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COMPARATIVE REVIEW ON FLAVONOID CONTENT IN KAITHA (*FERONIA LIMONIA*) AND BAEL (*AEGLE MARMELOS*)

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ABSTRACT: Background: For centuries, *Feronia limonia* (Wood Apple) and *Aegle marmelos* (Bael) have served as vital components of traditional medicine in the Indian subcontinent. Both members of the Rutaceae family are prized for their secondary metabolites, particularly flavonoids, which offer potent antioxidant, anti-inflammatory, and cardioprotective benefits. **Objective:** This review provides a comparative evaluation of the botanical characteristics, phytochemical diversity, and flavonoid concentrations of these two species to determine their relative therapeutic potential. **Methods:** The study synthesizes existing quantitative data, focusing on extraction efficiencies across various solvents and the biosynthetic pathways Shikimic, Mevalonic, and Malonic acid responsible for their bioactive profiles. **Results:** Analysis reveals that *Aegle marmelos* exhibits superior phytochemical diversity and higher flavonoid abundance, with maximum reported values reaching 135.17 mg QE/g in fruit extracts. Comparatively, *Feronia limonia* shows a maximum of 35.25 mg QCE/g. Discrepancies in content are primarily driven by the plant part utilized, solvent polarity, and fruit maturity stages. **Conclusion:** While both plants are significant sources of bioactive markers, *Aegle marmelos* demonstrates a more robust flavonoid profile. This comparative insight supports the optimization of extraction protocols for developing high-potency herbal formulations and nutraceuticals.

INTRODUCTION: Over the past 100 years, the development and mass production of chemically synthesized drugs have reformed health care in most parts of the word [1]. Plants have always been a vital part of human life, not just for food and shelter but also for healing. Across cultures and medical traditions, people have relied on plants to treat illnesses for thousands of years. Even today, many medicines come from plant-based compounds.

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Out of the many plant species in the world, a significant number have been used in traditional remedies, and countries like India play a major role in supplying medicinal plants globally. From easing physical pain to supporting mental well-being, plants continue to help us stay healthy and resilient [2].

Plants have been used for centuries in traditional medicine due to their rich phytochemical composition. Among these compounds, flavonoids are widely recognized for their health-promoting properties, including antioxidant, anti-inflammatory, and cardioprotective effects [3, 4]. Plant, being main source of various medicine, plays an important and significant role in the health of both plant as well as human [5].

This medicinal importance of plants is primarily attributed to the diverse bioactive compounds they contain. Phytoconstituents (often called phytochemicals) are the natural bioactive chemical compounds found in plants.

Unlike "primary metabolites" (like sugar and protein) which the plant needs to grow, phytoconstituents are often "secondary metabolites" produced to protect the plant from pests, UV radiation, and disease [6]. Phytoconstituents are not just random chemicals; they are highly organized molecules synthesized through specific metabolic pathways.

Most secondary metabolites originate from three main pathways:

- **Mevalonic Acid Pathway:** Leads to the creation of Terpenoids and Steroids.
- **Shikimic Acid Pathway:** The precursor to most Phenolics and Alkaloids.
- **Malonic Acid Pathway:** Primary source for Quinones and some Phenols.

Understanding these pathways allows scientists to "bio-engineer" plants or use microbes to produce high volumes of a specific medicine [7].

TABLE 1: MAJOR CLASSES OF SECONDARY METABOLITES [8, 9, 10]

Class	Key Characteristics	Common Examples
Alkaloids	Nitrogen-containing compounds; often have potent effects on the human nervous system.	Morphine, Caffeine, Nicotine, Quinine.
Flavonoids	Pigments responsible for the colors of fruits/flowers; powerful antioxidants.	Quercetin (onions), Anthocyanins (berries).
Terpenoids	Largest group; often responsible for plant fragrance and essential oils.	Menthol, Camphor, Taxol (anti-cancer).
Phenolics	Simple structures that protect against oxidative stress.	Resveratrol (grapes), Curcumin (turmeric).
Glycosides	Compounds linked to a sugar molecule; often affect heart or digestive function.	Digoxin (foxglove), Sennosides (senna).
Saponins	Soap-like compounds that foam in water; help lower cholesterol.	Found in Ginseng and Legumes.

In this framework, Kaitha (*Feronia limonia*) and Bael (*Aegle marmelos*) stand out as two important medicinal fruit-bearing plants known for their diverse pharmacological properties and bioactive constituents, particularly flavonoids.

***Feronia limonia*:** Wood apple is a thorny tree and most common underutilized fruit crop in India. It belongs to the family Rutaceae and is botanically known as *Feronia limonia* [11]. This species is indigenous to the Indian subcontinent and is extensively found in India, Sri Lanka, Bangladesh, and certain areas of Southeast Asia. It flourishes in various agro-climatic conditions, especially in arid and semi-arid regions, and is often seen growing wild or semi-wild along roadsides, forest edges, and marginal lands [12]. In India, it is known by various vernacular names such as [13]:

Language	Vernacular names
Assamese	Bal
Bengali	Koth bel
Gujarati	Kothu
Hindi	Kaitha
Kannada	Beladadhannu
Malayalam	Vilam kai
Marathi	Kavath
Oriya	Kaitha
Sanskrit	Kapitha
Tamil	Vilam pazham
Telugu	Vellagapandu

FIG. 1: *FERONIA LIMONIA* RIPE FRUIT

FIG. 2: *FERONIA LIMONIA* UNRIPE FRUIT

The tree is medium to large in size, grows slowly, is deciduous, and features sharp axillary spines. The leaves of *F. limonia* are arranged alternately, imparipinnate, and aromatic, usually consisting of 5 to 9 leaflets. Each leaflet is ovate to elliptic in shape, with either entire or slightly crenate edges, a glossy green upper surface, and a lighter-colored underside. When crushed, the leaves release a distinctive citrus-like scent due to the essential oils present, a characteristic common to the Rutaceae family. The morphology of the leaves is crucial for taxonomic identification and demonstrates the plant's adaptation to dry environments through reduced transpiration and thicker leaf tissues [14]. The fruit of *Feronia limonia* is round with a tough, woody outer shell. Inside, it contains a fragrant brown pulp that's rich in carbohydrates, minerals, vitamins, and beneficial plant compounds. People have traditionally eaten the pulp fresh or used it to make drinks, chutneys, and herbal remedies.

Beyond the fruit, other parts of the plant like the leaves and bark are also valued in traditional medicine. They've been used to help with digestive problems, diarrhea, inflammation, and liver-related issues. In particular, extracts from the leaves are known for their antimicrobial, antioxidant, and anti-inflammatory effects, making the plant an important part of natural healing practices [15].

***Aegle marmelos*:** *Aegle marmelos* (L.) Correa, popularly known as Bael, is a spiritually and medicinally revered tree belonging to the Rutaceae family and is considered one of the most important medicinal plants of the Indian subcontinent [16]. Native to India, it is distributed across Southeast Asian countries, including Sri Lanka, Pakistan, Bangladesh, and Burma [17]. The tree is highly resilient, thriving in diverse agro-climatic conditions from the foothills of the Himalayas to the dry deciduous forests of central and southern India, and is often found growing in wild or semi-wild states [18]. In India, it is known by various vernacular names such as, the branches often feature sharp, straight, axillary spines, though cultivated varieties may have fewer [19]. Unlike the 5–9 leaflets of the Wood Apple, Bael leaves are trifoliate (clusters of three). They are alternate and aromatic, with a pinkish-maroon hue when young that matures into a glossy dark green. When crushed, they emit a distinctive, slightly disagreeable medicinal odor. The flowers are greenish-white, sweet-scented, and grow in small clusters along young branchlets. The fruit is globose or pear-shaped with a smooth, woody shell that turns yellow or greenish-yellow upon ripening. Unlike the Wood Apple's grainy brown pulp, Bael pulp is orange, aromatic, and pasty, containing 8–20 triangular segments filled with a sweet, resinous mucilage [19, 2, 20].

Language	Vernacular names
Bengali	Bel
English	Bengal Quince, Golden Apple, Stone Apple
Hindi	Bel, Bael
Kannada	Bilva
Malayalam	Vilwam
Marathi	Bel
Gujrati	Bili
Tamil	Vilvam
Telugu	Maredu
Sanskrit	Bilva, Kapitha

FIG. 3: *AEGLE MARMELOS* (L.) UNRIPE FRUIT

FIG. 4: *AEGLE MARMELOS* (L.) RIPE FRUIT

Flavonoids: Flavonoids represent a diverse class of polyphenolic secondary metabolites that are ubiquitous in the plant kingdom, particularly within the Rutaceae family, which includes *Aegle*

marmelos (Bael) and *Feronia limonia* (Wood Apple) [21]. These compounds are not only essential for the plant's physiological survival but also provide significant therapeutic value to humans [22].

Flavonoids are low-molecular-weight polyphenolic compounds characterized by a basic phenylchromane skeleton (C_6-C_3-C_6) consisting of two benzene rings (A and B) linked by a three-carbon heterocyclic pyran or pyrone ring (C). They are naturally occurring pigments found in the nascent parts of plants, providing fragrance and taste to fruits and flowers while acting as key bioactive markers [22]. Following is the tree diagram of classification of the Flavonoids [23]:

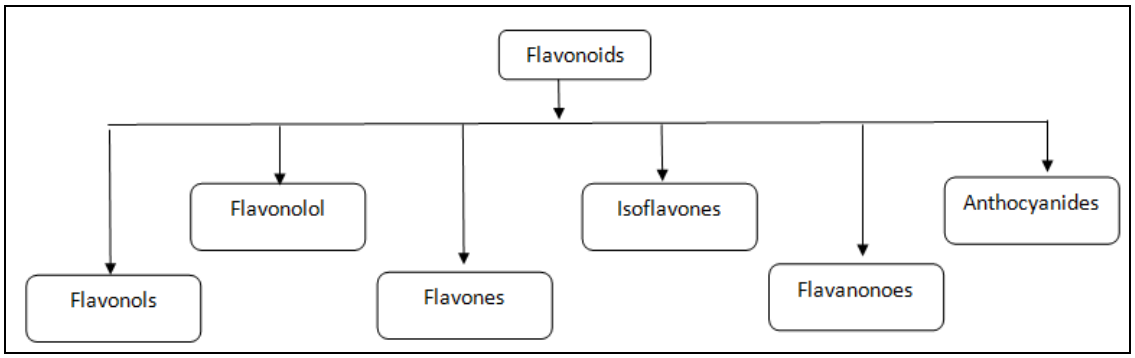

FIG. 5: CLASSIFICATION OF FLAVONOIDS

Flavonoids are biologically important plant polyphenols because they protect the plant and also contribute to many health-related effects in humans. In plants, they act as UV filters, pigments, signal molecules, and defense compounds, and they help the plant tolerate drought, heat, freezing, and other stresses by scavenging reactive oxygen species [24, 25].

Pharmacological Activities Linked to Flavonoids:

Antioxidant Protection: Flavonoids are best known for their antioxidant activity. They can directly neutralize free radicals, chelate metal ions that promote oxidation, inhibit enzymes that generate reactive oxygen species, and boost the body's own antioxidant defenses. Their antioxidant strength depends on their chemical structure, especially the number and position of hydroxyl groups [24, 26].

Anti-inflammatory Effects: Flavonoids help reduce inflammation by lowering oxidative stress and by modulating enzymes and transcription factors involved in inflammatory signaling. They can also influence immune-cell activation and secretion, which is why they are linked to protection against chronic inflammatory conditions [24, 27].

Cardioprotective Role: Dietary flavonoids are associated with cardiovascular protection because they help prevent lipid oxidation, reduce inflammation, improve endothelial function, support vasodilation, and may reduce platelet aggregation. These actions are one reason flavonoid-rich foods such as fruits, tea, wine, and vegetables are often linked with lower cardiovascular risk [25, 27].

Anticancer Potential: Flavonoids are studied for anticancer activity because they can interfere with several steps in tumor development. Reported mechanisms include inhibition of carcinogen activation, induction of apoptosis, cell-cycle arrest, suppression of angiogenesis, and modulation of signaling pathways linked to proliferation and survival [28, 29].

Antimicrobial and Antiviral Activity: Many flavonoids also show antimicrobial activity. They can disrupt microbial membranes, inhibit biofilm formation, and interfere with nucleic acid synthesis, energy production, and protein synthesis; some also show antiviral effects [30, 31].

Neuroprotective and Anti-aging Relevance: Flavonoids are also linked to neuroprotection and anti-aging effects because oxidative stress and inflammation are major contributors to neuronal damage and cellular aging. Their ability to reduce oxidative injury and modulate signaling pathways gives them potential relevance in age-related and neurodegenerative disorders [32, 33].

Antidiabetic and Immunomodulatory Effects: Some flavonoids influence glucose metabolism, insulin signaling, and inflammatory pathways, which is why they are often discussed in relation to antidiabetic potential. Others modulate immune responses by affecting immune-cell activity and signaling cascades [34, 35, 36]. Both plants are relevant to flavonoids because flavonoids are part of their phytochemical profile and help explain much of their medicinal value. In *Feronia limonia* (*Limonia acidissima*), flavonoids have been reported in the fruit, along with other bioactive constituents, which supports its traditional use and pharmacological interest. In *Aegle marmelos*, flavonoids are also identified as major phytochemicals in the fruit and other plant parts, and they are linked with antioxidant, antidiabetic, anticancer, antibacterial, antiviral, and hepatoprotective activities [37, 38].

TABLE 2: TAXONOMY, MORPHOLOGY, DISTRIBUTION

Feature	*Feronia limonia*	*Aegle marmelos*
Taxonomy	The currently accepted name is *Limonia acidissima* L., and *Feronia limonia* (L.) Swingle is a synonym. It belongs to family Rutaceae and order Sapindales [39, 40]	The accepted name is *Aegle marmelos* (L.) Corrêa. It belongs to family Rutaceae and order Sapindales [41]
Morphology	A slow-growing, deciduous, erect tree with a few upward-reaching branches that bend outward near the top and end in drooping branchlets. It is usually about 9 m tall, has sharp spines, and bears alternate leaves that are leathery, dark green, and slightly lemon-scented when crushed. The fruit is round to oval with a hard woody rind and aromatic pulp [42]	A slow-growing, deciduous shrub or tree that can reach 10 to 15 m in height. It has a short trunk, a dense crown, and spines on older branches and basal suckers; the leaves are alternate and compound, usually with 3 to 5 oval pointed leaflets, and the mature leaves are aromatic when bruised. The tree produces fragrant flowers and a hard-shelled fruit with aromatic pulp [43, 44]
Distribution	Native to the Indian subcontinent and Andaman Islands, especially India, Pakistan, Bangladesh, Sri Lanka, Assam, and the Andaman Islands. It is also introduced in Cambodia, Fiji, Laos, Myanmar, and Vietnam [39]	Native to the Indian subcontinent, especially Assam, Bangladesh, India, Nepal, Pakistan, and the West Himalaya. It has also been introduced into many tropical regions, including Sri Lanka, Myanmar, Cambodia, Laos, Vietnam, China South-Central, and others [45]

Phytochemical Composition:

***Feronia limonia*:** Major phytochemicals reported in the literature are phenolics, flavonoids, alkaloids, saponins, and tannins, with phenolics repeatedly highlighted as a major fraction in the fruit pulp and unripe fruit extracts [46]. The fruit pericarp has also been reported to contain coumarin-type constituents such as marmesin, psoralen, xanthotoxin, 2,6-dimethoxy-benzoquinone, and osthenol [46].

***Aegle marmelos*:** Major phytochemicals reported across leaves, fruit, roots, and bark include alkaloids, flavonoids, phenolic acids such as protocatechuic, gallic, and ellagic acid, coumarins, tannins, terpenoids, glycosides, fatty acids, and essential oils [16, 37, 47].

Specific compounds reported include marmelosin, marmesin, imperatorin, aegelin, aegelenine, dictamine, fragrine, skimmianine, and other volatile constituents such as cineole, citral, citronellal, cuminaldehyde, and eugenol [48, 49].

Comparative Insight:

- *Aegle marmelos* shows richer documented phytochemical diversity because the reviewed literature reports more chemical classes across multiple plant parts, including coumarins, alkaloids, flavonoids, phenolic acids, tannins, terpenoids, glycosides, fatty acids, and volatile compounds [49].
- *Feronia limonia* is also phytochemically rich, but the retrieved reviews emphasize a narrower profile centered on phenolics, flavonoids, alkaloids, saponins, tannins, and some coumarin-related constituents [46].
- Overlapping groups between both plants are mainly phenolics, flavonoids, alkaloids, tannins, coumarin-type compounds, and saponins [48, 49].

Methods Used in Studies:

- In *Feronia limonia*, one quantitative study extracted unripe fruit using distilled water, ethanol, methanol, and acetone at 60%, 80%, and 100% concentrations for 24 and 48 h, then

estimated flavonoids spectrophotometrically and reported them in quercetin equivalents [50].

- In *Aegle marmelos*, the common workflow is solvent extraction followed by Folin-Ciocalteu for total phenolics and the aluminum chloride colorimetric assay for total flavonoids, with quercetin used as the standard [51, 52].
- Several *Aegle marmelos* studies used methanolic or hydroalcoholic extracts and then quantified flavonoids by the same quercetin-based colorimetric approach [53].

Flavonoid Content in *Feronia limonia*

- The clearest numeric result in the retrieved studies is from the unripe fruit extract, where the highest flavonoid content was 35.25 mg QCE/g in 100% methanol extract [50].
- A stage-comparison study on wood apple measured total flavonoids at three fruit stages using spectrophotometry and reported that antioxidant activity was highest in the unripe stage, but the abstract does not give the stage-wise flavonoid numbers [54].
- Solvent also matters in wood apple: another study on *Limonia acidissima* fruit reported that flavonoid content was highest in methanol extract and lowest in chloroform extract, showing the same solvent-dependence pattern [55].

Flavonoid Content in *Aegle marmelos*:

- In methanolic extracts of fruit and leaves, total flavonoid content was 135.17 ± 2.02 mg QE/g for the fruit and 111.2 ± 3.67 mg QE/g for the leaves [56].
- In another leaf-focused study, total flavonoid content was 37.4 ± 2.65 µg quercetin equivalent/mg extract, which is the same as 37.4 mg QE/g [53].
- A comparative study of methanolic extracts from leaves, root, and stem bark reported total flavonoids ranging from 1.087 ± 0.002 to 8.248 ±0.029 mg/g, with leaves showing the strongest antioxidant profile in that study [56].
- In a seed study, total flavonoids ranged from 3.267 to 12.933 mg/g in the tested extracts, again using quercetin as the reference standard [57].
- A broader extraction study on bael-based plant foods reported flavonoid levels of 50.3 to 114.8 mg QE/g dried extract, which supports that *Aegle marmelos* extracts can be quite flavonoid-rich depending on the matrix and extraction protocol [58].

Comparative Reading:

- Based on the retrieved quantitative studies, *Aegle marmelos* shows the richer documented flavonoid profile, with reported values reaching 135.17 mg QE/g, whereas the clearest fruit value retrieved for *Feronia limonia* is 35.25 mg QCE/g [56, 50].
- The overlapping analytical pattern across both species is methanol-based extraction plus quercetin-equivalent reporting, which makes the flavonoid data broadly comparable at a conceptual level but not perfectly head-to-head because plant part, solvent strength, and extraction time differ across studies [50, 53, 56].

Comparative Evaluation: Using the reported quantitative studies, *Aegle marmelos* has the higher documented flavonoid content overall, with maxima up to 135.17 ± 2.02 mg QE/g in fruit extract, compared with the highest clearly reported *Feronia limonia* value of 35.25 mg QCE/g in unripe fruit methanol extract [56, 59].

This comparison is directionally reliable, but not perfectly standardized, because the studies report flavonoids in different matrices and units such as mg QE/g, mg QE/100 g fresh weight, mg CE/g dry weight, and mg rutin equivalents/g [56, 59, 60, 61].

TABLE 3: TABLE OF REPORTED FLAVONOID VALUES

Species	Plant part or stage	Extraction / Assay	Reported flavonoid content	Reference
Feronia limonia	Unripe fruit	100% methanol, 48 h; spectrophotometric QE	35.25 mg QCE/g	[59]

		assay		
Feronia limonia	Fruit during ripening	80% methanol; AlCl3 colorimetric method	Flavonoid content did not differ remarkably across S1, S2, S3; slightly increased from S1 to S2 and remained unchanged at S3	[60]
Aegle marmelos	Fruit extract	Methanolic extract; quercetin equivalent	135.17 Â± 2.02 mg QE/g	[59]
Aegle marmelos	Leaf extract	Methanolic extract; quercetin equivalent	111.2 Â± 3.67 mg QE/g	[59]
Aegle marmelos	Aqueous leaf extract	AlCl3 method; rutin standard	16.36 mg rutin equivalent/g extract	[61]
Aegle marmelos	Leaves, root, stem bark	Methanolic extracts; quercetin equivalent	1.087 Â± 0.002 to 8.248 Â± 0.029 mg/g	[62]
Aegle marmelos	Seeds	Aqueous and methanolic extracts; quercetin equivalent	3.267 to 12.933 mg/g	[57]

Why the Differences Occur:

Plant Parts Matters: In *Aegle marmelos*, fruit and leaf extracts can be much richer in flavonoids than root or stem bark, and the same plant can show strong part-wise variation in both flavonoid level and antioxidant activity [59, 62].

Solvent Polarity Matters: For *Feronia limonia*, methanol gave the highest flavonoid recovery among the tested solvents, and in bael-related studies methanolic extracts often outperformed ethanol for phytochemical recovery [59, 37]. The aqueous leaf extract of *A. marmelos* still showed measurable flavonoids, but the method and solvent choice clearly influenced the final value [61].

Ripening or Maturity Stage Matters: In wood apple, total flavonoids changed only modestly during ripening, while phenolics and antioxidant traits shifted more clearly, suggesting that maturity affects the broader phytochemical profile but not always flavonoids dramatically [60]. In bael, the review literature also reports variation in flavonoid-related compounds across maturity or processing conditions [37].

Reporting Units and Extraction Basis Differ: Some papers express content per gram of extract, others per 100 g fresh weight or dry weight, so numerical comparison across studies is approximate rather than strictly head-to-head [59, 60, 61].

Bottom-Line Interpretation/ Conclusion: Across the retrieved research and review papers, *Aegle marmelos* shows the higher reported flavonoid abundance overall, especially in fruit and leaf extracts, while *Feronia limonia* shows flavonoid-rich extracts but with a lower reported maximum in the accessible studies. The main drivers of variation are plant part, extraction solvent, maturity stage, and reporting basis [59, 62].

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