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(Review Article)

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Bael (*Aegle marmelos* (L.): Ethnobotany, Phytochemistry and Pharmacology: Cultivated varieties in India -An Update

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Abstract

This review paper of literature survey highlights medicinal importance of *Bilwapathri* or Bael (*Aegle marmelos*: Family- *Rutaceae*) and updates on therapeutic studies. The demand for bael fruits is increasing owing to nutraceutical, therapeutical, post-harvest values, and its usages in various Indian *Ayurvedic* system of medicines. Bael is available as both wild and cultivated varieties in all parts of India. **Riboflavin**, an essential vitamin, is only found in fully ripe fruits. Some of the well known commercially cultivated 20 varieties of Bael in India are CISH-B-1, CISH-B-2, **Goma Yashi**, Narendra Bael-5 (NB-5), Narendra Bael-7 (NB-7), Narendra Bael-9 (NB-9), Narendra Bael-16 (NB-16), Narendra Bael-17 (NB-17), Pant Aparna, Pant sujata, Pant Shivani, Pant Uravashi, CHESB-16, CHESB-11, CHESB-21, Thar Divya, Thar Neelkanth, Thar Shivangi, Thar Srishti, and Thar Prakrati. The pulp of fruits, bark, leaves, seeds, and roots of bael tree contain bioactive compounds such as coumarin, xanthotoxol, imperatorin, aegeline, high amount of riboflavin and marmeline. The fruit pulp extract of bael has been known for its pharmacological activities, including antioxidant, antidiarrheal, immunomodulatory, anticancer, antidiabetic, cardioprotective, hepatoprotective, radioprotective, antimicrobial, used to treat cirrhosis, bioadhesive property, antispermatogenic, wound-healing property, antimalarial, used in the treatment of glaucoma, antipyretic, antiviral, cardioprotective, antivenom, analgesic, anti-inflammatory, antimicrofilarial and antiulcer properties. Despite its exceptional flavor, nutritional and medicinal properties, Bael remains an underutilized fruit with enormous potential to be used in the functional food market. In the market, bael fruit pulp is predominantly consumed in processed forms such as jams, squash, murabba, powder, preserves, nectar, and toffee.

Keywords: *Aegle marmelos*; Anticancer; Antiulcer; Bael; Bilwapatri; Goma Yashi; Hepatoprotective; Pant Aparna; Marmeline; Radioprotective; Riboflavin; Thar Neelkanth

1. Introduction

Bael (*Aegle marmelos* (L.) Correa (Bael), or Bilwapatri is an important medicinal plant in Indian *Ayurvedic* medicine belongs to family *Rutaceae* [1-10]. Bael (*Aegle marmelos* Correa) is an important indigenous fruit of India and known

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since ancient times. *Aegle marmelos* is a native to Eastern Ghats and Central India [1-30]. Now both wild and cultivated varieties of Bael are available in India. There are 20 commercially cultivated varieties of Bael are available in India [296-331]. The wild variety of Bael is very common in the Western Ghat of Karnataka, Andhra Pradesh, Kerala, Goa, Tamilnadu, Gujarat, and Maharashtra[1-70]. Bael *(Aegle marmelos)* is prevalent throughout South and Southeast Asia, including India, China, Nepal, Myanmar, Pakistan, Bangladesh, Nepal, Vietnam, Laos, Cambodia, Thailand, Indonesia, Malaysia, Tibet, Sri Lanka, Java, the Philippines, and Fiji [107]. *Aegle marmelos* is widely utilized in traditional medicines due to its excellent pharmaceutical characteristics [1-70]. *A. marmelos* has been historically used for a variety of ethno botanical purposes[1-70-130]. *Ayurvedic* medicine is one of the world's oldest medical systems and remains one of India's traditional health care systems [146, 294-295]. *Aegle marmelos* Linn, also familiar as Bael belonging to the family *Rutaceae*, has been frequently utilized in the indigenous Indian system of medicine because of its diverse medicinal properties [1-70-120]. Bael trees can be found in India's Indo-Gangetic Plains, Sub-Himalayan tracts, North-Eastern area, and dry and deciduous forests of the central and southern peninsula [1-107]. Commercial cultivation of the high-yielding variety **Goma Yashi** has lately acquired pace in Rajasthan, Uttar Pradesh, Madhya Pradesh, Punjab, Tamil Nadu, Karnataka, and Gujarat states in the form of orchard or border plantation [1-107]. Bael has been used extensively in traditional medicine and *Ayurveda*. It has been discovered that every part of the bael tree has the ability to treat a variety of illnesses [1-107]. Bael is also known as begal-quince, golden apple, and stone apple in India [1, 2, 49, 107] and a sacred tree for Hindus in India, Nepal and Sri Lanka [1-107-130]. Bael trees are usually planted near temples dedicated to Lord Shiva and routinely worshiped by the devotees of Hindu religion in India, Nepal and Sri Lanka [1-120]. Bael is one of the most appreciated plants used in *Ayurvedic* medicine by the Indian and other South Asian inhabitants in ancient history [1-49-107]. Herbal drugs are abundantly available as they are cheap and have no side effects [293].

The ancient Indian medical system, also known as *Ayurveda*, is based on ancient writings that rely on a "natural" and holistic approach to physical and mental health [146, 294-295]. *Ayurvedic* medicine is one of the world's oldest medical systems and remains one of India's traditional health care systems [146, 294-295]. *Ayurvedic* treatment combines products (mainly derived from plants, but may also include animal, metal, and mineral), diet, exercise, and lifestyle [146, 294-295]. Bael (*Aegle marmelos*) is widely distributed throughout Indian Peninsula. The plant grows in most of the southeast Asian countries and grows well in tropical climates too at an altitude of 1200 m [146, 294-295]. According to the historical records, bael is used as a medicinal and food item since 5000 B.C. [1-49] and known to human beings even when writing the famous Sanskrit epic-poem Ramayana [1-49-120]. Bael is mentioned in the renowned book Charaka Samhita, a comprehensive compilation of all the essential *Ayurvedic* information, which is identified bael as a necessary item in *Ayurvedic* medicine [1-49]. The bael fruit serves as a rich reservoir of riboflavin, offering therapeutic benefits in combating beriberi [1- 49-107, 293]. In the market, bael fruit is predominantly consumed in processed forms such as jams, squash, murabba, powder, preserves, nectar, and toffee [1, 49-107, 293]. Particularly during the COVID-19 pandemic, these products have witnessed heightened demand due to their perceived *Ayurvedic* medicinal values, resulting in elevated market prices [1- 49-107, 293]. Consequently, bael cultivation is emerged as a lucrative venture for farmers, especially in arid and semi-arid regions [1-49-107, 293-351]. India has one of the most expanded plant-origin medical traditions in the world. In India, rural communities know around 25,000 potent plant-based remedies employed in traditional medicine. Plants, especially those with ethno pharmacological uses, have been the primary sources of medicine for early drug discovery [1-40, 49, 107, 293-351]. During COVID-19 outbreak in India, most of the traditional healers have suggested the consumption of bael fruit pulp due to antiviral and immunogenic properties. In the following section, etnobotany, phytochemistry, pharmacy, therapeutic studies, cultivation methods, micropropagation of bael, and commercially cultivated varieties of bael in India has been updated and discussed.

2. Bael Tree: Origin and Distribution

The origin of Bael tree is India particularly North India. The wild species reached the nearby countries in prehistorical times and recently to the other faraway lands through human movements [1-107]. The bael trees thrive well in dry, mixed deciduous, and dry dipterocarp forests and soils of India, Sri Lanka, China, Bhutan, Thailand, Pakistan, Bangladesh, Myanmar, Vietnam, the Philippines, Cambodia, Malaysia, Java, Egypt, Surinam, Trinidad, and Florida [1-45, 49, 107, 293-351]. Bael occurs in India since 800 B.C. as a wild crop species according to the historical reports. Bael is a subtropical species, although it can grow well in tropical environments [1-45, 49, 107, 293-351]. Bael can thrive well in high altitude as high as 1,200 m and withstand without any significant growth retardation at 50°C and −7°C [1-49, 107, 293-331]. In the prolonged droughts, fruiting may cease, but the plant can survive with shallow soil moisture. Bael trees generally required well-drained soil (pH: 5–8), but many studies and grower-reports suggest that it can grow equally well in alkaline, stony, and shallow soils [1- 49-107, 293]. Bael grows well and produces bountiful harvests of fruits in the "oolitic-limestone" soils of southern Florida [1-49, 107, 293]. In India and Sri Lanka, bael is famous as a fruit species, which can grow in very tough soils where other trees and other crops cannot grow [1-49-107, 293]. The tree is aromatic, and all the parts of Bael are medicinally important [1-49-107]. Fruits, leaves, bark, roots, and seeds are used in *Ayurvedic* and folk medicine systems to treat various ailments [1-49-107, 293].

Bael is an indigenous tree of India and also found growing in neighboring countries namely Nepal, Sri Lanka, Malaysia Pakistan, Bangladesh, Myanmar, Thailand and most of the South East Asian countries. Because of its status as sacred tree, it is also grown in north Malaya, the dry area of Java and to a limited extent in northern Luzol of Philippines and gardens of Egypt, Surinam and Thailand[1-49-107, 293]. In India, it is distributed throughout the country, but concentrated area under bael is in eastern parts of the Gangetic plains and nearby areas particularly in Uttar Pradesh, Karnataka, Uttaranchal, Maharashtra, Kerala, Tamilnadu, Andhra Pradesh, Bihar, Punjab, Madhya Pradesh, Chhatisgarh, Jharkhand, West Bengal, Punjab and Odisha[1-49-107, 293]. In Gujarat, bael trees are found growing naturally in the forest with great diversity[1-49-107, 293]. Most of the genotypes available in forest areas of Gujarat having small size fruits, but the plants growing in temple promise or in courtyard of house having big size fruits were brought by travelers, saints, pilgrims from north India[1-49-107, 293].

According to the report by Singh et al., (2018) [300-351], there are no systematic plantations of bael trees in India, now some systematic orchards of improved varieties are being established in the States of Rajasthan, Uttar Pradesh, Punjab and Gujarat [300]. Therefore, exact data on acreage and production is not available. Generally, the bael plantations are made as boundary plants, premises of temples or in home gardens [300-351]. Some seedling plantations are available in natural forest areas [300-351]. However, in recent years, concerted efforts have been made for collection of elite genotypes of bael from all over the country, their evaluation and establishment of germplasm block at ICAR Institutes/ Regional stations and State Agricultural Universities, India [300-351]. Some progressive farmers of Rajasthan, Uttar Pradesh, Madhya Pradesh, Punjab and Gujarat have started planting bael on large scale in the form of orchard or as boundary plantation [300-331]. As an estimate, about 1000 ha area is under plantation of improved variety of bael in India with about 10,000 tones of fruit production [300-331].

3. Bael Tree: Ethnobotany and Products

Bael tree possesses many medicinal values and therefore, used as an ingredient in *Ayurvedic* herbal medical preparations [1-49-107, 293]. Bael (*Aegle marmelos* L. Corrˆea) is an economically valuable tree species in South Asia [1, 49, 107]. *Aegle marmelos* has been widely utilized in traditional medicinal systems [1, 49, 107]. It has been reported to contain numerous phytochemical compounds such as polyphenol/phenolic compounds, carotenoids, alkaloids, pectin, flavonoids, tannins, coumarins, and terpenoids [1, 49, 107-130]. Similarly, various bioactive compounds from these groups have been isolated and identified [1- 49-107, 293]. These phytochemicals include various compounds, e.g., alkaloids, flavonoids, and phenolic acids (protocatechuic acid, gallic, and ellagic acid) [1-49- 107]. Despite having high nutritional and pharmacological value, research related to molecular mechanisms of bael fruit is still limited, and clinical trials are needed to ensure its safety as a product in the food and pharmaceutical industries [1- 49-107, 293]. The fruits, bark, leaves, seeds, and roots of bael contain bioactive compounds such as coumarin, xanthotoxol, imperatorin, aegeline, and marmeline [1- 49-107, 293]. These compounds can provide antidiabetic, anticancerous, antifertility, antimicrobial, immunogenic, and insecticidal activities [1- 49-107, 293]. Bael seeds possess a unique fatty acid (12-hydroxyoctadec-cis- 9-enoic acid or ricinoleic acid), a convertible item into biodiesel [1- 49-107, 293]. The processing of bael fruit also produced many waste materials such as seeds, fibers, peel, etc. which also contain many bioactive and pharmaceutical compounds [1- 49-107, 293]. The fruit pulp extract of bael has been also an important study area for its pharmacological activities, including antidiarrheal, antioxidant, antidiabetic, hepatoprotective, radioprotective, anticancer, and antiulcer properties [1- 49-107, 293]. The bael fruit can be used widely as powder, wine, preserve, jam, and juice, which can be very effective for patients with diabetes, oral-gastric ulcers, and cancer [1- 49-107, 293].

Various clinical experiments have been undertaken to guarantee that the bael fruit is safe to consume, but knowledge of its physiology and bioactivities in humans is limited [1-49-107, 293]. Despite its exceptional flavor, nutritional and medicinal properties, Bael remains an underutilized fruit with enormous potential to be used in the functional food market [1- 49-107, 293]. Bael being a seasonal fruit cannot be used throughout the year [1- 49-74]. Therefore, it can be processed into making different products like juice, beverages, candies, jams, and tea adding economic value to the end product [1- 49-107, 293]. Moreover, the hard shell, the sticky texture, and numerous seeds in the fruit make it difficult to eat which could be the reason that it is not as popular as other table fruits [1- 49-107, 293]. So, further processing is needed for the easy consumption of the fruit, which can be developed as a functional food product [1- 49-120, 293]. The ripen bael fruits are popular among people because of the delicious fruit pulp, which is ideal for making jam, syrup, and pudding [1- 49-107, 293].

4. Bael Tree: Botany and Morphology

A. marmelos, native to Northern India, are also widely dispersed over the Indian Peninsula, Burma, Bangladesh, Ceylon, Thailand and Indo–China [1-14, 293]. The size and the architecture of the bael tree are highly variable depending on the soil and climatic factors [1-49-100]. However, the essential botanical features remain constant regardless of the climatic factors. Bael tree is deciduous, and the crown is compact or dense, with no weeping branches [49, 293]. The medium-sized, slow-growing *A. marmelos* tree can grow up to 12–15 meters [1-49, 107]. It spreads with spiky branches, has a small trunk, thick, and soft peeling bark [1-14, 49, 293]. Usually, gum-like sap is secreting out from the wounds [49]. Initially, the sap secretions appear as long thick threads and later become dried up long solid crystals [49]. Fractured branches, a transparent, viscous liquid that resembles gum arabic, oozes out, hangs down in long strands, and gradually solidifies [1-49]. It starts tasting sweet but soon becomes unpleasant to the throat [1-14-107-293]. From an agricultural standpoint, growers must prune and manage the tree to a convenient size and maintain a suitable number of branches for maximum fruit production [49-107, 296-351]. Sometimes the lower limbs are drooping [49-107, 296-351]. The tree is tough and widely adaptable to adverse soil and climatic conditions [49]. The bael tree can grow up to 10m or higher with medium or large sizes with numerous branches [1-49]. The fruits mainly occur in the periphery of the canopy [49]. The trunk is short and thick with narrow oval shape ends [49]. The wood is rigid and slow-growing [49]. The young wood has a central pith [49]. Under natural habitats, the trees are smaller and irregular [49-107, 296-351]. The trees possess short, sturdy, non-spiny, or piercing-spiny branches [49]. The straight shaped spines are 3 cm in length when fully grown and originate from the leaves axis [49]. The trees bark is flacking, bluish-grey, soft, and contains irregular furrows on the younger branches [49]. The trees possess dimorphic twigs [49]. The regular twigs have 3–5 cm long internodes with a leaf at each node and one to two spines [49]. The other type of twigs, the foliage spurs, are arising on the primary branches [49]. The foliage spurs are shorter than usual twigs (1–3 cm) with copious diminutive internodes [49]. In foliage spurs, each node has a leaf [49]. However, the spine is absent [49]. The further twigs produced on the first-year twigs have glabrous surfaces, whereas the new twigs produced in the second- and third-year twigs have striated surfaces [49]. The prickles are generally absent on the stem, or if present, they are not persistent [49]. The suckers originate from the main bael trees when they grow up to a sufficient height and crown width [1-49]. The young suckers have the stout and sharpest spines to protect the suckers from the herbivores [1-49].

A wide range of genetic variability with respect to plant morphology have been observed in different bael accessions [293-351]. Considerable variations with respect to shape, margin, base and apex of leaf have been reported [293-351]. The leaves are alternate, single, or compound with one or occasionally two pairs of shortly stalked opposite leaflets [49]. The leaf petioles are glabrous, long, and with no wings absent [49]. The leaves are trifoliate and aromatic, mostly when chopped [49]. The leaves are deciduous, alternate, and borne as single or compound. In compound leaves, the leaflets appear in 2–5 oval-ovate or ovate shaped, pointed, and frivolously toothed leaflets (i.e., shallowly serratocrenate) [49]. A leaflet is 4–10 cm long and 2–5 cm wide [49]. The leaflets are thin, and their midribs are prominent from the beneath [49]. The terminal leaflet has a longer petiole [49]. The new foliage emerging after a dormant or a reproductive phase is glossy in appearance and pink or burgundy in color [49].

The bael fruits exhibit a diverse range of shape from round, oval, pyriform, or oblong and are 5–25 cm in diameter, also the seeds can be from 10 to 50 in number having flat-oblong shape and 1 cm long [49, 293]. The fruits have a hard, smooth woody shell (i.e., pericarp), a soft rind at immature stages (Figure-1) [49, 293]. The crust is gray-green at early stages, turns yellowish or orange at the ripening stage and becomes very hard and orange-red when dried [49]. The aromatic tiny oil glands appear as dots on the fruit shell [1-49]. Inside the fruit, there is a hard central core with 8 to 20 indistinctly apparent triangular segments with thin, dark-orange walls [49]. They contain aromatic, pale-orange, pasty, sweet, resinous, astringent pulp with a pleasing aroma [49]. The fruits are slow ripening, and they could take one year for full ripening [49]. The ripen fruit flesh is yellowish-orange in color, mucilage, fibrous, and aromatic [1-49](Figure-2, 3). The seeds embed in a pulp-adhesive transparent mucilage which solidified like a glassy crystal when dried [49, 293].

The number of seeds varies from 10–50 [49]. A seed is 1 cm long with a flattened-oblong shape [49]. The seeds also contain woolly hairs [49]. The seeds encase in a sack of sticky transparent mucilage or gummy substance that solidifies after drying [49]. The testa is white. The embryo has large cotyledons with a short superior radicle [49]. There is no endosperm [49]. Some seeds can get aborted during the development [49]. The seeds undergo no dormancy and germinate within 2-3 weeks [49]. The seedlings are ready for transplanting within 2-3 months [49]. The seedlings used as rootstocks are ready by the next year to produce grafted/budded plants [49]. Seedling tree requires 7-8 years to produce flower while grafted one starts flowering at the age of 3 years [293-351].

Figure 1 Bael fruit at early immature stage of growth

Figure 2 Matured Bael fruits ready to harvest

Figure 3 Sun dried Bael fruits pulp used as a medicine or energy drink

Bael tree flowers in April-June, fruit setting takes place by the end of May and continues till July in India [293-351]. Time of flowering may vary according to agro-climatic condition and genetic makeup of varieties [293-351]. The flowers are fragrant and form 4–7 clusters along the new branches [1-49]. A flower has four or five recurved and fleshy petals (the exterior color is green, and the inside color is yellow) with 50 or more greenish-yellow stamens [49]. The flower is 2 cm wide, sweet-scented, stalked, lax, erect, and occurred axillary or terminal cymes [49]. The calyx is shallow, with five short, broad teeth, and pubescent outside [49]. The stigma is capitate, and the ovary is oblong-ovoid and slightly tapering into the thick short style [49]. The bisexual flowers are born in clusters and they are greenish. white, axillary or terminal cymes [293-351]. Petals are oblong oval, 4 or 5 in numbers and pale greenish white in colour [293-351]. Stamens are numerous, hypogynous with short filaments [293-351]. Ovary is oblong-ovoid, slightly tapering in to the thick, short style which is thickened upward; stigma capitate, deciduous multi celled (8-20), arranged in a circle with numerous ovules (1-5) in each cell [293-351]. The style is open type having variable number of stylar canals depending on the number of carpels. The stigma is classified as wet stigma as it is covered by a sticky secretion at the time of pollination [293-351].

Flower bud emergence, flowering duration, time of anthesis, dehiscence of anther, stigma receptivity and pollen viability vary according to variety and locality [49, 293-351]. Size and shape of floral organs in terms of bud size, flower size, petal size etc. of the varieties evaluated at CHES, Godhra, Gujarat, India under rainfed condition of semi-arid ecosystem [293-351]. Floral biology of bael varieties and main pollinating agents has been reported by Singh et al., (2018) [300]. The nectar secreting disc found beneath the ovary is main source of attraction for the insects [293-351]. Singhal et al. (2011) [326] reported that the diploid and tetraploid trees showed normal meiosis and high pollen fertility [293-331]. Phenological events which included leaf fall, leaf emergence and floral bud break, flowering and fruiting are nearly the same in wild and cultivated trees [293-351]. Natural pollen transfer in the species was highly efficient [293-351]. Levels of fruit set following open pollination were quite high and it is reduced considerably by following hand pollination probably due to injury caused to stigma during emasculation [293-351]. In spite of synchronous nature of anther dehiscence and stigmatic receptivity, selfing in a flower is avoided due to herkogamy [293-351].

5. Bael Cultivation methods

5.1. Propagation by seeds

The seeds are the primary planting material of bael [49]. The nurseries must be established with the fully grown seeds collected from the mature fruits [49]. Bael is a great option for areas with scarce water supplies because it is high in vitamins and minerals [49]. The seedlings must be transplanted in the adequately prepared fields for better establishment and success rates [49]. However, the seeds often showed reduced germination rates, and the seedlings often display segregation of traits, especially regarding the fruit traits [49]. According to Singh et al., [293-351], traditionally bael was propagated by seeds [293-351]. However, there is an inherent limitation associated with the seedling progenies and generally they are not true to type [293-351]. Therefore, seed propagation is limited for the raising of rootstock [49, 287, 274-288-351].

The bael seed has no dormancy [293-351]. According to Singh et al., [293-351], fresh seeds can be sown 2-3 cm deep in the nursery within 10-15 days after extraction [293-351]. The fresh bael seeds germinate in 8-15 days after sowing during summer [293-351]. Since, bael belongs to recalcitrant category, the seeds cannot be stored for longer periods under normal storage conditions [293-351]. The seedlings become ready for transplanting in spring or next Monsoon in India [293-351]. If the seeds are sown too deep, seedling emergence is delayed and there may be chance of rotting due to poor aeration [293-351]. According to Singh et al., [293-351], the orchard raised by seedlings is not true to type and exhibits variability [293-351]. Sometimes seeds germinate while fruits are kept on tree for longer duration after ripening of tree (vivipary) [293-351]. To prevent the losses due to ‘damping off’ at nursery stage, seed treatment is essential [293-351]. According to Singh et al., [293-351], seed treatment with Thiram or Captan (1:400) can be done effectively [293-351]. Seed germination and seedling growth were influenced by sodic soils [293-351]. Delayed and poor seed germination and reduced plant growth were observed in response to increased sodicity [293-351]. Sodicity adversely affects the seed germination and seedling growth [293-351].

According to Singh et al., [293-351], the freshly extracted seeds are used for sowing for raising root stocks in the nursery [293-351], However, if required these can be stored up to 132 days with proper treatment [293-351], For storage, three days after extraction, the seeds should be treated with fungicides such as Thiram or Captan (1: 400) and stored in alkathene bags at room temperature [293-351]. For better germination, higher survival and establishment, well rotten FYM should be mixed with the soil before sowing of seeds in polythene bags nursery raising [293-351]. After fungicidal treatment, seeds can be sown in 2 cm depth in the nursery within 10-15 days of extraction in raised beds [293-351]. Seeds may also be sown in polythene bags with ratio of soil, FYM and sand (2:1:1) as it facilitates an easy handling of rootstocks and grafted plants [293-351]. According to Singh et al., [293-351], young seedlings should be protected from frost during winter under arid ecosystem and from intense radiation in rainfed semi-arid condition [293-351]. Performance of bael with respect to seed germination and plant growth was observed satisfactory in sodic soils up to 29.0 ESP without application of any chemical amendments [293-351]. The foliar sprays of plant biological regulators *i.e.* gibberellic acid (GA3) and IBA (both at 250, 500, 750 and 1000 ppm), and potassium nitrate (250, 500, 750 and 1000 ppm) improves seedling vigour by means of improved growth of stem and roots [293-351]. According to Singh et al., [293-351], utmost care should be taken while selection of the elite mother plants of bael cultivars [293-351]. For selecting mother plants of bael, following basic characteristics needs to be considered –

- Plants should be consistently high yielding [293-351].
- Quality of fruit should be very good with all desired traits [293-351].

- Plant should be free from diseases and pests
- It should be in full bearing stage [293-351].

According to Singh et al., [293-351], under dry land condition, leaf senescence initiated from January and leaf fall starts from March in early varieties while March–April in late varieties [293-351]. Leaf initiation starts after 15-25 days after leaf fall which varied in different varieties [293-351]. It is very difficult to get scion shoot during May-June under dryland conditions, some thumb size branches of mother plant are cut during March in India [293-351]. Number of new shoots emerges below the cut portion [293-351]. These shoots are used for budding purposes [293-351]. According to Singh et al., [293-351], for accelerated growth of shoot, plants should be irrigated after one week after cutting of branches, whereas for softwood grafting one season old shoots are used when plant starts putting forth new leaves [293-351]. Under dry land condition, mother plant should be irrigated one day before separation of scion shoots for budding for better success and survival [293-351].

5.2. Vegetative propagation techniques

True to type planting materials can be produced through vegetative means only [287, 293-351]. Among the vegetative propagation techniques; budding, grafting, layering and root suckers were common methods of multiplication of bael [49, 287, 274-288-351]. According to Singh et al., [293-351], now-a-days, patch budding and soft wood grafting is being adopted commercially for multiplication of bael [49, 287, 274-288-351]. Therefore, the superior bael trees must be propagated by using vegetative means such as budding, grafting, and in vitro micropropagation [49, 287, 274-288-351]. The four-week-old buds collected in the correct phenological stage could be budded onto two-year old health seedlings as rootstocks to obtain successful regeneration [49, 287]. The air-layering, root cuttings, and the separation of roots with shoots that appeared separately to the mother plants can also be used to propagate bael [49, 287, 293-351].

According to Singh et al., [293-351], the grafting is done to propagate the elite mother plants for cultivation [49]. Besides the selected mother plants, no standard cultivar produced through breeding is available for large-scale cultivation of bael [49]. The breeding is not conducted for bael mainly because it is a long-generation species, and the plant's reproductive biology is not well understood [49]. Cytogenetic studies have been conducted, and the ploidy level of *A. marmelos* could be diploid (2n = 18) or tetraploid (4n =6) with normal and remarkably high pollen fertility at each ploidy level [**49, 293]**. The large fruits are often correlated with the tetraploid genomes [49]. The phenological events such as leaf emergence, falling, flowering, and fruiting are the same for the wild and cultivated types [49]. Exceedingly, high open pollination is observed, and common pollination agents are insects and wind [49]. Fruiting is enhanced by insect pollinators such as honeybees [49]. However, propagation through seeds is lacking due to much lacks as ants and fungi damage seeds [49]. Therefore, vegetative propagation through agamospermy, coppices, and root suckers are prominent [49, 293].

According to Singh et al., [293-351], bud wood becomes available during the active growth period in rainy season [293-351]. The buds stick (1months old) with well swollen and recently matured buds (but still not open) are collected [293-351]. Immature and undeveloped buds from the upper part of the new shoots are not suitable. Similarly, over mature and inactive buds should not be used [293-351]. The active growth period is indicated by easy and clear separation of the bark from the wood of scion sticks [293-351]. After collection, the bud wood is often stored for some period or takes same time in transportation [293-351]. During this period, considerable loss of survivability may take place [293-351]. Bud woods retain good survival when kept under ventilated shade and wrapped in moist jute cloth [293-351].

According to Singh et al., [293-351], in case of patch budding, a healthy bud is selected from the axils of leaf [293-351]. Leaf blade is removed with the help of a sharp knife leaving petiole intact [293-351]. The upper cut is given about 1-1.5 cm above bud which goes downwards up to 1.0-1.5 cm below the bud without wood portion and then lower cut is given about 1.0 cm below the bud [293-351]. The similar rectangle incision is made on the rootstock by placing the bud on the root stocks to mark the exact size of the bud on them [293-351]. After removing the bark of root stock, the bud is placed at the juncture [293-351]. The bud is pressed by hand to remove open space if any and tied tightly except the place of bud with white polythene strip (200 gauge thickness and 2 cm wide) [293-351]. In case, the cuts on rootstock are wider, at least one side bark of scion and stock must be matched properly [293-351]. The rootstock is cut about 10 cm above the bud to facilitate bud to sprout [293-351]. After union, the top of the rootstock is cut a little above the bud union and polythene strips are removed carefully [293-351]. Time of budding influences the survival of plant in the different varieties [293-351].

According to Singh et al., [293-351, patch budding is very useful for transportation of sapling to distant places [293-351]. Patch budding and softwood grafting was found successful when performed in the month of May- June (before onset of rain) under rainfed semi-arid conditions of Gujarat, India [293-351]. In India, patch, forkert and shield methods of budding are generally employed for multiplication of bael [293-351]. The plants propagated through *in- situ* patch budding in the month of May and June (before onset of rain) recorded 94.14% and 90.82%, respectively [293-351]. For getting better success and survival of plant, patch budding may be practised in the month of May-June for multiplication of bael genotypes for establishment of orchards under dry land conditions [293-351]. According to Singh et al., [293-351], budding in bael in June and budding in July from one month old scion gave 80 per cent success. Patch budding is an ideal method of bael multiplication [293-351].

According to Singh et al., [293-351], Bael can be multiplied through inarching, cutting, root sucker, layering and stooling, but the success and survival is comparatively less than budding and grafting [293-351]. For uniform production of rootstocks, stooling with application of 5000 ppm IBA can be applied for better success [293-351]. However, success after separation with mother plant is less (30%) under dry land conditions [293-351].

6. *In vitro* Micropropagation of Bael

The beauty of plant tissue culture lies in the culture of small piece of plant material (explant) on a defined nutrient medium to produce large number of plantlets or clones within a limited time in a continuous process, irrespective of season, and weather on year round basis [176-273-292]. Plant tissue culture can be used for a wide range of purposes with various applications in research and industry [176-273]. Plant tissue culture is also defined as an *in vitro* aseptic culture of cells, tissues, organs or whole plant under controlled defined nutritional medium conditions often to produce the clones of plants [176-273]. The resulting clones are true to type of selected genotypes and used for the large scale plant multiplication [176-273]. Micropropagation using tissue culture techniques is often hailed as an effcient strategy for forest tree crop improvement, regeneration of endangered plant species, for introuding a desired gene of intetest into plants via genetic transformation, production of disease free resistant varities, and callus based nanoparticle synthesis [176-273]. Elite mother plants can be selected, mass propagated using tissue culture, and grown on a wide-scale [176-273-292]. Tissue culture technique offers several advantages over plant propagation under natural conditions. It is a rapid procedure as thousands of seedlings can be produced from small fragments (explants) of plants in a short period of time in contrast to conventionally propagated flora [176-273]. Plant *in vitro* propagation using tissue culture techniques have been exploited for the commercialization of ornamental plants (orchids), vegetable and fruit plants (papaya, mango, and grape), medicinal, woody, and conifers with economically important [176-273]. Plant tissue culture is an important biotechnological technique solving the problems of modern agricultural providing solutions to major food security issues [176-273-292]. Large-scale plant tissue culture has been shown to be an appealing alternative approach to traditional plantation methods since it provides a regulated supply of defined nutrients (including carbohydrate) independent of plant availability [176-273-292].

There are few reports of in vitro micropropagation of Bael has been reported [274--286. 288-292]. The tissue culture requirements for the shooting of bael are explained by Surana and other workers [274-292]. Using 8–10 mm sized explants of auxiliary and terminal buds taken from elite bael trees were tissue cultured by Arya and Shekhawat [275]. Juvenile buds must be taken at the vegetative stage of the tree [276-292] to improve the success rate, and 100 mg/L ascorbic acid and 150 mg/L citric acid were used in combination to avoid browning [276]. The Murashige and Skoog (MS) medium with 5 mg/l, 2-4D, and NAA was used for the induction of callus [276, 277]. Kinetin (1 mg/l) and BAP (0.5 mg/l) were used for the induction of rooting [276, 277]. High-frequency plantlet regeneration was achieved by using cotyledonary nodes of bael [276]. Nayak et al., (2007) [277-281], explained the precise requirements of plant growth regulators for efficient shooting and rooting of bael, and the number of workers tried with different explants [274–286, 288-292]. *In vitro* clonal propagation of bael was optimized through improved auxiliary branching of the mother plant, and the true-to-type of the daughter plants was confirmed from DNA fingerprinting [274–283].

A protocol for micropropagation of bael [*Aegle marmelos* (L.) Corr.] was developed by Gupta et al., (2008) [288]. Bael (family *Rutaceae*) is an indigenous medicinally important fruit of India and few in vitro micropropagation methods have been reported [274-288-292]. The nodal explants of 30 year old tree were used to initiate cultures [274-288-292]. Two cytokinins, viz., 6–benzylaminopurine (BAP) and Kinetin (Kn) were used in varied concentration (0.1-2 mg/l) for shoot multiplication [288]. BAP (2 mg/l) was found better than KN, where a 3-fold increase in the number of shoots was recorded in 4 weeks [288]. A synergistic influence of cytokinin and auxin was also observed in this study [288]. A combination of 0.5 mg/l BAP and 0.1 mg/l IAA induced the formation of maximum number (4.5) of shoots (2.5 cm) [288]. For rooting of in vitro shoots, different auxins, namely, NAA, IAA and IBA (0.1-2 mg/l) were tested [288]. IAA (0.01 mg/l) was found better than NAA and IBA [288]. It was concluded that elite cultivars of bael can be micropropagated, without undergoing callus phase, using the BAP (0.5 mg/l) plus IAA (0.1 mg/l) for shoot multiplication and IAA (0.1 mg/l) for rooting, to produce true–to–type *in vitro* plants [288]. The *in vitro* raised plantlets were acclimatized with 30% success [288].

7. Phytochemistry of Bael

Bail *(Aagle marmelos*) *(L.)* Correa has served as an economically viable culinary and medicinal herb for over 5000 years, making it a highly significant indigenous plant to the Indian subcontinent [1-107]. Bael fruit is one of several plants that had extensive therapeutic applications in Indian medicine since antiquity [1-107]. The pulp of the bael fruit is used to make desserts like murabba, puddings, and juice due to its medicinal properties [1-107]. The fruits are useful for dietetic purposes [1-107-140]. Moreover, it contains a high amount of **riboflavin** [1-107]. Although Bael is indigenous to northern India, it is widely cultivated in Thailand, China, Bangladesh, Pakistan, Sri Lanka, and Burma, among other places of India [107]. Every part of Bael tree, including the root, bark, leaf, flower, and fruit, can be used as medicine [1-107]. The wild form of fruit is smaller in size than the cultivated variant and is also less popular for commercial use [107]. Numerous plant compounds, such as coumarins, flavonoids, terpenoids, and alkaloids, have been discovered in Bael fruit pulp [1-107-150]. Methanol and water are the best solvents for extracting the metabolites of this plant, followed by ethanol [1-107-150]. High concentrations of coumarins, such as marmelosin and luvangetin, which have antihelminthic, antiulcer, antibacterial, and antispasmodic properties, are found in plants of family *Rutaceae* [107]. The *Rutaceae* family produces physiologically potent essential oils, which are well-known and present in many of the family members, ornamental, culinary plants, including orange, lemon, lime, grapes, and satinwood [107]. The phytochemicals present in the plant account for the flavor and color of the fruit [1-107-130]. More than that, they have been extensively studied for their antioxidant function as well as potential therapeutic benefits such as maintaining inflammation balance, reducing the risk of cancer, working against different pathogenic organisms, promoting eye health, cardiovascular, neurocognitive, and bone health in humans [1-107-130].

On the basis of literature survey, some of the key phytochemicals found in *A. marmelos* include: Alkaloids are nitrogen-containing compounds that are found in many plants and are known for their pharmacological activity [1- 107-175]. Several alkaloids have been identified in the leaves and roots of *A. marmelos*, including marmesin, marmelosin, and aegeline [1- 107-175]. Tannins are a group of compounds that are widely distributed in the plant kingdom and are known for their astringent and antioxidant properties [1- 107-175]. The fruit of *A. marmelos* contains high levels of tannins, which have been shown to have strong antioxidant and anti-inflammatory activities [1- 107-175]. Flavonoids are a group of compounds that are widely distributed in the plant kingdom and are known for their anti-inflammatory, anti-cancer, and antioxidant activities [1- 107-175]. Flavonoids have been identified in the leaves and roots of *A. marmelos*. Some of these compounds have been shown to have antinociceptive (pain-relieving) and antipyretic (fever-reducing) activities [1- 107-175]. Terpenoids are a group of compounds that are widely distributed in the plant kingdom and are known for their medicinal properties [1- 107-175]. Terpenoids have been identified in *A. marmelos*, and some of these compounds have been shown to have antifungal and antibacterial activities [1- 107-175]. Saponins are a group of compounds that are widely distributed in the plant kingdom and are known for their foaming and emulsifying properties [1- 107-175]. Saponins have been identified in the fruit and leaves of *A. marmelos*, and some of these compounds have been shown to have antinociceptive and anti-inflammatory activities [1- 107-175]. Glycosides are a group of compounds that are widely distributed in the plant kingdom and are known for their medicinal properties [1-107-175]. Glycosides have been identified in the fruit and leaves of *A. marmelos*, and some of these compounds have been shown to have antinociceptive and anti-inflammatory activities [1- 107-175].

The main constitution of *A. marmelos* nutrients is fatty acids, vitamins, glucose, amino acids, and minerals [1- 107]. It can prevent color loss and rancidity because it contains a valuable amount of vitamin A (55 mg), vitamin C (8 mg), and vitamin B, which can act as a potential antioxidant agent [1- 107-175]. Bael fruits have been characterized by high moisture content of nearly 61% [1- 107]. Bael fruits have high nutritional composition as it contains minerals (phosphorus, potassium, calcium, magnesium, iron, copper, zinc, chromium), fat, fiber (hemicellulose, cellulose, lignin, pectin), protein, carbohydrate, vitamins (B1, B2, B3, C), amino acids (threonine, valine, methionine, isoleucine, leucine, lysine), and fatty acids [1-107-175]. Bael fruit is a rich source of a variety of nutrients since it includes a number of vitamins and minerals [1-107-150]. Because it is abundant in vitamins, including vitamin A, vitamin B complex, and vitamin C [1-107]. In another study, bael fruit pulp was reported for numerous vitamin concentrations, including vitamin B1 (0.16 mg%), vitamin C (73.2 mg%), vitamin B2 (0.18 mg%), and vitamin B3 (0.87 mg%) [1-107-130]. According to vitamin analysis, the bael is recognized as a suitable source of ascorbic acid and several vitamins of the B group [1-107-130]. Vitamin C concentration was found to be 73.2 mg/100 g, which was significantly higher than that found in Thai bael fruit (26.17 mg/100 g) [1-107-130]. The bael fruit growing under Indian conditions have found vitamin C concentration of 40 mg/100 g [1-107-130]. Vitamin C levels in unripe bael fruit are relatively high (620 mg/100 g) [1-107-130]. Furthermore, vitamin C (8–60 mg), riboflavin (1.19 mg), vitamin A (55 mg), thiamine (0.13 mg), potassium (600 mg), calcium (85 mg), niacin (1.1 mg), and phosphorus (50 mg) are all known to be present in bael fruit [1-107-130].

Phytochemical profiling of bael fruit showed that it also contains many useful bioactive compounds and phytochemicals, which include polyphenols, coumarins (alloimperatorin, zanthotoxol, imperatorin, xanthotoxol, isoimperatorin, umbelliferone, marmelide, scopoletin, marmelosin, scopolentin, marmesin, psoralen-a, scoparone, marmin, methyl ether, psoralen); tannins (4,7,8-trimethoxyfuroquinoline, skimminianine); Alkaloids (aegelenine, halfordinol, aegeline, ethyl cinnamate, aegelinosides A, ethyl cinnamamide, aegelinosides B, dictamine, fragrine); phenolic acids (gallic acids, p-coumaric acid, 2,3-dihydroxy benzoic acid, vanillic acid, chlorogenic acid); organic acids; flavonoids (rutin); tocopherols; and carotenes [1-107-175]. Further, bael fruit has been discovered to work as an antioxidant, thus preventing rancidity and color loss [1-107-130]. The minerals reported from the part of bael fruit include calcium, iron, phosphorus, potassium, and salts. The unripe fruit is more beneficial for medicinal purposes than ripe fruit [1-107-130]. It includes mineral (1.9%), potassium (610 mg), phosphorus (52 mg), calcium (80 mg), fiber (2.9%), carotene (55 mg) and protein (1.6%), in fruit juice [1-107-130]. Another study Fruit pulp of *A. marmelos* comprises of calcium (80 mg), mineral content (1.7%), phosphorous (52 mg), copper (0.21 mg), potassium (610 mg), and iron (0.60 mg/100 g). The calorific value of bael fruit (88 cal/100 g) is higher than that of mango (36 cal/100 g), apple (64 cal/100 g), and guava (59 cal/100 g) [1- 107]. In a separate study, it was found that it is also high in vitamins such as riboflavin (1190–1200 mg/100 g), vitamin B1 (0.13 mg), vitamin A (55 mg), vitamin B2 (1200 mg), ascorbic acid (8 mg/100 g), vitamin C (8 mg) and thiamine (0.13 mg) [1- 107].

The carbohydrate and total sugar content of bael fruit were estimated to be 36.80–41.70% and 3.08–6.94%, respectively [1-107-130]. Another study estimated the important constituents of bael fruit during various ripening stages, the fructose, glucose, and sucrose content in bael fruit was found to be in range of 1.01–1.55%, 1.15–1.88%, and 2.45–12.01%, respectively [1-107-130]. The starch content was also estimated and found to be 3.6 g/100 g in bael fruit pulp [1-107-130]. A recent study confirmed that bael fruit contain 31.8% of carbohydrate content [1-107-130]. Furthermore, bael fruit was investigated for protein content, and showed 7.52–8.81% protein in fruit pulp at different stages of development [1-107-130-175]. A total of 4.35% of the protein was estimated in powdered bael fruit pulp [1-107-130]. A study discovered that the pulp of the bael fruit contains a number of restricted amino acids, with lysine having the highest amino acid score of 47, followed by valine (52), threonine (53), and isoleucine (97) [1-107-130]. Different studies indicated that the edible portion of *A. marmelos* fruit comprises 0.6% fat and that the fruit includes a significant number of proteins and little fat [1-107-130]. A recent study confirmed that *A. marmelos* seeds contain 34.4% oil, which is utilized in aromatherapy, cosmetics, and compressors [1-107-130].

Anti-inflammatory, antibacterial, antiseptic, antioxidant, carminative, astringent, cytophylactic, and disinfectant properties can all be found in *A. marmelos* oil [1-107-130]. *A. marmelos* is reported to contain chemical composition like alkaloids (aegeline, fragrine, aegelenine), coumarins (Marmin, Marmelide, Psoralen, Imperatonin), and terpenoids (cineol, Caryophyllene), etc [1-107-130]. The pulp of the bael fruit is rich in bioactive substances such as carotenoids, phenolics, alkaloids, pectins, tannins, coumarins, flavonoids, and terpenoids, according to studies [1-107-130]. Methanol and water are the best solvents for extracting the metabolites of this plant, followed by ethanol [1-107-130]. More than 100 different phytochemicals have been identified from various parts of Bael tree [1-107-130]. Alkaloids, terpenoids, coumarins, phenolic acids, flavonoids, tannins, carotenoids, amino acids, organic acids, and fatty acids are the major constituents [1-107-130]. The phytochemicals present in Bael are dependent on the fruit's maturity [1-107-130]. Like compound tannin, they are present in the unripe fruit, whereas marmelosin, auraptene, and marmelide are present in the fully ripe fruit [1-107-130]. Besides fruits, the other parts of the plant, i.e., bark, leaves, roots, and seeds, are also rich in bioactive compounds [1-107-175]. For example, fagarine is present in mature bark, and compound marmin and skimmianine are in immature bark [1-107-130]. Similarly, citronellal, lupeol, aegelin, eugenol, cineol etc. are present in the plant's leaves, and luvangetin is isolated from the seeds of the Bael fruits [1-107-130].

Skimmianine, an alkaloid present in the leaves of the Bael plant, has been studied for various health benefits, which exhibit anticancer activity against ovarian cancer [1-16]. It has also shown antidiuretic, hypothermic, antipyretic, anticonvulsive, analgesic, hypnotic, and sedative effects in various experimental animal models [1-15]. Similarly, aegelin present in the leaf is a cardioactive compound that has an antihyperglycemic property [1-17]. Cineole and eugenol have potent antioxidant properties. Furthermore, eugenol shows antibacterial activity along with hepatoprotective activity against CCl_4-induced hepatic damage [18, 19]. According to Shoba and Thomas [19], tannin in unripe fruit has astringent properties and is also an excellent treatment for diarrhea. Marmelide present in the fruit is shown to be antiviral, inhibiting the early stage of the viral replicative cycle [20]. Similarly, marmin present in the bark is found to be effective against ulcers [1-107-130].

A. marmelos fruit have been reported to contain carotenoids, imparting yellow color to the fruit [1- 107-175]. One of the study reported and identified different carotenoid in fruit of *A. marmelos*, viz., α-carotene (42.76–1698.22 μg/100 g), β-carotene (51.67–153.43 μg/100 g), Ɣ-carotene (18.43–467.17 μg/100 g) and γ-carotene (43.74–45.03 μg/100 g) [1-107-175]. However, there are very few studies related to the determination of carotenoid content in bael fruit.

Bael fruit is also characterized by many phytochemical compounds such as alkaloids (Aegelenine, Halfordinol, Aegeline, Ethyl cinnamate, Aegelinosides A, Ethyl cinnamamide, Aegelinosides B, Dictamine, and Fragrine), terpenoids (Caryophyllene, Valencene, Cineol, Terpinolene, cis-Limonene oxide, P-cymene, cis-Linalool oxide, Methyl perilate, Cubedol, Isosylvestrene, Elemol, Myrcene, Epi-cubebal, Humulene, Hexanylhexanoate, Linalool, and Limonene), tannins and polysaccharides (such as galactose, L-rahaminose, and arabinose) have been reported/determined from bael fruit [1- 107-175]. Bael fruit is considered a rich source of imperatorin, marmesin, alloimperatorin, marmelide, methyl ether, scoparone xanthotoxol, umbelliferone, scopolentin, and psoralen [1- 107-175]. Marmenol has also been reported in bael fruit [1- 107-175]. Furthermore, bael fruit also contains marmelosin, umbeliferone, imperation, scoporone, alloimperatorin, marmelide, marmesin, impertonin, umbelliferine, skimmianine, scopoletin, methyl ether, psoralen, marmin, xanthotoxol and armelide in considerable amounts [1- 107-175]. It is also determined that the coumarins such as umbelliferone marmelosin and skimmianine are recognized as medicinally important active principle compounds of bael fruit [1- 107-175].

Polyphenolic compounds are very important plant constituent as it is responsible for antioxidant activity [1- 107-175]. One of the study confirmed that polyphenol content in bael fruit ranges from 5.21% to 5.99% [1- 107-175]. Furthermore, the amount of tannic acid varied from 2.81 to 4.84 g 100/g at different development stages [1- 107-175]. In addition, significant variation in marmelosin (415.75–737 μg/g) in bael powder was noticed at various maturity stages [1- 107-175]. In a study conducted on *A. marmelos*, different phenolic compounds such as chlorogenic acid, ferulic acid, ellagic acid, gallic acid, quercetin, and protocatechuic acid in amounts of 136.8, 98.3, 248.5, 873.6, 56.9, and 47.9 μg/g, respectively were characterized through LC-MS and LC-MS/MS scans and HPLC method [24]. From different samples of bael fruit, a total of five phenolic acids, namely chlorogenic acid, gallic acid, p-coumaric acid, vanillic acid, and 2,3-dihydroxybenzoic acid, were detected in microwave dried sample (BM), sun-dried sample (BS), hot air-dried sample (BH), and freeze-dried sample (BF) [24]. The authors reported that gallic acid was maximum in BP (617.17 ± 2.58 mg/100 g), 2,3-dihydroxybenzoic acid in BH (35.94 mg/100 g), chlorogenic acid (CGA) in BM (56.31 mg/100 g), p-Coumaric acid (p-CA) in (361.42 mg/100 g) and vanillic acid (VA) was maximum in BS (102.40 mg/100 g) [24]. On the other hand, rutin (flavonoid) was found highest in BM (59.90 mg/100 g) and lowest in BP (32.25 mg/100 g) [24]. Other studies conducted in the last few years have also confirmed the presence of flavonoids and phenolic acids in bael fruit extract/pulp [24]. On the basis of the results, it was concluded that amount/content of different compounds varies with the method of drying [24]. It was revealed that there are very limited studies related to the investigation and quantification of phytochemical compounds in bael fruit [1-24].

8. Pharmacology of Bael: Therapeutic studies

Being as strong antioxidants, the phytochemical and nutritional components are involved in a variety of biological processes, making it a potential food ingredient [1- 107-175]. On the basis of literature survey, various studies have shown many bioactivities of bael fruit, which includes anti-diarrheal, antioxidant, antidiabetic, hepatoprotective, radio protective, anticancer, and antiulcer activities showing a high potential in pharma products [1- 107-175]. The bael fruits in ripe form is considered as astringent, tonic, laxative, restorative, and good medicine for brain and heart [1- 107-175]. The unriped fruits of *A. marmelos* are in the treatment of dysentery, also diarrhea since it is an astringent, digestive and stomachic [1- 107-175]. Extensive studies showed that *A. marmelos* has antidiarrhoeal, antimicrobial, antiviral, anticancer, chemopreventive, antipyretic, ulcer healing, antigenotoxic, diuretic, antifertility, and antiinflammatory properties [1- 107-175]. The various components of bael are used for its medicinal properties, such as managing asthma, fractures, anemia, wound healing, high blood pressure, jaundice, swollen joints, diarrhoea, and issues with typhoid during pregnancy [1- 107-175]. Following are few confirmed pharmacological activities of Bael.

8.1. Antioxidant activity

Antioxidants protect the body against the side effects of free radicals, which are responsible for a number of health-related disorders such as heart disorders, high blood pressure, cancer, and diabetes [1- 107-175]. Antioxidants are organic complexes that can safely interplay with free radicals and stop the chain reaction before harming fundamental molecules [1- 107-175]. Free radicals are highly reactive molecular species containing one or more unpaired electrons [1, 74, 88]. They are generated from regular metabolism while using O2 to burn food for energy [1, 74, 88]. It is generally known that reactive oxygen species (ROS) play a role in developing several illnesses, including cancer and cardiovascular disease [1-74, 88]. Plants include antioxidants or polyphenols that can successfully neutralize these ROS and prevent the spread of disease [66]. Oxidative stress is produced during normal metabolic processes in the body and induced by various environmental and chemical factors, which causes the generation of various reactive free radicals and subsequent damage to macromolecules like DNA, proteins, and lipids [1- 107-175]. In comparison to standard - gallic acid (IC_{50} 1.1 ± 0.08 μM), marmelosin exhibited potent antioxidant activity with an IC_{50} of ~15.4 ± 0.32 μM in ethyl acetate extract of bael fruit [1- 107-175]. Marmelosin was discovered to have better antioxidant properties than standard gallic acid [74, 89]. In this investigation, the *A. marmelos* fruit decoction showed good antioxidant activity with an IC_{50} of 17.37 ± 2.71 mg/ml and 379.9 ± 28.28 mg AEAC/100 g for standard ascorbic acid [74, 84].

One of the study by Rajan et al., (2011) [50] confirmed that fruit (pulp) extract of bael showed great antioxidant potential [50]. The authors reported that both alcoholic and aqueous extract of fruit produced more (44.36%) or less (40.12%) DPPH anion radical scavenging activity at dose of 100 μg/mL with IC_{50} value for both aqueous and alcoholic extract equal to 92.648 μg/mL and 106.15 μg/mL respectively [1, 50]. While alcoholic and aqueous extract showed reducing power (Fe3+ to Fe2+) equal to 28.7% and 50.33% at 100 μg/mL, with IC_{50} value of 283.06 μg/mL and 158.99 μg/mL respectively [1, 50]. The ethanolic and aqueous fruit pulp extract exhibit substantial free radical scavenging activity, against NO (nitric oxide) with inhibition of 52.02% and 63.74% at 100 μg/mL and extract was also capable of scavenging H_2O_2 in a dose-dependent manner reaching from 73.77% (aqueous extract) to 69.0% (ethanolic extract) with IC_{50} equal to 56.53 μg/mL (aqueous extract) and 52.19 μg/mL (alcoholic extract) [50]. One of the study conducted by Wijewardana et al., [55] reported the scavenging activity (DPPH assay) of *A. marmelos* fruit powder ranged from 24.31% to 81.33% at concentration 200 to 1000 μg/mL of methanolic extract [55].

In another study conducted by Andleeb et al., (2021) [54], the methanolic extract of bael fruit was evaluated for its antioxidant activity via, DPPH and FRAP (ferric-reducing antioxidant power) assay [1, 54]. Experimental results confirmed that fruit extract showed IC_{50} value of 52.06 μg/mL DW and 59.32 μmol/g DW for DPPH and FRAP assay, respectively [1, 54]. Andleeb et al., (2021) [54] of the above-mentioned study also compared the reducing capacity of fruit extract with leaves extract of *A. marmelos [*54]. Experimental results showed that fruit extract showed higher scavenging activity as compared to the leaves ($p < 0.05$) (IC_{50} = 46.5 μmol/g DW) [1, 54]. A study conducted by Gupta et al., (2018) [14] on methanolic extract of unriped *A. marmelos* fruit showed that fruit extract is active against DPPH free radical scavenging, as evidenced by its IC_{50} equal to 62.59 μg/mL [1, 14]. According to the study conducted by Rahman and Parvin [3], the chloroform and aqueous extract of dry and ripe *A. marmelos* fruit showed significant free radical quenching activity (reducing ferric chloride), ranging from 88% to 65% at 5–0.15 μ/mL extract concentration [3]. On the basis of literature survey and based on the findings of the studies [3], it was determined that the antioxidant potential of *A. marmelos* may be associated with the phytochemicals present in fruit, such as phenols, flavonoids and tannins [1, 3]. The antioxidant activity of *A. marmelos* supports that fruit may be used as antioxidant agent to treat cellular damage caused due to free radicals and it can be used as adjuvant with other drugs to increase effectiveness [1, 3].

8.2. Diarrhea

Diarrhea is a common symptom of gastrointestinal infections and occurs mainly due to an imbalance of natural microflora of the gut by broad-spectrum antibiotics [1- 107-175]. The etiology of diarrhea has been widely studied in the past years, including pathogens involved in the same [1- 107-175]. An *in vitro* investigation was carried out to evaluate the antidiarrheal effect of *A. marmelos* [1- 107-175]. For this, the activity of ethanolic extract of dried *A. marmelos* fruit pulp was tested against pathogens, namely, *Shigella dysenteriae*, *S. boydii*, *S. flexneri*, and S. *sonnei* [1- 107-175]. From the findings, it was revealed that S. dysenteriae showed the minimum activity with a minimum inhibitory concentration (MIC) equal to 250 μg/mL and a minimum bactericidal concentration of 400 μg/mL [1, 40]. It was also concluded that ethanolic extract was found to be more effective at the lower end of the concentration tested (0.5–1.0 mg/mL) [40]. In another study, the antidiarrheal activity of *A. marmelos* (unripe fruit extract) was studied on castor oil-induced diarrhea in mice animal models at 400 mg/kg and 800 mg/kg BW [1, 41]. The authors reported that doses of *A. marmelos* ethanolic fruit extract significantly reduce ($p < 0.05$) a considerable number of wet feces produced due to treatment of mice with castor oil [1, 40]. The inhibition frequency of defecation by fruit extract at 400 mg/kg and 800 mg/kg was evaluated to be 67.44% and 70.93%, respectively [41]. Similarly, methanolic extract of *A. marmelos* fruit was tested on castor oil-induced diarrhea in the SD rat animal model [1, 52]. The results revealed that methanolic extract showed a 100% inhibition rate, except in the first hour (78.13%), against diarrhea in an animal model [1-52]. The authors reported that methanolic extract of *A. marmelos* ripe fruit inhibited diarrhea caused due to castor oil in mice animal models [1, 52]. Tannic acid (extracted from fruit *A. marmelos*) does not showed an anti-diarrheal effect but is more likely to act as vasorelaxant in mice, with a significant relaxant effect (EC_{50} = 0.1527 μM, 95% C.I., 0.005853–3.986) [1, 52]. From the previous studies conducted on *A. marmelos* for determining antidiarrheal activity, it was estimated that it could be due to active phytochemical compounds such as alkaloids, saponins, tannins, and flavonoids present in fruit extract [1, 52]. Therefore, further investigations are required to confirm the exact mechanism of anti-diarrheal activity shown by fruit extract of *A. marmelos* [1, 52-107].

8.3. Anticancer activity

The anticancer potential of *A. marmelos* fruit extract was investigated in different studies [1, 9]. On the basis of literature review and the study of Akhouri et al., (2020) [9] confirmed that treatment with fruit extract of *A. marmelos* resulted in a reduction in breast tumour volume ($p < 0.05$), involving a significant drop ($p < 0.0001$) in serum biomarkers such as serum malondialdehyde (MDA), TNF-α, and glucose levels [9]. After therapy with ethanolic fruit pulp extract, considerable ($p < 0.0001$) improvements in both liver and kidney serum biomarker values were detected [9]. The ethanolic fruit pulp extract of *A. marmelos* displays anti-proliferative activity by slowing the progression of breast cancer in a tested animal model (rat) [9]. Hepato-renal protection is also a benefit of the plant extract [9]. Therefore, fruit pulp extract of *A. marmelos* could be used as a new and safe anticancer therapy against breast cancer cell lines [9]. Natural phytochemical substances are being used in cancer chemoprevention as a new way to prevent, postpone, or cure cancer [1, 9 60-64]. At a concentration of 100 g/mL of aqueous fruit pulp extract of *A. marmelos*, the maximal MCF7 cell death was 66.51%, and the IC_{50} was 47.92 μg/mL [1, 65]. The anticancer activity was measured using the MTT test method, which revealed an IC_{50} value of 47.92 μg/mL [1, 65]. Another study of Moongkarndi et al., (2004) [66] reported the methanolic extract of the fruit to have a cytotoxic impact (in vitro) on the SKBR3 cell line (human breast cancer cells) in preclinical studies [66]. The IC_{50} was found to be 144.00 ± 1.21 μg/mL indicating the pulp as an anticancer agent [66]. In another development, investigations in Swiss albino mice have revealed that a methanolic fruit pulp extract of *A. marmelos* has strong preventive properties against DMBA-induced cutaneous papilloma genesis [1, 42]. Bael fruit also decreased the overall number of tumours, frequency of occurrence per animal, and tumour production, implying that it could be used as a chemo-preventive drug [1, 42]. The *A. marmelos* of methanol and acetone extract of cytotoxicity against HEp-2, MDA-MB-231, and Vero cells were investigated [74, 94-96]. The IC_{50} for the methanol extract of *A. marmelos* was 47.08 g/ml, whereas the IC_{50} for the acetone extract of *A. marmelos* was 79.62 g/ml, making HEp-2 cells more sensitive to it [74, 94-96]. Both extracts of *A. marmelos* are toxic to cancer cells [74, 94-96]. However, Vero cells can survived for 24 hours [74, 94, 95]. MTT assays on the human breast cancer cell line MCF-7 at various concentrations confirmed the *in vitro* anticancer activity [74, 94-96]. The flavonoids in fruit extracts act as a potential reducing agent and are reasonable for forming gold nanoparticles [74, 95]. The aqueous fruit pulp extract from *A. marmelos* caused the most excellent MCF7 cell death at 100 g/ml and the IC_{50} at 47.92 g/ml concentrations [74, 94-96]. In an *in-vivo* study conducted by Jagetia et al., (2005) [97], Swiss albino mice with Ehrlich ascites carcinoma received an intraperitoneal injection of a 400 mg/kg hydroalcoholic extract of *A. marmelos* [97]. This treatment has significantly increased median survival time up to 28 days after tumor inoculation compared with the saline-injected control group [97]. The *A. marmelos* fruit pulp's ethanolic extract has anti-proliferative effect by inhibiting the proliferation of breast cancers in a rat model [98]. Both the breast tumour volume ($p < 0.05$) and the different blood biomarkers ($p < 0.0001$) significantly decreased after *A. marmelos* treatment [74, 98].

8.4. Antimicrobial activity

According to **Monika** et al., (2023) **[74],** the antimicrobial activity of *A. marmelos* has been reported [**74].** *Candida albicans, Aspergillus niger, Aspergillus fumigatus*, and *Staphylococcus aureus* all had MIC (Minimum inhibitory concentrations) values of 19.5 g/ml, 39 g/ml, 625 g/ml, and 1.25 g/ml, respectively [**84].** When used against *Candida albicans* and *Aspergillus niger*, it showed practical MFC (Minimum fungicidal Concentration) values of 2.5 mg ml^{-1} and 5 mg ml^{-1}, respectively **[84].** The decoction was more effective against fungi than food-pathogen bacteria **[84].** The control drug ampicillin was identified to be effective as similar to the ethanolic extract of *A. marmelos* fruit pulp by inhibiting the growth of pathogenic bacterial strains [**85].** The antibacterial activity of the different *A. marmelos* leaf extracts was tested using the disc diffusion method on multi-resistant strains of bacteria **[84, 86, 87].** On the basis of results, it can be shown that the petrolium ether extract exhibits greater action than regular streptomycin [**86].** In the ethyl acetate extract of *A. marmelos* leaf, the quinine compound was identified and possessed good antibacterial activity against gram-positive and negative bacteria [**87]. The** antibacterial effect of bael was found on pathogenic *Shigella dysenteriae*, and the inhibitory activity was believed to be from coumarin compounds present in the extract [173]. An antidiarrheal activity reported in Shoba and Thomas [173] could also be due to the same or similar compounds [173]. As an alternative to conventional antibiotics, a combination of bael and a popular antibiotic *2*-lactum was used, and inhibitory activity on *2*-lactam resistant *S. dysenteriae* was obtained [173]. The susceptibility was given by the differential expression of membrane porins, outer membrane protein (Omp) C and OmpF, and a cytosolic protein OmpR [49, 173]. When bael extract is administered, the OmpF gene was overexpressed, and OmpR was downregulated [49, 173]. Generally, these bacteria are resistant to *2*-lactum [49, 173]. However, fruit extract restores the inhibitory activity of *2*-lactam by changing porin channels' dynamics [173]. Antifungal activity is observed in essential oils extracted from bael leaves [49, 174]. Furthermore, a potential antifungal compound anthraquinone was also isolated from bael seeds [49, 175]. The essential oil extracts from leaves inhibit highly resistant *Fusarium udum* at 80% of efficiency under the concentration of 400 ppm included in the medium [49, 173, 175]. The spore germination of *F. udum* was inhibited [174] by the bael leaf extracts [49, 174]. Antifungal activities were also confirmed against *Aspergillus* and *Candida* spp. using the disk diffusion assay [49, 175]. The demonstrated antimicrobial activity implies that bael extracts can be used to control the fungal pathogens in skin diseases and the contamination of food [49, 175].

8.5. Radioprotective effects

A study was conducted in which the hydro-alcoholic fruit pulp extract of *A. marmelos* was examined for its radioprotective effects, which indicated that bael fruit is of medical and nutritional benefit [1,7, 43, 44]. Swiss albino mice animal model was administered a range of doses (5, 10, 20, 40, or 80 mg/kg) intraperitoneally (i.p.) for 5 successive days before being subjected to 10 Gy (exposure dosage) of gamma-radiation [1, 7, 43, 44]. Only 20 mg/kg groups showed a substantial increase in survival, with 50% (on 10 days) and 29% (on 30 days) survival after irradiation ($p < 0.001$) [1, 7, 43, 44]. Dose-dependent studies were also carried out by administering either a placebo or 20 mg/kg bael fruit extract before exposure to irradiation (6–11 Gy) [1, 7, 43, 44]. The LD $_{50/30}$ for the group that was exposed to radiation alone was 8.2 Gy, while the LD 50/30 for the group administered bael fruit extract before exposure to radiation was 8.8 Gy [1, 7, 43, 44]. As the DRF was found to be insignificant (1.1), no further research on the fruit extract was conducted [1, 7, 43, 44]. The radioprotective effect of hydroalcoholic *A. marmelos* fruit extract (AME) was evaluated by Jagetia et al., (2004) [8] in mice exposed to varying amounts of radiation [8]. The radioprotection optimal dose was found by giving AME i.p. 5 days (one per day) before being exposed to 10 Gy of radiation [1, 8]. Dosage of 20 mg/kg of AME (5 days prior to irradiation) was found to be most effective in radioprotection, as supported by the largest number of survivors after 30 days [1, 8]. Treatment of tested animals with AME before exposure to radiation reduced the effects of radiation sickness symptoms and mortality across all levels of radiation [1, 8]. On comparing the AME + irradiation group to the simultaneous sterile physiological saline (SPS) + irradiation group, the former group had a higher number of survivals. As shown by the higher number of survivors on days 10 and 30, AME pretreatment provides protection against bone marrow and gastrointestinal mortality [1, 8]. For 10 Gy ($p < 0.001$) and 9 ($p < 0.05$) irradiation, pretreatment with AME reduced 10-day mortality by 2- and 1.4-fold, respectively [1, 8]. With the 11 Gy dose of AME, a considerable % of the animals survived, but none of the animals in the contemporaneous control group survived past day 9 post-irradiation on day 10 [1, 8]. For 9 and 8 Gy irradiation, pretreatment with AME reduced 30-day mortality by 2.6- and 1.2-fold, respectively [1, 8]. The treatment with AME prior to exposure to 10 Gy radiation resulted in a survival rate of 41.6%, while no survivors were reported in the concurrent control group [1, 8]. The LD $_{50/30}$ was found to be 8.8 Gy for the AME+ irradiation group and 8.2 Gy for the SPS-treated group when the survival rate was plotted as log values v/s a linear irradiation dose scale [1, 8].

8.6. Hepatoprotective activity

In a literature survey, it was observed that the extract of bael fruit showed significant hepatoprotective activity [1, 58-175]. The liver is an important organ involved in the detoxification and disposition of toxic substances [1, 58]. A study conducted by Rajasekaran et al., (2009) [1, 58] confirmed that aqueous and ethanolic fruit extract showed moderate to significant hepatoprotective activity [1, 58]. Ethanolic extract (500 mg/kg; $p < 0.01$) was observed to have moderate activity for serum glutamate pyruvate transaminase (SGPT; 64.5 U/mL), serum glutamate oxaloacetate transaminase (SGOT; 81.3 U/mL) and alkaline phosphatase (ALP; 8.1 KA units) in CCl_4-induced liver damaged mice [58]. However, ethanolic extract of bael fruit holds the ability to restore normal functioning of the damaged liver caused due to CCl_4 treatment [1, 58-107]. Therefore, bael fruit could be used as a hepatoprotective agent [1, 58]. The study conducted by Chandel et al., (2018) [59] confirmed that upon administration of a diet containing (fruit) *A. marmelos* causes restoration of antioxidant status ($p < 0.05$) with reduction ($p < 0.05$) and increase in superoxide dismutase, catalase, lipid peroxidation, and glutathione and concentration in cisplatin-induced hepatotoxicity in tested animal models [1, 59]. In addition, administration of *A. marmelos* (2–4%) diets to model animals significantly reduces alanine aminotransferase (ALT), acid phosphatase (ACP), ALP, aspartate aminotransferase (AST), and bilirubin serum concentration levels [59]. However, it was concluded that the hepatoprotective effect of bael fruit could be due to its antioxidant potential, evident by increasing enzymatic and also reduction in serum levels [1, 59]. It was noticed that cisplatin treatment causes a reduction in enzymatic activity (antioxidant) and elevation of liver damage marker enzymes [1, 59]. In another development, the experimental study of Sastry et al., (2011) [6] confirmed the hepatoprotective potential of aqueous *A. marmelos* fruit was investigated [1, 6]. From the findings, it was observed that due to paracetamol (2 g/kg) treatment on Wistar albino rats, the elevated levels of serum parameters were reduced ($p < 0.001$) significantly after administration/treatment with fruit extract at 100–400 mg/kg BW in a dose-dependent manner, i.e., ALP (123–168 IU/L), Bilirubin (BLN; 1.5–1.22 mg/dL), SGPT/ALT (43–54.33 IU/L), and SGOT/AST (176–218.3 IU/L) [1, 6]. Therefore, the results of all the studies clearly indicated that the fruit of *A. marmelos* is effective in the treatment/prevention of hepato-cytotoxicity in model animals [1, 6]. Though, there is a need to investigate further in the same field, as there are very limited studies related to the hepatoprotective effect of *A. marmelos* fruit extract [1, 6]. Bael is used to treat hepatitis and CCl4-induced hepatotoxicity in rats [49, 167]. The administration of bael fruit and seed extract significantly reduced the CCl4-rendered elevation of plasma enzyme and bilirubin concentration in rats [49, 168].

8.7. Antidiabetic activity

Diabetes mellitus is a chronic metabolic disease with life threatening complications [67-72]. There are two types, one is Type-1 Diabetes and it is insulin dependent [67-72]. Another second one is Type-2 Diabetes which is non-insulin dependent [67-72]. Diabetes is a chronic disorder of carbohydrate, fat and protein metabolism characterized by increased fasting and post increased blood sugar levels [67-72]. Diabetes mellitus is a complex metabolic disorder resulting from either insulin insufficiency or insulin dysfunction [67-72]. Type I diabetes (insulin dependent) is caused due to insulin insufficiency because of lack of functional beta cells [67-72]. Patients suffering from this are therefore, totally dependent on exogenous source of insulin [67-72]. On the other hand patients suffering from Type II diabetes (insulin independent) are unable to respond to insulin and can be treated with dietary changes, exercise and medication [6-72]. The β-cells in the pancreas are the key players in glycemic homeostasis [67-72]. Pancreatic β-cells are the only endocrine cells known to produce insulin [67-72]. Insulin is a protein hormone that regulates the metabolism of glucose, fat, and protein in the body [67-72]. Any defect in insulin production and action leads to serious metabolic problems [67-72]. Type II diabetes is the more common form of diabetes constituting 90% of the diabetic population [67-72]. Symptoms for both diabetic conditions may include: (a) high levels of sugar in the blood; (b) unusual thirst; (c) frequent urination; (d) extreme hunger and loss of weight; (e) blurred vision; (f) nausea and vomiting; (g) extreme weakness and tiredness; (h) irritability, mood changes etc [67-72]. On the basis of literature survey and few of the following studies confirmed that fruit extract of *A. marmelos* has a antidiabetic effect [56, 57]. The active components in the leaf and callus materials reduce blood sugar levels in STZ-diabetic rabbits [74, 90]. Further, *A. marmelos* callus powder methanol extract is as powerful as the leaf extract in treating diabetes [74, 90]. This study indicates the aqueous seed extract of *A. marmelos* reduces the blood glucose level in normal as well as in severely diabetic rats [74, 90]. This has improved glucose tolerance in sub and mild diabetic animals and is referred to standard as tolbutamide [74, 91-93]. The alcoholic extract of *A. marmelos* leaves significantly inhibited the enzymes α-amylase and α-glycosidase with IC50 values of 46.21 and 42.07 μg/ml, respectively [74, 90]. *A. marmelos* significantly reduced ROS levels that were elevated due to high glucose and enhanced glucose consumption in HepG2 cells ($p < 0.05$) [74, 91]. The aqueous extract of *A. marmelos* fruits lowers blood sugar in streptozotocin-induced diabetes rat model [74, 91]. It boosts insulin secretion by partial regeneration from the β-cells of pancreatic islets [74, 91]. The effects seen in the fruit extract treated mice were better when compared with animals treated with glibenclamide [74, 91]. In one of the study reported by Saha et al., (2017) [99], an *in-vitro* assay demonstrated a potent antidiabetic effect from lectin extract, as measured by glucose uptake in yeast cells [99]. A fruit lectin extract with an IC_{50} of 3.36 μg/ml had greater efficiency than the usual medication metformin at increasing glucose uptake by yeast cells [74, 91]. This study found that *A. marmelos* fruit extract had hypoglycemic activity, which could be attributed to its antioxidant activity and high content of active constituents [56].

In one of the study by Abdallah et al., (2017) [56] reported that fruit extract of *A. marmelos* was studied for its antidiabetic effect [56]. The findings of this study reported that, fruit extract showed significant increase in ($p > 0.001$) in BWG (body weight gain) % (30.41–32.80) and FER (feed efficiency ratio) (0.087–0.096), while decrease in DFI (daily feed intake) (26.50–22.54 g/rat/day) when tested against alloxan diabetic rats [56].

Further, it was observed that, administration of *A. marmelos* fruit extract orally at dose of 125 mg/kg, 250 mg/kg and 500 mg/kg exhibit significant elevation in sugar (glucose) concentration ($p > 0.001$; 97.48–78.82 mg/dL) and reduction in insulin level ($p > 0.01$; 6.58–15.64 μIU/mL), when compared with untreated diabetic rats [1, 56].

In another study by Kamalakkanan et al., (2003) [57], aqueous extract of bael fruit (AMFEt) was tested in female albino Streptozotocin (STZ)-induced diabetic Wistar rats and normal rats [1, 57]. The study involves administration of STZ (45 mg/kg) intraperitoneally to induce diabetes in Wistar rats and AMFEt (250 mg/kg) two times daily for an interval of one month [1, 57]. From the findings, it was observed that there was major decrease in plasma insulin ($p < 0.05$) and significant increase in glucose level in blood ($p < 0.05$) in diabetic rats [1, 57]. While oral treatment of AMFEt decreases the blood glucose level ($p < 0.05$, 280.0–61.4 $mgdL^{-1}$), increases plasma insulin level (17.9–21.6 μUmL^{-1}) and improve body weight (178.6–194.0 g), food intake (51.2–54.8 g/day) and water intake (212.5–230.0 mL/day) in diabetic group and normal group, but no substantial change was observed in normal group ($p < 0.05$) [1, 57]. On the basis of above mentioned study results, it was confirmed that *A. marmelos* fruit extract has significant effect on plasma insulin and blood glucose levels [1, 57]. Therefore, these studies showed that fruit of *A. marmelos* can be used as antidiabetic agent [1, 56, 57].

8.8. Antiviral activity

According to Monika et al., (2023) [74], different portions of the *A. marmelos* are observed against human coxsackie viruses B1-B6 for *in-vitro* antiviral activity with ribavirin as a standard antiviral drug [74-77]. Thus Marmelide possessed 32-times more potent inhibitory activity than ribavirin [74, 75]. *A. marmelos* extracts were shown to be effective against the white spot syndrome virus in shrimp at a dose of 150 mg/kg of animal body weight [74-77]. The isolated volatile oil from *A. marmelos* is examined for its ability to inhibit the growth of eight different types of fungi [74-77]. At 0.05% concentration, the essential oil completely prevented all fungi from producing spores [74-77]. The majority of the fungus is significantly inhibited at around 75% and 90% at 0.03% and 0.04%, respectively [74-77]. At concentrations of 0.03% and 0.04% of the oil, the most resistant strain, *F.udum*, showed 65% and 80% inhibition rates, respectively [77].

8.9. Anti-inflammatory and Antipyretic activity

On the basis of literature survey by Monika et al., (2023) [74], one of the study examined the potential anti-inflammatory activities of the repeated extracts from *A. marmelos* leaves [1-74]. An apparent analgesic effect was demonstrated in mouse models of carrageenan-induced paw edema and cotton-pellet granuloma to establish the antipyretic and analgesic activities of the leaf extracts [1-74-175]. Additionally, the early and late phases of paw licking were diminished, and hyperpyrexia decreased [74, 78]. In another study, the anti-inflammatory properties of the aqueous extract of *A. marmelos* dried flowers are investigated in Wistar rats [74, 78]. The anti-inflammatory effects of water extract were most effective at 200 mg/kg two hours after administration [79]. Aqueous extract from unripe *A. marmelos* fruit was found to have a dose-dependent impact in a different investigation focused on inflammatory bowel disease in albino Wistar rats [74, 78, 79]. With much higher SOD and lower MDA levels and defense against mast cell de-granulation, *A. marmelos* fruit had anti-inflammatory, antioxidant, and mast cell stabilizing properties [74, 80].

8.10. Antimalarial activity

According to **Monika** et al., (2023) [74], an *In vitro* antimalarial activity of *A. marmelos* leaf methanol extract, which showed the highest activity against *Plasmodium falciparum*, elicited low cytotoxicity, and the promising antiplasmodial activity of *A. marmelos* of IC_{50} is found to be 7 g/ml [74, 81]. Infected mice with a suppressive effect on the parasite did not respond to *C. longa* treatment; however, *A. marmelos* at 20 and 40 mg/kg body weight inhibited parasite infection [74, 81]. Finally, *A. marmelos*, demonstrated strong antioxidant and antiplasmodial properties; it could be one of the traditional plants used to treat malaria [74, 82]. With an IC_{50} of 500.06 ppm, standard *Temephos* has better larvicidal activity toward *Anopheles stephensi* when compared with crude leaf extracts of *A. marmelos* Correa [83].

8.11. Antispermatogenic activity

The marmin and fagarine are high in *A. marmelos* bark extract reducing male fertility [100]. In one of the study reported by Srivastava and Singh (2022) [100], the ethanolic extract of *A. marmelos* bark on sperm motility was reported to have a beneficial effect on sperm locomotor activity [100]. It has also been reported that increasing the concentration of extracts reduces sperm motility [100]. The alkaloids isolated from *A. marmelos* leaf were significantly decreased the fertility in male albino rats in dose dependent manner [101]. *A. marmelos* extract is an excellent choice for male contraception, the extract has the ability to completely suppress pregnancy and restore fertility rapidly after treatment cessation [100]. The male albino rats reproductive systems were subjected to three various doses of a 50% ethanolic extract from *A. marmelos* leaves: 100, 200, and 300 mg\kg 1 day 1 for each rat for 60 days [100]. All of the significant accessory sex organs shrunk after ingesting the extract [102]. The cauda epididymis of the treated animals produced considerably less sperm, both in terms of motility and density. Male rat fecundity was completely decreased by *A. marmelos* at 300 mg [102].

8.12. Antiulcer activity

On the basis of literature survey by Monika et al., (2023) [74], methanolic and aqueous extracts of *A. marmelos* seeds were tested for antiulcer activity in indomethacin-induced ulceration, stress-induced ulceration, and pylorus ligation-induced ulceration by using ranitidine as standard (50 mg/kg) [74, 103]. Peptic ulcers are caused by the bacteria H. pylori [1, 74]. There is little or no literature on the effect of *A. marmelos* on Helicobacter pylori, so more research is required to determine its effect on H. pylori [103]. If it positively reduces AMR, it will be an excellent herbal drug to treat abscesses with no adverse effects [104]. *A. marmelos* is frequently used to heal ulcers and related illnesses in Ayurveda and observed for the oral administration of methanolic extract of *A. marmelos* for affected rats with stomach ulcers induced by lipopolysaccharide caused by Helicobacter pylori [74, 105]. A dose of 500 mg/kg of methanolic extract was shown in the trial to reduce stomach ulcers by 93.98%. Gastric secretory parameters, such as free and total acidity, acid output, stomach juice volume, and pepsin concentration, were inhibited, resulting in decreased gastric ulcers [74, 103-105].

8.13. Toxicity studies

A. marmelos dried fruit pulp is examined for its topical characteristics reported in the review paper by Monika et al., (2023) [74]. Swiss albino mice were tested for acute oral toxicity with an ethanol extract of the dried fruit pulp from *A.*

marmelos at 550 and 1250 mg/kg [74]. Test results indicated that the extract is not hazardous at these doses [74]. Mice's behaviour and physiological activity remained unchanged (14 days) throughout the trial [74, 106]. The findings showed that the test extract's LD50 is highly significant [74]. The oral acute toxicity study did not showed any toxic symptoms, changes in behavior, or mortality at 1250 mg/kg doses [74]. Thus, the ethanolic extract of *A. marmelos* dried fruit pulp extract has no discernable biologically significant toxic effect on the mice below LD50 [74, 106].

On the basis of literature survey by Khanal et al., (2023) [139], extensive use of Bael fruits and their parts has been found in *Ayurveda* and other traditional medicine systems [139]. The leaf of the plant is used as a remedy for jaundice and asthma [139]. They are also good in the treatment of conjunctivitis, along with curing constipation, deafness, and leucorrhea [1-139]. Furthermore, leaf powder is used to treat bowel syndrome [139]. Similarly, unripe fruit is used in abscess curing, whereas the fruit pulp is beneficial for urinogenital disorders, intestinal disorders, and other indigestion-related problems [139]. The mixture of powdered fruit and mustard oil is used in India to cure burn wounds [1-139]. Due to the antiseptic and astringent properties of the Bael plants flower, it is used in epilepsy and wound healing [10]. In addition, the root and bark of the tree are useful for intermittent fever, heart palpitation, and melancholia [1-139]. Bale tree root is among the most important components in the preparation of a popular Ayurvedic medicine known as "Dashmula," which has a variety of benefits, including proper nervous system functioning [1-139]. The toxicity studies of the herbal preparation of bael were conducted using rat models, and it was found that higher doses of bael preparation are less toxic, and higher therapeutic indices can be achieved through administering large quantities [1-49]. The very high margin of drug safety (i.e., very high LD_{50}) in bael preparations is significant in routine treatments for various ailments [1-49-107].

8.14. Cardioprotective activity

Heart and blood vessel illnesses are the most common causes of cardiovascular disease, which include arrhythmia, stroke, hypertension, myocardial infarction, and atherosclerosis [1-139]. A bioactive compound named linear furanocoumarin marmesinin, extracted from Bael, can protect against lipid peroxidation [1-139]. In a study performed on albino Wister rats having myocardial injury when tested by the compound at a dosage of 200 mg/kg, the result showed a lower in serum enzyme levels and restored the electrocardiographic changes towards normalcy [140]. In another experiment conducted by Kakiuchi et al., (1991) [141], the potential of a compound isolated from the leaf of Bael called cardenolide and periplogenin tested against cardiotoxicity and lipid peroxidation in rats [140]. The administration of these compounds at a concentration of 25 mg/kg appeared to be effective in inhibiting cardiovascular problems such as an increase in serum creatine kinase–MB (CK–MB) and glutamate-pyruvate transaminase (SGPT) [140, 141]. Further, the methanolic extract of Bael root were found to reduce heartbeat rate by up to 50% when administrated at a dosage of 100 g/ml on cultured mouse myocardial cells [141].

8.15. Bioadhesive property

Bael fruit gum is an excellent biopolymer having a different biomedical application [139, 142-145-147]. Bael fruit gum is a non-ionic polysaccharide containing a high amount of galacturonic acid and D-galactose providing a greater solubility and water-holding capacity [139, 142, 143]. A different study has shown the use of gum as a gelling agent in food items, as a carrier molecule for controlling drug release, and as an adhesive material [144]. In a study performed by Mirza et al., (2018) [145], a nanocomposite scaffold of Bael fruit with chitosan and hydroxyapatite revealed that the nanocomposite exhibits enhanced cell adhesion and proliferation [145]. Based on this study, a nanocomposite fabricated with Bael fruit gum has a high potential to be applied in bone tissue engineering [139, 145, 148]. Aqueous extract of bael can also act as a cardiac stimulant, smooth muscle relaxant, and uterine stimulant [157]. However, alcoholic extracts act as a cardiac depressant implying the importance of the medium of herbal preparations as one medium could ultimately reverse the intended function from the other [157]. Antioxidant activity and the membrane effects of furanocoumarin and marmesin isolated from bael evaluated for cardiac injuries by Vimal and Devika, (2004) [158]. This study demonstrated a protective effect against the damage [158].

8.16. Activated carbon

In addition to the food and medicinal values, activated carbon produced from bael fruit shells can be used as an efficient, low-cost adsorbent to remove heavy metals such as chromium from polluted or drinking water [49, 149]. The use of activated carbon derived from bael rinds could be a novel approach to detoxify the heavy metal contaminated drinking water in Dry Zone, Sri Lanka, to combat chronic kidney disease of unknown etiology (CKDU) [49]. Bael leaves could also be used as a potential biosorbant [49, 149]. The noxious lead ions were demonstrated to be removed from an aqueous solution by absorbing them into the bael leaves [150]. An unusual fatty acid, 12-hydroxyoctadec-cis-9-enoic acid (ricinoleic acid), is present in the bael seed oil, which has the potential to be manufactured as biodiesel in the future [151]. The structure of bael exudate gum was also determined [21–23] which could be further characterized for various industrial applications [151-154]. Bael is highlighted as a natural purifier of the environment and can be used as a supporting tree for wildlife and key species in reforestation of urban, rural, and dryer areas, and also it is useful as a shedding tree for nutrient recycling [155].

8.17. Nutritional Fruit pulp

Bael fruit pulp is a nutritionally rich fruit species [1-49-149-175]. Bael is mainly consumed as a fresh fruit in which the inner fleshy layer of the pericarp and placenta are edible [1-49]. All parts of the bael plant consist of immense medicinal properties [1-49-149-175]. The herbal medicinal preparations of bael are used to treat chronic diarrhea, dysentery, peptic ulcers, laxative for astringency, and respiratory ailments [1-49-149-175]. The bael fruit parts are also used to make pudding, juice, jam, and cakes [1, 49]. Bael fruit is rich in colorants and flavoring agents, which could be used as additives in the food industry [1,49]. The extracted nectar of fruit can also be used as a value-added product [1-49-175]. Bael fruits are also characterized by a higher abundance of soluble dietary fiber, volatile compounds with reducing sugars, carotenoids, and antioxidants [1-49]. Bael fruits contain xanthotoxol, imperatorin, alloimperatorin, 2-sitosterol, tannins, and alkaloids such as aegeline and marmeline [1-49-175]. Tannin was found to increase during ripening, where the highest tannin content was found in fully ripe fruits [1-49-175]. Riboflavin, an essential vitamin, is only found in fully ripe fruits [49]. However, the ascorbic acid content decreases significantly with fruit ripening, implying a marked reduction of antioxidant activity with maturation [1-49-175]. A glycoprotein was discovered in bael [1-49]. Another compound known as shahidine is also present, which is a newly reported molecule having very high labile oxazoline activity against few Gram-positive bacteria [1-49-175]. The gum of the surrounding environment of the seeds in bael fruit also contains phytochemicals [1-49]. Leaves contain alkaloids, mermesinin, rutin, phenylethyl cinnamides, anhydromarmeline, and aegelinosides, sterols, and essential oils [1-49-107]. Stem barks and roots contain a coumarin as aegelinol [1-49-175]. Roots also contain psoralen, xanthotoxin, coumarins, tembamide, mermin, and skimmianine [1-49-175].

8.18. Immunomodulatory activity

Anti-immunemodulatory activity of methanol fruit extract was verified using the neutrophil adhesion test and carbon clearance assay [1-49, 156]. Bael fruit extracts would augment the immune activity [1-49, 156-107] along with the other immunity enhancement mechanisms upon exposure to the infections [1-49, 156-107]. Immunomodulatory activity and the augmentation of the immune activity of bael were also reported by Patel et al., (2010) [156] and an antidyslipidaemic activity was also observed [49, 156].

8.19. Antivenom, Analgesic and Anti-inflammatory activities

The formulations made out of bael roots were found to possess antivenom activity against snake bites [1-49, 159]. Bael is long being used to treat ailments in the digestive tract, and this ability maybe because of the compound marmelosin in bael extracts [1-49, 160]. Moreover, analgesic activity and anti-inflammatory and antipyretic activities of bael were also reported [1-161-162].

8.20. Hyperthyroidism

Bael has an inhibitory effect on hyperthyroidism in mice [1-49, 163]. Crushed and dried bael leaves were slowly boiled into a aqueous slurry [49, 163]. This slury was administrated orally to mice at the concentration of 1 g per kg of body weight [49, 163]. Thyroid hormone concentrations were regulated by the administration of bael and exhibited the relative decreasing of the thyroid hormonal concentration in blood [49, 163]. However, the thyroxin level did not go down by the bael leaf extract [49, 163].

8.21. Gaucoma

The modulation of intraocular pressure (IP) is one of the treatment strategies for glaucoma. The IP ability of bael fruit extract was demonstrated using rabbit models [49, 164].

8.22. Wound healing

The wound-healing property of methanol extracts of bael was tested using the formulations of ointments and injections, which facilitated the healing process [165]. The efficiency of the healing process is comparable to nitrofurazone [49, 165].

8.23. Respiratory ailments

Bael preparations were known to be efficient against treating respiratory ailments [1-49, 161]. The contractile activity of tracheal elements was demonstrated using guinea pig and mouse models [49, 161]. The antihistamine activity was also shown, indicating the usefulness of using bael extracts against respiratory ailments such as asthma [1-49, 161]. Applying herbal preparations of bael modulated the expression of the I-18 gene in brachial epithelial cells showing the potential to use as an effective drug in treating cystic fibrosis in the future [49, 166].

8.24. Cirrhosis

It is logical to think that bael extracts could be used to treat cirrhosis, but further studies are required [1-49, 167]. Flavonoids in bael could be the attributing factor for repairing the structure and function of the liver [1-49, 167]. Oral administration of bael fruit extracts also reduced the hypovitaminosis C in rats by the compound hesperidin, which is also contributing to the hepatoprotective role [1-49, 167]. Eating bael fruit ad libitum is a preventative measure and a treatment against cytotoxicity in the liver [1-49, 167].

8.25. Antimicrofilarial activity

Bael fruit extract has shown significant antimicrofilarial activity [169] and insecticidal activity on nuisance Japanese encephalitis vector *Culex tritaeniorhynchus* [1, 49, 170]. Essential oils of bael are effective in fumigating stored gram and wheat samples at a concentration of 500 µg/ml [1, 49, 170]. The targeted insect pests were *Callosobruchus chinensis, Rhyzopertha dominica, Sitophilus oryzae,* and *Tribalism castaneum*[1, 49, 170]. Sahare et al., (2008) [171] also explained that coumarin present in bael leaves possessess antimicrofilarial activity [1-49, 171].

Bael extracts were found to reduce fertility in male rats [172]. The administration of herbal preparations of bael to rats causes weight shedding of sexual organs and reducing the motility and density of sperms [172]. The removal of treatment restored the fertility to normal, indicating the possible use of bael-based phytochemicals as a future birth-controlling drug [1-172].

9. Commercial uses of Bael

Bael fruits have been used as functional foods in the form of processed goods such as preserves, powder, jam, wine, slab, and syrup [1-40, 49, 107, 293]. In India many of the products are prepared from bael fruits such as bael sherbet, murabba and syrups [1-40, 49, 107, 293] [296-331]. In other countries such as Indonesia and Thailand, ripe bael fruits and their sliced pieces are consumed as food and syrups are used in making cake ingredients [1-40, 49, 107, 293] [296-331].

Historically, Bael has been used to treat several human diseases [1-49-175]. Despite its excellent flavor, nutritive content, and therapeutic values, it is still regarded as an underutilized fruit [1-49-175]. Because of the hard shell, the gluey texture, and the numerous seeds, the fruit is difficult to eat and is not popular as a table fruit [1-49-175]. So, further processing is needed for the easy consumption of fruits, which have an enormous potential to be developed as nutraceuticals [1-49-175]. The presence of different bioactive compounds and their nutritional composition makes it a potential fruit to be developed as a nutraceutical [1-49-175]. Apart from exploring the possibilities of using the different plant parts as medicine, the production of different functional products by using Bael fruits should be promoted at a commercial level [1-49-175]. In the future, Bael fruit could be developed as a functional food product and play a significant role in healthy living [1-49-175]. Bael candy, panjeri (a traditional Indian dish), Bael wine, and preserves can be prepared by different processing technologies [1-49]. These products are highly nutritious and different from market commodities [49]. They are minimally processed, preserving their freshness and making them ready to use and consume [1-49-175]. Because Bael fruit is not available all year, jam is a method of preserving it sometimes also in combination with other fruits [1-49-175]. Fruit slabs are also a good method to make fruit more usable and acceptable [1-49-175]. It was prepared by mixing the pulp with sugar, citric acid, and potassium metabisulfite [49]. Pulp TSS and acidity are maintained at 35% and 0.5%, respectively [1-49-175]. Toffee is a brittle confectionery made from a mixture of syrup and butter with added flavor and color [1-49-175]. They prepare the bale fruit toffee by incorporating herbs like cinnamon and cardamom [73]. To get the desired flavor and nutritional content, the toffee was made by mixing the fruit pulp with sugar, butter, milk powder, corn flour, and citric acid, as well as various quantities of cinnamon and cardamom [1-49-175]. The products were allowed for moisture, total ash, acidity, and the prepared toffee with 0.5 g was found to be the best [49]. Increasing demand for nutraceutical drinks has shifted the market towards natural drinks extracted from plant parts such as roots, flowers, fruits, leaves, or seeds that offer a variety of functional benefits [1-49-175]. Numerous studies have been conducted successfully for the preparation of different beverages from Bael [1-49-175].

Therefore, further research is required to explore the commercial potential of Bael fruit and to determine its economic viability as an ingredient in the food industry [1-49-175]. Bael fruit pulp-based leather using sugar, citric acid, a thickening agent to improve its palatability, and increase utilization was prepared [1-49-175]. The proximate analysis revealed that the final product contained 2% ash, 2.3% crude protein, 0.1% fat, 3.9% fiber, and 8.9% moisture [1-49-175]. The developed Bael fruit leather was found to be safe for storage for 6 months at room temperature under vacuumpacked conditions [1-49-175]. The products microbial, physicochemical, and sensory properties were evaluated and found to be satisfactory [1-49-175].

The processing of Bael fruit generates a significant amount of waste, including the peels, seeds, and pulp residues [1-49-175]. Bael fruit waste also presents a valuable resource that can be utilized for various purposes [1-49-175]. Recent studies have demonstrated the potential of Bael fruit waste in producing bioactive compounds, such as polyphenols, flavonoids, and carotenoids [1-49-175]. For instance, they can be utilized in the food industry to develop functional or enriched foods, in the health industry for the production of nutraceuticals, in textile industry, and other applications [1-49-175]. The conversion of fruit waste into bioactive components represents a critical pathway towards achieving sustainable development [1-49-175].

10. Bael Tree: Commercial varieties in India

The Indian Council of Agricultural Research (ICAR), Government of India, New Delhi, India and Agricultural institutes have developed new promising cultivated varieties of bael through selection in the recent years due to its well known therapeutic properties [1-40, 49, 107, 293] [296-351]. Bael is also essential as a species for reforestation, especially in the unfertile marginal lands. Commercial cultivation of the high-yielding variety **Goma Yashi** has lately acquired pace in Rajasthan, Uttar Pradesh, Bihar, Madhya Pradesh, Punjab, Tamil Nadu, Himachal Pradesh, Uttaranchal and Gujarat states in the form of orchard or border plantation [107]. Among local types, Ayodhya, Kagzi, Etawah, Gonda and Mirzapuri bael were popular in Uttar Pradesh, India due to their good yield potential and quality fruits [296-351]. In recent past, some promising varieties of bael have been developed through clonal selection at ICAR Institutes and Agricultural Universities [296-351]. According to ICAR-CISH, Lucknow, UP, India, there are commercial cultivated varities of Bael tree available in India are CISH B-1 and CISH B-2 [296-331]. **CISH-B-1**: This early maturing variety produces small to medium fruits with high seed content and attractive yellow pulp [296-351]. The fruits have a Brix value of 34° in pulp and 43° in mucilage. **CISH-B-2**: This variety yields medium-sized fruits with thick rind and light yellow pulp [296-351]. The fruits have a Brix value of 31° and are good for processing due to their thick rind and low mucilage [296-327]. The dedicated and sincere research efforts led to the development of 12 varieties of bael. **Goma Yashi** a popular variety among farmers, is known for its thornless, papery shell thickness, high-quality fruits, and small stature, making it ideal for high-density planting [296-331-351]. Bael is known to have extensive phenotypic variation arising owing to cross-pollination and effect of varied agroclimatic conditions on morphological characters in different parts of the country [296-331-351]. Farmers are experiencing the challenge of identifying cultivars but they are unfamiliar with the characteristics of many different varieties of bael [296-331-351]. In order to identify distinct characters of various bael cultivars, the morphological characterization is essential without considering the fruit characters [296-331-351]. This has necessitated the development of bael descriptors that can be used to recognize varieties with the help of morphological variability excluding fruit characters [296-331-351].

Varieties developed by N. D. University of Agriculture and Technology, Kumarganj, Faizabad, Uttar Pradesh, India are 1) **Narendra Bael-5 (NB-5)**: This variety has a semi-spreading growth habit and is known for its precocious and prolific bearing [296-351]. The fruits are medium-sized, round with a thin rind, and have light yellow pulp that is low in mucilage and seeds [296-331-351]. The taste is excellent with a Brix value of 33°, and it is suitable for both fresh consumption and processing [296-351]. 2) **Narendra Bael-7 (NB-7)**: This variety features large, round fruits with a very thick rind. It is a sparse bearer but highly suitable for processing due to its low mucilage and fiber content. The fruits have an attractive yellow pulp with a Brix value of 30°.2 [296-351]. 3) **Narendra Bael-9 (NB-9)**: Known for its compact canopy and high yield, NB-9 produces medium to large fruits with a thick rind and golden-yellow pulp. The taste is slightly acidic with a Brix value of 38°, making it ideal for both fresh use and processing [296-327-351]. 4) **Narendra Bael-16 (NB-16)**: This erect variety starts fruiting early and produces small, round fruits with a very thick rind [296-327-351]. The pulp is excellent in taste with a Brix value of 36°, suitable for powder production. 5) **Narendra Bael-17 (NB-17)**: With an erect and semi-spreading growth habit, NB-17 yields slightly large fruits with thin rind and attractive yellow pulp. The fruits are excellent in taste with a Brix value of 34° and are suitable for both table and processing purposes [296-331-351].

Varieties developed by G. B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India. 1) **Pant Aparna**: This variety is almost thorn-less with drooping foliage. The fruits are globose with thin rind and sweet, tasty flesh. It is a heavy bearer with good flavor, making it suitable for fresh consumption [296-331-351]. 2) **Pant Shivani**: An early mid-season variety, Pant Shivani produces large, ovoid-oblong fruits with lemon-yellow pulp [296-351]. The fruits have good storage quality and low mucilage and fiber, with a Brix value of 36°. 3) **Pant Sujata**: Despite the issue of fruit splitting, this mid-season variety has good flavor and storage life. The fruits are light yellow with a thin rind and low mucilage, making them pleasant to taste with a Brix value of 32° [296-327-351]. 4) **Pant Urvashi**: An early mid-season variety, Pant Urvashi is a heavy bearer with large, yellow fruits and light yellow pulp. The fruits have a Brix value of 33° and are suitable for both fresh consumption and processing [296-331-351].

Varieties developed by Central Horticultural Experiment Station (ICAR-CIAH), Vejalpur, Godhra, Gujarat, India. 1) **Goma Yashi:** This variety is highly suitable for making sherbet, squash, candy, and murabba [296-331-351]. It has high-quality attributes like papery shell, minimal fiber, mucilage, and attractive pulp color with pleasant aroma [296-331-351]. 2)**Thar Divya:** This early maturing variety is less affected by sunscald and produces medium-sized fruits with a Brix value of 35° to 39°. It is highly suitable for rainfed semi-arid ecosystems. 3) **Thar Neelkanth:** With compact growth and medium height, Thar Neelkanth is ideal for dry land conditions. It produces quality fruits with pleasant flavor and aroma, suitable for various processed products [296-331-351].

Varieties developed by ICAR-Central Institute for Sub-tropical Horticulture, Lucknow, Uttar Pradesh, India: **CHESB-11**: Known for its high yield and good flavor, CHESB-11 produces medium-sized fruits with a Brix value of 38° in pulp and 50° in mucilage [296-331]. It is rich in antioxidants and suitable for sherbet, murabba, and powder making. **CHESB-16**: This late maturing variety has a drooping growth habit and produces fruits with high antioxidant activity [296-331]. The fruits are excellent for making RTS (ready-to-serve) drinks, candy, and murabba. **CHESB-21**: With a high yield and good flavor, CHESB-21 produces large fruits with a Brix value of 39° in pulp. It is highly suitable for pickle, sherbet, candy, jam, and powder making [296-331].

Three new abiotic stress tolerant varieties (Thar Srishti, Thar Prakriti and Thar Shivangi) of bael have been developed by Central Horticultural Experiment Station (ICAR-CIAH), Godhra, Gujarat, India [296-331-351]. These varieties perform well in abiotic stress conditions, and have been identified at institute level for specific traits like Thar Srishti for highly centric locule (seed cavity) arrangement [296-331-351]. Thar Prakriti for high fibre and papery shell (1.4 cm). Thar Shivangi is known for high antioxidant activity having drooping branches [296-331-351]. Economic yield from full grown tree can be obtained up to 400 mm rainfall under rainfed hot semi-arid conditions of western India [296-351]. These varieties were evaluated purely under hot rainfed semi-arid conditions and have been recommended for commercial cultivation under dryland areas of country [298].

Thar Srishti can be used as table purpose owing to highly centric locule (seed cavity) arrangement and ideally suitable for powder making owing to richness in fibre content whereas [296-327-351]. Thar Prakriti and Thar Shivangi can be used for various processed products and ayurvedic formulations owing to high antioxidant values and richness in bioactive compounds [296-331-351]. They are recommending to the farmers to grow all the varieties developed by the Station, viz. Goma Yashi, Thar Divya, Thar Neelkanth and newly released Thar Srishti, Thar Prakrati and Thar Shivangi [296-327-351]. Hence these fruits can be made available in the market right from January to July [298]. These varieties are gaining popularity among the Indian farmers and fruit particularly growers of dryland areas [296-327-351]. This is mainly because of higher yield with quality fruits having specific traits, and better adaptability under aberrant agro-climatic conditions of the country [298]. Planting materials of these varieties are available at (ICAR-CIAH), Godhra, Gujarat, India Research Station during monsoon [298].

Existing biodiversity of bael in India can be grouped into two prominent categories i.e. one small fruit type, having bitter pulp with more seeds, mucilage, and fiber content [296-331-351]. Second of large fruit type with thin shell, less seed, fibre and mucilage and more sweet pulp [296-331-351]. The earlier type one is generally used in Ayurvedic preparation because of high marmelosin and psoralen content [296-331-351]. On the other hand, the second type is generally used as dessert fruit and for preparation of processed products [296-331-351]. Diverse germplasm of bael has been widely collected from various states of India viz., Uttar Pradesh, Bihar, Gujarat, Haryana, Madhya Pradesh and West Bengal by NDUAT, Faizabad, CHES, Godhra (CIAH, Bikaner), CISH, Lucknow, CCSHAU, Regional Research Station, Bawal, CAZRI, Jodhpur; Jharkhand, Bihar; Uttar Pradesh and Madhya Pradesh; Rajasthan and Gujarat [296-331-351]. Growth behavior of bael varieties has been reported by Singh et al. [296-331]. Characterization of bael genotypes has been undertaken at CHES, Godhra under rainfed hot semi-arid environment of Gujarat, India [296-331-351].

10.1. Cultivated Genotypes of Bael tree in India

10.1.1. CISH-B-1

It is early maturing variety. The plants are semi-tall and having spreading growth habit. The budded plants start fruiting in the 4th year [296-331-351]. The fruits are small to medium in size (16.50 cm x 12.00 cm), oval-oblong, with smooth surface, yellow at maturity, low in mucilage and fibrous, an attractive yellow pulp with high seed content [296-331-351]. Excellent in taste and flavour. The fruits have 30- 340 Brix total soluble solids in pulp and 430 Brix in mucilage. The fruit weight varies from 0.8 to 1.40 kg with average yield 67.00kg/plant during 8th year [296-331-351].

10.1.2. CISH-B-2

The average fruit yield of 8th year old plant is 56.78 kg [296-331-351]. The fruits are medium in size (16.00 cm x 14.00 cm), rounded with smooth surface, yellow at maturity and the rind is thick, low in mucilage and fibrous, light yellow pulp with low seed content [296-331-351]. Good in taste and flavour, the fruits have 310 Brix total soluble solids and titratable acidity (0.41%) [296-331-351]. The fruit weight ranges from 1.7 to 2.6 kg/fruit. Fruit does not ripe uniformly under natural condition. It is good for processing [296-331-351].

10.1.3. Goma Yashi

This variety matures during March and belongs to early maturing group under semi-arid ecosystem [296-331-351]. It possess high qualitative attributes like papery shell, very less fibre and mucilage and attractive pulp colour with pleasant aroma [296-331-351]. It is highly suitable for *sharbet*, squash, candy and *murabba* making. Because of dwarf stature, it is highly suitable for high density planting (5mx5m) [296-331-351]. Yield 65.45 kg/plant during 8th year, fruit weight 1.00-1.62 kg, fruit size 13.00 cm x 12.50 cm, fruit girth 41- 45 cm, shell thickness 0.15cm, seed weight 25.37-32. 50g, fibre weight 40.24-51.20 g, shell weight 180-210g, locules in cross section 13-15, pulp 68.00-72.25%, TSS pulp 35-390B, TSS mucilage 41-430B, acidity (0.29-0.34%) and vitamin C 19.00-22.00 mg / 100 g pulp [296-331-351].

10.1.4. Narendra Bael-5 (NB-5)

According to Singh et al., [296-331-351], growth habit is semi-spreading, precocious and prolific in bearing but fruit size uneven [296-331-351]. The fruits are medium in size (12.50 cm X 11.50 cm), round with smooth surface and very thin rind (0.16-0.17cm), straw yellow at maturity, low in mucilage, moderately fibrous, light yellow pulp with low seed content [296-331-351]. Pulp is soft, excellent in taste (330Brix) flavour and ascorbic acid 18.63 mg/100g of edible portion [296-331-351]. The average fruit weight is 700– 1300 g and average yield is 54 kg fruits/ tree during 8th year under semi-arid conditions [296-331-351].

10.1.5. Narendra Bael-9 (NB-9)

The plants are semi-vigorous and spreading having compact canopy [296-331-351]. The plants of this variety are of medium height (4-7m) having compact canopy. The variety is precocious and prolific bearer [296-331-351]. The average fruit yield of a eightyear old plant is 69 kg [296-331-351]. Fruits are medium to large in size (16.00 cm x 13.50cm), roundish-oblong with smooth surface and thick rind (0.24cm), light yellow at maturity, average in mucilage, moderately fibrous, slightly golden-yellow pulp with low seed content [296-331-351]. The fruits are good to taste containing 380 Brix total soluble solids in pulp, slightly acidic and ascorbic acid 19.20 mg/100 g of edible portion [296-331-351]. It can be used as fresh as well as processed into various post harvest products. Its keeping quality for storage is very good [296-331-351].

10.1.6. Narendra Bael-7 (NB-7)

Plants are tall and semi-spreading. This genotye is characterized by spreading growth habit with semi compact foliage, trunk colour grey with splitting of bark in rectangular manner, leaf medium sized, lanceolate, colour green with smooth surface, non-wavy margin [296-331-351]. They are sparse in bearing with large size fruit. The fruits are large in size (18.25cm x 22.50 cm), round and with smooth surface and very thick rind, yellow at maturity, low in mucilage and fiber, attractive yellow pulp, with low seed content [296-331-351]. Fruits are good in taste (300 Brix) and flavour and having 19.78 mg/100 g ascorbic acid [296-331-351]. The average yield of plant is 54.34 kg fruits/tree during 8th year. It is highly suitable for processing. Fruit does not ripe uniformly [296-331-351].

10.1.7. Narendra Bael-16 (NB-16)

The plants are erect in growth habit, precocious in bearing. The budded plants start fruiting in the 3th year [296-331-351]. The average fruit yield of eight-year old plant is 52.40 kg. The fruits are small in size (12.50 cm X 10.00 cm), round, with smooth surface and very thick rind (0.35cm), straw yellow at maturity, low in mucilage, and moderately fibrous, yellow pulp with high seed content [296-331-351]. Fruit pulp is of excellent taste (360Brix) and flavor and ascorbic acid 17.61 mg/100g of edible portion [296-331-351]. The fruit weight ranged from 750-800g and rind is very thick. It is highly suitable for powder making [296-331-351].

10.1.8. Narendra Bael-17 (NB-17)

This genotype is characterized by erect having semi spreading growth habit [296-331-351]. It is moderate and sparse in bearing. The budded plants start fruiting in the 4th year [296-331-351]. The average fruit yield of eight-year old plant is 51.39 kg [296-331-351]. The fruits are slightly large in size (20.00 cm X 15.50 cm), round, with smooth surface and very thin rind (0.24cm), straw yellow at maturity, low in mucilage, moderately fibrous and an attractive yellow pulp with low seed content [296-331-351]. Taste of pulp is excellent (340Brix) and ascorbic acid 19.63 mg/100g of edible portion. The fruit weight ranged from 1.65-1.8 kg [296-331-351]. It can be used for both table purpose and processing [296-331-351].

10.1.9. Pant Aparna

The trees are dwarf with drooping foliage, almost thorn-less, precocious and heavybearer [296-331-351]. The leaves are large, dark green and pear shaped [296-331-351]. Fruit has globose shape with average size of fruit 13.00 cm x 12.00 cm and weight of 0.8-1.25 kg [296-331-351]. Flesh yellow, sweet, tasty and having good flavor rind. Fruit pulp is yellow and rind is thin. TSS 35%, titratable acidity 0.67% and ascorbic acid 17.15 mg/100 g of pulp. Mucilage, seed and fibre are low [296-331-351]. Mucilage and seeds are enclosed in separate segments [296-331-351]. Flavour and taste are very good. Yield during 8th year is 61.06 kg/ plant [296-331-351].

10.1.10. Pant Shivani

It is an early mid-season variety [296-331-351]. Trees are tall, vigorous, dense, upright growth, precocious and heavy-bearer. Fruit shape is ovoid, oblong and the size being 18.50 cm x 15.00 cm [296-331-351]. Fruit weight ranges from 1.5 to 2.0 kg. Colour of fruit is lemon-yellow and its storage quality is good. Rind is medium-thin, pulp is lemon-yellow with pleasant flavour and mucilage, seeds and fibre are low to medium [296-331-351]. Taste is very good having 69% pulp, TSS 360 Brix, total titratable acidity 0.47% and ascorbic acid 19.55 mg/100 g of flesh. Average yield is 49.12 kg/plant during 7th yea [296-331-351].

10.1.11. Pant Sujata

It is mid-season variety but has problem of fruit splitting [296-331-351]. Trees are medium-dwarf with drooping and spreading foliage, dense, precocious and heavy bearer [296-331-351]. Thorns are stout and bigger. Fruit is globose shaped, depressed at both ends with average size of 14.50 cm x 13.50 cm and weight varied from 1.12 to1.70 kg under rainfed condition of hot semi-arid ecosystem of western India [296-331-351]. Fruit and pulp are light yellow. Storage life is better, thin rind, and seeds, mucilage and fibre is low [296-331-351]. Its flavour is pleasant and taste is very good [296-331-351]. Flesh is 72%, TSS 320 Brix, acidity 0.44% and ascorbic acid 17.10 mg/100 g of flesh. Average yield is 65.57 kg/plant during 8th year [296-331-351].

10.1.12. Pant Urvashi

It is an early mid-season variety [296-331-351]. Trees are tall, vigorous, dense, upright growing, precocious and heavy bearer [296-331-351]. Fruit is ovoid-oblong with average size of 14.50 cm x 17.20 cm and fruit weight ranges 1.5-2.50 kg. Fruit is yellow, rind is medium to thin and pulp is light yellow [296-331-351]. Fruit has 62.35% pulp with pleasant flavour [296-331-351]. Seeds and mucilage are medium, fibre content low, TSS 330 Brix, titratable acidity 0.49% and ascorbic acid 17.15 mg/100g pulp. Average yield is 60.15 kg/ plant during 8th year [296-331-351].

10.1.13. CHESB-16

According to Singh et al., [296-331-351], CHESB-16 is identified as a promising variety based on horticultural traits, which were collected from Vidyanagar, Gujarat, India during 2011 [296-331-351]. Average yield per plant 74.20 kg in 8th year [296-331-351]. Fruit weight ranged between 0.9- 1.20 kg, fruit size 15.50 cm x 11.40 cm, fruit girth 42.20 cm, shell thickness 0.20 cm, total number of seed 98.14, seed weight 0.19g, total seed weight 19.51g, fibre weight 31.42 g, shell weight 185.20g, locules in cross section 14-16,TSS pulp 37.130B, TSS mucilage 48.750B, acidity (0.34%) and vitamin C 20.80 mg/100g pulp were recorded. Growth habit is drooping. It is late maturing variety (3rd week of May) [296-331-351]. It is rich in antioxidants activity CUPRA C (micro M TE/g) was recorded 127.87 in mucilage and 90.87 in fruit pulp [296-331-351]. The fruits of this genotype are having good flavour and aroma. It is highly suitable for RTS , candy, murabba and powder making [296-331-351].

10.1.14. CHESB-11

This variety is identified as the promising genotype based on horticultural traits at CHES, Godhra, Gujarat, India [296-331-351]. Average yield per plant 84.10 kg in 8th year, fruit weight 1.48 kg, fruit size 14.10 cm x 15.20 cm, fruit girth

44.21 cm, shell thickness 0.14 cm, total number of seed 75, seed weight 0.20g, total seed weight 17.58g, fibre weight 25.60 g, shell weight 200.20g, locules in cross section 14-17, TSS pulp 38.130B, TSS mucilage 49.800B, acidity (0.29%) and vitamin C 22.83 mg / 100 g pulp were recorded [296-331-351]. It is medium maturing variety (1st week of May). It is rich in antioxidants activity. The fruits of this genotype are having good flavour and aroma. It is highly suitable for sherbet; murabba and powder making [296-331-351].

10.1.15. CHESB-21

It was collected from bael bagh near **Somnath temple, Gujarat**, India during the year 2012 [296-331-351]. Average yield per plant 62.57 kg in 7th year, fruit weight ranged between 1.25-1.50 kg, fruit size 21.200 cm x 13.40 cm, fruit girth 43.78 cm, shell thickness 0.21 cm, total number of seed 104.15, seed weight 0.20g, total seed weight 20.51g, fibre weight 40.42 g, shell weight 205.10g, locules in cross section 14-16, TSS pulp 39.150B, TSS mucilage 50.500B, acidity (0.37%) and vitamin C20.80 mg/100g pulp were recorded [296-331-351]. It is late maturing variety (1st week of May). The fruits of this genotype are having good flavor and aroma. It is highly suitable for pickle, sherbet; candy, jam and powder making [296-331-351].

10.1.16. Thar Divya

It starts ripening after 270 days of fruit setting under rainfed conditions of hot semi-arid ecosystem [296-331-351]. Fruits of this variety are comparatively less affected (40%) by sunscald due dense canopy and luxuriant growth [296-331-351]. The average yield/tree (kg) during 8th year, fruit weight (kg), fruit size (cm), fruit girth(cm), shell thickness (cm), number of locules in cross section (seed cavity), peel weight (g), pulp weight (kg), fibre weight (g), seed weight(g), total seed weight (g), total number of seed, TSS of pulp (obrix), TSS of mucilage (obrix), acidity (%),TSS /acidity ratio are 7.50, 1.62, 18.60x14.80, 45.80, 0.19, 14.72, 235.50, 1.30, 61.10, 0.13, 32.00, 120.75, 38.50, 51.00, 0.30 and 128.33, respectively [296-331-351]. This variety matures during February and belongs to very early maturing group and can be grown successfully under rainfed semi-arid ecosystem [296-331-351].

10.1.17. Thar Neelkanth

It is a superior genotype having compact growth, medium height, less spiny, better yield with quality fruits having pleasant flavour and attractive colour of pulp. It started flowering and fruiting from 3rd year of budding [296-331-351]. Average yield per plant 75.67 kg (8th year), average fruit weight 1.45 kg, fruit size 15.10 cm x 15.00 cm, fruit girth 47.30 cm, shell thickness 0.18cm, total number of seed 73, seed weight 0.21g, total seed weight 15.46g, fibre weight 110.17 g, shell weight 265.00g, locules in cross section 13-16, pulp 71.30%, TSS pulp 40.100B, TSS mucilage 51.500B, acidity (0.30%) and vitamin C 19.90 mg / 100 g pulp were recorded. The fruit of this genotype is having good flavour and aroma [296-331-351]. It is highly suitable in draught prone dry land conditions and also suitable for shsrbet, powder candy and squash making [296-331-351].

According to Singh et al., [296-331-351], a rich genetic diversity of Bael are available throughout India especially in the states of U.P., Bihart, Haryana, Gujarat, Punjab, Rajasthan, Uttarakhand, Jharkhand, Chhatisgarh, M.P, Karnataka, Himachal Pradesh etc. which should be exploited for selection of better genotypes [296-331-351]. Bael based farming models should be developed for higher yield, better return and proper land utilization [296-331-351]. Fruit drop, sun scald and fruit cracking are the major problems of bael cultivation in different parts of India [296-331-351]. To overcome these problems, suitable genotypes should be identified with high yield potential and better fruit quality [296-331-351]. Development of low seeded variety is necessary to lure this fruit [296-331-351]. More emphasis on post-harvest technology should be given for value added and export oriented processed products. Establishment of small scale processing units should be promoted [296-331-351].

11. Bael Tree: Pathogens and Disease

Bacterial shot hole, fruit canker and gummosis are some of the serious diseases of Bael [296-331-351]. More than a dozen insect pests have been found feeding on bael [296-331]. *Phyllocnistis citrella, Aonidiella aurantii* and *Papilio demoleus* are the important insects, which can easily be controlled by the use of suitable insecticides [296-331-351]. Fruit cracking, fruit drop and sunscald are the physiological disorders which affect the productivity as well as quality of bael [296-331-351]. Bael tree is not affected by serious diseases [296-331-351]. However, powdery mildew, shot hole and fruit canker, Alternaria leaf spot, Fusarium Rot, Shell Softrot of bael, Powdery Mildew, Fruit Rot, Black Leaf Spot, Bacterial Shot Hole and Fruit Canker, Stalk end rot of bael is caused by Fusarium solan, have been reported, which can be controlled by removing affected portion or by chemical sprays [296-331]. Like other *Rutaceous* plants of citrus family, oozing of gum is common in bael orchards [296-331]. The disease is characterized by oozing out of pale or amber coloured gummy substance initially from bark of lower portion of trunk and later on other branches also [296-331-

351]. The gum oozing takes place from vertical splits in bark which turns dark from outside at the point of oozing but from inside other surrounding bark tissues turn light brown or white and very soft and sticky when touched with fingers [296-331-351]. Because of gummosis, the vigour of tree is severely affected and in severely affected twigs defoliation and dieback occurs [296-331-351]. To manage the disease it is suggested to scrap off the infected portion of bark with the help of a sharp knife, which should be followed by application of Bordeaux paste [296-331-351]. Spray with Copper fungicides (Bordeaux mixture 1% or copper oxychloride (0.3%) are also suggested to be applied at monthly interval during and after rainy season [296-331-351]. Removal of highly infected twigs and incorporation of Trichoderma viridae propagules in the soil of rhizosphere of bael were found helpful to control the disease [296-331-351].

12. Conclusion

Bael [*Aegle marmelos* (L.) Correa], belonging to the *Rutaceae* family, holds significant prominence as an underutilized fruit crop in India and is well-known for its nutritional and therapeutic qualities. It is mainly found in tropical and subtropical locations and it is remarkably adaptable to difficult soil and environmental circumstances. It thrives in alkaline, rocky, and shallow soils and can tolerate temperatures between − 7 to 50 ^{o}C. Bael fruits, is composed of bioactive compounds such as carbohydrates, proteins, various vitamins, fatty acids, and minerals, along with many phytochemicals, flavonoids, saponins, tannins, phenolic acids, and glycosides. The bael fruit has also proved to possess antidiarrheal, antioxidant, antidiabetic, hepatoprotective, radioprotective, and anti-cancerous properties in various experiments conducted *in vivo* and *in vitro* on human cell lines and animal models. These investigations have shown that *A. marmelos* has therapeutic potential and contains elements that could be used to make new medications for the prevention, mitigation, or treatment of diabetes, cancer, and a variety of pathogenic illnesses. *A. marmelos* has been historically used for a variety of ethno botanical purposes. Unfortunately, most compounds still need to be thoroughly assessed to investigate novel lead molecules or pharmacophores. Furthermore, the mechanisms of a few bioactive chemicals have been discovered so far. Comprehensive research is necessary to ascertain the mechanisms of action, the bioactivity of numerous phytochemicals, and the effectiveness of *A. marmelos* medicinal characteristics. Therefore, it is essential to develop clinical research on this medicinal Bael plant and learn from traditional healers who have gathered knowledge through many generations of trial and error. In the future, clinical trials will be conducted for those activities.

The demand for Bael fruit is likely to increase due to its growing popularity as a health food and ingredient in various food and beverage products. Additionally, the growing interest in traditional and natural remedies for various health conditions is likely to drive demand for Bael fruit. The fruit contains about 61% of moisture and multiple vitamins like vitamin A, vitamins B1 and B2, and vitamin C, along with minerals like potassium, phosphorous, iron, and calcium. Furthermore, it contains fiber, protein, and sugars both reducing and nonreducing. Its food value is 88 calories per 100 g, which is more plentiful than other common fruits like apples, guavas, and mangos, with 64, 59, and 36 calorific values, respectively.

On the basis of above mentioned pharmacological properties of fruit pulp of *A. marmelos* it is concluded taht has *A. marmelos* has a promising future in treating and preventing different ailments, including cancer, infectious disorders and diabetic conditions. The pulp of the bael fruit is rich in bioactive substances such as carotenoids, phenolics, alkaloids, pectins, tannins, coumarins, flavonoids, and terpenoids, according to studies. The phytochemistry of *A. marmelos* has been extensively studied, and the plant has been found to contain a variety of biologically active compounds. The use of bael has gained popularity worldwide as its beneficial characteristics are being researched to develop new treatments potentially. As a result, the demand for novel therapeutic drugs with focused action and limited adverse effects justifies further clinical and preclinical research on Bael (*A. marmelos*).

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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