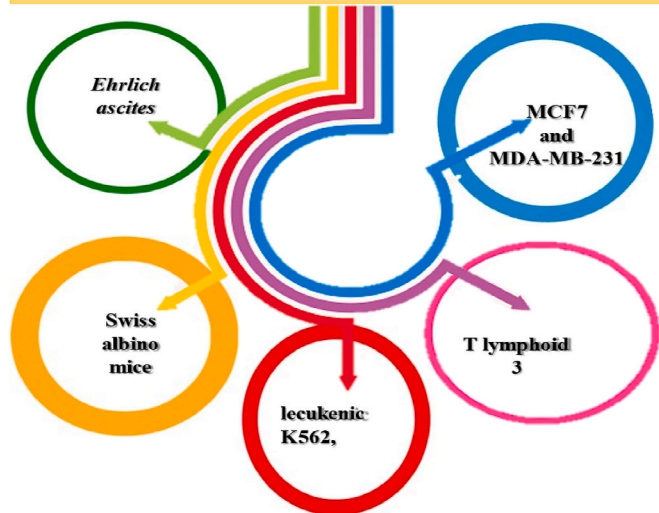


Fig. 3. Anticancer Activity of *A. marmelos*.

Table 1
Different properties of Bael and their impacts on human health.

Properties	Pharmacological Effect	Impact on Human Health	Reference
Rich in Antioxidants	Acts as a free radical scavenger, reducing oxidative stress	May help prevent chronic diseases and support overall well-being	[9,10]
High in Nutrients	Provides essential vitamins and minerals	Supports immune function, bone health, and overall nutritional needs	[11]
Anti-Inflammatory	Reduces inflammation in the body	May alleviate symptoms of inflammatory conditions	[12]
Antimicrobial	Exhibits antibacterial and antifungal properties	May aid in fighting infections and maintaining oral health	[9]
Digestive Health	Contains dietary fiber for improved digestion	Supports a healthy digestive system and prevents constipation	[13]
Cardiovascular Support	Helps lower cholesterol levels and blood pressure	May contribute to heart health and reduce the risk of heart diseases	[14]
Blood Sugar Regulation	Regulates blood sugar levels	Can be beneficial for individuals with diabetes or at risk	[15]
Respiratory Health	Possesses expectorant properties	May aid in relieving respiratory conditions such as cough and asthma	[16]
Anti-Cancer Properties	Shows potential in preventing certain types of cancer	Research suggests a protective effect against specific cancers	[17]
Immunomodulatory	Modulates the immune system	Supports a balanced immune response and overall immune function	[18]

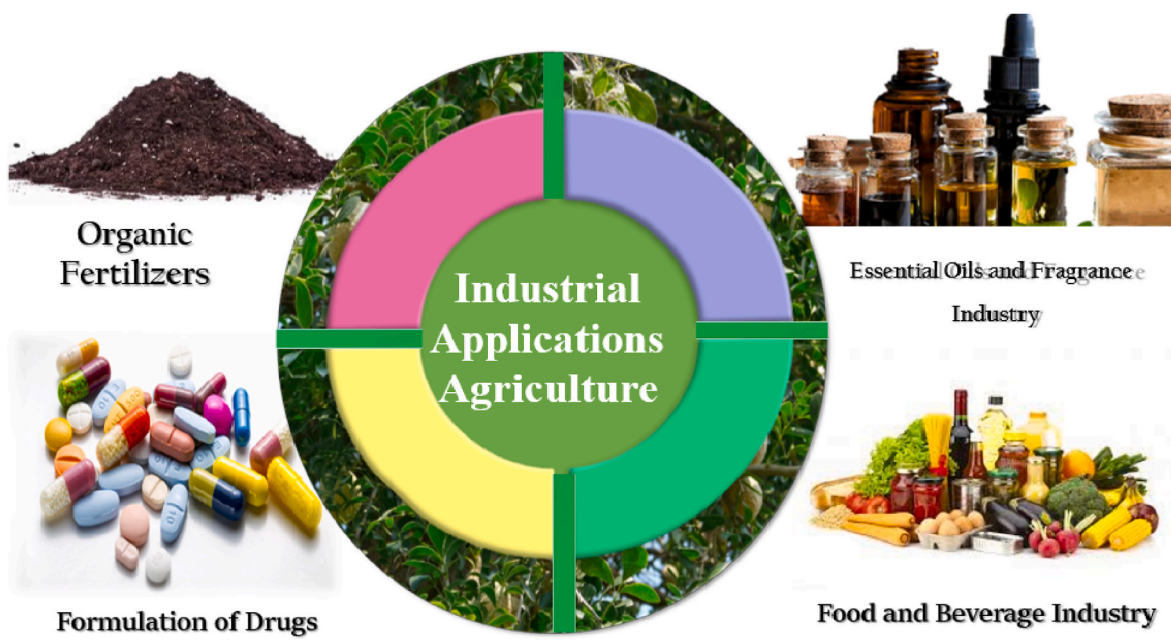


Fig. 4. Industrial applications in Agriculture *Aegle marmelos*.

alkaloids [26]. Marmin, marmesin, umbelliferone, and skimmianine were also detected in the bark and roots. Coumarins, such as umbelliferone, marmesin, scoparone, scopoletin, and skimmianine, are also found in roots and fruits. Polysaccharides, such as galactose, arabinose, uronic acid, and L-rhamnose, are abundant in fruits. Ascorbic acid, sitosterol, crude fibers, tannins, α -amyrin, carotenoids, and crude proteins are also found as minor elements, and the therapeutic activities of the bael plant include marmelosin, skimmianine, and umbelliferone. Aegeline, lupeol, cineole, citral, citronellal, cuminaldehyde, eugenol, marmesinin, marmelosine, luvangetin, aurapten, psoralen, marmelide, fagarin, marmin, tannins, and more than 100 more compounds have been discovered in addition to these chemical elements. These substances, which are separated from many plant sections, have demonstrated biological activities against a range of serious and mild illnesses [22]. Table 2 lists the active chemical constituents of Bael.

3. Pharmacological activities

3.1. Antidiabetic activity

Diabetes mellitus is a prevalent metabolic condition worldwide. Leaf extract has been used to treat diabetes in the Ayurvedic medical system because it stimulates the body's absorption of glucose, thus improving its utilization of exogenous glucose [31] (Sharma et al., 2016). The hypoglycemic effect of the root bark decoction (1 mL per 100 mg) in normal fasting rats has been shown by [32] Karunanayake et al. Sharma et al. (2016) assessed the ability of the leaf extract to reduce blood urea and cholesterol in alloxan-diabetic rats, while also producing an anti-hyperglycemic action. In diabetic rats, the leaf extract also demonstrated insulin-like action [33]. Das et al. found that aqueous leaf extract enhanced the functional condition of pancreatic cells in streptozotocin-induced diabetic rats. In rats with STZ-induced diabetes, the aqueous leaf extract with elevated plasma insulin levels caused a hypoglycemic effect. The leaf extract exhibited antidiabetic activity in

Table 2
Chemically active compounds present in different parts of Bael (*Aegle marmelos*).

Part of Bael (<i>Aegle marmelos</i>)	Chemically Active Compounds	Pharmaceutical Properties	Food Applications	Reference
Leaves	Alkaloids (e. g., marmeline, fagarine), Flavonoids, Tannins	Antimicrobial, Antidiarrheal, Anti-inflammatory	Used in traditional medicine for treating various ailments. Leaves can be used for making teas or as flavoring agents in cooking.	[27,28]
Fruit Pulp	Alkaloids, Flavonoids, Phenolic compounds	Antioxidant, Anti-inflammatory, Antimicrobial, Antidiabetic	Consumed fresh or used to make beverages, jams, and candies.	[29]
Seeds	Alkaloids (e. g., marmeline, fagarine), Essential oils	Antimicrobial, Antidiarrheal, Antioxidant	Seeds can be dried and powdered for medicinal use or used as a flavoring agent in cooking.	[30]
Bark	Alkaloids, Tannins, Essential oils	Antimicrobial, Anti-inflammatory, Antidiarrheal	Used in traditional medicine for its therapeutic properties. Bark extracts may be used in food preservation.	[2]

rats stimulated with an antihyperglycemic effect. The aqueous fruit extract decreased the levels of glycosylated hemoglobin and exhibited antihyperglycemic effects in STZ-induced diabetic albino Wistar rats [34]. Hypoglycemic and antioxidant activities of the leaves in male albino rats with diabetes. These results also indicate that *Aegle marmelos* may be useful in the treatment and control of hyperlipidemia by decreasing cholesterol [35]. The ethanolic extract of *Aegle marmelos* exhibited hypoglycemic potential, which showed significant antidiabetic action with effective protection against alloxan-induced diabetes. Subban et al. investigated the methanolic extract from *Aegle marmelos* roots and separated it into eight fractions by column chromatography. An in vitro model of glucose absorption based on isolated rat hemidiaphragm was employed to examine the antidiabetic effects of each fraction. Finally, column chromatography separation led to the isolation of two compounds, 6-methyl-4-chromanone and skimmianine.

3.2. Antioxidant and hepatoprotective activity

Oxidative stress is the outcome of changes in DNA and lipids caused by the production of different reactive free radicals, which are triggered by a range of chemical and environmental variables [36]. The ability of a chemical to reduce is a key marker of its possible antioxidant activity [1]. The hepatoprotective activity of *Aegle marmelos* is attributed to its strong antioxidant activity. The liver is an important organ in the human body and is involved in the detoxification and elimination of harmful chemicals. Hepatotoxins, xenobiotics, and various chemotherapeutic drugs compromise the liver function. Bael leaves possess excellent hepatoprotective properties against alcohol-induced liver damage, as measured using biochemical markers in albino rats [1,37]. Rajasekaran et al. [38] found that Wokgorcota exhibited greater potential to decrease the level of oxidative stress in rats treated with CCl_4 than in those not treated with CCl_4 . demonstrated the high activity of ethanoic acid and extracted fruit pulp of *A. marmelos*. *A. marmelos* (L.) Correa ethanolic extracts from fruit pulp were found to markedly protect against liver injury, as assessed histopathologically, and also significantly reduced CCl_4 -induced elevation of serum transaminases in rats. The traditional medicinal studies mentioned above have shown that this herb has hepatoprotective properties. Ramamurthy & Gowri, by the administration of *Aegle marmelos* extract, reported an increase in antioxidant levels as compared to controls, which is *S. aureus*-induced hepatic oxidative stress in the rat liver. This was evidenced by a reduction in lipid peroxidation products, an enhancement of antioxidant enzyme activity, and glutathione [39]. Similarly, extracts from bael fruit pulp and seeds have been reported to protective against CCl_4 induced hepatic cytotoxicity. These fruits and seeds could evoke 80 % and 70 % protection against CCl_4 poisoning when administered per os in an aqueous preparation. Rajashree et al., [40] reported that the intake of an herbal drug derived from *Aegle marmelos* had a protective effect by preventing oxidative stress induced by free radicals, in addition to enhancing elevated catalase activity in liver tissues [41].

3.3. Diarrhea and dysentery

Both ripe and unripe bael fruits are considered the best preparations for treating dysentery and diarrhea. Constipation, diarrhea, and chronic dysentery can all be effectively treated with fruit powder [42]. Millions of people die each year from intestinal infections, which cause illness and mortality (Nair et al., 2016, [2]). *A. marmelos* decoction can help manage several infectious diarrheal illnesses caused by different microbes, as well as rotavirus infections and giardiasis, to a certain degree. At 400 mg/kg, *Aegle marmelos* demonstrated significant anti-diarrheal action in rats with castor oil-induced diarrhea, which was nearly equivalent to that of the common medication loperamide [43]. Tanning, flavonoids, and mucilaginous compounds, the primary anti-diarrheal components found in bael fruits, have been shown to have antibacterial, anti-secretory, and intestinal motility properties [44]. Antidiarrheal

action was demonstrated by the ethanolic extract of the dried fruit pulp of *Aegle marmelos*. While *S. dysenteris* showed moderate activity, *Shigella boydii*, *S. sonnei*, and *S. flexneri* showed significant activity. When evaluated in vitro, the chloroform extract of *Aegle marmelos* root exhibited strong bactericidal activity that was similar to that of ciprofloxacin [45]. Furthermore, by preventing intestinal peristalsis, diarrhea was reduced in rats.

3.4. Antimicrobial and antifungal

Antibiotics or antimicrobial pharmaceuticals are usually a type of medication used for the treatment of water- and food-borne diseases. Ingredients with antibacterial properties that appear in a number of therapeutic plant extracts may target the pathogen. Several studies have demonstrated the antibacterial activity of *Aegle marmelos* extract. The bael extract also showed activity against *Proteus vulgaris*, *Staphylococcus epidermidis*, and *S. aureus*. The leaf and flower extracts of *A. marmelos* were tested against five clinical pathogens (*S. aureus*, *P. aeruginosa*, *Proteus mirabilis*, *E. coli*, and *Salmonella typhi*) at different concentrations (50, 100, and 200 ppm). *E. coli* is the most sensitive pathogen to treatment [46]. Moreover, bael leaf oil exhibited varying degrees of inhibition against different fungal isolates, including the resistant fungus *Fusarium udum*, in a concentration- and time-dependent manner (Neeraj et al., 2017). Bael leaf essential oil likely interrupts the metabolism of Ca^{+2} dipicolonic acid. Thus, it inhibits the development of fungal vegetative bodies in solid media or inside the host, which suppresses fungal activity [47]. Antimicrobial and anthelmintic properties have also been recorded against unsaponifiable substances as well as pure *Aegle marmelos* oil [48]. According to Khanal et al. (2020) and Sharma et al. [11], extracts obtained from different parts of the bael have been proved to inhibit the growth of many bacterial strains. Similarly, Choudhary et al. [49] and Murthy et al. [1] evaluated the antifungal effects of *Aegle marmelos* leaves and fruits. Newer findings also support the age-old value of *A. marmelos* fruit as an herb to treat numerous ailments, which was corroborated by a recent study that showed that the crude methanolic extract of bael fruit exhibited potent and efficacious antimicrobial activity against various gram-positive and gram-negative bacterial pathogens [50]. The study also included the green synthesis of AgNPs from *Aegle marmelos* fruit, with higher activity than that of the crude extract. This study further supports the use of *Aegle marmelos* fruit as an inexpensive, readily available, and environmentally friendly source material for the production of human-useful herbal products. Fig. 1 schematically shows the extraction and profiling procedure used to report the antimicrobial activity of the bael.

3.5. Anticancer activity

Following the administration of an aqueous alcoholic extract of bael leaves, an animal model of Ehrlich ascites carcinoma demonstrated anticancer activity [1,51]. Bael extracts prevent proliferation of human tumor cell lines, such as leukemic K562 and T lymphoid 3, in vitro. In Swiss albino mice, 400 mg/kg of the extract produced the most anticancer effect [52]. The extract of *Aegle marmelos* demonstrated cytotoxicity against tumor cell lines in both the methyl thiazolyl tetrazolium (MTT)-based test and brine shrimp lethality experiment (Pant et al., 2019). The extract has an antiproliferative effect on the breast cancer cell lines MCF7 and MDA-MB-231 (Rama et al., 2023). Furthermore, research has shown that *A. marmelos* extracts inhibit cell proliferation and that MDA-MB-231 (ER α -negative breast cancer cells) expresses more ER α gene [53].

3.6. Radio protective activity

In rats, Bael extract can reduce the severity of radiation-induced symptoms. The radioprotective effect of thiamine can be attributed to

free radical scavenging, inhibition of lipid peroxidation, and increased glutathione concentration [2,54]. The hydroalcoholic extract of AME was screened for potential radioprotective effects by using human peritoneal blood cells in the micronucleus test. AME reduced micronucleus frequency in HPBLs, which correlated with the dose of AME. Similarly, there was a significant inverse correlation between the frequency of radiation-induced micronuclei and 30 min of treatment with various doses of AME. When mice were administered bael fruit extract before X-irradiation, there was a marked increase in GSH concentration and a significant decrease in lipid peroxidation [55]. A radioprotective effect was observed with different doses of leaf extract administered intraperitoneally to male Swiss albino mice. In addition, bael leaf extract significantly reduced lipid peroxidation and attenuated glutathione depletion [56,57].

3.7. Antipyretic and analgesic

Plant-based antipyretic medications are far safer than synthetic ones, demonstrating Bael's value in treating pain and fever [54,58]. Significant suppression of carrageenan-induced paw edema, cotton pellet granuloma, and paw itching in mice and rats supported the antipyretic and analgesic properties (Tan et al., 2022; Panda et al., 2021). When mice were administered acetic acid to induce writhing and tail flick, the methanolic leaf extract from *Aegle marmelos* had a notable analgesic effect [59].

3.8. Wound healing activity

Rats were administered a methanolic extract of *Aegle marmelos* ointment or an injection to examine the effects of topical and intraperitoneal therapy on two different types of wound models. The injection and ointment of methanolic extracts of *A. marmelos* elicited a substantial response in both animals. The outcomes were similar to those of nitrofurazone, a common medication [60,61]. According to Yang et al. [62], there are four stages in the wound healing process: (i) coagulation, which stops blood loss; (ii) inflammation and wound debridement; (iii) repair, which includes cellular proliferation; and (iv) tissue remodelling and collagen deposition. Plant products have high therapeutic potential as anti-inflammatory agents and wound healing promoters because they contain active terpenes, alkaloids, and flavonoids [54,63]. In both the excision and incision wound models, the methanolic extract of *Aegle marmelos* showed possible wound healing activity. It also significantly enhanced hydroxyproline levels, which suggests higher collagen production and tensile strength.

3.9. Antiproliferative activity

The leukemic K562, T-lymphoid Jurkat, B-lymphoid Raji, erythroleukemic HEL, melanoma Colo38, and breast cancer MCF-7 and MDA-MB-231 cell lines are among the human tumor cell lines whose in vitro growth can be inhibited by *Aegle marmelos* correa extracts. The molecules found in the examined *Aegle marmelos* C. extracts were identified using gas chromatography/mass spectrometry analysis; three derivatives, butyl p-tolyl sulfide, 6-methyl-4-chromanone, and butylated hydroxyanisole, were found to have strong activity in suppressing the growth of human K562 cells in vitro. These substances showed potential antiproliferative action on par with well-known anticancer drugs, such as 5-fluorouracil, cisplatin, chromomycin, and cytosine arabinoside. The most powerful fraction (AME-2) with an IC₅₀ of 12.5 μ g/ml was isolated from a recent study that examined the ethanol extract of *A. marmelos* leaves' considerable antiproliferative activity against human cancer cell lines (Rajasekar 2018).

3.10. Antigonadal activity

Using a male albino rat as an animal model, the anti-gonadal activity

of an aqueous methanolic (40:60) extract of *Aegle marmelos* leaf was demonstrated by assessing sperm count, sperm viability, sperm motility, plasma testosterone level, and androgenic key enzyme activities in the testis, all of which were found to significantly decrease following leaf extract treatment. Testis and sperm pellet catalase activity and thio-barbituric acid reactive substance (TBARS) levels were recorded. Through the hypothalamico-hypophyseal axis, this extract has the ability to induce anti-gonadal action, which might eventually result in the creation of an herbal male contraceptive. All the main accessory sex organs lost weight following the administration of the extract, and the cauda epididymis sperm showed a noticeable decrease in density and motility. Male rat fecundity was 100 % decreased by *A. marmelos* at the 300 mg dosage level. Blood tests confirmed that there was no discomfort in the key organs. After 120 days, Akter reported that the removal of the extract brought all the changed parameters back to normal, including organ weight, fertility, testosterone levels, and tissue biochemistry [64]. Following the aforesaid extract germ cell treatment, the number of distinct generations at stage VII of the seminiferous epithelial cell cycle decreased drastically. Following the administration of the medication, no toxicity was observed in the kidney or liver. Thus, the aqueous extract of *Aegle marmelos* leaves has a strong ant testicular action, according to Jana et al. [65].

3.11. Anticonvulsant activity

Most plants with saponins or flavonoids have anticonvulsant properties. Investigating naturally occurring chemicals that could belong to new structural classes is a method used to identify novel antiepileptic medications. One approach to the search for novel antiepileptic medications is to investigate naturally occurring substances. According to a study by Gupta et al. [66], traditional antiepileptic medications such as sodium valporate, carbamazepine, and phenytoin shown neurotoxicity (Bruni et al., 2019). When using pentylenetetrazole to produce seizures in human patients, Edavanputhillath et al. found that the aqueous extract of *Aegle marmelos* leaves has antiepileptic properties [67]. *Aegle marmelos* fruit and leaf alcoholic extract can prevent seizures induced by pentylenetetrazole (PTZ) or maximum electroshock (MES) [68]. With ED50 values of 100 and 200 mg/kg, the aqueous extract demonstrated dose-dependent anticonvulsant efficacy against MES- and PTZ-induced seizures [68]. MES and PTZ convulsions were then postponed using the methanolic extract of *Aegle marmelos*.

3.12. Insecticidal activity

According to Khatoona et al. (2017), the essential oil extracted from *Aegle marmelos* leaves can control insect infestation of wheat from *Rhyzopertha dominica* (F.) (Bostrychidae), *Sitophilus oryzae* (L.) (Curculionidae), and *Tribolium castaneum* (Herbst) (Tenebrionidae), as well as stored grammar from *Callosobruchus chinensis* (L.) (Bruchidae). To ascertain the insecticidal efficacy of five essential oil concentrations (0 %, 4 %, 8 %, 12 %, 16 %, and 20 %), adult *T. castaneum* was subjected to an impregnated filter paper test. Data on deaths were collected after seven days of therapy. The essential oil of *A. marmelos* contains 120 different components, with the following main compounds: p-mentha-1,5,8-triene (7.97 %), 2-hexenal, (e)- (7.34 %), betamyrcene (3.26 %), beta-pinene (4.38 %), ethanol, 2-methoxy-, acetate (2.58 %), α -phellandrene (2.01 %), beta-elemene (1.98 %), beta-phellandrene (2.74 %), and delta-elemene (1.24 %). After 120 h of exposure, 20 % *A. marmelos* essential aromatic oil showed the most insecticidal action against *T. castaneum* when compared to acetone as the control. The results of this study suggest that the essential oil of *A. marmelos* leaves can be used to manage *T. castaneum* [69]. The essential oil of *A. marmelos* contains 120 components. The main component was 2,7-dimethyl-3-octen-5-yne (22.63 %). *A. marmelos* has been shown to exhibit insecticidal action against the red flour beetle *T. castaneum*, and its essential oil has the potential to kill 100 % of its adults. *Aegle marmelos* essential oil reduces

the environmental risks associated with the use of synthetic pesticides, making it an interesting alternative to traditional chemical control techniques [69].

3.13. Immunomodulatory activity

Neeraj et al. (2017) investigated and demonstrated its immunomodulatory action. Both the carbon clearance assay and neutrophil adhesion test were used to evaluate the cell immunity. However, an indirect hemagglutination assay and rodent lethality test were used to assess humoral immunity. The oral administration of 100 and 500 mg/kg FEAM was confirmed using the stair-case technique (up and down). *Ocimum sanctum* (OSE, 100 mg/kg, p.o.) was used as the standard. According to the carbon clearance assay, FEAM significantly increased neutrophil adhesion and the phagocytic index at dosages of 100 and 500 mg/kg. Both high and moderate doses of FEAM successfully prevented death in mice infected with bovine *Pasteurella multocida*. The amount of circulating antibodies was significantly higher in rats treated with FEAM and OSE, according to the indirect hemagglutination test. In models of cellular immunity, a low dose is more effective than a large dose. However, each dosage offered similar protection to humoral immunity. The data indicated above suggest that FEAM has a higher ability to boost immunological activity through humoral and cellular-mediated pathways at low doses (100 mg/kg) than at high doses (500 mg/kg).

3.14. Antigenotoxicity activity

Antigenotoxic agents prevent harmful chemicals from causing cell alterations that eventually result in cancer. Bael exhibits antigenotoxic effects. One study found that methanol decreased genotoxicity by reducing the SOS response (*E. coli* PQ37) to aflatoxin-induced toxicity and hydrogen peroxide. Methanol reduced hydrogen peroxide-induced toxicity by 70.48 %. Studies have shown that bael extract polyphenolic compounds reduce aflatoxin B1-induced toxicity by inhibiting cytochrome P450 activity [70].

3.15. Effect on biotransformation enzyme systems

To assess the impact of an aqueous alcoholic extract of *Aegle marmelos* leaves on carcinogen-metabolizing phase-1 and phase-11 enzymes, antioxidant enzymes, glutathione content, lactate dehydrogenase, and lipid peroxidation in the liver of mice, 50 and 100 mg/kg doses of dried extract were prepared on a regular basis for 14 days. The basal levels of cytochrome P450, NADPH-cytochrome P450 reductase, cytochrome b5, NADH cytochrome b5 reductase, glutathione S-transferase, superoxide dismutase, catalase, glutathione peroxide, and glutathione reductase significantly increased following extract treatment. Furthermore, by reducing the activity of lactate dehydrogenase and the production of malondialdehyde in the liver, both extract dosages demonstrated a cytoprotective function and offered a defense against pro-oxidant-induced membrane damage. These notable alterations in antioxidative profiles and drug-metabolizing enzyme levels are suggestive of the chemopreventive potential of this plant, particularly against chemical carcinogenesis. Significant increases in the levels of drug-metabolizing enzymes and antioxidative profiles demonstrated the chemopreventive ability of the plant.

4. Industrial applications in agriculture, food & pharma industry

Extracts from its leaves and fruits exhibit pesticidal properties against agricultural pests, thereby offering a natural alternative to synthetic pesticides. Additionally, Bael-based formulations enhance soil fertility, water retention, and microbial activity, thereby promoting sustainable crop production. These industrial applications contribute to reducing reliance on chemical inputs and fostering environmentally

friendly agricultural systems. A few specific applications are discussed below.

4.1. Bael as a source of organic fertilizers

Bael (*Aegle marmelos*) has great potential as a source of organic fertilizers, ensuring sustainability in agricultural practices and improving soil health. Bael trees often grow in low-nutrient soils and are known for their ability to thrive in a wide range of soils. The components of the Bael tree (leaves, fruits, and bark) are well-drained sources of micro-nutrients, including iron and zinc, and macroelements, such as calcium, magnesium, phosphorus, potassium, and nitrogen. When used as an organic fertilizer, these nutrients can enhance plant growth and soil fertility. In addition to being an organic fertilizer, a hydrocarbon-soaked bael is slowly and gradually decomposable and has great potential for soil nutrition [71]. The slow-release feature optimizes nutrient uptake by plants for longer periods and reduces the risk of nutrient leaching and runoff and, consequently, the risk of environmental contamination. Bael organic fertilizers are known to have a great influence first by improving soil structure and then by enhancing its ability to conserve water and by promoting microbial activity, all of which make the soil conditioned. The organic matter in Bael fertilizers enhances the organic carbon content of the soil, which maintains an active soil ecosystem that supports earthworms and other useful soil microbes. Bael organic fertilizers have been reported to contain natural chemicals that can act as antibiotics. When mixed with soil, these chemicals can potentially help to reduce soil-borne pathogens, minimize plant diseases, and promote sustainable farming practices. The use of Bael as a source of organic fertilizers is in line with sustainable agricultural principles, as it reduces the dependence on synthetic chemical fertilizers. Bael-derived organic fertilizers help mitigate their adverse impacts on soil, water, and ecosystems because they are renewable, biodegradable, and ecologically friendly [72]. Bael trees are a good source of organic material for fertilizer production because they are widely distributed in tropical and subtropical regions. In remote areas, farmers can earn additional income by harvesting bael leaves, fruits, or bark for fertilizer production [54].

4.2. Essential oils and fragrance industry

Alkaloids, coumarins, and steroids are among the elements of the bael tree that have been isolated from different tree sections and are responsible for its pharmacological actions. Extracted bael oil and chemicals have been shown to have biological effects against a number of serious non-communicable illnesses such as diabetes, cardiovascular disease, and cancer. The essential oils of the leaves contained d-limonene, citronellal, cineol, a-d-phellandrene, citral, pycnolone, and cuminaldehyde. Limonene-rich oil extracted from the rind of bael fruit is used as a yellow pigment in calico printing and as a hair-oil scent. Additionally, the oil extracted from the leaves relieves cold and recurring respiratory and bronchial illnesses. Additionally, the antifungal properties of the essential oils extracted from the bael are also acknowledged. Twenty-three components were discovered in the bael seed oil. The oil contained dodecanoic acid, pentadecanoic acid, pentadecanoic acid, methyl tetradecanoate, octanoic acid methyl esters, heptadecanoic acid, octadecenoic acid, heptadecanoic acid, octadecenoic acid (Z), and 9,12-octadecadienoic acid. SFA derivatives with medicinal qualities comprise the majority of the components [73]. 99.8 % of the essential oil composition was made up of 82 components. According to a study on 1.5 % yield of essential oil extracted from *A. marmelos* leaves, 99.8 % of the essential oil was composed of 82 components. According to a study on Nepalese cultivars, the main component of the essential oil isolated from the leaf is limonene (64.1 %). Later studies revealed a wide range of chemical components in essential oils extracted from the leaves. For instance, Nabaweya et al. (2015) determined that α -phellandrene (20.97 %), α -pinene (17.76 %), and γ -carene (16.37 %) are the main constituents of monoterpenes. Of the total, 21.03 % were sesquiterpene

hydrocarbons, of which γ -cadinene comprised the highest percentage (8.01 %). Trans-2-hydroxycinnamic acid (6.65 %), monoterpene alcohols (2.77 %), aldehydes (0.75 %), sesquiterpene alcohols (0.43 %), and esters (0.61 %) are oxygenated chemicals that constitute 11.41 % of the total [74].

4.3. Food and beverage industry

Marmelosin is beneficial in conditions that affect the intestine. It also has diuretic and cathartic effects. Non-fermented products, including candy, preserves, sherbet, wine, and squash, are commonly made from bael fruits [75]. Despite its exceptional flavor, nutritional value, and therapeutic properties, bael remains an unexplored fruit with enormous potential in the functional food industry. Since bael is a seasonal fruit, it is not advised to eat it year-round. As a result, its economic value may be increased by refining it into a range of products, including tea, preserves, chocolates, juice, and drinks. Furthermore, the fruit is difficult to eat because of its sturdy skin, viscous viscosity, and large number of seeds, which may explain why it is less popular than other table fruits. As a result, more processing is needed to make the crop edible, so that it can potentially be developed into a useful culinary product [76].

4.4. Bael extracts in the formulation of drugs

According to a recent study by Shirsat and Shilimkar [77], fruit extract from *Aegle marmelos* was used to create new nanoparticle formulations that showed notable antidiabetic potential. Furthermore, this method of administration improved the therapeutic effectiveness of the herbal formulation by increasing its bioavailability and lowering its toxicity. Using an extract from *Aegle marmelos* leaves, Sriramulu et al. [78] synthesized ZnFe₂O₄ nanoparticles that showed strong antibacterial activity against gram-positive (*S. aureus* and *B. subtilis*) and gram-negative (*E. coli* and *P. aeruginosa*) pathogens. In addition to demonstrating the potential of the extract as a source of antibacterial agents, the current study also showed that the phytoconstituents generated from nanoparticles might be a good drug delivery vehicle for carfilzomib. In conjunction with the extract of *Aegle marmelos*, one study documented the effective synthesis and characterization of phytosomes that function as a new drug delivery mechanism (Rajendra et al., 2023). Owing to the formulation's high entrapment efficiency and drug loading capacity, the dissolution profile of phytosomes demonstrated better drug release, which further increased the bioavailability and cellular uptake level.

5. Future prospects and innovations

Various communities have long used adaptable fruit bael (*Aegle marmelos*) for their therapeutic qualities. Exploring industrial uses outside of traditional medicine has gained attention in recent years. Because of its distinct flavor and high nutritional content, bael fruit pulp can be used in a variety of food and drink items. The production of fruit snacks, jams, preserves, and juices made from bael is an emerging trend. These goods meet the rising demand for functional meals using the fruit's inherent sweetness and health advantages. Because of its antibacterial and antioxidant properties, bael extract is becoming increasingly popular in the personal care and cosmetic sectors. Its application in skincare products, including face masks, lotions, and creams, is currently being investigated. Because of its ability to improve skin health and fight aging, bael is now used in a variety of cosmetic formulations aimed at customers seeking natural and environmentally friendly substitutes. The therapeutic benefits of bael have long been acknowledged in traditional medicine. The development of bael-based formulations for the treatment of a range of conditions, including diabetes, inflammation, and digestive problems, is an emerging trend in pharmaceuticals. To maximize the bioavailability and effectiveness of Bael in pharmaceutical products, researchers are investigating

innovative extraction and formulation processes. The increased interest in creating biodegradable packaging materials from natural sources is a result of increased concern about environmental sustainability. The possibility of using bael-based films and coatings as environmentally benign substitutes for traditional plastics is being investigated. These materials are appropriate for a range of packaging applications since they have the benefits of being renewable, biodegradable, and perhaps antibacterial. Oil from the bael seeds can be extracted and used to produce biodiesel. Exploring non-edible oil sources for the manufacture of biodiesel is becoming increasingly popular as the need for renewable energy sources continues to increase. The high oil content and widespread availability of Bael seeds make them a suitable feedstock for biodiesel manufacturing.

6. Conclusion

An overview of bael, a significant herbal plant, summarizes its immense relevance to the food, cosmetics, and nutraceutical industries from both traditional and pharmaceutical perspectives. Bael's extensive phytochemical composition, which contains alkaloids, coumarins, flavonoids, tannins, and other compounds, accounts for its many pharmacological properties, including antibacterial, antioxidant, anti-inflammatory, and anti-diabetic properties. Its current qualities support its centuries-old use in Siddha, Unani, and Ayurvedic medicine, and bode well for the creation of new therapeutic agents. Bael is utilized in many food and beverage preparations in the restaurant industry because of its unusual flavor and reputation for its health advantages. Owing to its high vitamin and mineral content, it is regarded as a functional food that has positive effects on health. The pharmaceutical industry uses some of the bioactive components found in bael to prepare medications for conditions such as diabetes and digestive disorders. Because bael has antibacterial and antioxidant properties that assist in improving skin health and slowing the aging process, bael extracts are employed as active ingredients in a variety of beauty care products. Bael offers a great deal of promise for application in conventional, Ayurveda, and contemporary medicine, according to the pharmacological data that are now accessible. Nevertheless, there are a number of issues with published research articles on bael, including inconsistent research methodology, extremely limited study focus areas, a lack of standardization, and a dearth of large-scale clinical trials. This is crucial for fulfilling Bael's potential and resolving the upcoming problems that stand in its way. Therefore, it is necessary to verify and enhance the medicinal and commercial uses of bael. In summary, comprehensive research models, well-established standardized procedures, and scientifically sound clinical trials will advance the industrial and medicinal uses of bael. In addition to advancing the scientific understanding of the bael, future approaches to resolving existing constraints will pave the way for its commercial acceptance and application in the food, nutrition, and industrial sectors. To ensure that people continue to gain these benefits and become established as an appropriate regular supply, this method must be further investigated and effectively incorporated into the standard operating procedures.

CRedit authorship contribution statement

Farina Mujeeb: Writing – original draft, Review and editing. **Ahmad Faiz Khan:** Writing – review & editing, Methodology. **Vinay Kumar Pandey:** Writing – review & editing, Supervision. **Ashapurna Sinha:** Methodology. **Mukul Machhindra Barwant:** Investigation. **Sarvesh Rustagi:** Writing – review & editing. **Béla Kovács:** Writing, Review and editing, Supervision, Funding acquisition. **Ayaz Mukarram Shaikh:** Writing, review and editing, Methodology, Investigation, Software.

Funding

Project No. TKP2021-NKTA-32 was implemented with support from the National Research, Development, and Innovation Fund of Hungary, financed by the TKP2021-NKTA funding scheme and supported by the University of Debrecen Program for Scientific Publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

Acknowledgement

The authors express their deep gratitude to Integral University, Lucknow-226026, India, for their generous support of this work and for providing the manuscript communication number (IU/R&D/2025-MCN0003302). All authors are also thankful to the Faculty of Agriculture, Food Science, and Environmental Management, Institute of Food Science, University of Debrecen, for their collaboration and support.

Data availability

No data was used for the research described in the article.

References

- [1] H.N. Murthy, M.A. Bhat, D. Dalawai, Bioactive compounds in bael (*Aegle marmelos* (L.) correa). Bioactive Compounds in Underutilized Fruits and Nuts, 2020, pp. 459–486.
- [2] T. Sarkar, M. Salauddin, R. Chakraborty, In-depth pharmacological and nutritional properties of bael (*Aegle marmelos*): a critical review, Journal of Agriculture and Food Research 2 (2020) 100081, <https://doi.org/10.1016/j.jafr.2020.100081>.
- [3] H. Pynam, S.M. Dharmesh, Antioxidant and anti-inflammatory properties of marmelosin from Bael (*Aegle marmelos* L.) Inhibition of TNF- α mediated inflammatory/tumor markers, Biomed. Pharmacother. 106 (2018) 98–108.
- [4] A.K. Singh, A.K. Chaurasiy, S. Mitra, The quality attributes of Bael (*Aegle marmelos* Corr.) preserve and candy, Int. Food Res. J. 24 (1) (2017).
- [5] S.K. Hazra, T. Sarkar, M. Salauddin, H.I. Sheikh, S. Pati, R. Chakraborty, Characterization of phytochemicals, minerals and in vitro medicinal activities of bael (*Aegle marmelos* L.) pulp and differently dried edible leathers, Helyon 6 (10) (2020).
- [6] M.A. Kuchay, D.D. Sharma, B. Kaushal, S. Altaf, V. Kumar, Pharmacological properties and screening of antibacterial activities of bael (*Aegle marmelos* L.), Research Biotica 3 (1) (2021) 81–87.
- [7] Pathirana, C.K., Ranaweera, L.T., Madhujith, T., Ketippearachchi, K.W., Gamlath, K. L., Eeswara, J.P. & Sooriyapathirana, S.S. (2020) Assessment of the elite accessions of bael [*Aegle marmelos* (L.) Corr.] in Sri Lanka based on morphometric, organoleptic, and elemental properties of the fruits and phylogenetic relationships. *PLoS One*, 15, e0233609. DOI: 10.1371/journal.pone.0233609, PubMed: 32442219.
- [8] K. Bhar, S. Mondal, P. Suresh, An eye-catching review of *Aegle marmelos* L. (Golden Apple), Pharmacognosy Journal 11 (2019) 207–224, <https://doi.org/10.5530/pj.2019.11.34>.
- [9] A.H. Aodah, M.F. Balaha, T. Jawaid, M.M. Khan, M.J. Ansari, A. Alam, *Aegle marmelos* (L.) correa leaf essential oil and its phytoconstituents as an anticancer and anti-Streptococcus mutans agents, Antibiotics 12 (5) (2023) 835.
- [10] V. Lobo, A. Patil, A. Phatak, N. Chandra, Free radicals, antioxidants, and functional foods: impact on human health, Phcog. Rev. 4 (8) (2010) 118.
- [11] N. Sharma, M. Kumar Radha, B. Zhang, N. Kumari, D. Singh, Lorenzo J.M. Lorenzo, *Aegle marmelos* (L.) Correea: an underutilized fruit with high nutraceutical value: a review, Int. J. Mol. Sci. 23 (18) (2022) 10889.
- [12] A. Rajaram, G.R. Vanaja, P. Vyakaranam, A. Rachamalla, G.V. Reddy, K. Anilkumar, P. Reddanna, Anti-inflammatory profile of *Aegle marmelos* (L.) Correea (Bilva) with special reference to young roots grown in different parts of India, J. Ayurveda Integr. Med. 9 (2) (2018) 90–98.
- [13] T.M. Barber, S. Kabisch, A.F. Pfeiffer, M.O. Weickert, The health benefits of dietary fibre, Nutrients 12 (10) (2020) 3209.
- [14] J.D. Schwalm, M. McKee, M.D. Huffman, S. Yusuf, Effective resource strategies to prevent and treat cardiovascular diseases, Circulation 133 (8) (2016) 742–755.
- [15] C.G. Yedjou, J. Grigsby, A. Mbemi, D. Nelson, B. Mildort, L. Latinwo, P. B. Tchounwou, Management of diabetes mellitus using medicinal plants and vitamins, Int. J. Mol. Sci. 24 (10) (2023) 9085.
- [16] N. Mammari, Q. Albert, M. Devocelle, M. Kenda, N. Kočevar Glavač, M. Sollner Dolenc, Oeonom, Natural products for prevention and treatment of common cold and viral respiratory infections, Pharmaceuticals 16 (5) (2023) 662.

- [17] S. Baliga, V.O. Yildiz, J. Bazan, J.D. Palmer, S.R. Jhawar, D.J. Konieczkowski, J. Grecula, D.M. Blakaj, D. Mitchell, C. Henson, K. Hu, K. Yamoah, M.E. Gamez, Disparities in survival outcomes among racial/ethnic minorities with head and neck squamous cell cancer in the United States, *Cancers* 15 (2023) 1781, <https://doi.org/10.3390/cancers15061781>, PubMed: 36980667.
- [18] S. Tieu, A. Charchoglyan, L. Wagter-Lesperance, K. Karimi, B.W. Bridle, N. A. Karrow, B.A. Mallard, Immunocytotoxicity: harnessing their immunomodulatory potential to promote health and wellness, *Nutrients* 14 (19) (2022) 4075.
- [19] R. Chopra, *Indigenous Drugs Of India*, Academic Press Publishers, Calcutta, 1982.
- [20] Monika, S., Thirumal, M. & Kumar, P.R. (2023) Phytochemical and biological review of Aegle marmelos Linn. *Future Science OA*, 9, FSO849. DOI: [10.2144/fsoa-2022-0068](https://doi.org/10.2144/fsoa-2022-0068), PubMed: 37026028.
- [21] N. Kumawat, J. Pantwalwalkar, Y. Vispute, R. Tade, S. Nangare, An overview on phytochemistry, pharmacology, pharmaceutical, traditional and economical aspects of Aegle marmelos, *Asian Journal of Pharmacy and Technology* 11 (2021) 166–174, <https://doi.org/10.52711/2231-5713.2021.00028>.
- [22] K. Biswas, U. Bandyopadhyay, I. Chattopadhyay, A. Varadaraj, E. Ali, R. K. Banerjee, A novel antioxidant and antiapoptotic role of omeprazole to block gastric ulcer through scavenging of hydroxyl radical, *J. Biol. Chem.* 278 (2003) 10993–11001, <https://doi.org/10.1074/jbc.M210328200> [PubMed: 12529378].
- [23] S.S. Mali, R.L. Dhupal, V.D. Havaladar, S.S. Shinde, N.Y. Jadhav, B.S. Gaikwad, A systematic review on Aegle marmelos (Bael), *Research Journal of Pharmacognosy and Phytochemistry* 12 (2020) 31–36, <https://doi.org/10.5958/0975-4385.2020.00007.2>.
- [24] Bari, B., Corbeil, M.A., Farrow, H., Menzies, S., Pflug, B., Smith, B.K., Vasquez, A. & Berard, L. (2020) Insulin injection practices in a population of Canadians with diabetes: An observational Study. *Diabetes Therapy: Research, Treatment and Education of Diabetes and Related Disorders*, 11, 2595–2609. DOI: [10.1007/s13300-020-00913-y](https://doi.org/10.1007/s13300-020-00913-y), PubMed: 32893337.
- [25] Krishnamoorthy, K., Mathew, T. & Mukherjee, S. (2008) Normal-based methods for a gamma distribution: Prediction and tolerance intervals and stress-strength reliability. *Technometrics*, 50. Available at 69-78.study. *Diabetes Therapy*, 11, 2595–2609. DOI: [10.1198/004017007000000353](https://doi.org/10.1198/004017007000000353).
- [26] D.K. Patel, K. Patel, M. Rahman, S. Chaudhary. Therapeutic potential of 'Aegeline,' an important phytochemical of Aegle marmelos: Current health perspectives for the treatment of disease, Springer, Singapore, 2020, pp. 383–392, https://doi.org/10.1007/978-981-15-1664-1_14.
- [27] F. Mujeeb, P. Bajpai, N. Pathak, Phytochemical evaluation, antimicrobial activity, and determination of bioactive components in leaves of *Aegle marmelos*, *BioMed Res. Int.* 2014 (2014).
- [28] H. Mahato, B. Kumar, Medicinal uses of *Aegle marmelos* with immense economic potential and nutritional properties: a Concise Review, *Biocomposites; Books on Demand: Norderstedt, Germany* 133 (2022).
- [29] H.S. Arruda, M.V.L. Araújo, M.R.M. Junior, Underexploited Brazilian Cerrado fruits as sources of phenolic compounds for disease management: a review, *Food Chem.: Molecular Sciences* (2022) 100148.
- [30] S. Alam, M.A. Rashid, M.M.R. Sarker, N.U. Emon, M. Arman, I.N. Mohamed, M. R. Haque, Antidiarrheal, antimicrobial and antioxidant potentials of methanol extract of *Colocasia gigantea* Hook. f. leaves: evidenced from in vivo and in vitro studies along with computer-aided approaches, *BMC Complementary Medicine and Therapies* 21 (1) (2021) 1–12.
- [31] K. Sharma, S. Shukla, E.S. Chauhan, Evaluation of *Aegle marmelos* (Bael) as hyperglycemic and hyperlipidemic diminating agent in type II diabetes mellitus subjects, *Journal of Pharmaceutical Innovation* 5 (5) (2016) 43.
- [32] E.H. Karunanayake, J. Welihinda, S.R. Sirimanne, G.S. Sinnadorai, Oral hypoglycaemic activity of some medicinal plants of Sri Lanka, *Journal of Ethnopharmacology* 11 (1984) 223–231, [https://doi.org/10.1016/0378-8741\(84\)90040-0](https://doi.org/10.1016/0378-8741(84)90040-0), PubMed: 6492834.
- [33] Mudi, S.R., Akhter, M., Biswas, S.K., Muttalib, M.A., Choudhury, S., Rokeya, B. & Ali, L. (2017) Effect of aqueous extract of *Aegle marmelos* fruit and leaf on glycaemic, insulinemic and lipidemic status of type 2 diabetic model rats. *Journal of Complementary and Integrative Medicine*, 14, 20160111. DOI: [10.1515/jcim-2016-0111](https://doi.org/10.1515/jcim-2016-0111), PubMed: 28284036.
- [34] Hannan, J.M.A. (2016). *Evaluation of Anti-hyperglycemic Effect of Ethanolic Extract of Aegle marmelos in Long Evans Rats* (Doctoral dissertation, Department of Pharmacy, East West University).
- [35] K. Sharma, S. Shukla, E.S. Chauhan, Evaluation of *Aegle marmelos* (Bael) as hyperglycemic and hyperlipidemic diminating agent in type II diabetes mellitus subjects, *Journal of Pharmaceutical Innovation* 5 (5) (2016) 43.
- [36] Manandhar, B., Paudel, K.R., Sharma, B. & Karki, R. (2018) Phytochemical profile and pharmacological activity of *Aegle marmelos* Linn. *Journal of Integrative Medicine*, 16, 153–163. DOI: [10.1016/j.joim.2018.04.007](https://doi.org/10.1016/j.joim.2018.04.007), PubMed: 29709412.
- [37] A.K. Singh, S. Singh, P.L. Saroj, H. Krishna, R.S. Singh, R.K. Singh, Research status of bael (*Aegle marmelos*) in India: A review, *Indian Journal of Agricultural Sciences* 89 (2019) 1563–1571, <https://doi.org/10.56093/ijas.v89i10.94576>.
- [38] Rajasree, C.R., Rajamohan, T. & Augusti, K.T. (1998) Antiperioxide effect of garlic protein in alcohol fed rats. *Indian Journal of Experimental Biology*, 36, 60–64. PubMed: 9536654.
- [39] V. Ramamurthy, R. Gowri, Hepatoprotective study on *Aegle marmelos* leaf extract against *Staphylococcus aureus* intoxicated albino rats, *Am. J. Phytomed. Clin. Ther.* 3 (2015) 120–128.
- [40] Rajasree, C.R., Rajamohan, T. & Augusti, K.T. (1998) Antiperioxide effect of garlic protein in alcohol fed rats. *Indian Journal of Experimental Biology*, 36, 60–64. PubMed: 9536654.
- [41] Chandel, S.S., Shirsat, M., Sahu, R.K. & Nayak, S.S. (2018) Modulatory effect of dietary inclusion of *Aegle marmelos* fruits against cisplatin-induced hepatotoxicity in Wistar rats. *Annals of Hepatology*, 17, 482–489. DOI: [10.5604/01.3001.0011.7393](https://doi.org/10.5604/01.3001.0011.7393), PubMed: 29735797.
- [42] R. Rakulini, S. Kalaichelvi, A review of anti-diarrheal activity of *Aegle marmelos*, *Journal of Complementary and Alternative Medical Research* 7 (2019) 1–10, <https://doi.org/10.9734/jocamr/2019/v7i230095>.
- [43] D.V.A. Raju, V. Sandhya, M.V. Chandra, M.M. Reddy, B. Bhattacharya, Evaluation of antidiarrheal and anti-inflammatory activity of *Aegle marmelos* in albino Wistar rats, *Eur. J. Exp. Biol.* 6 (2016) 26–29.
- [44] J.K. Mahato, S.K. Gupta, Modification of Bael fruit shell and its application towards Natural organic matter removal with special reference to predictive modeling and control of THMs in drinking water supplies, *Environmental Technology and Innovation* 18 (2020) 100666, <https://doi.org/10.1016/j.eti.2020.100666>.
- [45] B. Devi, K. Pal, Antioxidant activity of *Aegle marmelos* leaves, *World Journal of Pharmaceutical Research* 5 (2016) 1159–1166.
- [46] K. Suresh, P.K. Senthilkumar, B. Karthikeyan, Antimicrobial activity of *Aegle marmelos* against clinical pathogens, *J. Phytol.* 1 (2009).
- [47] P. Barhe, C. Diwane, P. Waghmare, V. Patil, P. Jadhav, Review on AEGLE MARMELOS, *World Journal of Pharmaceutical Research* 11 (2022) 716–729.
- [48] R. Rakulini, S. Kalaichelvi, A review of anti-diarrheal activity of *Aegle marmelos*, *Journal of Complementary and Alternative Medical Research* 7 (2019) 1–10, <https://doi.org/10.9734/jocamr/2019/v7i230095>.
- [49] P. Choudhary, M. Bhagat, S. Gupta, M. Sangral, Evaluation of *Aegle marmelos* extract for antibacterial, antifungal, antioxidant, and cytotoxic properties, *Current Trends in Biomedical Engineering & Biosciences* 9 (2017) 1–4, <https://doi.org/10.19080/CTBEB.2017.09.555766>.
- [50] M. Devi, S. Devi, V. Sharma, N. Rana, R.K. Bhatia, K.A. Bhatt, Green synthesis of silver nanoparticles using methanolic fruit extract of *Aegle marmelos* and their antimicrobial potential against human bacterial pathogens, *J. Tradit* 10 (2) (2020) 158–165.
- [51] Manandhar, B., Paudel, K.R., Sharma, B. & Karki, R. (2018) Phytochemical profile and pharmacological activity of *Aegle marmelos* Linn. *Journal of Integrative Medicine*, 16, 153–163. DOI: [10.1016/j.joim.2018.04.007](https://doi.org/10.1016/j.joim.2018.04.007), PubMed: 29709412.
- [52] Manandhar, B., Paudel, K.R., Sharma, B. & Karki, R. (2018) Phytochemical profile and pharmacological activity of *Aegle marmelos* Linn. *Journal of Integrative Medicine*, 16, 153–163. DOI: [10.1016/j.joim.2018.04.007](https://doi.org/10.1016/j.joim.2018.04.007), PubMed: 29709412.
- [53] Akhouri, V., Kumari, M. & Kumar, A. (2020) Therapeutic effect of *Aegle marmelos* fruit extract against DMBA induced breast cancer in rats. *Scientific Reports*, 10, 18016. DOI: [10.1038/s41598-020-72935-2](https://doi.org/10.1038/s41598-020-72935-2), PubMed: 33093498.
- [54] A.K. Singh, S. Singh, P.L. Saroj, Bael: an emerging crop of wasteland, in: *Dryland Horticulture*, CRC Press, 2021, pp. 289–311.
- [55] I.Z. Abdallah, I. Salem, A. El-Salam, A.S. Nayrouz, Evaluation of antidiabetic and antioxidant activity of *Aegle marmelos* L. Correa fruit extract in diabetic rats, *Egyptian Journal of Hospital Medicine* 67 (2017) 731–741.
- [56] Chandel, S.S., Shirsat, M., Sahu, R.K. & Nayak, S.S. (2018) Modulatory effect of dietary inclusion of *Aegle marmelos* fruits against cisplatin-induced hepatotoxicity in Wistar rats. *Annals of Hepatology*, 17, 482–489. DOI: [10.5604/01.3001.0011.7393](https://doi.org/10.5604/01.3001.0011.7393), PubMed: 29735797.
- [57] K. Kulprachakarn, S. Ounjaijean, S. Srichairatanakool, D. Kanjanapothi, Evaluation of cytotoxicity and antioxidant potential of bael leaf (*Aegle marmelos*) on human hepatocellular carcinoma cell line, *Pharmacognosy Research* 12 (2020).
- [58] Venhodka, A., Chhikara, N., Mann, S., Garg, M.K., Sofi, S.A. & Panghal, A. (2021) Bioactive compounds of *Aegle marmelos* L., medicinal values and its food applications: A critical review. *Phytotherapy Research*, 35, 1887–1907. DOI: [10.1002/ptr.6934](https://doi.org/10.1002/ptr.6934), PubMed: 33159390.
- [59] S.G. Ghodki, S.B. Borade, H. Pise, V. Motghare, R.S. Mehani, P. Wadgbalkar, Evaluation of analgesic activity of *Aegle marmelos* steam bark in experimental animals, *International Journal of Basic and Clinical Pharmacology* 5 (2016) 1081–1086, <https://doi.org/10.18203/2319-2003.ijbcp20161572>.
- [60] S. Akter. *Assessment of the Effect of Aegle marmelos on Gastrointestinal Motility in Albino Mice* (Doctoral dissertation, East West University, 2017).
- [61] A.K. Singh, S. Singh, P.L. Saroj, G.P. Singh, Improvement and production technology of bael (*Aegle marmelos*) in India—A review, *Current Horticulture* 9 (2021) 3–14, <https://doi.org/10.5958/2455-7560.2021.00001.7>.
- [62] R. Yang, J. Huang, W. Zhang, W. Xue, Y. Jiang, S. Li, X. Wu, H. Xu, J. Ren, B. Chi, Mechanoadaptive injectable hydrogel based on poly (γ -glutamic acid) and hyaluronic acid regulates fibroblast migration for wound healing, *Carbohydrate Polymers* 273 (2021) 118607, <https://doi.org/10.1016/j.carbpol.2021.118607>, PubMed: 34561006.
- [63] L.M. Bhakshu, K.V. Ratnam, R.R.V. Raju, Bioactives and pharmacology of *Aegle marmelos* (L.) Correa, in: *Bioactives and Pharmacology of Medicinal Plants*, Apple Academic Press, 2022, pp. 15–42, <https://doi.org/10.1201/9781003281658-2>.
- [64] S. Akter. *Assessment of the Effect of Aegle marmelos on Gastrointestinal Motility in Albino Mice* (Doctoral dissertation, East West University, 2017).
- [65] D. Jana, U.K. Das, R. Maiti, D. Ghosh, Effect of aqueous extract of leaf of *Aegle marmelos* on testicular activities in rats, *Iran. J. Pharmacol. Ther.* 5 (2006) 21–25.
- [66] Y.K. Gupta, G. Chaudhary, A.K. Srivastava, Protective effect of resveratrol against pentylentetrazole-induced seizures and its modulation by an adenosinergic system, *Pharmacology* 65 (2002) 170–174, <https://doi.org/10.1159/000058044>, PubMed: 12037381.
- [67] R. Edavanputhillath, L. Joseph, K. Kademane, S.N. Rao, Anticonvulsant activity of *Nigella sativa*, *Aegle marmelos* and *Benincasa hispida* in pentylenetetrazole-induced seizures in Swiss albino mice, *Asian J. Med. Sci.* 7 (2015) 97–102.
- [68] S.P.G. Rasool, H.A. Dehghan, Comprehensive review on medicinal plant: *Aegle marmelos* (Linn) Correa, *European Journal of Pharmaceutical and Medical Research* 9 (2022) 193–203.

- [69] R. Wanna, J. Krasaetep, Chemical composition and insecticidal activity of Indian borage essential oil against maize weevil, *Geomate Journal* 16 (2019) 59–64.
- [70] S.S. Lamia, M.S. Shimo, S.S.B. Rashed, A.A. Prima, A.T. Mony, P.R. Dash, Phytochemistry and pharmacological properties of *Aegle marmelos* L. (Rutaceae): A review, *Phytochemistry* 3 (2018) 45–54.
- [71] G. Vishwakarma, A.L. Yadav, A. Kumar, A. Singh, S. Kumar, Effect of integrated nutrient management on the physicochemical characteristics of Bael (*Aegle marmelos* Correa) cv. Narendra Bael-9, *Int. J. Curr. Microbiol. App. Sci* 6 (6) (2017) 287–296.
- [72] D. Panday, N. Bhusal, S. Das, A. Ghalegholabbebhahani, Rooted in nature: the rise, challenges, and potential of organic farming and fertilizers in agroecosystems, *Sustainability* 16 (4) (2024) 1530.
- [73] M. Choudhary, K. Grover, Bael (*Aegle marmelos*) oil, in: *Fruit Oils: Chemistry and Functionality*, Springer International Publishing, 2019, pp. 605–613, https://doi.org/10.1007/978-3-030-12473-1_30.
- [74] M. Choudhary, K. Grover, Bael (*Aegle marmelos*) oil, in: *Fruit Oils: Chemistry and Functionality*, Springer International Publishing, 2019, pp. 605–613, https://doi.org/10.1007/978-3-030-12473-1_30.
- [75] Garg, N., Kumar, S. & Yadav, P. (2021) Indian goose berry fortified, anti-oxidant rich bael (*Aegle marmelos*) fermented beverage. *Journal of Food Science and Technology*, 58, 4437–4441. DOI: 10.1007/s13197-021-05129-x, PubMed: 34538927.
- [76] A. Khanal, Bael (*Aegle marmelos*), an underutilized fruit with enormous potential to be developed as a functional food product: a Review Dall, *Journal of Food Processing and Preservation* 2023 (2023) 8863630.
- [77] M. Shirsat, V. Shilimkar, Design and Development of nanoparticle-based antidiabetic formulation of *Aegle marmelos* plant, *International Journal of Pharmaceutical Research* 12 (4) (2020) 5399–5413.
- [78] M. Sriramulu, D. Shukla, S. Sumathi, *Aegle marmelos* leaf extract-mediated synthesis of zinc ferrite: antibacterial activity and drug delivery, *Material Research Express* (2018).