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REVIEW

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Thermal and nonthermal processing of an underutilized fruit *Emblica officinalis* (Amla): a sustainable approach

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Indian gooseberry or amla (*Emblica officinalis*) belongs to the Euphorbiaceae family and is undoubtedly the chief medicinal plant of the Indian Ayurvedic medicine system. The unique array of biologically active compounds in amla endows it with ethnomedical and pharmacological value. Almost every part of the amla tree can be utilized in various medicinal formulations for the treatment of several ailments including cancer, dyslipidemia, diabetes, digestive issues and neurological disorders. However, the post-harvest losses of this fruit are as high as 30–40%, and thus the production of value-added products of amla fruit is profitable to both consumers and farmers, as it helps in capturing the benefits throughout the year. Therefore, in this comprehensive review, we provide a better understanding on the quality of amla based on its various bioactive components. Also, we present the thermal and non-thermal processing, packaging and storage, value-added product and health aspects of the amla fruit in detail.

Sustainability spotlight

Amla (*Emblica officinalis*) is a unique fruit due to the presence of numerous bioactive compounds, which offer a wide range of therapeutic values. However, because of its perishable nature, it is necessary to develop sustainable techniques to process amla fruit and extend its shelf life with the maximum retention of its bioactive compounds. Recently, minimal processing techniques have gained popularity because of their numerous advantages in terms of operation and energy consumption. Therefore, the other uses of amla (*Emblica officinalis*) and its sustainable technological development need are to be comprehensively reviewed and made available to the scientific fraternity and society. Therefore, herein, we review all the recent scientific findings to address the above-mentioned problems and their relation with the United Nations sustainability development goals: good health and well-being (SDG 3) and responsible consumption and production (SDG 12).

1. Introduction

Emblica officinalis, a member of the genus Phyllanthus (Family Euphorbiaceae), is an underutilized fruit, which is known as Indian gooseberry, emblic myrobalan, malacca and amla. This fruit is often utilized in Ayurveda and Unani medicine and cultivated throughout India, thriving well in tropical and subtropical regions. Amla is a non-climacteric seasonal fruit, which grows abundantly in various regions of the world including Sri Lanka, Malaysia, China, Pakistan, Bhutan, Bangladesh, Thailand, Vietnam, Iran, Iraq, Japan, Panama, Puerto Rico and Florida. India ranks first in the world for the production of this fruit,[1] which was 1.2 million tonnes in 2021–2022, with Madhya Pradesh occupying the first rank in its production, followed by Uttar Pradesh and Tamil Nadu.[2]

This fleshy yellow greenish fruit has an astringent flavor and is eaten raw, roasted or in a pickle form in various regions of India. It is the major ingredient for ayurvedic medicinal preparations and health foods such as chyawanprash and triphala. It is regarded as a general tonic that is beneficial for enhancing the mental and physical health of all age groups. Its fruit is hard and round in shape and is divided into 6–7 segments. Also, its color varies from pale green, when unripe to light yellow after ripening. The size of the fruit can be as large as plum and as small as a marble. Its surface is shiny with a translucent and thin skin. Besides its salty taste, amla possesses five tastes out of six given by nature. It is sour on the first bite but becomes sweet after mixing with saliva. Amla is also referred to as *amritphal* and *tridoshic*, which has the potential to cure all three doshas of our body according to the Ayurveda medicinal system, making it a divine fruit.[3]

Amla is a well-known fruit possessing an excellent nutritional profile, which makes it a super fruit. It is a reservoir of several phytochemicals including polyphenols, tannins, ascorbic acid and other alkaloids.[4] Various investigations have revealed the presence of flavonoids such as quercetin and kaempferol.[5] Different spectral studies have also confirmed the presence of alkaloids such as phyllantine and phyllantidine. It

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also contains various micro and macro elements such as calcium, magnesium, selenium, boron. The presence of these phytochemicals makes amla fruit useful in ayurvedic preparations and contributes to various defensive actions against bacteria and viruses. These actions include free radical scavenging, metal chelation, and singlet oxygen quenching. The therapeutic uses of amla fruit include the treatment of diseases such as diabetes, inflammation, various skin disorders, liver ailments, neurological issues, digestive dysfunctions, cancer, and immunological disorders.[6] Muzaffar *et al.*[7] gave insight into the biochemical composition, post-harvest processing and therapeutic potential of Indian gooseberry. Ahmad *et al.*[8] reviewed the therapeutic benefits of *Phyllanthus emblica*, whereas Gul *et al.*[9] reviewed the nutraceutical and functional benefits of amla. Recently, there has been a surge in the consumption of amla-based products, and therefore more focus is needed on the nutritional value of these product and minimal processing techniques. Herein, we review the varietal compositional changes with a comprehensive understanding of the different processing techniques and changes in the functional constituents of amla.

2. Varieties and characteristics of amla fruit

Different varieties of amla fruits are cultivated in various parts of India. NA-6, NA-7, NA-8, NA-9, NA-10, Banarasi, Chakaiya, Krishna, Francis (or Hathijhool), Kanchan, Gujarat-1, Gujarat-2, Goma Aishwarya, Neelam, Desi, Bansi red, and Laxmi-52 are some of the common varieties.[10] Some characteristic features of the different varieties of amla fruit are presented in Table 1. Generally, amla varieties are categorized into three groups

Table 1 Characteristics of different varieties of amla fruit

Name of variety	Size and color	Other characteristic features
Banarasi	Large in size and lobed	Thin and semi-translucent skin and bears less fruits per tree than other varieties. Poor keeping quality
Chakaiya	Small to medium in size and whitish-green in color	Moderate keeping quality, no premature dropping of fruits, and most preferred for pickles and shreds
Kanchan	Small-size fruits and yellowish-green in color	This variety developed through unintentional breeding of Chakaiya and has moderate ascorbic acid concentration
Francis/Hathijhool	Big in size, flattened and whitish green in color	Low in ascorbic acid content but rich in iron. Highly susceptible to necrosis
NA-6	Medium size fruits, oval-round in shape and light green in color	This variety developed through unintentional breeding of Chakaiya and suitable for making jam and preserves due to its appreciable keeping quality
NA-7	Medium to large in size with conical apex, smooth yellow to greenish in color	Selected seedling emerging from open pollinated strain of Francis, contains moderate amount of ascorbic acid and free from necrosis
NA-8	Smaller in shape with rough light green colored thick skin	This variety developed through unintentional breeding of Chakaiya, susceptible to necrosis, and affordable keeping quality
NA-9	Large oblong shape and flattened at the tips	This variety developed through unintentional breeding of Banarasi variety with high ascorbic acid content, ideal for making preserves, candy and jam
NA-10	Average size, round, flattened, rough and light yellowish in color with pink tinge	Also known as Agra bold, developed through unintentional breeding of Banarasi and mildly vulnerable to necrosis
Lakshmi-52	Large in size and light pink in color at early stages but color diminishes at maturity stages	This variety developed through unintentional breeding of Francis, bears larger number of fruits per tree and superior potential for processing into various value-based products including syrups, murabbas, and preserves
Goma Aishwarya	Medium in size	Bears average fruits per tree, yield per tree is lesser than Lakshmi-52, contains approximately 45–47% juice and suited for export purposes and processing
Desi	Small in size, round in shape with tiny dots of white color	Has largest and erect tree among all varieties with moderate bearing capability, moderate ascorbic acid content and usually used as rootstock for growing other varieties
Bansi red	Medium-sized fruit, slightly triangular to oval in shape	Has whitish spots on surface, flesh is fibrous and used for medicinal purposes

depending on their maturity stages. Banarasi, NA-9, NA-10 and Krishna are early-maturing varieties available from mid-October to mid-November. Median maturing varieties include Francis, Kanchan, NA-6 and NA-7, which have fruiting season from mid-November to mid-December. Chakaiya and Balwant fall in the late-maturing category with a short season of availability starting from mid-December to mid-January.

Various attempts have been made by researchers to study the physical and morphological traits of different varieties of amla fruit. Proper knowledge of its physical traits is indispensable when designing processing equipment.[4] Anand Aonla-II has an average vertical diameter of 38.80 mm and horizontal diameter of 33.28 mm. The weight of its fruit and pulp is 31.80 g and 28.21 g, respectively.[11] The physical characteristics of six varieties of amla, namely, Balwant, NA-7, NA-9, Chakaiya, NA-10 and Hathijhool, revealed non-significant differences in the surface hardness of their fruit. The fruit of the NA-7 variety was bigger in size and surface area. NA-10 had highest fruit volume, whereas Hathijhool had the lowest. The rolling resistance of Chakaiya fruit was the maximum and Hathijhool had the minimum. Irrespective of the variety, the rolling resistance was found to be higher on a canvass surface and lower on stainless steel.[4] The fruits of the NA-7, NA-10, Banarasi, Chakaiya and Wild varieties were observed for their morphological variations. The weight of both the fruit and pulp and the pulp thickness were the best in Banarasi cultivar.[12] NA-7 had the highest volume (21.91 mL) and density (1.21 g cm^{-3}) among the cultivars. The average length and diameter of the wild variety (2.72 cm and 3.00 cm) were lower than that of the Chakaiya variety[12] (3.8 cm and 3.0 cm), respectively. However, the juice yield of the wild variety (48.3%) was higher than that of the Chakaiya variety (41.9%). Significant variations were found in the physical dimensions of the fruit with respect to different altitudes.[14] The fruit weight ranged from 3.39 to 8.86 g and the fruit diameter varied from 1.78 to 2.34 cm. The fruit length was observed to be highest in Khola, which is located at an altitude of 919 meters above sea level (m asl). Paukhal located at 1263 m asl had the lowest fruit length. The specific gravity was maximum (1.31) in Dangchaura located at 692 m asl, whereas Chamoli seed source (1.01) had the lowest specific gravity located at 1062 m asl among amla fruits of 28 different locations. The pulp: stone ratio varied from 1.93 (Paukhal) to 9.82 (Chauki) among the populations. A significant ($p < 0.05$) positive relationship between the fruit weight *versus* malic acid, citric acid, tartaric acid and sugar content was observed. The variation in the different properties of the fruit was attributed to different climatic factors of their growth locations. Also, the variations were more evident in the fruits grown at a higher altitude, which was due to the differences in solar radiation.[14]

3. Composition of amla fruit

3.1 Proximate composition

The proximate composition of fruits includes moisture, fat, protein, fiber, ash, and total carbohydrate content. Various external factors including the environment affect their nutritional composition. The proximate composition of amla fruit reported by various researchers is summarized in Table 2. The moisture content of amla fruits reported in various studies ranged from 81.00 to 82.80%. A higher moisture exposes fruit to higher chances of spoilage, which can be avoided with proper storage conditions. The protein content of fresh amla fruits varied from 0.5 to 3.2%. Prominent amino acids reported are glutamic acid, proline, aspartic acid, alanine, cysteine and lysine.[15] The total amino acid content in the fresh amla fruit has been reported to be 4.45 mg g^{-1}, in which glutamic acid and proline constituted 29.6% and 14.6% of the total amino acids.[16] Amla fruit is approximately 2.7 times richer in amino acids than an apple. Its protein composition varies with maturation level and cultivars. A lower amount of fats (0.1–0.5%) has been reported in amla fruits in different studies (Table 2). Lipids such as myristic acid, lauric acid, pentadecanoic acid, palmitoleic, and hexadecenoic acid have been reported in fresh amla fruit. Omega-6 fatty acids such as α- and γ-linolenic acids, which are essential fatty acids, have also been identified in fresh amla fruits.[17] Amla fruit is an important source of carbohydrates (7.6–14.1%) (Table 2). Other carbohydrates present in this fruit are starch and pectin, where pectin is an important structural carbohydrate. Sugars and other carbohydrates play an important role in deciding the flavor of amla fruit. Fibers promote the peristalsis movement of the intestine. Thus, a higher content of fiber present in amla fruit (0.3–5.1%) is beneficial for digestive ailments. However, this is disadvantageous when the aim is to produce pulp and pulp-based products.

3.2 Physicochemical composition

Amla fruit possesses a rich nutritional profile containing different constituents. It is a significant source of ascorbic acid, the second richest after Barbados cherry. A wide variation in the concentration of ascorbic acid in amla fruit can be found in the literature (Table 2). Ascorbic acid is a water-soluble vitamin with an extraordinary antioxidant property. This vitamin is vital for immunity, collagen synthesis, blood vessels, bones and eyes. The lowest reported value is 191.13 mg/100 g,[14] while 720 mg/100 g is the highest reported value.[18] The total phenolic content reported in amla fruit varies from 24.61 to 31.12 mg gallic acid equivalent per gram (mg GAE per g) (Table 2). Phenolic acids are secondary metabolites, which have redox properties. Gallic acid and ellagic acids are the predominant phenolic compounds found in amla fruit. Chakaiya cultivar has been reported to contain 31.12 mg GAE per g polyphenols.[19] The amount of phenolics differs widely with geographical locations and extraction methods. Naringin is one of the flavonoids present in amla fruit. The amount of naringin present depends on the maturity stage. The decrease in naringin content during complete maturation may be due to the higher expression of rate-limiting enzymes in the bio-synthesis of flavonoids. Generally, the naringin content declines as maturity progresses.[20] The highest flavonoids in citrus fruits have been reported during the middle stages of development and the decrease during complete maturation may be probably due to the higher expression of chalcone isomerase and Chalcone synthase-1 (*CHS-1*), the rate-limiting enzymes in the

Table 2 Composition of amla fruit

Parameters	Reported values	References
Proximate composition (%)		
Moisture	81.00–82.80	Ganachari *et al.*, 2005,[30] Singh *et al.*, 2011,[31] Yadav *et al.*, 2020,[32] Hussain *et al.*, 2021 (ref. 33)
Protein	0.50–3.20	Ganachari *et al.*, 2005,[30] Singh *et al.*, 2011,[31] Yadav *et al.*, 2020,[32] Hussain *et al.*, 2021 (ref. 33)
Fat	0.10–0.46	Ganachari *et al.*, 2005,[30] Singh *et al.*, 2011,[31] Saxena and Chaturvedi, 2015,[34] Tewari *et al.*, 2019,[4] Yadav *et al.*, 2020 (ref. 32)
Carbohydrate	7.60–14.10	Ganachari *et al.*, 2005,[30] Singh *et al.*, 2011,[31] Saxena and Chaturvedi, 2015,[34] Yadav *et al.*, 2020,[32] Hussain *et al.*, 2021 (ref. 33)
Fiber	3.0–5.10	Ganachari *et al.*, 2005,[30] Singh *et al.*, 2011,[31] Saxena and Chaturvedi, 2015,[34] Yadav *et al.*, 2020 (ref. 32)
Ash	0.50–2.30	Ganachari *et al.*, 2005,[30] Singh *et al.*, 2011,[31] Yadav *et al.*, 2020,[32] Hussain *et al.*, 2021 (ref. 33)
Physicochemical composition		
Ascorbic acid (mg/100 g)	498.81–720.00	Tewari *et al.*, 2019,[4] Kavita *et al.*, 2013,[18] Tewari *et al.*, 2021,[19] Goyal *et al.*, 2008,[22] Pareek *et al.*, 2011,[23] Singh *et al.*, 2011 (ref. 31)
Total phenolic content (mg GAE per g)	24.61–31.12	Sarangam and Chakraborty, 2015,[35] Tewari *et al.*, 2019,[4] Tewari *et al.*, 2021 (ref. 19)
Naringin (mg/100 g)	3.00	Tewari *et al.*, 2019 (ref. 4)
Acidity (% citric acid)	2.24–2.34	Goyal *et al.*, 2008,[22] Pareek *et al.*, 2011 (ref. 23)
Total sugar (%)	3.11–3.31	Goyal *et al.*, 2008,[22] Pareek *et al.*, 2011 (ref. 23)
Reducing sugar (%)	2.37–2.45	Goyal *et al.*, 2008,[22] Pareek *et al.*, 2011 (ref. 23)
Non reducing sugar (%)	0.74–0.79	Goyal *et al.*, 2008,[22] Pareek *et al.*, 2011 (ref. 23)
Tannin (%)	0.50–1.95	Goyal *et al.*, 2008,[22] Pareek *et al.*, 2011,[23] Gorya and Bajwa, 2015,[36] Kulkarni *et al.*, 2017 (ref. 11)
TSS (°Brix)	12.70–14.00	Goyal *et al.*, 2008,[22] Pareek *et al.*, 2011,[23] Kulkarni *et al.*, 2017 (ref. 11)
pH	1.97–2.88	Goyal *et al.*, 2008,[22] Pareek *et al.*, 2011,[23] Parveen and Khatkar, 2015,[28] Kulkarni *et al.*, 2017 (ref. 11)
Pectin (%)	0.54–0.55	Goyal *et al.*, 2008,[22] Pareek *et al.*, 2011 (ref. 23)
Malic acid (%)	1.43–3.67	Naithani *et al.*, 2020 (ref. 14)
Citric acid (%)	1.37–3.61	Naithani *et al.*, 2020 (ref. 14)
Tartaric acid (%)	3.21–8.46	Naithani *et al.*, 2020 (ref. 14)
Vitamin B1 (mcg)	28.00	Kavita *et al.*, 2013 (ref. 18)
Vitamin B3 (mg/100 g)	0.20–0.40	Singh *et al.*, 2011,[31] Kavita *et al.*, 2013 (ref. 18)
Vitamin E (mg/100 g)	0.16	Judprasong *et al.*, 2013 (ref. 37)
Mineral composition (mg/100 g)		
Potassium	116.00–282.00	Barthakur and Arnold, 1991,[16] Waheed and Fatima, 2013 (ref. 29)
Calcium	15.00–50.00	Barthakur and Arnold, 1991,[16] Singh *et al.*, 2011,[31] Kavita *et al.*, 2013,[18] Parveen and Khatkar, 2015 (ref. 28)
Phosphorous	21.00–28.20	Pareek *et al.*, 2017,[1] Kavita *et al.*, 2013,[18] Barthakur and Arnold, 1991 (ref. 16)
Magnesium	11.80	Barthakur and Arnold, 1991 (ref. 16)
Sulphur	16.60	Barthakur and Arnold, 1991 (ref. 16)
Iron	1.00–6.93	Barthakur and Arnold, 1991,[16] Kavita *et al.*, 2013,[18] Parveen and Khatkar, 2015,[28] Filipiak-Szok *et al.*, 2015 (ref. 27)
Zinc	1.60–17.90	Barthakur and Arnold, 1991,[16] Filipiak-Szok *et al.*, 2015,[27] Waheed and Fatima, 2013 (ref. 29)
Boron	0.22	Barthakur and Arnold, 1991 (ref. 16)
Copper	0.28–2.73	Barthakur and Arnold, 1991,[16] Filipiak-Szok *et al.*, 2015 (ref. 27)
Sodium	4.20–7.36	Barthakur and Arnold, 1991,[16] Waheed and Fatima, 2013 (ref. 29)
Chloride	35.50	Barthakur and Arnold, 1991 (ref. 16)
Selenium	0.05–2.23	Barthakur and Arnold, 1991,[16] Filipiak-Szok *et al.*, 2015,[27] Waheed and Fatima, 2013 (ref. 29)
Cobalt	0.27	Waheed and Fatima, 2013 (ref. 29)

biosynthesis of flavonoid.[21] The naringin content of 3.00 mg/100 g was reported in fresh amla fruit.[19] Naringin is the primary component responsible for bitterness in citrus fruits. Titratable acidity or simply acidity is one of the important indicators of fruits given that it measures the total amount of organic acids present. Upon ripening, the acidity declines and total sugars increase due to the hydrolysis of starch. The acidity (% citric acid) of 2.24–3.11% has been reported in fresh amla fruits in various studies.[22,23] Monosaccharides such as D-glucose and D-fructose have been detected in the ethanolic extract of amla fruit. Residues of xylosyl, arabinose, mannosyl, galactosyl and glucosyl were also found in trace amounts.[24] Carbohydrates such as raffinose, glucose, galactose, and fructose have also been reported in amla fruit.[25]

The tannins present in amla fruits are known to retard the oxidation of ascorbic acid. Tannins with a content of 0.55% were reported in a study by Goyal *et al.*[22] The total soluble solids are the measure of soluble solids present in fruits. It is also an indicator of the level of sugar, soluble proteins, and other organic constituents. The TSS of fresh amla fruits ranged from 12.10 to 14.00 °B (Table 2). TSS is a significant quality parameter, which has a great effect on the taste of fruit. Fruits of different varieties present a greater variation in ascorbic acid and other organic acids. Organic acids are responsible for the flavor of fruits and play an important role in their growth. Citric acid and malic acid ranged between 1.37–3.61% and 1.43–3.78%, respectively, in 28 varieties of amla fruits.[14] The pH of amla fruit is generally in between 1.97 and 2.88, as found in various studies, which reveals its highly acidic nature (Table 2). Amla fruit also contains a hetero-polysaccharide, *i.e.*, pectin, which is a structural polysaccharide present in its cell walls and intercellular layers. Pectin has been found to be useful in lowering serum cholesterol levels.[26] Various studies have reported a content of pectin in the range of 0.54–0.55% in amla fruit.[22,23] Water-soluble vitamins such as B2 and B3 and fat-soluble vitamin E have also been reported in amla fruit (Table 2).

3.3 Mineral composition

Amla fruit is also rich in minerals and contains an appreciable content of iron, calcium and phosphorous. The elemental analysis of amla fruit by X-ray fluorescence, ICP-MS, and ion chromatography revealed the presence of macro- and micro-elements.[27] Reports suggest the presence of 6.93 mg/100 g iron, 3.39 mg/100 g zinc and 2.73 mg/100 g copper (Table 2). A higher bioavailability of iron can be achieved by increasing the intake of ascorbic acid-rich fruits. Thus, the ascorbic acid-rich amla fruit helps in preventing a reduction in ferric to ferrous ion, making it available for uptake by mucosal cells. Macro elements such as calcium and potassium were also reported in the nutritional analysis of amla fruits by Parveen and Khatkar.[28] The calcium content ranged from 2.03 to 50.00 mg/100 g in different studies on amla fruits. Amla fruit also contains the essential micro element boron (0.22 mg/100 g) (Table 2). Instrumental neutron activation analysis (INAA) of amla fruits also revealed the presence of minerals such as cobalt and sodium.[29] Potassium was found to be a major element (116 mg/100 g), whereas the sodium content was 7.36 mg/100 g in amla fruits. The presence of an adequate amount of sodium in amla helps in regulating the water content in the body, whereas the potassium in amla fruit maintains the pH level of the blood. Cobalt with a concentration of 0.27 mg/100 g present in amla fruits ensures the proper absorption of vitamin B12, thus helping to combat anemia. Another important micro elements found in amla fruit is selenium, which ranged from 0.24 to 0.58 mg/100 g. Selenium is an important cofactor of various enzymes such as glutathione peroxidase and other reductase enzymes.

4. Volatile constituents of amla fruit

Amla fruit also contains a variety of volatile compounds, which are mainly essential oils known for their antimicrobial activity. These compounds are a complex mixture of alcohols, esters, terpenes and hydrocarbons (Table 3). Hydrocarbons such as nonacosane (3.54%), undecane (7.55%), decane (6.82%), tetracosane (16.20%) and butyl cyclohexane (2.97%) have been found in amla fruit.[38] Hydro distillation and supercritical fluid extraction analysis of amla fruits of Guangdong Province, China revealed the presence of compounds such as hydrocarbons, terpene, terpenoid and carboxylic acid. Among them, the predominant compounds were tetracosane (16.20%), 1-octene-3-ol (13.57%) and β-caryophyllene (13.57%).[39] Forty-two compounds constituting 96.13% of essential oil were identified during GC/MS analysis of amla fruit grown in Egypt.[38] The main identified components were esters (33.26%) and hydrocarbons (30.29%). Among them, the major compounds detected were methyl salicylate (14.28%) and undecane (7.55%) (Table 3). Various compounds were detected in amla fruit cultivated in Sichuan, China.[40] The major compounds were α-furfural (17.93%), 2-chloro-bicyclooct-5-ene-2-carbonitrile (7.69%), salicylic acid, methyl ester (7.25%), *trans*-2-decenal (5.05%), and hexahydrofarnesyl acetone (5.03%), accounting for 97.42% of the total area of the peaks. Volatile compounds are responsible for the flavor and taste of amla fruits. These compounds play a significant role in determining the principal sensory identity and acceptability by consumers. The concentration of volatile compounds is affected during processing. Generally, an increase in temperature during processing leads to a decline in volatile compounds, while volatile compounds also decrease at chilling temperatures, and therefore both chilling and non-chilling temperatures can cause a reduction in volatile compounds.[41]

5. Astringency in amla and effect of processing

Astringency is an oral sensory attribute, which has a huge influence on the choice, acceptability and consumption of fruits. Amla fruit is very astringent in nature, which limits its palatability despite being laden with strong antioxidant activity. Amla fruit exhibits different tastes such as sweet, sour, bitter and astringent. The presence of sucrose, fructose and their derivatives such as sugar alcohol and some amino acids, amines and some non-carbohydrates are the reason for the sweetness in fruits. Sourness in fruits comes from organic acids such as malic acid, citric acid, oxalic acid, and succinic acid tartaric acid. Astringency is a tactile feeling in the mouth, which is mainly due to the presence of tannins and other polyphenolic compounds such as catechin, epicatechin, cyanidin, proanthocyanidins, methyl gallate, ellagic acid and punicalagin. Generally, the feeling of astringency is experienced together

Table 3 Volatile constituents of amla fruit

Class	Compounds	Reported values (%)	References
Hydrocarbon	Nonacosane	3.54	El-Amir *et al.*, 2014 (ref. 38)
	Undecane	3.10, 7.55	Liu *et al.*, 2009,[39] El-Amir *et al.*, 2014 (ref. 38)
	Decane	6.82	El-Amir *et al.*, 2014 (ref. 38)
	Tetracosane	16.20	Liu *et al.*, 2009 (ref. 39)
	Butyl cyclohexene	2.97	El-Amir *et al.*, 2014 (ref. 38)
Alcohol	1-Octen-3-ol	13.57	Liu *et al.*, 2009 (ref. 39)
	Coahuilensol	4.57	El-Amir *et al.*, 2014 (ref. 38)
Ketone	Acetophenone	4.16	El-Amir *et al.*, 2014 (ref. 38)
Aldehyde	Benzaldehyde	11.98	El-Amir *et al.*, 2014,[38] Wang *et al.*, 2009 (ref. 40)
	Cumin aldehyde	4.64	
	trans-2-Decanal	5.05	
Ester	2-Methyl butyl acetate	8.60	El-Amir *et al.*, 2014 (ref. 38)
	Ethyl benzoate	8.03	
	Methyl salicylate	14.28, 7.25	El-Amir *et al.*, 2014,[38] Wang *et al.*, 2009 (ref. 40)
Carboxylic acid	Palmitic acid	8.51	Liu *et al.*, 2009 (ref. 39)
Furan	α-Furfural	17.93	Wang *et al.*, 2009 (ref. 40)
Terpene	β-Elemene	9.68	Liu *et al.*, 2009 (ref. 39)
	β-Caryophyllene	13.57	Liu *et al.*, 2009 (ref. 39)
	Hexahydrofarnesyl acetone	5.03	Wang *et al.*, 2009 (ref. 40)
Terpenoid	Thymol	5.94	Liu *et al.*, 2009 (ref. 39)
	Nerol	2.96	Liu *et al.*, 2009 (ref. 39)
	Methyl eugenol	3.30	Liu *et al.*, 2009 (ref. 39)
	Camphor	9.70	Liu *et al.*, 2009 (ref. 39)

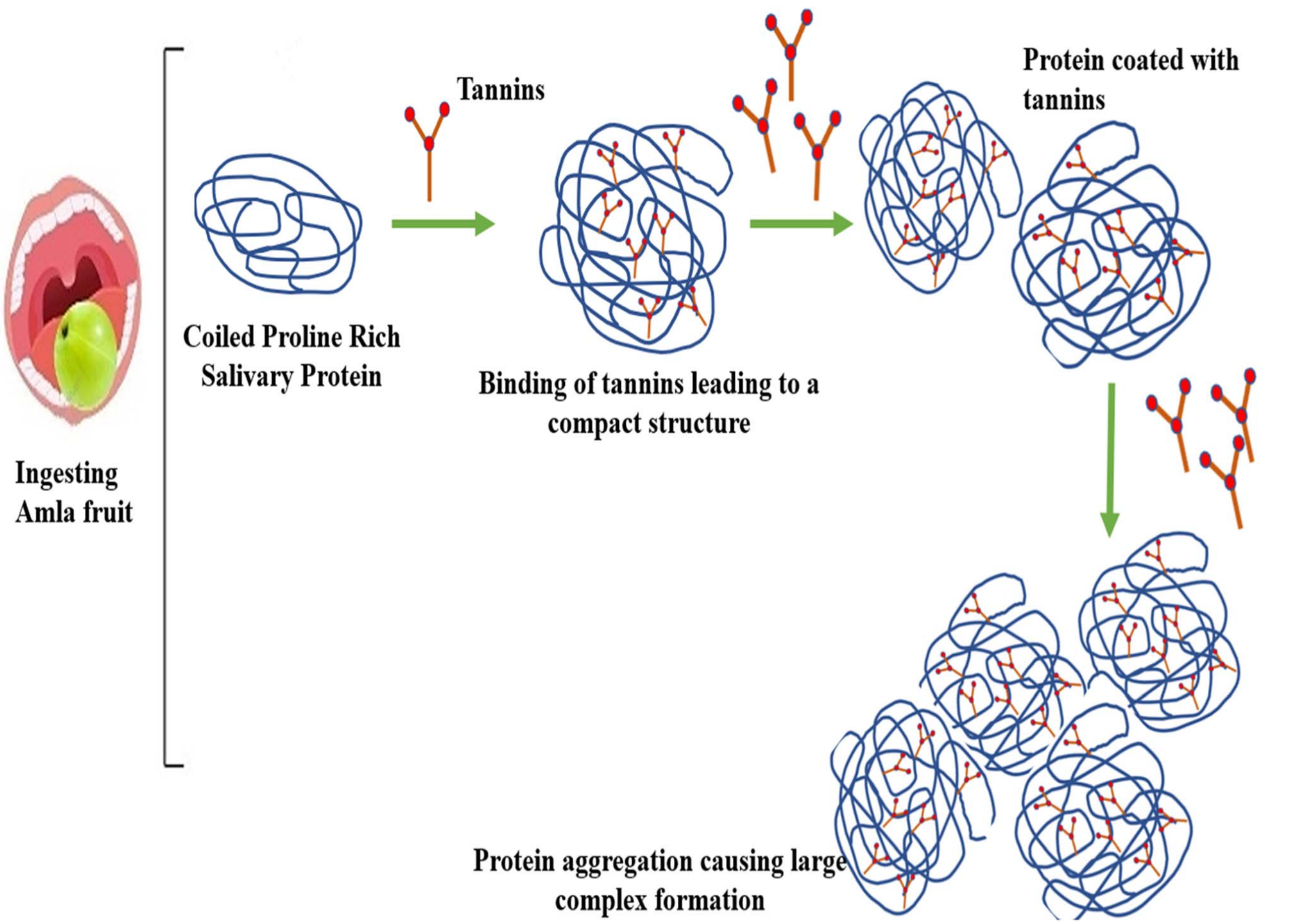

Fig. 1 The possible mechanism of astringency occurring in the oral cavity after eating the amla fruit.

with sourness and bitterness. Actually, it is a sensation in the oral cavity, which induces drying, roughing and puckering of the mouth epithelium.[42] The reason for this astringent feeling has been established by various researchers over time.[43,44] Reports have explained that astringency occurs because of the interaction of tannins and salivary proteins, which are rich in proline amino acid, leading to precipitation. This causes the loss of lubrication in the mouth, leading to contraction of epithelial tissues in the tongue, which generates a dry perception in the mouth. This process is known as astringency or convergence. Jobstl *et al.*[45] reported the mechanism of astringency occurring in the oral cavity after consuming amla fruit, which is illustrated in a simplified form in Fig. 1. Tannins in amla fruit are released in the oral cavity. The proline-rich protein (PRP) present in the saliva binds to multidentate tannins and other polyphenols. At low concentration of tannins, compression of the loosely coiled PRP takes place. However, a higher concentration of tannins initiates cross-linking and other intermolecular interactions. These interactions cause the protein structure to aggregate and precipitate. Thus, precipitation induces the loss of lubrication, and consequently astringency. Amla fruit is rich in tannins with the raw fruit containing nearly 2.25 g/100 g and sundried powder containing 1.85 g/100 g.[19] Catechin, epicatechin, cyanidin, proanthocyanidins, methyl gallate, ellagic acid, punicalagin are main tannins responsible for the astringency in amla. However, besides this, tannins have various other benefits. Tannins are considered significant in curbing free radicals, and thus assist in resisting the senescence of tissues. A moderate concentration of tannins can enhance the flavor of fruits. However, not much research has been regarding removing or lowering the astringency of fruits. No work has been reported with the direct aim to remove the astringency in amla fruit to date. However, it has been well established in the literature that some processing operations such as blanching,[46,47] pretreatment,[19] drying,[19,48] and addition of chemicals such as potassium metabisulphite (KMS)[49] result in the loss of tannins (17.5–22.00%) in amla fruit. Consequently, this loss of tannins can substantially lessen its astringency. Unit operations such as blanching and pasteurization can help lower the tannin concentration. This reduction can lead to higher acceptability of amla as a table fruit together with its use in various foods and beverages. Microfiltration has emerged as a promising technique, which can remove the low molecular weight compounds causing astringency. Pretreatment of fruit juices with enzymes such as tannase and cellulase has been reported to increase the efficiency of the microfiltration process.[50] Ares *et al.*[51] carried out a study to reduce the astringency of two Uruguayan native plant extracts by adding sucrose, sucralose, polydextrose and milk. Sucrose and milk were found to be the most effective inhibitors of astringency and bitterness.

6. Processing of amla fruits

The highly perishable amla fruit needs to be processed as its astringent and blunt taste limits its usage in raw form. Thus, post-harvest management of amla has become indispensable as its fruits have a shelf life of 5–6 days.[1] However, post-harvest losses occur primarily due to mechanical, physical or pathological factors. Furthermore, chilling injury and white specks are the primary physiological disorders of amla fruit. Chilling injury leads to splitting of the fruit peel, which can be prevented by controlling the temperature at 12 °C for storage.[52] White specks can be prevented by preserving fruits in a solution of potassium metabisulphite and sodium chloride.[53] Another prominent disorder is pink spots, which occur due to boron deficiency. This can be controlled by spraying fruits with 0.6% borax solution.[52] Amla fruit is also highly susceptible to post-harvest fungal pathogens including anthracnose, rust and fruit rot. Spraying of 0.5% sulphur has proven to be effective against rust.[54] Also, 0.1% carbendazim has been proven to be useful in getting rid of anthracnose (causative organism: *Colletotrichum gloeosporioides*). Anthracnose fungal disease produces fruits with sunken, small, brown lesions on their surface.[55] Phoma rot disease (causative organism: *Phoma exigua*) is characterized by small lemon-colored lesions, which then become enlarged and covers the whole fruit.[56] Losses during storage due to rodents such as house rats and soft fur field rats have been reported in amla fruit. Deterioration due to above-mentioned factors lowers the marketability and acceptability among consumers. Thus, to curtail the post-harvest losses, which are nearly 30–40%,[22] the processing of amla fruit becomes desirable and more significant compared to other fruits. Processing of amla fruit reported in the literature can be categorized in two major parts, which are discussed in the subsequent section.

6.1 Thermal processing

Thermal processing is a very popular commercial cost-effective method for the processing of fruits and vegetables, which reduces microbial and enzymatic activity. Thermal treatment also increases the bioavailability of nutrients and improves the taste and texture of the product; however, it also has some negative aspects such as the loss of nutritional, functional and sensory quality of foods. The various thermal treatments on amla and its products are summarized in Table 4.

Pasteurization and treatment of KMS (1.5 g L^{-1}) have been reported to be effective in preserving the quality of juice up to 6 months.[57] Pasteurization (90 °C/1 min) and preservation with 500 ppm KMS (without heat treatment) of amla juice stored at (a) 20–35 °C and RH 30–70% and (b) refrigerated at a temperature of 4 °C showed better retention of nutrients and other phytochemicals in a pasteurized sample.[58] Blanched amla (90 °C/60 s) impregnated at 13.5 kPa with osmotic solution containing honey (50 °B) resulted in a product that had color stability, remarkably less moisture and higher carbohydrate and TSS content.[59] A continuous decrease in ascorbic acid, polyphenols and TSS has been reported with prolonged steeping. Steeping in water for up to 10 days could retain the maximum nutrients in juice for up to 4 months of storage.[60]

In the case of amla fruit, sun and solar drying are the most common method for its processing. Besides, tray/cabinet or vacuum drying has also been exploited to some extent. Murthy

Table 4 Effect of thermal processing on quality attributes of amla fruits[a]

Amla products	Processing condition	Quality attributes	References
Juice	Pasteurization • Temperature: 75–95 °C • SO_2: 500 ppm • Storage at temperature 18–36 °C relative humidity: 40–80% & storage for 9 months	• Decrease in AA (60%) & TPC but increase in gallic acid and NEB • Best treatment obtained at 80 °C having shelf-life of up to 9 months	Bhattacherjee *et al.*, 2011 (ref. 69)
	Thermal pasteurization: 100 °C Chemical preservation • KMS at 1.0 and 1.5 g L^{-1} • Sodium benzoate at 1.0 and 1.5 g L^{-1}	During storage • Chemical: KMS at 1.5 g L^{-1}, minimum change in TSS, no major change in sugars, maximum retention of ascorbic acid • Pasteurization: maximum organoleptic score, lesser AA • Best treatment obtained in KMS at 1.5 g L^{-1} having shelf-life up to 6 months	Lather *et al.*, 2015 (ref. 57)
	Thermal pasteurization: 90 °C/1 min Chemical preservation: KMS 500 ppm Storage at • 20–35 °C at 30–70% RH • Refrigerated temperature (4 °C)	• No changes in AA, TPC, TA, TSS of KMS-treated samples • Significant changes in AA, TPC, TSS and TA of pasteurized sample • Decline in AA, TA during storage • Higher NEB at room temp than refrigerated • Best treatment obtained at 90 °C/1 min having shelf-life up to 180 days at 4 °C	Kumari and Khatkar, 2019 (ref. 58)
	Pasteurization • Temperature at 90 °C/2 min & preserved with 500 ppm SO_2 • Juice stored for 0, 2, 4, 5, 6, 9 and 12 months at RT • Spray drying of stored juice at inlet temp: 190 °C, feeding rate 16 rpm and 2% maltodextrin	• AA in juice decreased during storage, 1.55% decrease in TPC during 12 months of storage • Good quality spray dried powder from amla juice stored up to 5 months at RT • Significant reduction of AA in powder, no major change in TPC, reduction in color values	Bhattacherjee *et al.*, 2014 (ref. 64)
	Spray drying • Inlet temp: 125 °C, 150 °C, 175 °C, 200 °C • Maltodextrin: 3%, 5%, 7%, 9%	• Decrease in DPPH, moisture content, hygroscopicity with increase in maltodextrin • Decrease in density, smaller particle size and higher L^* values and reduced TPC at higher temperature	Mishra *et al.*, 2014 (ref. 62)
Fruit	Blanching • 70–90 °C/20–60 s VI • Pressure: 6.8–13.5 kPa and with osmotic solution of sucrose (mixed with honey) of 30–50 °Brix	• Inactivation of POD, higher L^* and b^* of blanched samples • VI at 13.5 kPa and 50 °Brix samples had lower moisture and AA, increased color stability, higher carbohydrate and TSS	Chinprahast *et al.*, 2012 (ref. 59)
	• Steeping in water: 30 days • Juice of steeped fruit withdrawn at 0, 5, 10, 15, 20 and 30 days and pasteurized at 90 °C and preserved with 500 ppm SO_2	Decrease in • TSS from 6.7 to 2.6 °Brix, TA from 1.52 to 0.48%, AA from 292.0 to 36.5 mg/100 g and TPC from 1.32 to 0.76% • Best results for fruits steeped in water up to 10 days • The resulted juice having shelf-life of 4 months	Bhattacherjee *et al.*, 2013 (ref. 60)

Table 4 (*Contd.*)

Amla products	Processing condition	Quality attributes	References
Flakes	Drying • Vacuum: 65 °C and 75 °C, absolute pressures: 7, 10 and 13 kPa • Low-pressure superheated steam dryer (LPSSD) with absolute pressures: 7, 10 and 13 kPa, temp: 65 and 75 °C	• AA retention (vacuum): 64–94% & 93–96% for LPSSD • Decrease in L^* and increase in a^* than control • Vacuum drying: shorter drying time • Vacuum system 75 °C, absolute pressure of 7 kPa most suitable	Methakhup *et al.*, 2005 (ref. 70)
Shreds	Blanching (80 °C/3 min) • Hot water • Salt solution • 0.3% KMS Drying • 60 °C ± 3 °C in a cabinet tray dryer, 1.2 m s^{-1} airflow	• L^* value decreased with drying time • Sharp increase in a^* and b^* value • Least changes in color in KMS blanching • Color degradation: control > salt > hot water > KMS • Color change followed zero order kinetics	Gupta *et al.*, 2011 (ref. 71)
	Blanching • 0.3%KMS • 80 °C/3 min (1 : 5 product–solution ratio) Cabinet tray drying • Air speed: 1.2 m s^{-1} • 50–60 °C	• Reduced drying time in blanching • AA loss: 69% (blanched), 27.78% (unblanched) • E_a (blanched): 43.98 kJ mol^{-1} • E_a (unblanched): 47.21 kJ mol^{-1}	Gupta *et al.*, 2014 (ref. 63)
	Cabinet drying • Five varieties (Banarasi, Chakaiya, Desi, Kanchan and NA-7) • 40 °C, 50 °C, 60 °C, 30% RH	• Higher AA & TPC at 50 °C • Lower AA & TPC at 40 °C • Newton model best to describe drying behaviour • No significant difference between pH, TSS	Kumari and Khatkar, 2018 (ref. 65)
Slices	• Fluidized bed drying 60 °C, 70 °C, and 80 °C (115 m min^{-1} air velocity) • Sun drying • Tray drying: 50m min^{-1} and 70 °C	• Higher AA in fluidized bed drying • Drying period: sun drying, 660 min & fluidized bed drying, 120 min, tray drying, 270 min	Murthy and Joshi, 2007 (ref. 61)
Gratings	Cabinet tray dryer • 55 °C ± 2 °C/8 h • Krishna, Kanchan, NA-7 and Chakaiya • Salt pretreatment (1%) • Storage: ambient, refrigerated, accelerated	• Salt pretreatment: better nutrients, color, AA: 79.51–84.89%, TPC: 176.5–220.3 mg GAE per g db • Ambient storage better. NA-7 cultivar amla, pretreated with 1% salt-dried for 8 h is the most suitable	Sonkar *et al.*, 2020 (ref. 66)
Segments	Solar tunnel drying, sun drying Pretreated • 2% NaCl • 0.1% KMS	• Solar tunnel was better than sun drying • Solar tunnel had highest AA retention, lower moisture content, 20–30% less drying time, highest RR, lowest water activity	Priyanka and Carolinrathinakumari, 2020 (ref. 67)
	Pretreatment: 360 W/8.5 min Drying • Sun (30–38 °C/7 h), tray (60 °C, 1.15 m s^{-1}) • Vacuum (60 °C), freeze (−40 °C)	• Retention of AA (99.33%), TPC (94.45%), naringin (97.11%), DPPH activity (96.61%) in the freeze drying • Drying time: 260, 290, 525 and 690 min in vacuum, tray, sun and freeze drying	Tewari *et al.*, 2021 (ref. 19)

Table 4 (*Contd.*)

Amla products	Processing condition	Quality attributes	References
Candy	Solar tunnel greenhouse dryer • 40° inclination angle • Temperature: 55–60 °C Open sun drying	• Color and taste of candy better in solar dryer • Modified Page model best to describe drying behavior • Payback age of 17 months	Patil and Gawande, 2018 (ref. 72)
Powder	• Spray drying: 200 °C inlet, 150 °C outlet temperature 40% aspiration speed, 5% maltodextrin • Freeze drying • Sun drying • Vacuum drying: 50 °C • Tunnel drying: 70 °C	• Powder yield in sun drying: 10.11%, tunnel drying: 8.78%, vacuum drying: 12.48%, spray drying: 4.90% and freeze drying: 2.23% • Highest AA & minerals in freeze drying and lowest in sun drying • Freeze-dried lighter in color and sun-dried darkest in color	Mishra *et al.*, 2009 (ref. 13)

[a] SO_2: sulphur dioxide, AA: ascorbic acid, TPC: total phenolic content, NEB: non-enzymatic browning, KMS: potassium metabisulphite, TSS: total soluble solids, RH: relative humidity, TA: titratable acidity, VI: vacuum impregnation, POD: peroxidase enzyme, DPPH: 2,2-diphenyl-1-picrylhydrazyl, E_a: activation energy, GAE: gallic acid equivalent, RT: room temperature, and RR: rehydration ratio.

and Joshi[61] attempted to examine the fate of ascorbic acid during fluidized bed drying. Fluidized bed drying took the shortest time to dry slices at 80 °C with an air velocity of 115 m min^{-1} and it retained more ascorbic acid than sun drying. A comparative study on the physicochemical properties of two varieties (Wild and Chakaiya) of amla dried by different drying techniques showed that the powder yield was highest in vacuum drying (12.48%) and lowest in freeze drying (2.23%).[13] The freeze-dried samples had the maximum retention of ascorbic acid and minerals, while the sundried samples showed the maximum loss. Mishra *et al.*[62] showed that an appreciable quality of spray-dried powder from amla juice can be prepared at an inlet temperature of 175 °C and 7% maltodextrin. Amla shreds, blanched in 0.3% KMS solution at 80 °C for 3 min reduced the drying time. Vitamin C content of blanched dried shreds decreased by 69.36% whereas unbalanced dried reduced up to 27.78%.[63] The pasteurized amla juice of cv Chakaiya was spray dried at an inlet drying temperature of 190 °C and feeding rate of 16 rpm 2% maltodextrin. High-quality amla powder could be prepared by spray-drying with a shelf life of 5 months at room temperature.[64]

The drying kinetics revealed that the maximum ascorbic acid and total phenolics were retained at 50 °C, while the lowest values were observed at 40 °C.[65] A similar study was performed on 4 different cultivars of amla, wherein the effect of salt pretreatment on the drying of amla grating was evaluated. Fruits of Krishna, Kanchan, NA-7 and Chakaiya cultivars were grated and mixed with 1% common salt, followed by cabinet tray drying at 55 °C for 8 h. Salt pretreatment increased the retention of the nutrients and color of the gratings. The retention of ascorbic acid and polyphenols was 79.51–84.89% and 65.12–75.57%, respectively, in the salt-pretreated samples compared to the untreated sample. Among them, the salt-pretreated NA-7 variety was the best to produce dry amla powder. The need for blanching was prevented due to salt pretreatment, which was proven to be effective to prepare dry amla powder with a higher concentration of nutrients.[66]

Pre-treated, amla segments with 2% NaCl and 0.1 KMS followed by solar tunnel drying resulted in 20–30% reduction in drying time compared to sun drying. The NaCl-treated solar tunnel dried samples had the lowest water activity. The overall quality of the solar tunnel-dried samples was better than that of the sun-dried samples.[67] Amla pretreated in a microwave (360 W) and dipped in water (1 : 10 ratio) for 8.5 min was subjected to four different drying techniques.[19] The results exhibited that freeze drying took the longest for drying (690 min), while vacuum drying took the least time (260 min). The quality of segments was significantly affected due to drying and reported a loss of 5.54–19.88% and 2.89–12.81% in total phenolic and naringin, respectively. SEM revealed the non-shrunken, porous structure of freeze dried sample. Raaf *et al.*[68] revealed the crystalline amorphous structure of amla and confirmed the presence of polyphenols, pectin and ascorbic acid.

6.2 Non-thermal processing

Generally, the non-thermal techniques used for the processing of foods are microwave, ultrasonication, ohmic, radio-frequency, high-pressure processing and pulsed electric field. Alternatively, there is a lack of research on the non-thermal processing of amla. The effects of non-thermal treatment on the quality of different products of amla fruit are summarized in Table 5. The high-electric field (HEF) technique has been employed for increasing the shelf life of amla fruit.[73] The effect of an alternating current (AC) and direct current (DC) with an HEF strength of 430 kV m^{-1} was observed on amla fruits. Keeping quality of fruits in closed and open polyethylene pouches was studied at 4 °C, 20 °C and 35 °C for 15 days. The application of an AC HEF was better for the shelf-life extension and retention of nutrients compared to DC HEF. Ohmic heating can be a promising technique for the processing of amla pulp. The quality characteristics of ohmic-heated amla pulp were examined by Singh *et al.*[49] Amla pulp was heated at 90 °C for 1 min at 11, 13, 15 and 17 V cm^{-1} voltage gradients. The

Table 5 Effect of non-thermal processing on quality attributes of amla fruit[a]

Amla product	Processing condition	Quality attributes	Reference
Whole fruit	High electric field (HEF)	AC HEF better than DC HEF, physiological loss of mass less in AC HEF, no adverse effect on AA	Bajgai *et al.*, 2006 (ref. 73)
	• Field strength 430 kV m^{-1} for 2 h • Storage at 4 °C, 20 °C and 35 °C	Shelf-life 25 days at 4 °C	
Pulp	Ohmic treatment • 11, 13, 15, 17 V cm^{-1} at 90 °C/1 min • KMS 0.2%	Best results at 17 V cm^{-1}, higher TA and TN, 7.14–17.13% loss of vitamin C	Singh *et al.*, 2013 (ref. 49)
Juice	PEF	93.12% DPPH inhibition, no significant changes in pH, TSS, BI and conductivity	Bansal *et al.*, 2013 (ref. 74)
	• Field strength 24 kV cm^{-1}, treatment time 500 μs monopolar rectangular pulse of 1 μs width	Shelf-life 6 weeks at 4 °C	
Juice	PEF	63% retention of vit C, 68.5% retention of TPC, lower BI, 5.1 log cycle reduction of *Zygosaccharomyces bailii*	Bansal *et al.*, 2015 (ref. 75)
	• 26 kV cm^{-1}, 1 Hz frequency for 500 μs and monopolar rectangular pulse of 1 μs width • Juice inoculated with *Zygosaccharomyces bailii*	Shelf-life 40 days at 4 °C	
Juice	Nano and ultrafiltration • Polyamide membrane with MWCO of 15 kDa, pore diameter 59 Å, 300 psi pressure for NF and 150 psi for UF	71.4% recovery rate in NF, improved color and clarity, retained maximum AA	Dawale and Jawade *et al.*, 2016 (ref. 76)
Juice	Thermal assisted high-pressure processing (THPP) • 200–500 MPa, 1 s to 20 min and 30–60 °C	85% AA retention, increased L^*, TAC and TPC increased to 20 & 28% respectively	Raj *et al.*, 2019 (ref. 78)
Juice	Pulsed light • Intensity: 1504–3012 J cm^{-2} • Voltage: 2.7, 2.8 and 2.9 kV • Treatment time: 3, 4, and 5 min	Complete inactivation of PPO &POD at 2.9 kV/5 min, 3012 J cm^{-2} at 10.04 W cm^{-2}, retention of TPC, antioxidants and vitamin C: 45%, 54, and 61% respectively	Chakraborty *et al.*, 2020 (ref. 79)
Juice	Ultrasonication • Power: 455 W and frequency of 20 kHz • Amplitude: 20–70% • Exposure time: 5–15 min • Pulse duration (4–6 s ON/10 s)	PPO inactivation rate 90.72%, POD inactivation rate 73.18%, optimal process conditions achieved at 70% pulsed at 5 s ON and 5 s off for 7 min 30 s. Increase in AA of sonicated amla juice as well as antioxidant activity	Aslam *et al.*, 2023 (ref. 80)

[a] AC: alternating current, DC: direct current, AA: ascorbic acid, TA: titratable acidity, TN: tannins, PEF: pulsed electric field, DPPH: 2,2-diphenyl-1-picrylhydrazyl free radical scavenging activity, TSS: total soluble solids, BI: browning index, TPC: total phenolic content, MWCO: molecular weight cut off, NF: nanofiltration, UF: ultrafiltration, TAC: total antioxidant capacity, PPO: polyphenol oxidase enzyme, and POD: peroxidase enzyme.

retention of vitamin C, tannins and color was higher at 17 V cm^{-1} than that at other gradients and showed better quality attributes than other pulp samples.

The effect of a pulsed electric field (PEF) was studied on amla juice. The juice was PEF treated using a static chamber at 24 kV cm^{-1} for 500 μs with a pulse width of 1 μs. Another juice sample was thermally treated at 90 °C/60 s and both samples were stored at 4 °C for 6 weeks.[74] PEF proved to be a better technique for processing the juice than the conventional technique, which substantially reduced the non-enzymatic browning (NEB) and the retention of antioxidants was superior to the conventional treatment. In another study, Bansal *et al.*[75] examined the effect of PEF on amla juice inoculated with *Zygosaccharomyces bailii*. PEF treatment at 26 kV cm^{-1} for 500 μs successfully inactivated *Z. bailii* with a 5.1 log cycle reduction. The treated juice had a high retention of vitamin C (63%) and antioxidant capacity (88.9%). Although thermal treatment caused a 4.9 log cycle reduction in *Z. bailii*, it resulted in a significant reduction in vitamin C and antioxidant capacity. Both PEF and thermal treatments did not cause any changes in pH and soluble solids of amla juice. An examination of the morphology using electron microscopy depicted the leakage of cellular debris due to the breakage of cells of *Z. bailii* during PEF treatment.

Purification and concentration of amla juice were carried out using a spiral wound membrane module with a molecular weight cut-off of 15 kDa.[76] Browning of fruit juices after processing due to polyphenol oxidase and peroxidase activity is one of the critical issues in the food industry.[77] A novel technique known as thermal-assisted high-pressure processing (THHP) was employed for the processing of amla juice. The juice processed using THHP was nutritionally superior to the thermally treated samples. The extractability of phenolics and other antioxidants increased due to the high pressure together with the good retention of ascorbic acid and color upon THHP treatment.[78]

The pulsed light (PL) technique can be utilized as substitute for conventional pasteurization.[79] A PL intensity of 1504–3012 J cm^{-2} was applied to amla juice. Deactivation of the PPO (polyphenol oxidase) and POD (peroxidase) enzymes was achieved at 2.9 kV (3012 J cm^{-2} at 10.04 W cm^{-2}), helping to preserve the total phenolics, antioxidants and vitamin C content with a retention of 45%, 54%, and 61%, respectively. Thermal treatment (95 °C/30 min) of mechanically extracted amla juice also inactivated the enzymes but browning was higher than that in the PL treated juice. Ultrasonication (US) uses high energy, low frequency sound waves and has attracted significant attention in recent times as a non-thermal technique for the processing of foods. A probe-type ultrasonication system was found to be effective for the inactivation of the PPO and POD enzymes in fresh amla juice.[80] Ultrasonic pre-treated slices (frequency of 40 kHz for 10 min) were found to have improved mass transfer dynamics during osmotic dehydration[81] but it affected the color and vitamin C content of the slices.[82] The in-depth and systematic application of non-thermal techniques can be undertaken to determine the best methodology for treatment and processing.

7. Health aspects of amla fruit

The consumption of fruits on a regular basis reduces the risk of various diseases due to the fact that fruits contain potent phytochemicals. These bioactive compounds are responsible for counter attacking the toxins in the body after the consumption of fruits. *Emblica officinalis*, amla has been used traditionally for ages to combat various diseases including lifestyle-related disorders such as diabetes, hypertension, hyperlipidemia and obesity. Amla is a powerful rejuvenator and helps in delaying and repairing tissue cells. Amla fruit is useful in the management of numerous diseases including cancer.

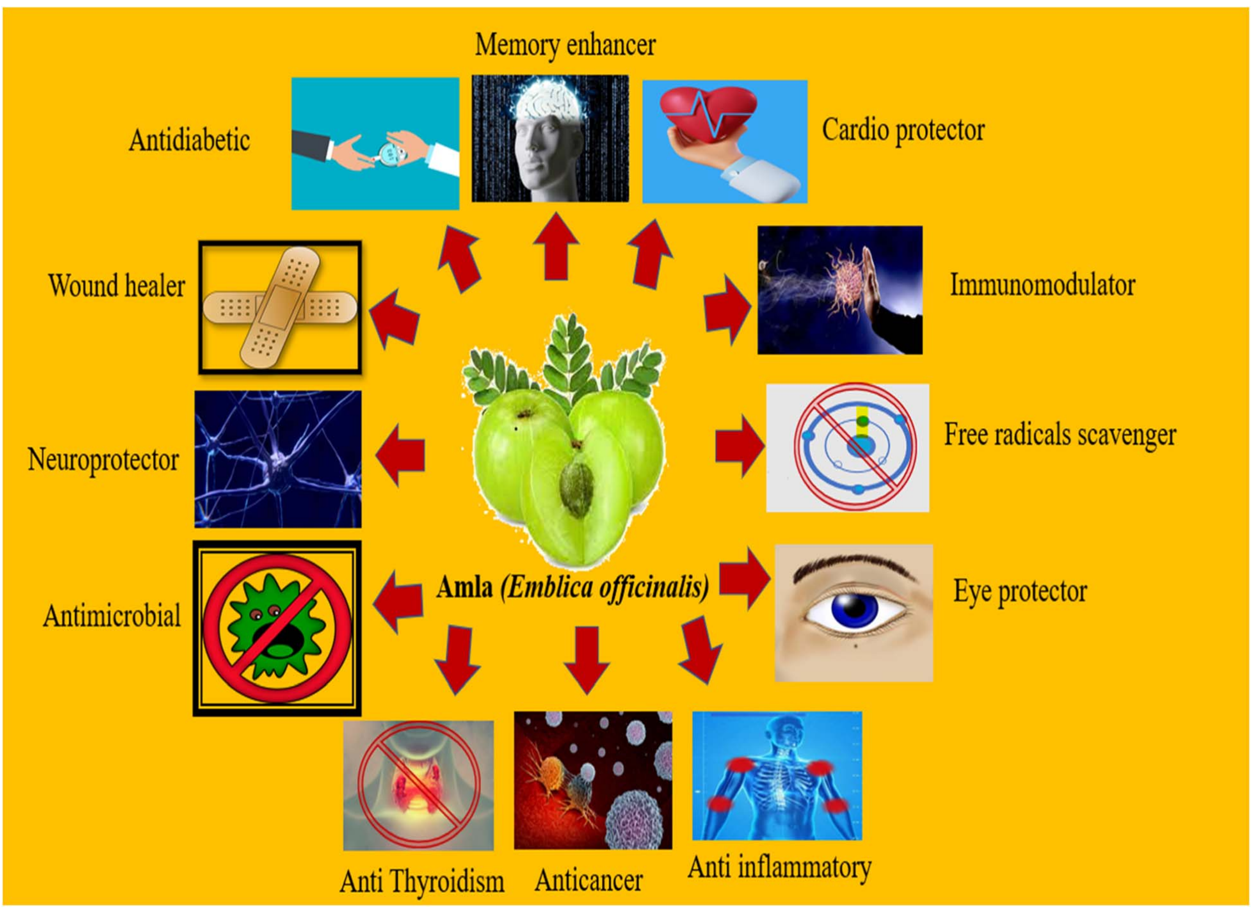

Fig. 2 Various pharmacological effects of the amla fruit.

Table 6 Phytochemicals present in amla fruits and their biological actions

Phytochemicals	Examples	Biological activity	References
Hydrolysable tannins	Emblicanin A and B	Antioxidant	Madhuri *et al.*, 2011 (ref. 111)
	Punigluconin	Antioxidant	Bhattacharya *et al.*, 1999 (ref. 112)
	Pedunculagin	Antioxidant	Chang *et al.*, 1995,[113] Bhattacharya *et al.*, 1999 (ref. 112)
	Chebulagic acid	Antioxidant, anti-inflammatory	Chen and Li, 2006,[107] Reddy *et al.*, 2009 (ref. 108)
	Corilagin	Antioxidant, anti-atherosclerotic	Singh *et al.*, 2011,[31] Srinivasan *et al.*, 2018 (ref. 83)
	Geraniin	Antioxidant, anti-atherosclerotic	Kumaran and Karunakaran, 2006,[114] Kim *et al.*, 2010,[115] Tewari *et al.*, 2021 (ref. 19)
Phenolic compounds	Gallic acid, methyl gallate	Antioxidant, anti-proliferative, antidiabetic, cardioprotective, antibacterial, anti-inflammatory	Singh *et al.*, 2011,[31] Srinivasan *et al.*, 2018,[83] Tewari *et al.*, 2021 (ref. 19)
	Ellagic acid	Antioxidant, anti-inflammatory, anti-proliferative, antidiabetic, anticancer	Singh *et al.*, 2011,[31] Srinivasan *et al.*, 2018 (ref. 83)
Vitamins	Ascorbic acid	Antioxidant, antidiabetic	Chauhan *et al.*, 2005,[116] Khan, 2009,[117] Tewari *et al.*, 2019 (ref. 4)
Flavonoids	Quercetin	Antioxidant, protein kinase inhibitor, antibacterial, anti-inflammatory, immunomodulatory	Baliga and Dsouza, 2011,[118] Madhuri *et al.*, 2011,[111] Tewari *et al.*, 2021 (ref. 19)
	Kaempferol	Antioxidant, neuroprotective, anticancer, anti-osteoporotic	Jung *et al.*, 2008,[119] Charoenteeraboon *et al.*, 2010,[120] Tewari *et al.*, 2021 (ref. 19)
Organic acids	Citric acid	Antimicrobial, neuroprotective	Kulkarni and Ghurghure, 2018,[109] Hassan *et al.*, 2020 (ref. 110)
	Malic acid	Antimicrobial, neuroprotective	Kulkarni and Ghurghure, 2018,[109] Hassan *et al.*, 2020 (ref. 110)
	Shikimic acid	Antimicrobial, neuroprotective	Kulkarni and Ghurghure, 2018,[109] Hassan *et al.*, 2020 (ref. 110)

Fig. 2 shows different pharmacological effects of amla fruit including antidiabetic,[83,84] anti-inflammatory,[85,86] cardioprotective,[87,88] immunomodulator,[89] memory enhancer,[90] wound healer,[91] neuroprotector,[92,93] free radical scavenger,[94,95] eye protector,[96] antithyroidism,[97] antimicrobial,[98] and most important anticancer.[99,100] Amla can also be helpful in treating a plethora of diseases and disorders including hyperacidity, constipation, colitis, haemorrhoids, dyspepsia, gastritis, ophthalmic issues, anaemia, cough, asthma, osteoporosis, premature greying of hair, weakness and fatigue, nerve debility and liver complaints.[101] The clastogenicity and mutagenicity caused by certain metals are also inhibited by fruit extracts. Research on amla has demonstrated that it can decrease cyclo phosphamide-induced DNA damage in mouse bone marrow cells. Furthermore, it has been shown to decrease the cytochrome (Cyt) P450 levels, increase the glutathione levels and antioxidant enzymes (glutathione peroxidase (GPx), glutathione reductase) and boost the detoxifying enzyme glutathione-*S*-transferase (GST).[102]

The various phytochemicals present in amla fruit and their biological actions are summarized in Table 6. The unique array of polyphenols including flavonoids and tannins imparts anticancerous property to amla. Polyphenols act on multiple metabolic pathways in different forms and regulates bodily mechanisms related to carcinogenesis.[103] Various studies on amla revealed that 97.67% of the phenolics in amla are in the free form and the major constituents of the total phenolics are gallic acid, ellagic acid, tannins, quercetin, anthocyanidin and rutin. Gallic acid and methyl gallate have been reported to have antioxidant, antidiabetic and antiproliferative activities (Table 6). An extract of amla exhibited an inhibitory effect against enzymes involved in diabetes (α-amylase, α-glucosidase, and dipeptidyl peptidase-4). The inhibitory potential of the extract was effective in the control of type II diabetes mellitus.[95] Ellagic acid has been proven to be an anticancer compound.[83] *In vivo* studies of amla extract showed that it has antitumor activity against cancer cell lines including A549 (lung), HepG2 (hepatocytes), MDB-MB-231 (breast, triple negative), HeLa (cervical), SK-OV3 (ovarian), and SW620 (colorectal).[104]

As an excellent source of ascorbic acid, amla fruit is known to act as a potent antioxidant (Table 6). A report cited a significant reduction in LDL level, C-reactive protein and protection against heart disorders after long-term use of amla.[105] Treatment with amla induced a significant increase in HDL levels, lowering the total cholesterol, LDL VLDL, and triglycerides.[106] The tannins present in amla such as emblicanin-A and B, ellagic acid, gallic acid, and corilagin have protective action against various cardiac disorders.[3] Emblicanin A and B, punigluconin, and pedunculagin have excellent antioxidant activities. Chebulagic acid has anti-inflammatory activity in addition to being

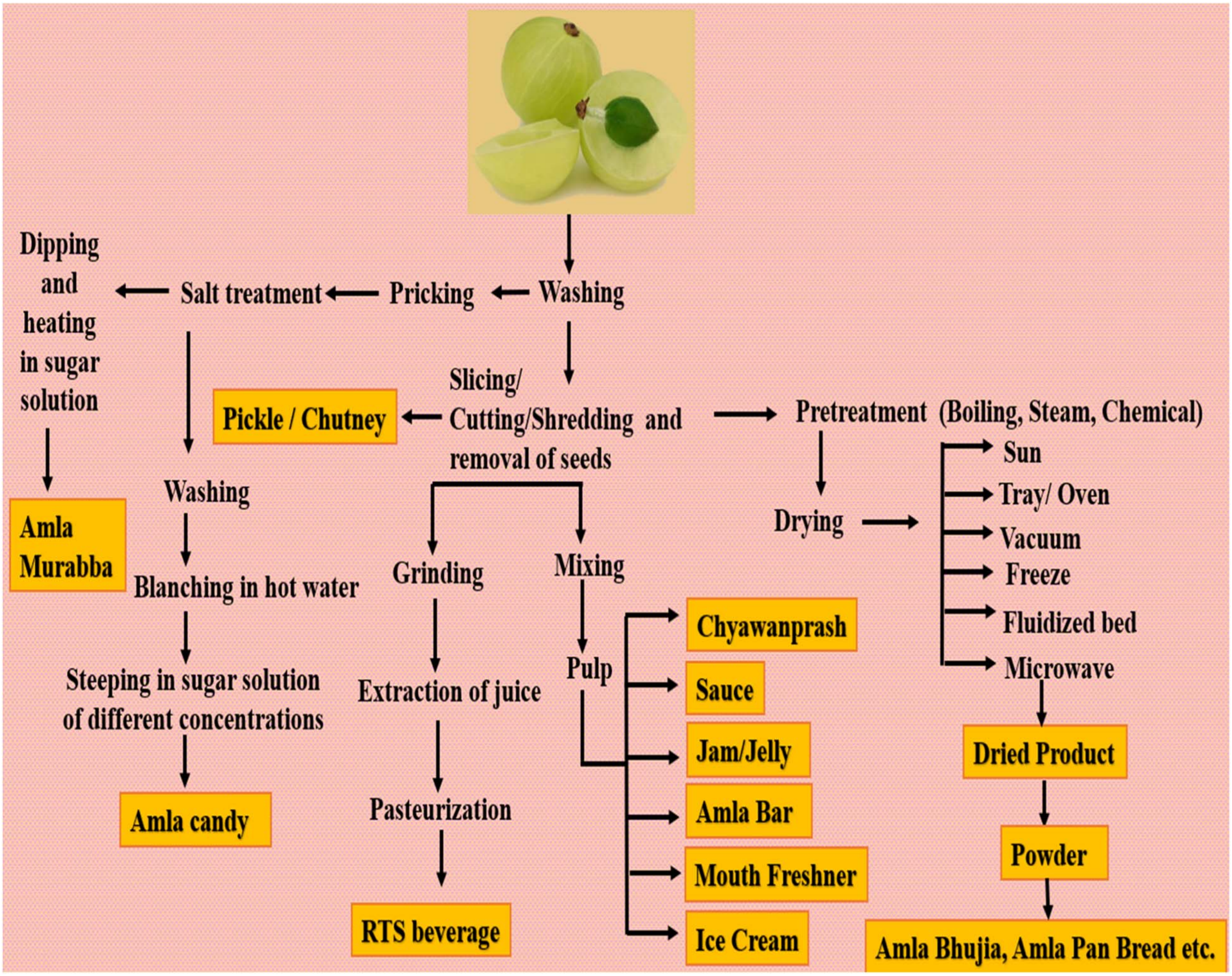

Fig. 3 Flow diagram representing the processing of amla and its value addition.

an antioxidant.[107,108] Organic acids of amla fruit are well known for their antimicrobial and neuroprotective effects.[109,110]

8. Value addition of amla fruits

The shelf life of amla fruit is short, *i.e.*, 5–6 days, and is highly susceptible to browning, bruises and necrosis. Furthermore, the post-harvest losses due to discoloration, brushing and microbial growth reduce its market potential. Thus, to overcome these losses, the fruit must be processed into value-added stable products with the aim of increasing its consumption and acceptance among consumers. Processing also adds value to the astringent and acidic nature of amla fruit together with an increase economic gains and provides high returns to farmers. Numerous amla-based products are already in the market. Presently, the increasing concern for health has expanded the market of value-added products from amla. Fig. 3 explains the processing of raw, fully mature amla fruit into various products.

Amla murabba or preserve is one of the age-old products of its fruit. The preserve is made from steeping the fruit into heavy sugar solution until it becomes tender and transparent in color.[121] Murabba is claimed to impart energy and strength to the body and is often advised by Vaidyas and Ayurvedacharyas to the patients. Usually, large size fruits are used for the preparation of preserve. Other popular products of amla are chyawanprash and triphala. Chyawanprash is believed to be a potent immunomodulator and many studies have claimed that it induces a significant boost in white blood cells in rodents. Amla is a rich source of ascorbic acid and its L-enantiomer, commonly referred as vitamin C, which is an essential micronutrient in different metabolic processes of the body. The importance of vitamin C has prompted fortification of this micronutrient in different food products. However, the important aspect to be investigated is the stability of this micronutrient in different popular products because of its high reactivity and instability. It is oxidized into DHA (dehydroascorbic acid) reversibly when exposed to heat, light, metal ions (transition) and alkaline pH.[77,122] DHA is further irreversibly hydrolyzed to 2,3-diketogluconic acid. Therefore, the stability of ascorbic acid in amla-rich products such as chyawanprash and triphala needs to be critically studied. However, different studies have reported losses in ascorbic acid in chyawanprash due to the heat treatment of amla pulp. The degradation of ascorbic acid has also been reported during storage.[123] Therefore, it is a challenge to render stability to ascorbic acid in amla-rich products to give benefits to the consumers. Bio-macromolecules can be used as carrier agents and micronutrients can be encapsulated by using different techniques such as spray drying, microfluidics, homogenization, complex coacervation, emulsification and spray chilling to protect them from the external environmental factors.

Triphala is an ayurvedic medicine made up of equal amounts of *Terminalia chebula*, *Phyllanthus emblica*, and *Terminalia belerica*. Polyphenols, vitamin C, and flavonoids are abundant in triphala, which impart therapeutic properties to it. Smaller-size fruits are utilized in making pickles and chutney. During the pickling process, astringency is removed through brining in potassium metabisulphite solution. Gajanana *et al.*[124] proposed and standardized a recipe for amla syrup using amla juice, lime, ginger juice and sugar. Ready to serve (RTS) drink was prepared by mixing amla juice and bitter gourd in a ratio of 75 : 25. The addition of bitter gourd helped to remove the astringency of amla juice.[125]

Fruit wine was prepared by fermenting amla using *Saccharomyces cerevisiae*.[126] The alcohol content was 9.29% and compounds such as *n*-butanol, iso-butanol and *n*-propanol were detected in trace amounts. Amla candy, which falls in the category of intermediate moist foods, is also a popular product. Candies prepared from blanched amla retained more nutrients than lye-peeled amla.[127] Dried amla shreds are also a valuable form of amla fruit. Shreds prepared from KMS blanched amla had superior quality.[128] Amla bhujia was prepared from amla pulp, gram flour and spices. Sensory evaluation of amla bhujia had high acceptable scores.[129] A fruit beverage containing amla juice, pomegranate, and musk melon was developed with the optimum proportion of 5%, 57%, and 38%, respectively.[130] The functional and nutritional properties of ice cream were enhanced due to the addition of amla shreds, candy, pulp, preserve and powder. The inclusion of amla in processed form increased the phenolic and antioxidant properties but decreased the overrun in ice cream.[35] A functional pan bread prepared from dried amla powder exhibited superior sensory and nutritional quality. Supplementing the bread with amla powder increased the loaf volume and bread volume.[86] Amla mouth freshener, a substitute of pan masala, gutka and tobacco, was developed using amla fruit.[131] The pulp of Desi and Banarasi cultivars of amla, carboxymethyl cellulose, areca nut, cardamom, sugar and milk powder was mixed in a proportion to prepare a nutritious and palatable amla mouth freshener, which was packed in HDPE bags at ambient temperature. The storage analysis proved that the content of ascorbic acid decreased, but the overall acceptability was not affected.[132] A nutritious fruit bar was developed using amla and guava pulp,[133] which had appreciable sensory score with high nutritional value. Amla candy can be prepared (cv Kanchan) using different spices and sugar syrup. Also, 68% sugar syrup and 10% spices have been recommended due to their good organoleptic properties and high shelf life.[134]

9. Packaging and storage of amla fruits

Packaging plays very important role in enhancing the shelf-life and maintaining the quality parameters. Firstly, fruits are sorted, and then packed for transportation. Generally, amla fruits are packed either in cloth sacks or jute gunny bags (capacity 50–100 kg) or corrugated boxes (capacity 20 kg). During their transportation, injuries are caused due to vibration and stacking. However, there is a lack of research on the effective packaging of amla. The use of corrugated fiber boxes (CFB) with paper liners has been suggested for the packing of amla fruit.[135] Cloth sack storage without any liners suffered maximum spoilage (30.19%), whereas CFB with newspaper liners experienced the least spoilage (16%) and polythene liners had 17% spoilage after 13 days of storage. The lowest respiratory activity (81.1 mg CO_2 per kg per h) with minimum loss and 11 days of extended shelf life in CFB under ambient conditions for the NA-7 cultivar of amla was reported.[136] A perforated polythene bag was found to be useful in reducing the physiological loss with acceptable physiochemical quality of amla fruits. The fruits had an extended shelf life of 15 days at ambient temperature after treatment with 6% waxol and 4×10^5 μL cycocel chlormequat chloride (CCC)/L.[137]

Dipping the fruits in different PGR (plant growth regulators) such as GA_3 (gibberellic acid), NAA (naphthalene acetic acid) and chemicals such as $CaCl_2$ have been found to be useful for extending the shelf life of fruits.[138–140] However, there is a discrepancy in the temperature reported by various authors required for the proper storage of amla fruits. The quality and storage of amla fruits were significantly affected after treatment with $CaCl_2$ and GA_3. Treatment of amla fruits with calcium nitrate at 1.5% + perforated polythene bag and GA_3:100 ppm + perforated polythene bag resulted in a reduction in physiological weight loss up to 16% and 16.34%, respectively.[135] This treatment also decreased the respiratory activity (72–80 mg CO_2 per kg per h). Treatment with GA_3 yielded better retention of ascorbic acid and malic acid.[141] Amla fruits cv Chakaiya were treated with different concentrations of GA_3 (50 ppm and 100 ppm), naphthalene acetic acid, NAA (20 ppm and 30 ppm) and $CaCl_2$ (1% and 1.5%), followed by air drying, and then stored at room temperature in 5 ply corrugated boxes lined with newspaper with 5% ventilation, which showed physiological weight loss (4.94%, 7.06% and 9.04%) during storage at 4, 8 and 12 days, respectively, in $CaCl_2$ (1%) treated fruits.[142]

Different authors also reported various treatments useful to extend the shelf life of amla fruits. Treatment with borax can reduce pathological losses, whereas physiological weight can be reduced by treating with calcium nitrate. The study by Nath *et al.*[143] demonstrated an extension in the shelf-life of amla fruit *via* three different treatments, including GA_3 (50 ppm), borax (4%) and calcium nitrate (1%). It was found that up to 9 days of storage, the borax-treated sample showed zero pathological losses and reduced physiological weight loss was observed upon calcium nitrate treatment.

Goyal *et al.*[22] reported a temperature of 0–2 °C for the storage of amla fruit, whereas other authors reported a temperature of 5–7 °C,[144] 12 °C (ref. 145) and 15 °C.[146] Storing amla fruits at 12 °C proved to be effective and reduced the effects of chilling injury.[52] Amla fruits impregnated in liquid and treated with 15% NaCl + 0.05% sodium benzoate + 0.1% EDTA and 15% NaCl + 0.05% sodium benzoate + 0.2 calcium lactate in association with EDTA or calcium lactate in liquid medium were found to have an extended shelf-life of up to two months at ambient temperature.[147] Amla cut fruits having pretreatments with 0.05% sorbitol, 1% calcium chloride and 3% citric acid were packed in three different modified atmosphere packaging (MAP). MAP_1 had $O_2 = 5\%$, $CO_2 = 10\%$ & $N_2 = 85\%$, MAP_2 had $O_2 = 10\%$, $CO_2 = 20\%$ & $N_2 = 70\%$, whereas MAP_3 consisted of $O_2 = 15\%$, $CO_2 = 30\%$ & $N_2 = 55\%$. The fruits were stored at temperatures of 5 °C and 10 °C with a relative humidity of 90–95%. The samples packed in MAP_1 remained fresh and retained the maximum polyphenols and antioxidant capacity with the least changes in firmness and puncture strength at both 5 °C and 10 °C. However, the weight loss increased with storage time.[148]

Presently, research is still lacking on understanding the post-harvest management of underutilized amla fruit. There is an urgent need for sustainable technology to realize a better shelf life and packaging of amla fruits. Newer techniques such as dynamic controlled atmosphere (DCA), and ultralow oxygen (ULO) storage need to be explored and introduced for the storage and reduction of post-harvest losses.

10. Recent application of nanoparticles from amla extract

In the past few years, there has been a significant increase in the use of plant-based nanomaterials because of their unique advantages such as eco-friendly nature, cost-effectiveness, low energy utilization, and simple and scalable approach to manufacture nanoparticles (NP). Furthermore, NP of different sizes and shapes can be produced from plant extracts. The size of nanoparticles typically varies between 1 and 100 nm, which determines the surface area, being an important characteristic that affects the distribution of nanoparticles in a system. NP with a size of <10 nm can easily pass through blood vessels, cleared by the kidneys and have less ligand-to-receptor interaction, whereas larger nanoparticles offer a higher surface area for reactions, hence imparting higher reactivity.

Many reports have demonstrated that gold and silver nanoparticles from different plant sources exhibit strong antibacterial properties. Gold nanoparticles generated from *Citrus maxima*,[149] *Carica papaya*,[150] *Ananas comosus*[151] and *Punica granatum*[152] are some of the important plant sources that have been reported to show strong antibacterial properties. Numerous studies have also reported the antifungal, and most importantly anticancer properties of plants. Amla is one of these plants, and various attempts have been made to produce NP using its extract. Ankamwar *et al.*[153] conducted a study, wherein silver and gold nanoparticles were produced from amla fruit extract. The extract acted as a reducing agent for the production of extracellular silver and gold nanoparticles. On treating the extract with an aqueous solution of silver sulphate and chloroauric acid solution, rapid reduction of the ions was observed. Transmetallation reaction resulted in the formation of highly stable silver and gold NP, which ranged in size from 10 to 20 and 15 to 25 nm, respectively. A similar approach was adopted by Mookriang *et al.*[154] for the synthesis of NP using amla extract as the reducing agent. The time, temperature, and concentration of silver nitrate and amla extract were the factors influencing the synthesis of silver NPs. Treatment of silver nitrate dissolved in deionized water with amla fruit extract resulted in the formation of silver NP with an average diameter of 41.2 nm. In another study, the low-cost biogenic synthesis of silver NP using amla fruit extract was reported. The particle size ranged from 19.8 to 92.8 nm with an average diameter of 39 nm and the NP were characterized using FTIR, electron microscopy, X-ray diffraction and UV spectroscopy.[155] The synthesized particles showed significant antimicrobial activity against the pathogen *Acidovorax oryzae* strain RS-2 of rice bacterial brown stripe at 20 $\mu g\ mL^{-1}$. The study concluded that silver NP can be a good eco-friendly option to curb rice bacterial disease. A similar study by Meena *et al.*[156] revealed the remarkable antibacterial activity of silver NP against *E. coli*. Silver NP were synthesized using amla fruit extract as the reducing and capping agent. The characterization of NP was done using XRD, TEM and UV spectroscopy, which revealed that their size was 20–25 nm. Also, the study revealed that the zone of inhibition increased on increasing the concentration of silver NP. As a miraculous plant and fruit, investigations are needed to compare the properties of nanoparticles from amla to that from other different plant sources for different uses and to prove their superiority or competitiveness.

11. Conclusion and future aspects

Amla fruit (Indian gooseberry), as rich source of antioxidants and phenolics, is an excellent fruit for maintain human health. Thus, it is necessary to extract the maximum benefits of this super berry by processing it into value-added functional products. Processing techniques such as blanching and drying result in the loss of bioactive compounds. Thus, to combat this loss, minimal processing methods need in depth exploration. Research must focus on making technology available to farmers at low cost. The utilization of bioactive compounds of amla fruit can enormously add value to the processed product. Post-harvest management of amla is also poor, which needs improvement. The medicinal property of amla is due to the presence of bioactive phytochemicals including ascorbic acid. Compounds such as gallic and ellagic acid, quercetin, kaempferol, vanillic acid, isocorilagin, and punigluconin have excellent antioxidant properties. In this case, many clinical trials have been conducted with the aim to reveal the therapeutic potential of amla fruit. However, evidence-based studies need to be the focus. The application of advanced techniques may be further helpful for the isolation of bioactive compounds from the fruit and value addition of this miraculous fruit.

Author contributions

The author RT wrote the first draft of the manuscript. VK and HKS contributed as the principal authors to critically revise the manuscript and gave its final shape. All authors have read, critically reviewed, and approved the final manuscript.

Conflicts of interest

The authors declare that there is no conflict of interests.

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