IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 7, October 2026
Impact Factor: 8.2

Stone Apple (Limonia Acidissima L.): A Comprehensive Review of its Nutritional, Phytochemical, Anti-Inflammatory Potential

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Abstract: *Stone apple (Limonia acidissima), a member of the family Rutaceae, is an edible fruit-bearing plant with significant nutritional and medicinal value. Despite being widely available in India, its therapeutic potential is still largely unexplored. Ayurvedic medicine has traditionally used the plant's leaves, bark, roots, fruits, and seeds to treat a variety of illnesses. The stone apple (Limonia acidissima) is widely consumed as an edible fruit and used to make a variety of food products, such as traditional preparations, jams, chutneys, and refreshing drinks. Different parts of the plant seem to be used in traditional medicine for their laxative qualities and to treat gastrointestinal issues like constipation, peptic ulcers, dysentery, and diarrhea. The biological activities of L. acidissima may be influenced by these components. These bioactive substances imply that stone apples may have the ability to control inflammatory reactions and inhibit the growth of specific harmful bacteria. However, additional research is required to determine its therapeutic efficacy and safety, especially in vivo studies and clinical research.*

Keywords: Limonia acidissima, Stone apple, Phytoconstituents, Flavonoids, Phenolic compounds, Anti-inflammatory activity, Antibacterial activity

I. INTRODUCTION

Stone apple is an underexploited tropical fruit that possesses substantial nutritional, medicinal, and functional food value. Ithas become traditionally consumed in India and various regions of South and Southeast Asia and has been utilized in traditional systems of medicine for centuries. [1]Stone apple provides several dietary fiber, minerals, and vitamin C. In addition, it contains a variety of biologically active phytochemicals, such as terpenoids, and coumarins. Its antioxidant potential is associated with constituents such as carotenoids, ascorbic acid, tocopherols2] Traditionally, stone apple has traditionally been employed management of various health conditions, including diarrhoea, dysentery, cough, sore throat, digestive problems, wounds, and inflammatory disorders. Research on different fruit extracts and their bioactive constituents has demonstrated antioxidant, antimicrobial, hypoglycaemic, and potential anticancer activities.[3]. Beyond its traditional medicinal significance, *Limonia acidissima* offers additional possibilities for food product development, processing, and the commercial utilization of its nutritional resources. Its pulp May be explored for use in the preparation of various products including juices, ready-to-serve beverages, jams, jellies, preserves, candies, pickles, yoghurt, and other processed foods. Such processing approaches can enhance the utilization, shelf life, and commercial potential of this less-exploited fruit. [4] Further systematic research on its phytochemical composition, biological properties, processing techniques, and value-added products could contribute to the wider utilization and commercialization of this underexploited tropical fruit.[5]

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DOI: 10.48175/IJARSCT-40430

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Figure No.1 Stone Apple Fruit(Limonia acidissima)

A) Source of Phytochemical in L. acidissima

1. Leaves

Traditional medicinal literature has associated leaf-based preparations with potential diuretic, cardiotonic, and liver-protective properties. However, these reported effects require further scientific investigation to establish their efficacy and underlying mechanisms [6].

2. Bark

The bark of *Limonia acidissima* has attracted attention as a valuable source of pharmacologically relevant natural compounds. Investigations of the plant's chemical profile have reported multiple classes of phytoconstituents, ranging from alkaloids and flavonoids to saponins, tannins, steroids, glycosides, resins, and phenolic substances.[7]

3. Fruit

The fruit represents the principal edible component of *Limonia acidissima* and contributes to its nutritional, medicinal, and commercial significance. Laboratory investigations have focused on the biological potential of the fruit and its constituent compounds, with reported areas of investigation including antioxidant, antimicrobial, antidiabetic, and anti-inflammatory activities. Nevertheless, these findings should be interpreted in accordance with the available experimental evidence, as traditional applications and laboratory observations do not independently establish clinical effectiveness [8].

4. Fruit Pulp

The edible pulp constitutes an important nutritional component of stone apple and contains a variety of nutrients and naturally occurring phytochemicals. Comparative analyses have suggested that the pulp may contain a relatively greater proportion of protein than certain other parts of the fruit, although the reported composition can vary according to the sample and analytical method. [9].

5. Fruit Rind

The outer shell of *Limonia acidissima*, recognized as the fruit rind, constitutes another plant material of interest because of its diverse phytochemical composition. Certain comparative investigations have also reported a the presence of comparatively high levels of amino acids in the rind compared with some other examined fruit components.

6. Seeds

The seeds of *Limonia acidissima* are embedded within the fruit pulp and are associated with a mucilaginous substance. Research has revealed the occurrence of fixed oils and fats in the seeds, while some compositional studies have identified carbohydrates as an important component. [10].

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Figure No.2 Source of Phytochemical in L. acidissima

B) Chemical Constituents of Stone Apple (Limonia acidissima)

The major chemical groups include saponins, steroids, glycosides, coumarins, triterpenoids, fatty acids, gums, mucilage, proteins, carbohydrates, and amino acids. The phytochemical profile may differ have confirmed the existence of diverse examined and the extraction method used.

1. **Flavonoids**
   Flavonoids constitute an important group of polyphenolic compounds found in stone apple. Kaempferol, catechin, and proanthocyanidins have been reported mainly in the fruit pulp. Leaves also contain flavonoids such as orientin, vitexin, and saponarin. [11]
2. **Phenolic Compounds**
   Among the phenolic acids identified in stone apple, *m*-coumaric acid and syringic acid are notable constituents. Analysis of the plant's chemical composition has revealed that thefruit pulp contains these compounds, with *m*-coumaric acid being particularly prominent in the reported analyses.
3. **Alkaloids**
   Alkaloids are nitrogen-containing secondary naturally occurring compounds characterized in different parts of L. acidissima. Phytochemical screening has demonstrated their presence in the bark, leaves, rind, pulp, and seeds. The occurrence of alkaloids have a role in promoting the diverse biological and pharmacological properties associated with the plant.[12]
4. **Tannins**
   Tannins are plant-derived polyphenolic substances known for their characteristic astringent properties. These phytochemicals are of research interest due to their possible role in neutralizing free radicals and producing a tissue-tightening effect.

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5. **Saponins**
   Saponins constitute another group of naturally occurring secondary metabolites reported in Limonia acidissima. Saponins have been linked to a range of biological functions in plants. ; however, their specific pharmacological effects in Limonia acidissima require further investigation.
6. .Steroids and Phytosterols
   Phytochemical investigations of *Limonia acidissima* have identified several plant-derived sterols, among which β-sitosterol and stigmasterol are notable constituents. These phytosterols have shown documented in analyses of different plant materials, particularly the fruit, seeds, and foliage. [13]
7. **Triterpenoids**
   Phytochemical studies of Limonia acidissima have revealed the occurrence of several triterpenoids, including lupeol and β-amyrin, which were reported mainly in analyses of the fruit and seeds.
8. **Coumarins**
   Different coumarin and furanocoumarin derivatives have shown noted in stone apple. Reported compounds include bergapten, psoralen, osthole, marmesin, isopimpinellin, isoimperatorin, and methoxsalen. [14]
9. **Gums and Mucilage**
   Gums and mucilage are also reported in stone apple, especially in the fruit pulp and rind. These substances contribute to the **morphological Features and Physical Properties of the Fruit** and may also have nutritional and pharmaceutical significance.15]

C) Uses of Stone Apple in Various Preparation

The edible pulp of stone apple (Limonia acidissima) offers opportunities for various food-related applications because of its nutritional composition and potential functional properties.Because of its characteristic sweet-sour flavour, aroma, fibre, and pectin content, the fruit can be converted into several value-added products.

- **Juice:** The ripe pulp is separated from the hard shell, mixed with water, sweetened if required, and filtered to prepare stone apple juice. It can be consumed as a refreshing fruit beverage. [16]
- **Sherbet (Sarbat):** Stone apple pulp is traditionally used to prepare sherbet or sarbat by mixing the pulp with water and sugar or another sweetener. Its characteristic sweet-sour flavour makes it suitable for beverage preparation.
- **Squash and Syrup:** The pulp can be processed with sugar to produce fruit squash and syrup.
- **Chutney:** It may be combined with sugar or jaggery, salt, chilli, and other spices. The natural acidity and aroma of the pulp contribute to the characteristic taste of the product. [17]
- **Jam and Jelly:** The pulp is suitable for jam and jelly preparation. Stone apple contains pectin, which contributes to gel formation and helps provide the required consistency in jelly and similar products.
- **Fruit Bar:** Stone apple pulp can be concentrated and dried to prepare fruit bars.
- **Pulp Powder:** The pulp can be dried and converted into powder .
- **Pickle:** Stone apple can also be included in pickle preparations, particularly using
- less mature or acidic fruit, together with salt, spices, and other ingredients.[18]
- **Traditional Medicinal Preparations:** Different parts of L. acidissima, particularly the fruit, leaves, seeds, gum, and bark used in preparation. Traditionally, the immature fruit has been used for various purposes.for complaints such as diarrhoea and dysentery, while other preparations are considered gastrointestinal ciated with digestive and other traditional uses. These are traditional uses and should not be presented as established clinical treatments
- **Nutraceutical and Functional Food Preparations:** Because stone apple contains phenolic compounds, flavonoids, pectin, dietary fibre, vitamins, minerals, and other phytochemicals, nutraceutical products, antioxidant-rich beverages, and other value-added food formulations.[19]

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D) Life Cycle of a Stone Apple (Limonia acidissima)

Its life cycle consists of several stages, beginning with seed germination and continuing through seedling development, vegetative growth, flowering, pollination, fruit formation, fruit maturation, and seed dispersal. The growth and reproductive behavior of the plant can vary depending on environmental conditions, soil characteristics, geographical location, and propagation method.

1. **Seed Germination**
   The seeds are small and hairy, with thick green cotyledons. Germination is epigeal, in which the cotyledons emerge above the soil surface. Under favorable nursery conditions, germination Is commonly completed within approximately 2–3 weeks. Studies have reported variation in germination among different populations of L. acidissima, indicating that the source of seeds can influence germination and early plant development.[20]
2. **Seedling Stage**
   After germination, the young plant develops its initial stem, roots, and leaves. During this stage, the seedling establishes its root system and gradually develops shoots and foliage. Stone apple can be propagated through seeds as well as vegetative methods. Techniques such as softwood grafting and budding have also been utilized for multiplication, with softwood grafting reported as a useful method for producing plants from suitable rootstocks.
3. **Vegetative Growth**
   Following seedling establishment, the plant enters an extended vegetative growth phase. Wood apple develops into a strong, woody tree characterized by a spreading crown, compound leaves, and thorny branches. It is well adapted to dry and semi-arid environments and can withstand relatively unfavorable climatic conditions. During vegetative development, the trunk, branches, leaves, and root system progressively become established. Sufficient vegetative growth is necessary for the plant to attain reproductive maturity. Plants raised from seeds generally take longer to reach the fruit-bearing stage, whereas vegetatively propagated plants may begin producing fruits earlier.[21]
4. **Flowering Stage**
   After reaching reproductive maturity, the stone apple tree enters the flowering stage. Flowers are generally produced on new shoots and occur in small terminal or lateral clusters. The flowers may include both staminate and bisexual forms. The flowering season is not identical in all regions because it is influenced by environmental and climatic conditions. In some Indian regions, flowering are considered reported mainly during February to April. Therefore, the flowering period may vary according to geographical location.
5. **Pollination and Fruit Set**
   Following flowering, insect-mediated pollination facilitates fertilization and subsequent fruit formation. Fruit set may occur approximately 7–15 days after flowering. During the early stages of fruit formation, rapid cell division and enlargement take place. The initial fruit-development phase generally continues for about 30–45 days. During this period, the young fruit increases in size and undergoes active cellular development.[22]
6. **Fruit Development**
   Stone apple produces a characteristic round to oval fruit surrounded by a hard, woody shell. Following fertilization, the developing fruit gradually increases in size, while the pulp and seeds develop within the protective outer shell. After the initial rapid-growth period, fruit development continues for several months. During this stage, the fruit becomes larger, the woody shell becomes more prominent, and biochemical changes occur within the developing pulp.
7. **Fruit Maturation and Ripening**
   The final phase of fruit development is maturation and ripening. During this period, the pulp undergoes changes in texture, colour, aroma, and flavour. The fruit develops its characteristic mature properties and

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becomes suitable for consumption. Ripening is accompanied by biochemical changes involving sugars, organic acids, pectin, and other constituents.

8. **Seed Formation and Dispersal**
   Following fruit maturation, the seeds become available for propagation and natural regeneration. When the seeds are released and reach suitable environmental and soil conditions, they can germinate and produce new seedlings. Thus, seed dispersal completes the reproductive phase and initiates a new life cycle of the stone apple plant.[23]

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Figure No.3 Life Cycle of Stone Apple

E) Nutritional Composition of Stone Apple Fruit

Stone apple (Limonia acidissima) is a less-utilized tropical fruit that possesses considerable nutritional and functional-food potential. The edible pulp contains carbohydrates, proteins, dietary fibre, minerals, vitamins, organic acids and amino acids. [24]

Table No.1: Nutritional Composition and Functional Significance of Stone Apple

Sr.No	Nutritional component	Major constituents	Nutritional or functional significance
1	Carbohydrates	Glucose, fructose and other	Provide energy and contribute to the

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		carbohydrates	sweetness of the fruit.[25]
2	Proteins	Proteins and various amino acids	nutritional value of the pulp[.26]
3	Dietary fibre	Soluble and insoluble fibre	Contributes to the fibre content and suitability of the pulp for food products.[
4	Fats and lipids	Small quantities of lipids	Contribute to the overall nutritional composition of the fruit.[27]
5	Sugars and organic acids	Glucose, fructose, citric acid and tartaric acid	Contribute to sweetness, acidity and characteristic flavour.[28]
6	Vitamins	Vitamin C, vitamin B1, vitamin B2 and β- carotene	Contribute to micronutrient intake and normal physiological functions.[29]
7	Minerals	Calcium, phosphorus, potassium, magnesium, iron and zinc	Support normal physiological processes and contribute to nutritional quality.
8	Pectin	Pectic polysaccharides	Supports gel formation and texture in jams, jellies and other fruit products.[30]
9	Phenolic compounds	Phenolic acids and related compounds	Associated with antioxidant activity reported in experimental studies.
10	Flavonoids and tannins	Various flavonoids and tannins	May contribute to the antioxidant properties of fruit extracts.[31]
11	Fatty acids	α-linolenic acids	Represent saturated and unsaturated fatty acids demonstrated in th fruit's lipid fraction.
12	Value-added products	Beverages, syrups, jams, jellies, chutneys and fruit bars	Provide opportunities for food processing and functional-food development.[32]

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DOI: 10.48175/IJARSCT-40430

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Figure No.4.Nutritional Composition of Stone Apple Fruit

F) Anti-Inflammatory Activity of Stone Apple Fruit (Limonia acidissima)

Stone apple (Limonia acidissima) is an edible tropical fruit belonging to the family Rutaceae and is recognized for its nutritional and phytochemical composition.[33]

- **In-vitro anti-inflammatory activity**
  The albumin-denaturation method is commonly employed as an initial screening procedure for plant extracts with possible anti-inflammatory properties.[34]
- **Phytochemical contribution to activity**
  A comprehensive review of stone apple fruit has reported several groups of phytochemicals, including polyphenols, tannins, saponins, phytosterols, triterpenoids, coumarins, amino acids and vitamins. The biological properties attributed to the fruit are considered to be related, at least in part, to this complex chemical composition. [35]
- **Relationship between antioxidant and anti-inflammatory properties**
  Oxidative stress and inflammation are closely associated biological processes. The body's production of harmful reactive oxygen molecules.can promote cellular damage and may contribute to the activation of inflammatory pathways. Consequently, the antioxidant properties of plant-derived compounds may have a supportive role in their overall inflammation-modulating effects. Stone apple fruit has demonstrated antioxidant activity in experimental investigations. The fruit contains phenolic and flavonoid compounds that can contribute to its antioxidant capacity.[36]
- **Importance of fruit pulp and rind**
  Consequently, the reported 74.55% inhibition cannot be attributed exclusively to the edible pulp. Constituents originating from both the pulp and rind may have contributed to the observed response. [37]

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Influence of phytochemical composition on biological activity

Research on stone apple fruit has demonstrated the presence of fatty acids, plant sterols and other phytoconstituents in different solvent extracts. A 2023 investigation identified compounds such as oleic acid, n-hexadecanoic acid, palmitoleic acid, octadecanoic acid, sitosterol and stigmasterol in fruit extracts and discussed the potential relevance present in the fruit to antiarthritic and related research.

The availability of these chemically diverse constituents indicates that the biological activity of stone apple fruit may result from the combined contribution of several compounds. However, the specific role of individual constituents in anti-inflammatory activity remains insufficiently characterized. Further fractionation, compound isolation and bioactivity-guided studies would therefore be valuable.[38]

- **Possible mechanism of action**

  Further investigations are needed to determine whether the stone apple fruit constituents affect established inflammatory mediators and pathways, including cyclooxygenase, lipoxygenase, nitric oxide production and pro-inflammatory cytokines.[39]

II. RESEARCH SIGNIFICANCE

The anti-inflammatory potential of stone apple fruit is particularly relevant because the fruit is edible and contains both nutritional and biologically active components. Recent literature has described stone apple as an underutilized fruit with functional and nutraceutical potential because of its polyphenols, flavonoids, tannins, saponins and organic acids.

The experimental finding of 74.55% inhibition of protein denaturation at 1000 µg/mL provides quantitative evidence supporting further investigation. However, the concentration used in an invitro assay should not be considered a therapeutic dose. Biological activity observed outside the body cannot be directly translated into human efficacy because absorption, metabolism, distribution and elimination can substantially affect the concentration of active compounds reaching target tissues.[40]

III. DISCUSSION

Stone apple(Limonia acidissima) is a valuable but underutilized fruit that contains a wide range of nutrients and biologically active compounds. Phenolic compounds, flavonoids, tannins, and other components in its phytochemical profile may be the cause of its possible health advantages.Stone apple extracts may offer anti-inflammatory and antioxidant properties, according to preliminary laboratory research. However, more research is required to determine their biological significance and explore their mechanisms of action. Its appropriateness for functional food products and medicinal uses may be ascertained with further research on safety, efficacy, and formulation development.

IV. FUTURE PROSPECTS

- **Identification of bioactive compounds:** Further research can focus on isolating and identifying the specific compounds responsible for the biological activities of *Limonia acidissima*.
- **Understanding the mechanism:** Molecular and cellular studies can help clarify how stone apple constituents produce anti-inflammatory and antibacterial effects.
- **Evaluation of individual plant parts:** The fruit pulp, rind, seeds, leaves, and bark can be investigated separately to compare their phytochemical composition and biological activities.
- **Improved in-vitro investigations:** More advanced laboratory models can be used to confirm the anti-inflammatory and antibacterial potential observed in preliminary assays.
- **Extract standardization:** Standardized extraction procedures and appropriate chemical markers can be developed to maintain consistent quality, composition, and biological activity.
- **Development of nutraceutical products:** The nutritional and phytochemical properties of stone apple can be utilized to develop nutraceuticals, functional foods, and health-oriented beverages.

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- **Commercial and value-added applications:** Further research can promote the development of products such as juice, syrup, jam, jelly, fruit bars, and dried pulp powder, increasing the utilization and economic value of this underexploited fruit.

V. CONCLUSION

Stone apple (Limonia acidissima) has considerable potential as a natural source of essential nutrients and biologically active constituents. Initial scientific findings indicate that its phytochemical components may contribute to antioxidant and anti-inflammatory effects. Nevertheless, these properties require further investigation through systematic experimental studies, comprehensive safety evaluations, and well-designed clinical trials before their therapeutic relevance can be confirmed. In addition, its diverse nutritional composition offers opportunities for the development of value-added food products and functional food formulations.

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