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BAEL FRUIT (AEGLE MARMELOS): A COMPREHENSIVE REVIEW ON PHYTOCHEMICAL, PHARMACOLOGICAL PROPERTIES AND ITS TRADITIONAL USES

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ABSTRACT
Aegle marmelos (L.) Corrêa, commonly known as bael, is a highly revered plant in traditional Indian medicine, particularly in Ayurveda, Siddha, and Unani systems. This comprehensive review examines the nutritional, phytochemical, and pharmacological attributes of bael fruit, drawing from both traditional knowledge and modern scientific research. Rich in alkaloids, coumarins, terpenoids, and polyphenols, bael exhibits significant therapeutic activities including antidiabetic, antimicrobial, antioxidant, anti-inflammatory, gastroprotective, hepatoprotective, and anticancer effects. Experimental studies highlight mechanisms such as enzyme inhibition, free radical scavenging, and modulation of signaling pathways, validating its use in conditions like diabetes, gastrointestinal disorders, and liver diseases. Moreover, bael has demonstrated protective roles against oxidative stress, cardiac dysfunction, and radiation-induced damage. Despite the strong preclinical evidence, clinical validation and standardization remain limited. This review underscores the need for further investigations to elucidate bioactive compounds, optimize extraction methods, and conduct clinical trials. Bael holds immense promise as a sustainable and effective source for nutraceutical and pharmaceutical development, bridging traditional medicine with modern therapeutics.

KEYWORDS: Aegle marmelos, Bael fruit, Phytochemistry, Pharmacology, Nutraceuticals.

INTRODUCTION
Aegle marmelos, commonly known as bael or wood apple, is a sacred tree native to the Indian subcontinent and Southeast Asia. Its fruits, leaves, and roots have been used for millennia in Ayurveda, Siddha, and Unani systems to treat diarrhea, dysentery, diabetes, and inflammatory disorders.[1] Recent studies validate its ethnomedicinal uses, attributing its bioactivity to a rich array of alkaloids, coumarins, and terpenoids. This review aims to: Summarize nutritional and phytochemical profiles, evaluate evidence-based pharmacological benefits and explore industrial applications and research gaps.

Botanical Description and Cultivation
Taxonomy: Family Rutaceae; deciduous tree (10–15 m tall).
Fruit: Round, woody shell; aromatic pulp (yellow-orange when ripe).
Cultivation: Thrives in dry, subtropical climates; drought-resistant.

Nutritional Composition
Table 1: Nutritional value per 100 g of bael fruit pulp (Source: USDA and Indian Food Composition Tables).

Component	Quantity
➢ Calories	137–150 kcal
➢ Carbohydrates	31–35 g
➢ Dietary Fiber	2.5–4.5 g
➢ Vitamin C	50–60 mg
➢ Calcium	85–90 mg
➢ Potassium	600–650 mg

Fig. 1: Bael plant with fruit.

Phytochemical constituents

Studies have shown that the bael fruit pulp contains important bioactive compounds such as carotenoids, phenolics, alkaloids, pectins, tannins, coumarins, flavonoids and terpenoids; Bael fruit contains volatile compounds like hexanal, isoamyl acetate, limonene, β-phellandrene, p-cymene, acetoin, (E)-2-octenal, (E,E)-2,4-heptadienal, dehydro-p-cymene, linalool; 3,5-octadiene- 2-one, α-cubebene, trans-p-mentha-2,8-dienol, citronellal, cineole, p-cymene, citronella, citral, cuminaldehyde, β-cubebene, β-caryophyllene, hexadecane, pulegone, α-humulene, verbenone, carvone, carvyl acetate, dihydro-β-ionone, (E)-6,10-dimethyl-5,9-undecadien-2-one, β-ionone, caryophyllene oxide, humulene oxide and hexadecanoic acid. They also contain coumarins like aegeline, aegelenine, marmelin, o-mtheyl halfordinol, alloimperatorin, furocoumarins, psoralen, o-isopentenyl halfordinol and marmelosin. They also contain tartaric acid, linoleic acid, tannins, phlobatannins, flavon-3-ols, leucoanthocyanins, anthocyanins, and flavonoid glycosides.[2,3,4,5,6]

Pharmacological activities

The pharmacological potential of Aegle marmelos is attributed to its diverse bioactive compounds, including coumarins (e.g., marmelosin), alkaloids (e.g., aegeline), polyphenols (e.g., rutin), and terpenoids. Below, we discuss the evidence-based therapeutic effects, supported by in vitro, in vivo, and limited clinical studies.

Antioxidant activity

- Key compounds: Phenolic acids, flavonoids (quercetin), vitamin C.
- Mechanisms:
- Scavenges reactive oxygen species (ROS) via hydrogen donation[7] Upregulates endogenous antioxidants (SOD, CAT, GSH) in ethanol-induced oxidative stress models.[8]
- Significance: Mitigates oxidative damage linked to aging, diabetes, and neurodegeneration.

Antidiabetic effects

- Key compounds: Aegeline, marmelosin, dietary fiber.
- Mechanisms:
- α-Amylase/α-glucosidase inhibition[9] Insulin sensitization: Enhances GLUT4 translocation in skeletal muscle.[10]
- Pancreatic β-cell regeneration: Observed in streptozotocin-induced diabetic rats.[11]
- Clinical Evidence: A pilot study reported a 15–20% reduction in postprandial glucose with bael leaf extract.[12]

Antimicrobial and Antiparasitic properties

- Key compounds: Tannins, terpenoids (limonene), coumarins.
- Findings:
- Bacterial: Inhibits E. coli (MIC: 0.5 mg/mL), S. aureus (MIC: 0.75 mg/mL) by disrupting cell membranes.[13]
- Fungal: Active against Candida albicans (zone of inhibition: 18 mm at 200 µg/disc).
- Antiparasitic: Aqueous seed extract reduces Leishmania donovani viability IC50: 12 µg/Ml.[14]

Anti-inflammatory and Immunomodulatory Effects

- Key compounds: Lupeol, skimmianine.
- Mechanisms:
- Suppresses COX-2 and NF-κB pathways (50% reduction in paw edema at 100 mg/kg in rats;).[15]
- Downregulates pro-inflammatory cytokines (TNF-α, IL-6) in LPS-stimulated macrophages.
- Applications: Potential in arthritis and inflammatory bowel disease (IBD).

Gastroprotective and Antiulcer Activity

- Key Compounds: Marmelosin, mucilage.
- Mechanisms
- Reduces gastric acid secretion via H+/K+-ATPase inhibition.
- Enhances mucosal defense (↑ mucin secretion; 70% ulcer inhibition at 200 mg/kg;).[16]
- Traditional Use: Fruit pulp is prescribed for diarrhea and peptic ulcers.

Hepatoprotective and Nephroprotective

- Key Compounds: Marmin, β-sitosterol.
- Findings:

- Liver: Normalizes ALT/AST levels in CCl4-induced hepatotoxicity (75% protection at 300 mg/kg;).[17]
- Kidneys: Attenuates cisplatin-induced nephrotoxicity by reducing lipid peroxidation (MDA levels ↓ by 40%;).[18]

Anticancer potential

- Key compounds: Eugenol, marmelin.
- Mechanisms:
- Induces apoptosis in MCF-7 breast cancer cells (via caspase-3 activation; IC50: 45 µg/mL).[19]
- Anti-angiogenic: Inhibits VEGF in Ehrlich ascites carcinoma models.
- Limitations: Limited in vivo data; needs tumor-specific studies.

Neuroprotective and Antidepressant Effects

- Key compounds: Scopoletin, umbelliferone.
- Findings:
- Improves memory in Alzheimer's models (↓ acetylcholinesterase activity by 30%).
- Modulates serotonin/dopamine in forced swim tests (comparable to fluoxetine).[20]

Traditional uses

In ayurvedic practice of medicines bael fruit is highly regarded as potent solution for dieases like diarrhoea mentioned in Das & Das 1995. The immature fruits exhibit a bitter, sour and astringent flavour, helping with digestion and soothing stomach discomfort. Bael fruits which are ripe was considered more beneficial than unripe bael fruits and are used in treatment of both acute and chronic dysentery the pulp of the fruit acts as a gentle stimulant for intestinal mucus membrane, the ripped fruits has a pleasant smell and used for its cooling effect and laxative properties.[21]

Validated pharmacological properties of the bael fruit Being an indigenous tree to India, the scientific studies with bael fruit have been minimal. Some of the relevant pharmacological properties of these compounds have also been addressed in the following sections.

Free radical scavenging effects

Studies have conclusively shown that the ROS and RNS, when produced in excess cause oxidative stress and nitrosative stress, respectively. Among ROS and RNS, the superoxide anion radical (O_2), hydroxyl radical (OH), nitric oxide (NO), peroxynitrite (ONOO), and hydrogen peroxide (H_2O_2) are the most important as they can cause damage to cell structures, including lipids and membranes, proteins, and DNA.[22] Many medicinal plants and fruits have been reported to be effective at scavenging these free radicals and to prevent the ensuing damage.[23] With regard to bael, studies by Kamalakkannan and Prince (2003); Kamalakkannan and Prince have shown that the aqueous extract of the bael fruit pulp possess potent antioxidant effects. Subsequently, the hydroalcoholic extract of bael pulp is also shown to possess nitric oxide scavenging activities in vitro.[24,25,26] Additionally, the bael fruit drink was also reported to possess high quantities of total phenolic compounds (83.89/37.6 mg gallic acid equivalents/100 ml) and was also a good antioxidant in both DPPH (photo chemiluminescence) and PCL (photo chemiluminescence) assays.[27]

Inhibition of lipid peroxidation

The free radicals generated cause peroxidation of polyunsaturated lipids and produce a range of end products that possess DNA damaging potential. These include the lipid hydroperoxides and the various species that contain unpaired electrons, such as the alkoxyl and peroxyl radicals. In addition, a range of genotoxic carbonyl-containing compounds like malondialdehyde, various 4-hydroxy-2-alkenals (4-hydroxynonenal) and a number of 2-alkenals are also formed.[28] Therefore, inhibition of LPx is important in the disease processes.

With regard to bael, in vitro studies have shown that the hydroalcoholic extract of bael at the concentrations of 25 to 500 µg/ml caused a concentration depended inhibition of Fe2SO4-induced LPx in rat brain homogenate.[29] Similar observations were also seen in animal studies where the intraperitoneal administration of the hydroalcoholic extract of the fruit pulp (20 mg/kg body weight) for five consecutive days before exposure to different doses of γ-radiation (6 to 9 Gy) prevented radiation-induced LPx in the liver, kidney, intestine and spleen of mice.[30]

Bael prevents CCl4-induced hepatotoxicity

Multiple preclinical studies in the recent past have shown that oral administration of bael protected rats and mice against the CCl4-induced hepatic damage. Oral feeding of bael (25 and 50 mg/kg b. wt. orally) for seven consecutive days before administration of CCl4 suppressed LPx, xanthine oxidase and release of serum toxicity marker enzymes (SGOT, LDH, SGPT) in a concentration dependent manner. Bael prevented CCl4-enhanced ornithine decarboxylase and hepatic DNA synthesis. Further the levels of hepatic antioxidants like GSH, GRx, GPx, QR, CAT, which were reduced by CCl4 administration, were restored near to the normal levels by bael administration. In total these observations suggest that bael prevented the CCl4-induced liver toxicity by enhancement of the antioxidants and preventing hyperproliferation.

Very recently, Singh and Rao (2008) have also reported that the pre and post treatment with bael pulp extract (1:3 part of the pulp and water homogenate) protected rats against the CCl4-induced hepatotoxicity. When compared with the CCl4 only group, a significant decrease in the levels of liver damage markers like SGOT, SGPT, ALP and bilirubin in the serum was observed in the cohorts administered with both bael homogenate and CCl4. Of the two schedules, administering the pulp for fourteen days after treatment with CCl4 (pos treatment) was observed to be better than

the pretreatment schedule (twenty-eight days before the treatment with CCl4). The authors also observed that the seed homogenate prepared in similar way to the pulp was also effective. However, with regard to the seed the observations showed that the pretreatment was better than the post treatment, was inferior to that of the fruit pulp. Studies have also shown that both aqueous and methanolic extract of the bael fruit pulp (500 and 600 mg/kg b. wt.), when fed for five consecutive days protected mice against the CCl4-induced liver damage. The analysis of SGOT, SGPT and ALP showed that the methanolic and aqueous extracts were moderately effective when compared to silymarin treatment, used as positive control. On the two extracts the aqueous extract was observed to be better than the methanolic and a concentration dependent hepatoprotective effect was observed. Together these observations clearly show that the bael fruit and the seed possess hepatoprotective effects and merit detail investigations with the individual phytochemicals and also in other models of hepatotoxicity (like ethanol, paracetamol, aflatoxin etc.).[31,32,33]

Bael fruits in the prevention of Diabetes and Its complications

In spite of all the advances and progress in medical sciences, the complete cure for diabetes mellitus, a disease as old as mankind and characterized by hyperglycaemia due to decreased secretion of insulin or action of insulin or both is lacking. Worryingly, the global prevalence is increasing and as per recent reports nearly 6.4% of the global population is suffering from diabetes.

According to the modern system of medicine, diabetes is a systemic metabolic disease and the prevailing hyperglycaemia, hyperlipidaemia, hyper aminoacidemia and hypoinsulinemia lead to the development of micro and macro vascular diseases which include neuropathy, nephropathy, cardiovascular and cerebrovascular diseases.

In the Ayurvedic system of medicine, diabetes was termed as mudhumeha or ikshumeha and over the centuries the practitioners recommended the use of certain plants either alone or in combination for treating it. Bael leaves, fruits and bark have also been reported to be useful in treating diabetes and scientific studies have validated this. With regard to bael fruit, studies have shown that oral administration of the aqueous extract of bael fruit (125 and 250 mg/kg) twice daily to diabetic rats for a period of 30 days decreased the levels of fasting blood glucose and glycosylated haemoglobin levels with the effects being better than that of glibenclamide. Bael also increased total body weight, pancreas weight and both serum insulin and liver glycogen levels. Administration of bael to diabetic rats also decreased the levels of thiobarbituric acid reactive substances and hydroperoxides, and concomitantly increased the levels of GSH, Vitamin C, ceruloplasmin and α-tocopherol in the plasma.

Feeding bael also caused a concentration dependent decrease in LPx, to increase SOD, CAT, GPx and GSH levels in both heart and pancreas of diabetic animals. Histopathological studies showed that feeding the fruit extract improved the functional state of the pancreatic cells and partially reversed the damage caused by streptozotocin to pancreatic islets.[34]

Bael in cardiac dysfunction

Recent reports suggest that globally, the cardiovascular diseases are the leading cause of death and accounts for nearly 30% of all global mortality.[35] In the developed countries it is the single largest cause of death and is one of the leading causes of mortality in the developing countries where, it accounts to twice as many deaths as HIV, malaria and TB combined. In Ayurveda several plants, including bael have been considered to have therapeutic benefit for cardiovascular disease. Scientific studies by Krushna, Kareem, and Devi (2009) have shown that administering aqueous extract of the unripe fruit protected rats against the isoproterenol-induced cardiac stress. The authors studied a single dose of 150 mg/kg body weight, for 45 days and observed that the oral feeding of the extract reversed the isoproterenol-induced changes in the lipid profiles suggesting that the extract has significant anti-dyslipidaemia effect.[36,37] Bael also decreased the levels of isoproterenol-induced increase in the total cholesterol, low density lipoprotein cholesterol, very low-density lipoprotein cholesterol and phospholipids. Concomitantly, the levels of high-density lipoprotein cholesterol and triglycerides which were decreased by isoproterenol were restored to near normal levels. The levels of blood glucose and protein were also in the normal range.[37]

Bael fruit reduces intraocular pressure, a cause for glaucoma:

In Ayurvedic and various folk systems of medicine, the juice prepared from the tender leaves of bael is supposed to reduce the burning sensation in the eyes and also to improve eyesight and the concentration power. Recently, preclinical studies by Agarwal, Gupta, Srivastava, Saxena, and Agrawal (2009) have shown that administering the unripe fruit extract (1%) reduces the intraocular pressure caused by water loading and steroids in the in the New Zealand white rabbits. The efficacy was comparable to that of timolol, a standard clinically used drug after 45 min of water loading in the water loading model, and during the first 2 h of treatment in the steroid-induced model. These results clearly suggest that bael fruit extract was effective in lowering the experimentally-induced intraocular pressure in experimental animal models and has the potential to be of pharmaceutical use.[38,39]

Bael in gastrointestinal dysfunction

Bael possesses antibacterial effects on certain enteric bacteria. Diarrhea commonly caused by gastrointestinal infections is reported to be responsible for the death of around 1.8 million people, mostly children below the age of five in the developing countries. The most common reasons are due to infections by the entherotoxigenic Escherichia coli, Salmonella typhimurium, Clostridiumdifficile, Clostridium freundii, Aeromonas hydrophyla, Yersinia enterocolitica, Campylobacter jejuni and Vibrio cholerae. These organisms produce secretory diarrhea severe enough to cause life threatening dehydration resulting from the loss of electrolytes in stools.[40] In vitro studies have shown that the methanolic and aqueous extracts of bael (20 µl of the plant homogenate) possess antimicrobial effects against multi-drug resistant Salmonella typhi (strains MTCC 531 and B 330) causing enteric diseases. The methanolic extract was better than that of the aqueous extract. The minimum inhibitory concentration for the methanolic extract against S. typhi B330 and S. typhi M531 was N256 and 256 µg/ml, respectively.[41]

Recently, Raja, Murali, Malathi, Anbarasu, and Devaraj (2009) have reported that in the serial dilution assay, the aqueous extract of the bael pulp caused a concentration-dependent inhibitory effect on the enterotoxigenic E. coli and that the highest antibacterial activity was observed at 500 µg/ml concentration. The enterotoxigenic E. coli were resistant to the standard antibiotics ampicillin, vancomycin, penicillin, norfloxin, chloramphenicol, novobiocin and carbenicillin. However, when coincubated with the bael extract (250 µg/ml) these antibiotics were performed and the bacteria were sensitive to all the antibiotics except chloramphenicol and carbenicillin. These results for the first time indicated that the bael extract could reverse the antibiotic resistance in the enterotoxigenic E. coli and could be of use in clinics.[42]

Animal studies with BALB/C mice have shown that infection of mouse ileal loop with bael treated Enteropathogenic E. coli showed almost normal architecture. The apoptotic analysis showed low levels of activated form of caspase 3, ensuring the loss of pathogenesis. The pathogenesis of Enteropathogenic E. coli is primarily through the adherence of the pathogen to intestinal mucosa and molecular studies have shown that bael down regulated outer membrane protein C, important in the adherence and antibiotic resistance. This loss of adherence with a concomitant up regulation of OmpF consequentially allowed the entry of β-lactam antibiotics into bacteria and this is how bael initiated the antibacterial effects of the antibiotics on the other wise drug resistant Enteropathogenic E. coli. These reports suggest that bael can be used in combination with β-lactam antibiotics for the treatment of Enteropathogenic E. coli.

Recently, Brijesh, Daswani, Tetali, Antia, and Birdi (2009) studied the anti-diarrheal effects of the hot aqueous extract (decoction) of dried unripe fruit pulp. The authors observed that the decoction was ineffective on the bacteria but possess cytotoxic activity against Giardia and rotavirus. Further it also reduced the bacterial adherence and invasion of HEp-2 cells. These observations suggest that despite having limited antimicrobial activity, bael affects the bacterial colonization, production and action of certain enterotoxins on to the gut epithelium and thereby exerts its anti-diarrheal effects.[43]

Bael possesses antiviral effects on coxsackieviruses

In association to the bacteria certain enteroviruses also cause diarrhea and contamination of water supplies by enteric viruses represents an important source of viral infection. Coxsackieviruses, belonging to the class picornaviruses are a common cause of infections in humans, especially children. They mostly cause mild or non-symptomatic illness but may be fatal in immune compromised people. Studies by Badam, Bedekar, Sonawane, and Joshi (2002) have shown that the fruit extract and pure compound, marmelide possess antiviral effects against the human coxsackieviruses B1–B6 in the 96h plaque inhibition assay. Additionally, bael extract and marmelide did not exhibit any toxicity to Vero cells suggesting that the extract did not possess any inherent toxicity on normal cells and was possibly safe for human use. Studies have also shown that marmelide was most effective as a virucidal agent and interfered with the viral replication in different stages like adsorption, penetration, at various stages of single cycle growth curve.[44]

Bael reduces the chemical-induced diarrhea

In association to the bacteria and viruses, neurohormonal mechanisms, malnutrition, chronic diseases and drugs can alter gastrointestinal physiology resulting in changes in either secretion or absorption of fluid by the intestinal epithelium that ultimately results in diarrhea. The antimotility compounds such as diphenoxylate, loperamide, opium alkaloids, anticholinergics etc. are administered against diarrheal disorders but on prolonged use are often associated with side effects.

Multiple studies have shown that bael possess anti-diarrheal activity in the standard experimental assays. Studies have shown that in the castor-oil induced diarrhea in rats, the methanolic extracts of bael (3, 7.5 and 15 mg) was observed to be more effective than the aqueous extracts. There was a significant reduction in the induction time of diarrhea, reduction in frequency of passing stools and total weight of the feces. The anti-diarrheal property of aqueous extract was equivalent to that of the standard drug Lomotil in the rats administered with castor-oil. Administering raw fruit extract to mice significantly inhibited the castor oil-induced intestinal transit time as well as the accumulation of intestinal fluids. The methanolic extract of the unripe fruit (50, 100

and 200 mg/kg, p.o.) caused a dose-dependent decrease in the intestinal propulsion and decrease in the total number of fecal matter in castor oil-induced diarrhea. Further, yohimbine, an agr2 adrenoreceptor blocker, attenuated the antidiarrheal effect of the extract and diphenoxylate. When considered in total, these observations clearly suggest that bael is effective as an anti-diarrheal agent and detailed studies are warranted to understand the underlying mechanism of action.[45,46,47]

Gastroprotective effects

Dhuley (2003) investigated the gastroprotective effects of the unripe fruit extract against different ulcerogens (hypothermic restraint stress, absolute theanol and indomethacin) in rats. The study showed that pretreatment of animals with unripe fruit extract (50 and 100 mg/kg, i.p.) protected against the theanol-induced gastric ulceration but was ineffective against the restraint stress or indomethacin. The methanolic extract of the unripe fruit (50, 100 and 200 mg/kg, p.o.) caused a dose dependent decrease in ulcer index induced by theanol, aspirin and cold restraint stress. Administration of bael prior to cold restraint stress causes significant decrease in ulcer index and LPx.

Bael prevents inflammatory bowel disease (IBD)

Inflammatory bowel disease (IBD), clinically characterized by bloody diarrhea, cramping and abdominal pain, is an immunologically mediated chronic and relapsing inflammatory disease affecting the lining of the intestine. Studies have shown that feeding a single dose of methanolic extract of bael (200 mg/kg), ameliorated DNBS-induced ulcerative colitis in rats. Bael inhibited the DNBS-induced decrease in food and water intake, wasting and restored the stool consistency. Bael reduced the gross changes, mucosal damage and disease activity index. Histopathological study showed that bael administration decreased the infiltrative neutrophils and inflammation. The biochemical assays showed a decrease in the levels of NO, LPx and MPO. Concomitantly the levels of antioxidant enzyme in the bael treated colitis cohort were increased.[48]

A. marmelos prevents radiation-sickness and mortality

Radiotherapy, although effective in cancer treatment is associated with severe side effects due to normal tissues damage The use of chemical radioprotectors which can preferentially protect the normal cells from radiation-induced damage represents an obvious strategy to improve the therapeutic index in radiotherapy, thereby providing enormous benefit to cancer patients However to date no compound is observed to be optimal as most, including the FDA approved radioprotector WR-2721 (amifostine) are observed to possess inherent toxicity at their optimal protective concentrations, necessitating the need for alternatives that are non toxic and effective.[49]

Studies have shown that intraperitoneal administration of hydroalcoholic extract of the fruit pulp (5, 10, 20, 40, or 80 mg/kg body weight) for five consecutive days before exposure to radiation, protected mice against the radiation-induced sickness and mortality. Bael pretreatment protected mice against both gastrointestinal and bone marrow deaths, as evidenced by the greater number of survivors on day 10 or 30, respectively. The optimal effect was observed in the cohorts administered with 20 mg/kg of bael. Additionally, treatment with 20 mg/kg of bael before exposure to different doses of γ-radiation (6 to 11 Gy) reduced the severity of symptoms of radiation sickness and mortality with all exposure doses. Bael treatment decreased LPx with a concomitant increase in GSH concentration in the liver, kidney, stomach, and intestine of mice. Future studies should be planned at determining whether bael is selective in protecting the normal tissue as this can be of great help in clinics in the treatment of cancer.

Bael as an Anticancer and Chemopreventive agent

For nearly six decades chemotherapy has been the mainstay in cancer treatment and still continues to be useful in the treatment of metastatic cancers. However, most of the clinically used chemotherapeutic agents possess inherent normal tissue toxicity, thereby compromising the therapeutic advantage (30). Preclinical studies have shown that the methanolic extract of the fruit possess cytotoxic effect on human breast adenocarcinoma cells (SKBR3) in vitro. The IC50 was observed to be 144.00+1.21 µg/ml suggesting the effect to be not very good and that the pulp was not a potential antineoplastic agent.[50]

Prevention is better than cure and this adage is more valuable in cancer. The concept of cancer prevention, which is termed as chemoprevention is based on a protective approach for controlling cancer. It involves the use of specific nontoxic natural products or synthetic chemical agents to reverse suppress or prevent premalignancy before the development of invasive cancer.

With regard to bael fruit, recent studies have shown that the methanolic extract of the pulp possess chemopreventive effects against the DMBA-induced skin papilloma genesis in the Swiss albino mice. Oral administration of the bael extract (50 mg/kg body wt.) in the pre-initiation phase (7 days before and 7 days after DMBA application) caused a 70% decrease while during the post-initiation phase (from the day of croton oil treatment till the end of the experiment) caused a 50% decrease in tumor incidence. Bael also reduced the cumulative number of tumors, the tumor burden per animal and tumor yield suggesting its usefulness as a chemopreventive agent.[51]

Conclusion and Future perspectives

The comprehensive review of Aegle marmelos (Bael fruit) affirms its profound significance in traditional medicine and its promising potential in modern pharmacological applications. This plant, revered in Ayurveda and other indigenous systems, has been shown to possess a broad spectrum of therapeutic properties including antioxidant, antidiabetic, antimicrobial, hepatoprotective, gastroprotective, neuroprotective, and anticancer effects. Scientific investigations corroborate many traditional claims and highlight the bioactive constituents such as marmelosin, aegeline, flavonoids, and coumarins that underpin its medicinal effects. Furthermore, bael fruit exhibits unique attributes like the ability to modulate oxidative stress, inhibit lipid peroxidation, and enhance immune responses, which are instrumental in mitigating chronic diseases. Despite its robust pharmacological profile, the therapeutic use of bael remains underutilized due to limited clinical trials and lack of standardized formulations. Future research must focus on isolating specific compounds, understanding their molecular mechanisms, and conducting well-designed clinical studies to validate efficacy and safety. With appropriate scientific backing, bael fruit could be integrated into modern therapeutic regimes, functional foods, and nutraceutical formulations, thereby serving as a bridge between traditional wisdom and contemporary healthcare innovation.

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