RASĀYAN *J. Chem.*
Vol. 19 | No. 3 | 1672-1682 | July-September | 2026
ISSN: 0974-1496 | e-ISSN: 0976-0083 | CODEN: RJCABP
http://www.rasayanjournal.com
http://www.rasayanjournal.co.in

ASCORBIC ACID IN AGRO-WASTE: INSIGHTS INTO ITS CHEMISTRY, BIOSYNTHESIS AND EXTRACTION APPROACHES

Emil Jebaz Devasundar[1], Naushad Edayadulla[1,✉] and Chandraraj Shanmuga Sundari[2]

[1]Department of Chemistry, Vel Tech Rangarajan Dr. Sagunthala R & D Institute of Science and Technology, Avadi, Chennai-600 062, Tamil Nadu, India.

[2]Department of Chemistry, The Oxford College of Engineering, Bommanahalli, Bangalore-560 068, Karnataka, India.

✉Corresponding author: edayam2004@gmail.com

ABSTRACT

Food waste generated from fruits and vegetables has increased recently due to rising food consumption and the expansion of the food industry. Therefore, techniques for reducing food waste have been upgraded through recycling, leading to the development of various beneficial products. Ascorbic acid, commonly referred to as vitamin C, is found not only in the juices of fruits and vegetables but also in their waste parts, including peels and seeds. Ascorbic acid is an organic compound with a molecular mass of 176.12 g/mol and the chemical formula $C_6H_8O_6$. Ascorbic acid is biosynthesised in the mitochondria by several pathways, including the L-gulose, the D-galactopyronic acid, the Smirnoff-Wheeler, and the myo-inositol pathways. Ascorbic acid can be extracted from the fruit and vegetable waste by conventional and non-conventional methods. Due to their lower energy consumption, cost-effectiveness, and environmental sustainability, non-conventional methods are more efficient than conventional approaches, particularly in the context of recovering valuable compounds like ascorbic acid from agro-food waste. Recovery of ascorbic acid from agro-food waste not only reduces environmental burden but also supports the valorisation of by-products into value-added compounds with a lot of applications in many industries.

Keywords: Ascorbic Acid, Vitamin C, Fruit Waste, Vegetable Waste, Biosynthesis, Extraction Technique.

RASĀYAN *J. Chem.*, Vol. 19, No.3, 2026

INTRODUCTION

In recent years, the expansion of the food industry and the growing demand for food have caused a notable increase in food waste, especially from fruits and vegetables. Currently, these wastes are among the primary contributors to municipal solid waste.[1] Among these wastes, residues from fruits and vegetables have become a major environmental concern, especially in urban regions.[2] To address this issue, recent initiatives have focused on improving food waste management, emphasising the value of resource recovery and recycling. Utilising agro-waste as a rich source of phytoconstituents is one promising strategy. These bioactive compounds can be isolated and turned into useful products that have positive effects on the environment and the economy.[3] Citrus fruits contain a huge amount of flavonoids, ascorbic acid (AA), and phenolic compounds, which have potent natural antioxidants.[4] Every year, a huge amount of by-products, including peels, seeds, and pulp, are produced because citrus fruits are mostly processed into juices and flavoured beverages. Interestingly, these discarded parts are frequently abundant in bioactive substances like flavonoids, phenolics, and AA, which makes them a prospective material for the generation of value-added products.[5] Long before vitamin C was discovered, it was observed that citrus fruits could prevent scurvy—a disease that claimed the lives of nearly two million sailors between 1500 and 1800.[6] Albert Szent-Györgyi, Charles Glen King, and Joseph L. Svirbely, together with a group of Hungarian scientists, were able to isolate vitamin C and identify it as AA between 1928 and 1933. AA has been one of the most celebrated compounds since its discovery in the late 1920s, and vitamin C's health-promoting properties are widely recognized.[7,8] AA, also called vitamin C, is essential for maintaining human health. It is a water-soluble compound with a similar structure to a monosaccharide.[9] According to nutritionists, the main source of vitamin C is food, which provides 10% to 25% of the daily

http://doi.org/10.31788/RJC.2026.1939766

recommended intake while being relatively low in calories.[10] In 1989, 60 mg was established as the Recommended Dietary Allowance (RDA) for adults. It was thought to be sufficient to prevent scurvy and maintain the body's vitamin C stores for roughly 30 days, giving a fair margin of safety. However, in April 1999, experts recommended raising the RDA to 120 mg daily according to new findings.[11] As of 2000, the recommended daily intake of AA in the United States was 75 mg for females and 90 mg for males. Due to their elevated oxidative stress, smokers are advised to take an additional 35 mg daily. The recommended consumption rises to 120 mg during lactation and 85 mg during pregnancy for 19-year-old women and older. In a press statement issued on April 10, 2000, the National Academy of Sciences (NAS) determined that the maximum tolerable daily intake of vitamin C for adults is 2000 mg (2 g).[12] AA's primary metabolic function is definitely connected to its ability to function as a beneficial reducing agent. Acting as a chelating agent, it interacts with certain metal ions to improve their mobilisation and distribution throughout the body as well as their absorption from the diet. Because it is present in bodily fluids, AA behaves as an antioxidant, protecting cells from oxidative damage.[13]

In addition, it strengthens the immune system, decreases allergic reactions, supports the removal of different steroids, encourages the gallbladder, and facilitates the absorption of vital minerals like iron, calcium, and folic acid. Additionally, AA is necessary for the manufacture of collagen, the protein that makes up the structural framework of teeth, bones, cartilage, skin, and healing tissues.[14] Its pharmacological benefits exhibit a wide range of health conditions, including cardiovascular diseases, scurvy, the common cold, cancer, osteoarthritis, hypertension, diabetes, gout, asthma, wounds, pregnancy-related issues, and eye disorders.[15] AA has been used in numerous medicinal and cosmetic compositions due to its numerous beneficial properties.[16]

This review aligns closely with SDG-12: Responsible Consumption and Production by emphasising the sustainable recovery of AA from fruit and vegetable waste. Despite the growing interest in the recovery of phytoconstituents from food waste, a comprehensive understanding of AA extraction from vegetable and fruit waste products remains limited. Existing studies often focus on individual extraction techniques or specific waste sources, with less emphasis on integrating the chemistry, biosynthesis, pretreatment strategies, and comparative efficiency of conventional and non-conventional extraction methods. Therefore, this review aim's to deliver a systematic overview of AA, including its chemical properties, biosynthetic pathways, pretreatment requirements, and extraction approaches from fruit and vegetable waste. This review aims to fill the research gap by consolidating dispersed information into a single framework, enabling a clearer understanding of sustainable extraction strategies and their practical relevance. By compiling and critically evaluating existing knowledge, this review supports future research on sustainable extraction technologies and promotes the valorisation of agro-food waste into value-added bioactive compounds.

Chemistry of AA

AA is an organic product with the chemical formula of $C_6H_8O_6$. The IUPAC name for AA is l-threo-Hex-2-enono-1,4-lactone or (R)-3,4-Dihydroxy-5-((S)-1,2-dihydroxyethyl) furan-2(5H)-one. There are two enantiomers (mirror-image isomers) of AA, which are generally represented by the letter's "l" (for "levo") and "d" (for "dextro"). Among these, the L-isomer is the naturally occurring and biologically active form of vitamin C. Its epimer, erythorbic acid, and its mirror-image form, D-ascorbic acid, show only partial vitamin C activity. The molecular mass of AA is 176.12 g/mol, and its melting point ranges from 190 to 192 °C. The enolic hydroxyl groups from the C3 and C2 carbon atoms in vitamin C, which is a 5-carbon lactone, can separate to generate a dibasic acid. The proton of the hydroxyl C3 group becomes a strong acid (pK_1 = 4.25) in comparison to the proton group from C2 (pK_2 = 11.79) when the remaining 2.3-endiol conjugates with the lactonic carbonyl group. The 2,3-endiol group of L-ascorbic acid can donate one or more electrons, leading to the formation of the well-known intermediate semi-dehydro-L-ascorbic acid and eventually the oxidised product, dehydro-L-ascorbic acid.[17] AA is an active optical agent because it contains two asymmetric carbon atoms, C4 and C5. The plane of positive polarised light is rotated by L-ascorbic acid. Increasing the solution's acidity has no discernible effect on optical rotation; however, increasing the solution's alkalinity causes substantial variations formed as colourless monocyclic crystals from oversaturated water solutions. It has a distinctive absorption spectrum at λ =

265 nm and is an active optical material $[\alpha]^{20}D = 32.5$ ° (H_2O) and 48° (methanol). AA readily oxidises in solutions, particularly when copper and silver ions are present. The cold lowers Fehling, $AgNO_3$, $KmnO_4$, and 2.6-dichlorphenolindophenol, and heating in HCl passes in furfural at 100 °C.[18]

Biosynthesis of AA

The biosynthesis of AA in the mitochondria of higher plants has been explained by a number of different routes. The Smirnoff–Wheeler pathway, also referred to as the D-mannose/L-galactose pathway, is the most significant and most extensively studied pathway. The D-galacturonic acid pathway is a second main pathway that starts with pectins from the cell wall of plants.[19] Another proposed route involves the conversion of GDP-L-gulose from GDP-D-mannose, which is then transformed into L-gulono-1,4-lactone, an important precursor of AA.[20] Furthermore, another mechanism implies that myo-inositol can be converted into ascorbate.[21] Fig.-1 displayed the simplified diagram of these biosynthetic pathways.

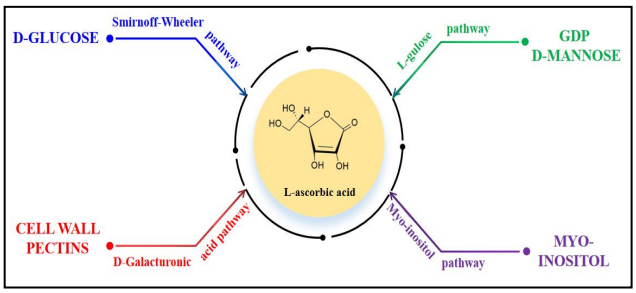

Fig.-1: Simple Representation for the Biosynthetic Pathway of AA

The Smirnoff-Wheeler pathway begins with six steps that produce GDP-Man and GDP-L-Gal, which are essential for cell wall biosynthesis and protein glycosylation. In the seventh and final step of L-ascorbic acid synthesis, the enzyme VTC2 (GDP-L-Gal phosphorylase) utilises the GDP-L-Gal generated by GME to form L-Gal-1-P. Subsequently, VTC4 (L-Gal-1-P phosphatase) converts L-Gal-1-P into L-Gal in the ninth step. The enzymes L-galactose dehydrogenase and L-galactono-1,4-lactone dehydrogenase, which depend on NAD and ferric cytochrome c, then oxidize L-Gal to L-galactono-1,4-lactone and finally to L-ascorbic acid. In the D-galacturonic acid pathway, methyl esterase and D-galacturonate reductase catalyze the conversion of methyl galacturonate, the end product of degradation, into L-galactonate. L-galactonate is then transformed into L-galactono-1,4-lactone by the enzyme aldonolactonase, which subsequently contributes to ascorbate biosynthesis. Similarly, the L-gulose pathway, although branching from GDP-D-mannose, resembles the Smirnoff-Wheeler pathway that starts with glucose. The enzymes GDP-D-mannose-3′,5′-epimerase, GDP-L-gulose-1-P-phosphatase, and L-gulose-1-P-phosphatase sequentially convert GDP-D-mannose into L-gulose. This L-gulose is further converted into L-gulono-1,4-lactone, which is finally oxidized to AA by L-gulono-1,4-lactone dehydrogenase.[19] Myo-inositol oxygenase, glucuronate reductase, and aldono lactonase catalyze the three processes that transform myo-inositol into L-gulono-1,4-lactone in the myo-inositol pathway. Finally, ascorbate synthesis uses gulono-1, 4-lactone.[21] Every step in the four biosynthetic pathways was displayed in Fig.-2.

Pre-treatment

The first step in the extraction process is choosing the raw materials, which include fruits and vegetable waste like pulp, peels, and seeds. The collected materials were cleaned with distilled water to eliminate the unwanted elements. The cleansed material can then be pre-treated using techniques like heat-drying, freeze-drying, or freezing, or it can be used fresh. Once prepared, it is typically ground into a fine powder for extraction. The yield of AA will decrease when the temperature is increased (50–60 °C) because of its extreme heat sensitivity.[22] Freeze-drying has been shown to be the most successful drying method for increasing AA concentration. Although a minimum loss of AA occurs compared to fresh samples, the use of low temperature helps to achieve a higher concentration than other methods.[23] One of the best is ultrasonic pretreatment, which can change the material's structure without raising the temperature too much. The pulsed electric field, a more modern pretreatment technique, electroporates cell membranes to aid in the recovery of bioactive chemicals during a subsequent extraction process.[24]

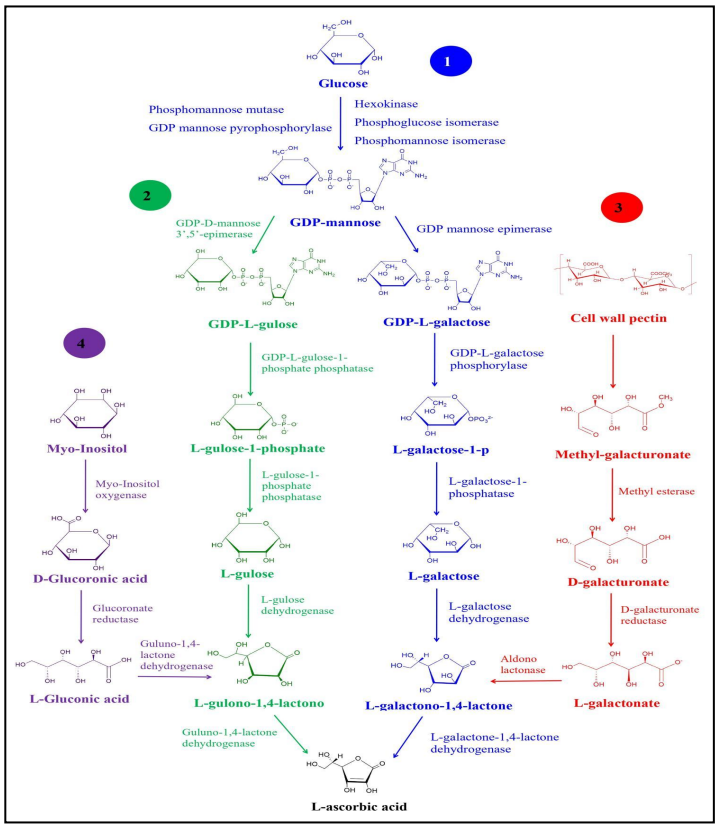

Fig.-2: Path 1, 2, 3 and 4 represent the Smirnoff-Wheeler, D-Galacturonic, L-gulose Pathway, and Myo-inositol Pathway

Extraction of AA

Several techniques for removing phytochemicals from natural sources have been developed recently. Certain of them, like Soxhlet and maceration, are based on solvent extractions (traditional approach), although they have shown certain limitations in terms of economics, energy costs, and environmental sustainability. As a result, numerous non-conventional green alternative approaches have emerged in recent decades, such as supercritical fluid, ultrasound-assisted, pressurised liquid, microwave-assisted, and pressured hot water extraction, which are thought to be efficient substitutes.[25] Conventional solvent extraction is one of the most widely used and well-known methods for solid-liquid extraction. Decoction, maceration, percolation, hydro distillation, Soxhlet, and reflux method are examples of conventional extraction techniques that often include the use of water or organic solvents and demand substantial solvent volumes and prolonged extraction durations. On the other hand, non-traditional extraction methods that use fewer solvents and time include microwave-assisted extraction, pressurised liquid extraction, supercritical fluid extraction, enzyme-assisted extraction, ultrasound-assisted extraction, and pulsed electric field extraction.[26] AA extraction from fruit and vegetable waste using both conventional and non-conventional methods is displayed below in Tables-1 & 2.

Table-1: Extraction of AA from the Waste of Fruits and Vegetables by the Conventional Method

Solvent	Pretreatment	Source	S/L ratio & Time	Reference
Mixture of acetone, ethanol, methanol & water	Fresh	Pomegranate peels	-	27
Metaphosphoric acid-acetic acid	Freeze-dried	Orange peel Pomelo peel Mandarin peel Lemon peel Lime peel	-	28

		Grapefruit peel (Red) Grapefruit peel (Green) Grapefruit peel (White)		
Citric acid (21 g/L), methanol 5% & EDTA (0.5 g/L)	Fluid-bed dried	Camu-Camu seeds and peels	-	29
Ethanol	Freeze-dried	Grapefruit peel Lemon peel Orange peel	1:25 / 24 h	1

Table-2: Extraction of AA from the Waste of Fruits and Vegetables by Non-Conventional Method

Process	Source	Pretreatment	Solvent	Parameters	Reference
UAE	Orange peel	-	Ethanol 50%	30 min / 400W	30
UAE	Mandarin peel	-	Ethanol 50%	30 min / 400W	31
UAE + PEF	Orange peel	Freeze-dried	Ethanol 100%	PEF: 1000 Hz, 10 µs, and 1.0 kV/Cm 37 kHz	32
SFE	Grape skin & seeds	Freeze-drying	Ethanol	2–0.4 ml/min / 250 bar / 70 °C	33
PFC	Orange peel	Drying in oven & maceration	-	20 min / 400 rpm / -12 °C	23
MAE	Peach waste	Frozen	Ethanol–water (70:30)	50s / 540 W	34
MAE	Potato peels	Freeze-dried	Methanol	15 min / 10% power	35

By using the conventional method

Czech *et al.*[28] gathered a number of citrus fruits, including lemons, mandarins, key limes, oranges, pomelos, and red, yellow, and green grapefruits, in order to extract AA. Every fruit was divided into two parts. In the first part, the peel and pulp were homogenised individually. While the other part was processed as a single sample (peel + pulp). Each fruit was trimmed in half; one part was separated into peel and pulp and homogenized individually, while the other half was peeled and treated as a whole sample (peel + pulp). The homogenized samples were kept at -80 °C in polypropylene containers until they were analysed. Grapefruit cultivars, especially the white and red kinds, had the lowest AA concentrations in the pulp (17.19 and 22.42 mg/100 g, respectively), while pomelo had the higher concentration of the vitamin (72.26 mg/100 g) than other samples.

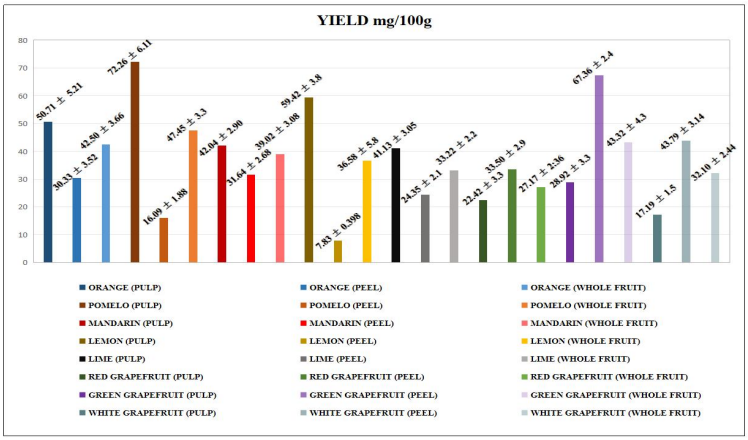

Fig.-3: Concentration of AA in the Peel, Pulp, And Entire Fruit of Oranges, Pomelo, Mandarins, Lemons, Key Limes, And Grapefruit (Red, Green, White)

The AA concentration of the citrus peels also varied significantly; the highest concentration was found in the green grapefruit peel (67.36 mg/100 g), while the lowest content was found in the lemon peel (7.83 mg/100 g). Interestingly, the AA content in lemon pulp was over seven times greater than that in its peel. Similar patterns were observed for limes, mandarins, oranges, and pomelos, where the pulp had greater levels of AA than the peel. On the other hand, every grapefruit variety showed the opposite pattern, with the peel having higher amounts than the pulp. AA content was lowest in red grapefruit (27.17 mg/100 g) and greatest in pomelo (47.45 mg/100 g) when the entire fruit was taken into account. The reason for the difference is probably that the pulp has almost 4.5 times greater concentration of AA than the peel. A comparison of the AA concentration of pulp and whole fruit indicates that the use of whole grapefruits in the food industry improves their nutrient-rich value in terms of their AA content. AA levels in the pulp and entire grapefruits varied from around 90% for white grapefruit to more than 20% for red grapefruit. Fig.-3 displays the amount of AA in the pulp, peel, and entire fruit of oranges, pomelos, mandarins, lemons, key limes, and grapefruit (red, green, and white). Yunfeng Li *et al.*[27] have taken pomegranate pulp and peel for the extraction of AA. The pulp and peel of the pomegranate were manually separated. After being sliced into pieces, the fresh peels were extracted using a variety of solvents, such as acetone, ethanol, methanol, and their combination. The extract was filtered using Whatman No. 41 filter paper, and the same solvent was subsequently used to re-extract the residues. The resulting extract was ground into powder and kept in a desiccator. The pomegranate pulps were processed in a similar manner. Pomegranate peel had 0.99 ± 0.02 mg/g of AA, while pomegranate pulp had 0.85 ± 0.02 mg/g, as displayed in Fig.-4a.

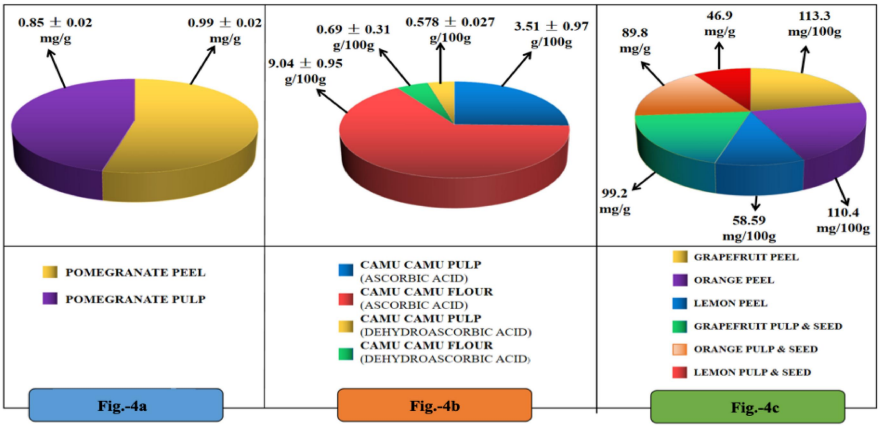

Fig.-4: AA Content in (4a) Pomegranate Peel, Pomegranate Pulp (4b) Camu Camu Pulp, Camu Camu Flour (4c) Peel of Grapefruit, Orange and Lemon, Pulp of Grapefruit, Orange and Lemon, and Seed of Grapefruit, Orange and Lemon

The AA concentration of pomegranate peel and pulp does not differ much. As a result, AA in pomegranate peel or pulp extract cannot be a significant antioxidant. Daniela Fracassetti *et al.*[29] chose two separate powders of Camu-Camu fruits to be used to extract AA. The first, pulp powder, was made from fruit pulp that had been dried with a spray dryer set to 185 °C at the entrance and 95 °C at the exit. To minimise stickiness and enhance the stability of the final product, 10% maltodextrin was incorporated during drying. Following extraction, the leftover peel and seeds that still had pulp traces were ground into the second powder, known as Camu-Camu flour. This material was dried at temperatures between 45 and 55 °C in a fluid bed dryer. The two powders were then vacuum-sealed and kept at 4 °C until they could be examined further. In terms of composition, the fruit peels accounted for 24.2% of the fresh fruit's weight and contained 81.9% moisture, while the pulp represented 43.6% with 92% moisture, and the seeds made up 32.2% with 62% moisture. Compared to fresh fruit, the dried samples had a much higher AA content, mainly because of their lower moisture content. In particular, the pulp powder had 3.51 ± 0.97 g/100 g of AA, while the Camu-Camu flour had 9.04 ± 0.95 g/100 g, as displayed in Fig.-4b. The oxidised dehydroascorbic form accounted for 6.4% of the flour and 19.5% of the pulp powder's total vitamin C (ascorbic + dehydroascorbic acid). Khitma A Sir Elkhatim *et al.*[1] collected three citrus fruits in order to

extract AA: grapefruit, orange, and lemon. The skins were manually removed, and the fruits were pressed to extract the juice, separating it from the pulp and seeds. After that, a freeze-drying technique was used to dry the components that had been collected. The sample was combined with ethanol at room temperature and left to stand for 24 hours. The mixture was filtered using Whatman No. 1 filter paper, and the resulting filtrate was concentrated and vacuum-dried with a rotary evaporator to obtain the extract. AA content in grapefruit, orange, and lemon peels was 113.3, 110.4, and 58.59 mg/100 g, respectively, as displayed in Fig.-4c. However, the inner portions of grapefruit, lemon, and orange were found to contain 99.2, 89.8, and 46.9 mg/g, respectively.

By using Non-conventional method

Abigail Montero-Calderon *et al.*[30] selected orange in order to extract AA using ultrasound-assisted extraction (UAE). The orange peels were carefully separated from the fruit's edible portions, and both the albedo and flavedo were removed. The peels were sliced into small pieces, about 0.6 cm on each side, using a basic vegetable chopper. The extraction solvent was then added to a beaker containing a 1:10 (g/mL) ethanol–water mixture. To prevent the extraction temperature from rising above 40 °C during ultrasonication, the beaker was placed in an ice bath while the temperature was monitored using a thermometer. The extraction was successfully carried out under the following parameters: ethanol concentration (0%, 25%, and 50%), ultrasonic irradiation time (5, 17.5, and 30 minutes), and ultrasonic power (100, 250, and 400 W). The response value under the optimal conditions was 63.20 mg AA/100 g of AA. Interestingly, these optimal conditions were nearly fulfilled by the greatest experimental values, which were obtained at 50% ethanol, 30 minutes, and 400 W, as tabulated in Table-3. An AA quantity of 53.78 mg AA/100 g was obtained under the specified conditions, indicating that the recovery of bioactive components from orange peel may be accomplished effectively using UAE with less resource use.

Table-3: Concentration of AA in Orange Peels with Extraction Parameters using UAE

Parameters	Optimal conditions	Concentration of AA
Power (W)	400	53.78 mg AA/100 g
Time (min)	30	
Solvent (%)	50	

Mayra Anticona *et al.*[31] chose three mandarin varieties, such as Clemen villa, Ortanique, and Nadorcott, to extract AA using ultrasound-assisted extraction (UAE). After sorting the fruits according to size and peel colour consistency, they were thoroughly washed with distilled water and peeled manually. To achieve consistency in extraction, the peels were sliced with a kitchen cutter into uniform 5 mm² pieces. A small glass containing 6 g of mandarin peel was filled with 60 mL of 50 % ethanol as a solvent. Ultrasonication was performed at three different durations: 5, 15, and 30 minutes. After treatment, Whatman No. 1 paper was used to filter the extract, which was then transferred to light-protected volumetric flasks and preserved at 20 °C. The AA concentration in the samples ranged between 63.4 ± 22.2 and 136 ± 56 mg AA/100 g, and was tabulated in Table-4. The AA concentration of Clemenvilla was the greatest among the types (122 ± 56 mg AA/100 g), followed by Ortanique (84.0 ± 36.3 mg AA/100 g) and Nadorcott (70.8 ± 22.5 mg AA/100 g).

Table-4: AA Content of Three Different Oranges with their Extraction Time using UAE

Extraction Time	Clemenvilla	Nadorcott	Ortanique
5	105 ± 50 mg AA/100g FW	63.4 ± 22.2 mg AA/100g FW	72.0 ± 32.3 mg AA/100g FW
15	124 ± 59 mg AA/100g FW	75.0 ± 21.0 mg AA/100g FW	88.5 ± 32.3 mg AA/100g FW
30	136 ± 56 mg AA/100g FW	76.0 ± 24.0 mg AA/100g FW	92.7 ± 42.1 mg AA/100g FW

Vassilis Athanasiadis *et al.*[32] extracted AA from fresh oranges using pulsed electric field (PEF) and ultrasound-assisted extraction (US) methods. After being thoroughly washed with tap water, the fruits, which had green twigs, orange-colored skin (epicarp), and weighed between 150 and 200 g were dried using paper towels. After carefully separating the orange peels, they were cut into tiny pieces (about 2 cm) and freeze-dried for a whole day to eliminate any remaining moisture. An average size of 470 μm was used for extraction after the dried peels had been ground and sieved to provide uniform particle sizes. Extraction experiments were carried out using different concentrations of ethanol under varying extraction times (15–180 minutes) and temperatures (20–80 °C). For every attempt, 1 g of powdered

orange peel was added to a 25 ml Duran bottle that contained 20 ml of the selected solvent. The standard extraction (ST) involved stirring the mixture at controlled conditions of time and temperature (details tabulated in Table-5). Some of the samples were pretreated with pulsed electric field (PEF), ultrasound (US), or a combination of US + PEF to the conventional extraction. The US pretreatment consisted of 10 minutes of moisturization followed by 20 minutes of ultrasound treatment at 37 kHz and 30 °C. PEF pretreatment involved moisturising the samples for 10 minutes and then exposing them to PEF for 20 minutes at a 1.0 kV/cm electric field strength with 10-second pulses and a 1 ms period (1000 Hz frequency). In the combined treatment (PEF + US), samples were moisturised for 10 minutes, followed by 20 minutes of PEF and 20 minutes of ultrasound. Following extraction, centrifugation was carried out to separate the supernatant and residue. The upper portion was then carefully moved to glass vials and stored in a refrigerator for further analysis. It was found that the best method for improving the extraction yield of AA was to use the ultrasound (US) exclusively before the standard extraction procedure (ST). Furthermore, the extracts that were made with 100% ethanol had the highest concentration of AA. Finally, the extraction yield was not significantly affected by temperature or extraction duration, indicating that extracts with a higher AA content can be made quickly and with little energy. Additionally, the peel's albedo (the inner, white portion) and flavedo (the outer, orange portion) were analysed. The findings of their extraction using the best parameters for each variable under investigation are tabulated in Table-6.

Table-5: Optimization of Extraction Parameters such as Technique, Concentration, Time and Temperature

Technique	Concentration (%, v/v)	Time (min)	Temperature (°C)
ST	0	15	20
US + ST	25	30	35
PEF + ST	50	60	50
PEF + US + ST	75	120	60
-	100	180	80

Table-6: AA Content and Optimal Conditions of Albedo and Flavedo using US + ST

Parameters	Optimal Conditions	Albedo (AA Concentration)	Flavedo (AA Concentration)
Technique	US + ST	448 ± 2 mg/110 g dw	1381 ± 5 mg/110 g dw
Concentration (%, v/v)	100		
Time (min)	180		
Temperature (°C)	80		

Antonella Aresta *et al.*[33] utilised supercritical fluid extraction technology to extract AA from grapes. pomace, seeds, and skins were the three parts of the grapes that were separated in order to provide various specimens for examination. A 10 mL extraction cell was filled with each sample, sealed under pressure, and then placed in the oven. To increase the extraction efficiency of polar compounds like AA, ethanol was introduced as a cosolvent to improve the polarity of carbon dioxide. Dynamic extraction was performed at 60 °C and 250 bar following a three-minute static extraction phase. The ethanol and CO_2 flow rates were adjusted to 0.4 mL/min and 2 mL/min, respectively. During the procedure, the micrometric valve was kept at 70 °C. After 15 minutes, the final extract was stored in a vial. The concentration of ascorbic acid that was obtained in three parts of grapes using SFE was tabulated in Table-7.

Table-7: AA Content in Grapes (pomace, skin and seed) using SFE

Sample	Optimal Conditions
Pomace	2612.0 ± 440.0
Skin	2261.9 ± 335.9
Seed	2720.1 ± 333.4

Abdulmajeed Abdurrahman Isa *et al.*[34] extracted AA from oranges via gradual progressive freeze concentration (PFC) and maceration. Peels were taken from the oranges. After washing with distilled water to get clear of any remaining dirt, the peels were dried for at least 12 hours at 30 °C in an oven. An electronic blender was used to chop the peels into tiny particles. The same process was carried out at 35, 40, and 45 °C for varying drying temperatures. A sieve was used to remove the larger peels from the

extracted solution. To get rid of the extra peels, filter paper was used to continue the filtration process. Water and ethylene glycol were used as a coolant in a ratio of 1:1 to create the PFC's refrigerator bath. After turning on, the refrigerated bath was adjusted to four different temperatures: -10, -12, -14, and -16 °C. A cylindrical jar was added to the chilled bath once the temperature was attained and attached to a retort stand to stop the bath from moving. The cylindrical tank was then gradually filled with a stirrer and a clear cover. The cooling timer was set to 20, 25, 30, and 35 minutes, while the stirrer was set to 200, 400, 600, and 800 rpm. The maximum AA recovery was 72.06 % at drying temperatures of 35 °C, coolant temperatures of -12 °C, cooling times of 20 minutes, and stirring rates of 400 rpm, as tabulated in Table-8. S. Plazzotta *et al.*[35] collected peach waste for the extraction of AA through microwave-assisted extraction (MAE). Waste from ground peaches was either dried at 140 °C or frozen at -18 °C. Before being used, the dry and frozen peach wastes were both allowed to acclimate to 20 °C. Dispersions of peach waste with an ethanol concentration of 0.70 g/g were produced. To prepare the extracts, 120 g of peach waste dispersions were mixed for one minute, sealed with a plastic cap to prevent solvent evaporation, subjected to extraction treatments, and finally filtered through 1.2 µm filters to remove solid residues. Prior to analysis, the latter were kept at -18 °C in the dark. Samples were added to beakers (60 mm in diameter, 110 mm high) for ultrasound-assisted extraction. The probe had a 20-mm depth and was positioned in the middle of the sample. In this instance, US treatments were carried out at various durations (20, 70, and 120 s) and amplitudes (20, 60, 100%, equivalent to 25, 75, 125 µm).

Table-8: Extraction Parameters & Maximum Percentage of AA in Orange Peel using PFC

Parameters	Optimal Conditions	% of AA
Heating Temperature (°C)	35	72.06 %
Temperature in Coolant (°C)	-12	
Time taken for cooling (min)	20	
Stirring Rate (rpm)	400	

Then, it was added to 1 L beakers (110 mm in diameter, 145 mm high) for microwave-assisted extraction. At various nominal powers (180, 540, and 900 W) and periods (10, 30, and 50 s), MW treatments were then carried out. MAE treatment at 50 s and 540 W and UAE therapy at 120 s and 23 % amplitude were found to be effective in the frozen trash case. The desirability function determined the ideal MAE treatment for dry waste at 900 W and 50 s, as well as the ideal UAE treatment at 100% amplitude and 120 s. In contrast, a comparison of the results from dried and frozen peach waste showed that the dried sample reduced the amount of AA in the peach waste, indicating that frozen peach trash is a preferable raw material for AA extraction. The higher concentration of AA with the extraction method and their parameters was tabulated in Table-9.

Table-9: Extraction Parameters & Concentration of AA in Peach Waste using MAE & UAE

Extraction	Power	Amplitude	Time	Concentration
MAE(Frozen waste)	540 W	-	50 s	108.04 ± 1.30 mg/100 g dm
UAE(Frozen waste)	-	23 %	120 s	68.40 ± 3.31mg/100 g dm
MAE(Dried waste)	900 W	-	50 s	Not Detected
UAE(Dried waste)	-	100 %	120 s	Not Detected

Ashutosh Sing *et al.* selected potato trash to extract AA via microwave-assisted extraction (MAE). The freeze-dried potato peel was used to extract AA using the MAE method. The amount of AA was significantly affected by power, but variation in solvent percentage and extraction time had no discernible impact. The highest content of AA in dried potato peel powder was 1.44 ± 0.5 mg/g dw.[23]

CONCLUSION

This review focused on AA's potential as a sustainable supply of natural antioxidants by thoroughly examining its chemistry, biosynthesis, and extraction from fruit and vegetable waste. AA, being a thermolabile and water-soluble compound, requires careful selection of extraction methods to preserve its stability and maximise recovery. Conventional extraction techniques like solvent extraction and maceration are still frequently employed since they are easy to use and affordable. The highest concentration of AA among the traditional extractions examined was found in camu-camu, confirming its

remarkable nutritional value and possible industrial significance as a natural source. However, the development of non-conventional extraction methods, including microwave-assisted, pulsed electric field, and ultrasound-assisted, has been aided by the increased focus on sustainability and green chemistry. These innovative methods minimise environmental impact, save energy and solvent consumption, and improve extraction efficiency. Notably, when extracted with ultrasonic assistance, orange peel produced the highest amount of AA, proving that UAE is effective at extracting bioactive compounds from citrus waste under mild conditions. In conclusion, both conventional and advanced extraction methods have their advantages depending on the sample material and desired application. Overall, the results support the possibility of using effective and sustainable extraction techniques to turn agricultural waste into valuable products. Valorising fruit and vegetable by-products can help to execute a "waste-to-wealth" strategy, which turns waste materials into resources that are both profitable and good for the environment. This approach also aligns with SDG 12: Responsible Consumption and Production by promoting sustainable waste management, resource efficiency, and the valorisation of agro-food by-products into value-added compounds.

ACKNOWLEDGMENTS

The authors sincerely acknowledge the Department of Chemistry, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, for their motivation and support.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-12: Responsible Consumption and Production*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

Emil Jebaz Devasundar https://orcid.org/ 0009-0007-2362-363X
Naushad Edayadulla https://orcid.org/0000-0002-3970-5775
Chandraraj Shanmuga Sundari https://orcid.org/0000-0001-7814-2074

Cite this article as: E. J. Devasundar *et al.*, *Rasayan J. Chem.*, 19(3), 1672-1682(2026), https://doi.org/10.31788/RJC.2026.1939766

REFERENCE

1. K.A. Sir Elkhatim, R.A.A. Elagib, A.B. Hassan, *Food Science & Nutrition*, **6**, 1214(2018), https://doi.org/10.1002/FSN3.660
2. G.F. Deng, C. Shen, X.R. Xu, R.D. Kuang, Y.J. Guo, L.S. Zeng, L.L. Gao, X. Lin, J.F. Xie, E.Q. Xia, S. Li, S. Wu, F. Chen, W.H. Ling, H.B. Li, *International Journal of Molecular Sciences*, **13**, 8308(2012), https://doi.org/10.3390/IJMS13078308
3. C.M. Ajila, K.A. Naidu, S.G. Bhat, U.J.S.P. Rao, *Food Chemistry*, **105**, 982(2007), https://doi.org/10.1016/j.foodchem.2007.04.052
4. F.Y. Al-Juhaimi, K. Ghafoor, Pakistan *Journal of Botany*, **45**, 1193(2013)
5. D.A. Vattem, K. Shetty, *Food Biotechnology*, **16**, 189(2002), https://doi.org/10.1081/FBT-120016667
6. A. Abbasi, M. Niakousari, *Pakistan Journal of Biological Science*s, **11**, 1365(2008), https://doi.org/10.3923/PJBS.2008.1365.1369
7. K.J. Carpenter, *Annals of Nutrition & Metabolism*, **61**, 259(2012), https://doi.org/10.1159/000343121
8. R.P.F. Guiné, Vitamin C: Dietary Sources, Technology, Daily Requirements and Symptoms of Deficiency (2013)
9. S.R. Pinnell, H. Yang, M. Omar, N.M. Riviere, H.V. DeBuys, L.C. Walker, Y. Wang, M. Levine, *Dermatologic Surgery*, **27**, 137(2001), https://doi.org/10.1046/j.1524-4725.2001.00264.x

10. J.S. Hampl, C.A. Taylor, C.S. Johnston, *Journal of the American College of Nutrition*, **18**, 582(1999), https://doi.org/10.1080/07315724.1999.10718892
11. A.C. Carr, B. Frei, *The American Journal of Clinical Nutrition*, **69**, 1086(1999), https://doi.org/10.1093/ajcn/69.6.1086
12. Institute of Medicine (US) Panel on Dietary Antioxidants and Related Compounds, Dietary Reference Intakes for Vitamin C, Vitamin E, Selenium, and Carotenoids (2000), https://doi.org/10.17226/9810
13. S.P. Fortmann, B.U. Burda, C.A. Senger, J.S. Lin, E.P. Whitlock, *Annals of Internal Medicine*, **159**, 824(2013), https://doi.org/10.7326/0003-4819-159-12-201312170-00729
14. C.L. Linster, E. Van Schaftingen, *FEBS Journal*, **274**, 1(2007), https://doi.org/10.1111/j.1742-4658.2006.05607.x
15. K. Fediuk, N. Hidiroglou, R. Madère, H.V. Kuhnlein, *Journal of Food Composition and Analysis*, **15**, 221(2002), https://doi.org/10.1006/jfca.2002.1053
16. M. Doseděl, E. Jirkovský, K. Macáková, L.K. Krčmová, L. Javorská, J. Pourová, L. Mercolini, F. Remião, L. Nováková, P. Mladěnka, *Nutrients*, **13**, 1(2021), https://doi.org/10.3390/nu13020615
17. B.J. West, S. Deng, A.K. Palu, *Journal of Biosciences and Medicines*, **8**, 116(2020), https://doi.org/10.4236/jbm.2020.812012
18. I. Lavilla, V. Romero, P. Costas, C. Bendicho, *Analytical Methods*, **15**, 951(2023), https://doi.org/10.1039/d2ay01795d
19. L. Zhang, H. Thiewes, J.A.L. van Kan, *Fungal Genetics and Biology*, **48**, 990(2011), https://doi.org/10.1016/j.fgb.2011.06.002
20. R. Vardanega, D.T. Santos, M.A. de Almeida, *Pharmacognosy Reviews*, **8**, 88(2014), https://doi.org/10.4103/0973-7847.134231
21. Leal PF, Almeida TS, Prado GHC, Prado JM, Meireles MAA, *Separation Science and Technology*, **46**, 1848(2011), https://doi.org/10.1080/01496395.2011.572575
22. Y. Rajesh, N.M. Khan, A. Raziq Shaikh, V.S. Mane, G. Daware, G. Dabhade, *Materials Today: Proceedings*, **72**, 2610(2023), https://doi.org/10.1016/j.matpr.2022
23. A.A. Abdurrahman Isa, S. Samsuri, N. Aini Amran, *IOP Conference Series: Earth and Environmental Science*, **268**, 012101(2019), https://doi.org/10.1088/1755-1315/268/1/012101
24. F. Blasi, B. Yoon, A. Sawabe, B. Biernacka, F. Susa, R. Pisano, *Processes*, **11**, 3167(2023), https://doi.org/10.3390/pr11113167
25. F. Susa, T. Limongi, F. Borgione, S. Peiretti, M. Vallino, V. Cauda, R. Pisano, *ACS Biomaterials Science & Engineering*, **9**, 5871(2023), https://doi.org/10.1021/acsbiomaterials.3c00678
26. D. Goti, D.S. Dasgupta, *Journal of Pharmacognosy and Phytochemistry*, **12**, 202(2023), https://doi.org/10.22271/phyto.2023.v12.i3c.14682
27. Y. Li, C. Guo, J. Yang, J. Wei, J. Xu, S. Cheng, *Food Chemistry*, **96**, 254(2006), https://doi.org/10.1016/j.foodchem.2005.02.033
28. A. Czech, A. Malik, B. Sosnowska, P. Domaradzki, *International Journal of Food Science*, **2021**, 6662259(2021), https://doi.org/10.1155/2021/6662259
29. D. Fracassetti, C. Costa, L. Moulay, F.A. Tomás-Barberán, *Food Chemistry*, **139**, 578(2013), https://doi.org/10.1016/j.foodchem.2013.01.121
30. A. Montero-Calderón, C. Cortés, A. Zulueta, A. Frígola, M.J. Esteve, *Scientific Reports*, **9**, 1(2019), https://doi.org/10.1038/s41598-019-52717-1
31. M. Anticona, J. Blesa, D. Lopez-Malo, A. Frígola, M.J. Esteve, *Food Bioscience*, **42**, 101185(2021), https://doi.org/10.1016/j.fbio.2021.101185
32. V. Athanasiadis, T. Chatzimitakos, K. Kotsou, D. Palaiogiannis, E. Bozinou, S.I. Lalas, *Sustainability*, **14,** 13926 (2022), https://doi.org/10.3390/su142113926
33. A. Aresta, P. Cotugno, N. De Vietro, F. Massari, C. Zambonin, *Analytical Letters*, **53**, 2585(2020), https://doi.org/10.1080/00032719.2020.1749846
34. S. Plazzotta, R. Ibarz, L. Manzocco, O. Martín-Belloso, *Ultrasonics Sonochemistry*, **63**, 104954(2020), https://doi.org/10.1016/j.ultsonch.2019.104954
35. A. Singh, K. Sabally, S. Kubow, D.J. Donnelly, Y. Gariepy, V. Orsat, G.S.V. Raghavan, *Molecules*, **16**, 2218(2011), https://doi.org/10.3390/molecules16032218 [RJC-9766/2026]