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Published version

SHANKER, M. Anjaly, KRISHNAN, Reshma, KUMAR, Gopika S., MOHAMMED, Thasniya, HYMAVATHI, Arunima Suresh, ROSAMMA, , RAGESH, Nivedya, GEORGE, Sony, RANA, Sandeep Singh and ABDULLAH, S. (2024). Insights on the astringency of non alcoholic beverages: fruit, vegetable & plantation based perspective. Food Chemistry Advances, 4: 100630.

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Food Chemistry Advances 4 (2024) 100630

Contents lists available at ScienceDirect

Food Chemistry Advances

journal homepage: www.elsevier.com/locate/focha

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M Anjaly Shanker [a], Reshma Krishnan [b], Gopika S Kumar [c], Thasniya Mohammed [d], Arunima Suresh Hymavathi [e], Rosamma [f], Nivedya Ragesh [g], Sony George [f], Sandeep Singh Rana [a], S Abdullah [g,*]

[a] Department of Bio Sciences, School of Bio Science and Technology (SBST), Vellore Institute of Technology, Vellore 632014, India
[b] Agro Processing Technology Division, CSIR – National Institute for Interdisciplinary Science and Technology (CSIR-NIIST), Thiruvananthapuram, Kerala 695019, India
[c] Food Consumer Marketing and Product Development, Sheffield Business School, Sheffield Hallam University, Sheffield, South Yorkshire S1 1WB, United Kingdom
[d] Food Safety and Quality Assurance Management, Lambton in Toronto at Cestar College, Toronto 400-265, Canada
[e] Food Science and Technology: Quality Assurance, School of Chemistry, Food and Pharmacy, University of Reading, Whiteknights, PO Box 226, Reading RG6 6AP, United Kingdom
[f] Department of Food Technology, Saintgits College of Engineering, Kottukulam Hills, Kottayam, Kerala 686532, India
[g] Department of Food Technology, TKM Institute of Technology, Kollam 691505, Kerala, India

ARTICLE INFO

Keywords:
Astringency
Astringents
Tannins
Thermal and non-thermal treatments

ABSTRACT

Sensory parameters of food and beverages secured much importance with mounting changes in diet preferences. The taste and flavour of these food groups are largely affected by astringency which in turn influence the sensory experience. Derived from Latin, astringency deals with the sensation of extreme dryness, roughness or puckering involving the secretions of salivary glands. Accountable astringent clusters majorly revolving around the presence of tannins in food trailed by the incidence of salts of multivalent cations like Al, Zn, Cr etc, and dehydrating agents like mineral acids, alcohol etc. To augment the sensory feeling and to broaden the marketing possibilities related to beverages, it is important to accomplish techniques to reduce or control the development of these sensations. De-astringency practices performed in foods can be broadly catalogued into thermal and non-thermal treatments. While the former majorly included hot water, steam and microwave treatment, the latter concentrated mainly on innovative techniques like high hydrostatic pressure, pulsed electric field, thermo-sonication, ultrasonication etc. The effectiveness of these procedures is largely dependent on the mechanisms associated with the development of astringency feelings in foods. Understanding the mechanism underlying astringency sensation is still in a nascent stage and needs more exploration to state the explicit reason behind the process. This review chiefly covers the explanation of astringency, the mechanism involved and the different de-astringency techniques as per the prevailing astringency models.

1. Introduction

Mounting alertness and apprehensions among the customer population levy the significance of the inclusion of fluid intake in the regular diet. With a wide range of options offered in the market extending from water to different types of beverages like fruit beverages, health drinks, alcoholic beverages as well as non-alcoholic beverage fractions, the fluid intake is found to be necessary entailing to their contribution towards maintaining body hydration (Benelam & Wyness, 2010). Non-alcoholic fluid fractions are a growing segment of beverages which are operated by the introduction of innovations in different facets. They are defined as virgin drinks/ non-intoxicating drinks devoid of alcohol owing to the absence of yeast which contributes towards the conversion of sugar into alcohol. Marketing and supply of these beverage fractions involve the distribution of packed fluids in a bottle or canned forms. As these drinks are devoid of any alcohol content, these groups lack stringent government policies and regulations. As of today, a variety of non-alcoholic beverages are available including fruit and vegetable beverages, herbal juices, fermented and non-fermented milk, tea, coffee, juices from oil seeds namely coconut, sesame seed, badam, and major sets of

* Corresponding author.
E-mail address: abdullahfpe@gmail.com (S. Abdullah).

https://doi.org/10.1016/j.focha.2024.100630
Received 23 May 2023; Received in revised form 17 December 2023; Accepted 27 January 2024
Available online 30 January 2024

carbonated beverages (Anilakumar et al., 2017). Dealing with the consumption and distribution of these drinks, the major market issue encountered is the development of astringency in them. Considered as an important shortcoming, astringency developed is known to affect the sensory profile of the food altering the consumer acceptance. Counting the entire beverage profile, we could articulate the higher percentage of astringency development in fruit juices as well in regularly expended beverage fractions like tea and coffee. Elevated levels of astringency are specifically steering towards their component profile affecting their marketing and scalability.

Derived from Latin, astringency sensation is defined as "the complex of sensations due to shrinking, drawing or puckering of the epithelium as a result of exposure to substances such as alums or tannins" American Society for Testing and Materials (ASTM ,2004). In simple terms, astringency is a dry, rough, and puckering sensation in the mouth which is assumed to be stimulated by components that bind oral epithelia and salivary proteins. However, the feeling is not restricted to a definite part of the mouth and can be felt throughout the oral epithelia. Hence, astringency arises when the oral cavities are exposed to the sensation-instigating molecules. The astringent molecules cause a minimum of three distinct sensations inside the mouth: puckery in the cheeks and face muscles, dryness in the mouth and roughness in the oral tissues. The studies implicating the molecular mechanisms of astringency are still in a nascent stage and no conclusive hypothesis has been developed (García-Estévez et al., 2018).

Midst of the unidentified profile of the astringency mechanism, there is an evident picture about the components involved in the development of this sensation. Phenols, metallic salts, multivalent organic and mineral acids, proteins, and dehydrating agents are the main astringent compounds found in natural foods and its mechanism of astringency varies depending on the chemical structure (Huang & Xu, 2021). Acids, alcohols, and salts of metals are other groups of compounds imparting astringency. There are many fruit-based products which are not getting the required acceptability among consumers due to the astringent taste that develops due to the presence of various unknown compounds. Apart from developing astringency these compounds also cause browning and turbidity in products which again reduce their acceptability. Cashew apples and pomegranates are taken as examples usually as their astringent mouth feels due to tannins being highly expressed (Abdullah et al., 2021; Singh et al., 2019). Similarly, the tannin and some unspecified oily-type compounds in certain fruit fractions imparts an astringent taste, which is one of the reasons behind their less marketability (Das and Arora, 2017). So, the number of astringent compounds that can remain in natural foodstuffs is necessary to recognise. But the problem with this is, the perception of astringency changes with individual preferences. Also, some other factors affect the perception of astringency such as pH, temperature, viscosity and even the composition of the food matrix.

As the astringent effects provided by various chemical compounds in natural food products are unacceptable, the benefits imparted by those compounds are also lacking for consumers. This emphasis the importance of reduction or control on the development of this sensation. Different physical, chemical, and enzymatic methods are widely applied for the removal of astringency in unwanted cases. Heat treatment and membrane filtration are the physical methods, whereas the application of different clarifying agents like proteins, polysaccharides, and synthetic polymers are the chemical treatments involved and the use of enzymes which can hydrolyse tannin compounds constitute the enzymatic treatment method (Abdullah et al., 2021; Prommajak et al., 2020).

Astringency removal or the process of defining a particular level of astringent compounds to increase acceptability sounds a little bit difficult. There are extra taste characteristics like sourness and bitterness which are ultimately linked to the astringent stimuli which increase the difficulty in studying the astringent sensation (Niimi et al., 2017). With the aforementioned factors in consideration, this review primarily centres on different astringent compounds, the mechanism and significance of astringency, and the various processes involved in reducing astringency specifically in non-alcoholic beverages.

2. Understanding astringency: mechanism, perception, and compounds

The five staple tastes such as sweetness, sourness, bitterness, saltiness and umami are well studied, while the astringent taste, which is more unique, is not widely explored due to the complexity of its mechanisms (Gibbins and Carpenter, 2013). Pires et al., (2020) mentioned the refusal of accepting astringency as a taste by the scientific community during earlier times since astringency was considered just a feeling induced by some other tastes. Especially, astringency is meant to be a feel developed in the mouth by the interaction of tannin compounds with the salivary proline-rich proteins (Abdullah et al., 2020).

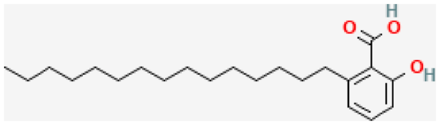
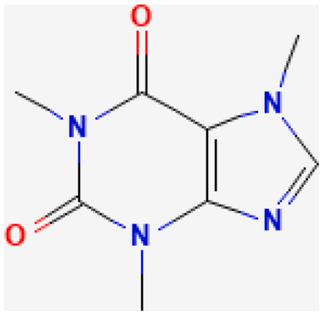
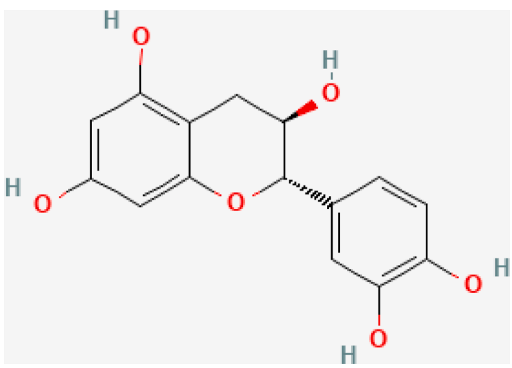
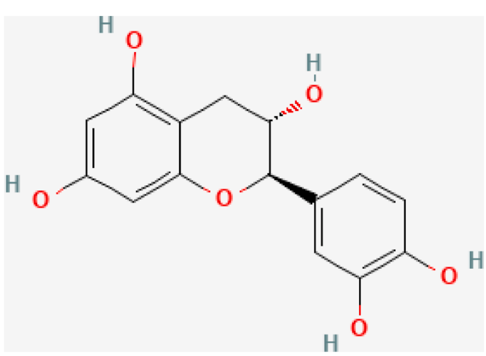
The rationalisation of the astringency sensation is correlated with the compounds accountable for the astringency development owing to their difference in mechanisms associated. Among the different classes of accountable fractions, phenolic compounds are known for the incidence of this sensation in voluminous varieties of foods and beverages (Smutzer et al., 2020). Catalogued into ≥15 different classes, dietary phenolic compounds ranging from simple monomeric molecules to polymers with high molecular weight are of utmost importance in this context. Among the former cluster, flavonoids are the chief components attributing to this sensation and are divided broadly into 13 different classes of compounds including flavanones, flavonols, flavones, isoflavones, flavans (catechins), and anthocyanins (Roche et al., 2017). The structure and mechanism of the compounds responsible for astringency is tabulated in Table 1.

Presence of catechin is known to be the contributory factor in the development of astringency particularly in green tea compositions. Catechin, a known flavanol imparts the final friction coefficient increasing the roughness and thereby elevating the astringency sensation. Author also elucidates about the prospect of variance in the advance of astringency according to the difference in the substituents of catechin (Han et al., 2017). Analogues to this the alternate forms of anthocyanins a common flavonoid in fruits and vegetables has different levels of the sensation. For example, glycosylated forms induce higher levels of astringency compared to the acetylated forms of anthocyanins (Paissoni et al., 2018).

Plant tannins are polyphenols which are high in molecular weight (>500) whereas lower weight phenolic fractions tend to be bitter, with the former more prone to develop astringency sensation (Smutzer et al., 2020). With reported incidence in many fruits, vegetables, herbs, cereals, legumes, condiments, and spices, they are the chief source of astringency in foods and beverages (Hassanpour et al., 2011). This class of compounds are primarily found in cocoa (*Theobroma cacao*), tea (*Camellia sinensis*), guarana (*Paullinia cupana*), coffee (*Coffea spp.*), and kola nuts (*Cola vera*) and in plants acclimatised to warm climates such as Sericea lespedeza (*Lespedeza cuneata*), sorghum (*Sorghum bicolor*), etc. Depending on the plant source, the prevalence of tannin is retrieved in different parts of the plant including leaves, roots, stems, fruits, peel, seeds, shells, and bark.

Several articles report the incidence of significant tannin levels in various plant parts such as leaves and seed coat. Similarly, a significant amount of tannin was reported in fruits such as berries, majuphal, amla, munakka, raisins, red supari, dates, grapes, apricots, pomegranate, peach, plum, apple juice etc (Kumari and Jain, 2015; Ma et al., 2014). Furthermore, tannin is the most abundant constituent in most vegetables, following cellulose, lignin, and hemicellulose (Santhiravel et al., 2022). Different authors have reported the incidence of high-level tannin content in different herbs (Ghosh 2015), beans including common beans, cowpeas, pinto beans, and kidney beans (Kumari and Jain 2012), and in condiments and spices like tamarind, turmeric, coriander, and chillies which are used as a flavouring agent in many dishes. Preferences for the beverages are widely influenced by the age group of the

Table 1
Compounds responsible for astringency - structure and mechanism (Data retrieved from National Center for Biotechnology Information, 2023).

Compound	Structure	Astringency mechanism
Anacardic acid		Not clearly mentioned in the literature
Caffeine		Astringency might be strongly related to the pH of the coffee because while roasting of coffee beans occurs, its colour changes from lighter to darker, its pH increases, astringency is generally stronger when pH is lower.
(-)-Catechin		Not clearly mentioned in the literature
(+)-Catechin		Not clearly mentioned in the literature

(continued on next page)

Table 1 (*continued*)

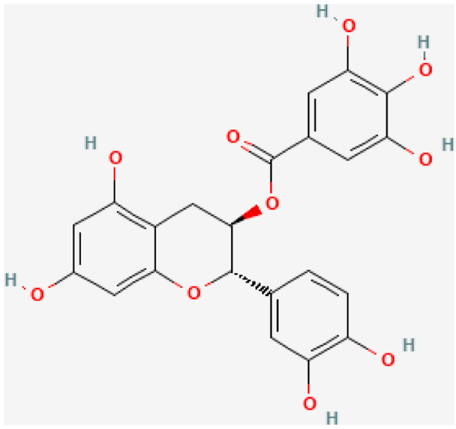
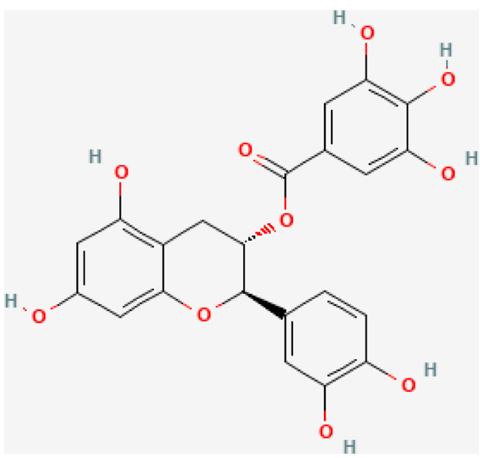
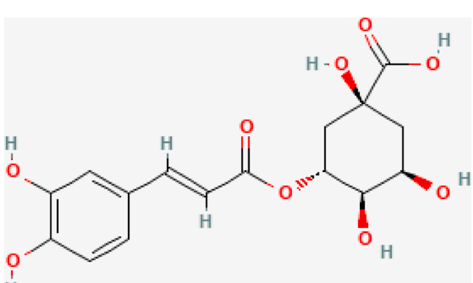
Compound	Structure	Astringency mechanism
(-)-Catechin gallate		Not clearly mentioned in the literature
(+)-Catechin -3-O-gallate		Not clearly mentioned in the literature
Chlorogenic acid		Not clearly mentioned in the literature

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Table 1 (*continued*)

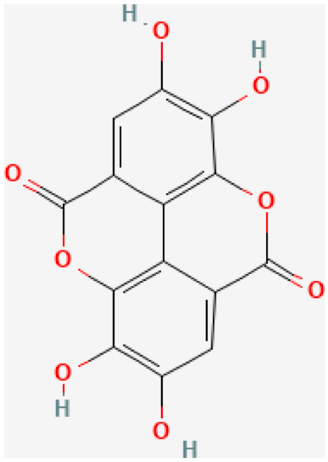
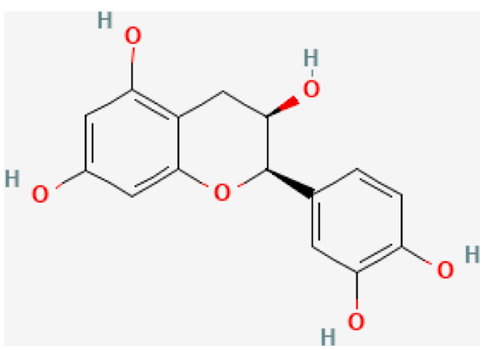
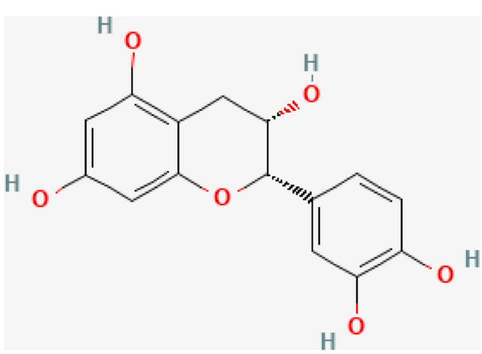
Compound	Structure	Astringency mechanism
Ellagic acid		Not clearly mentioned in the literature
(-)-Epicatechin		Not clearly mentioned in the literature
(+)-Epicatechin		Not clearly mentioned in the literature

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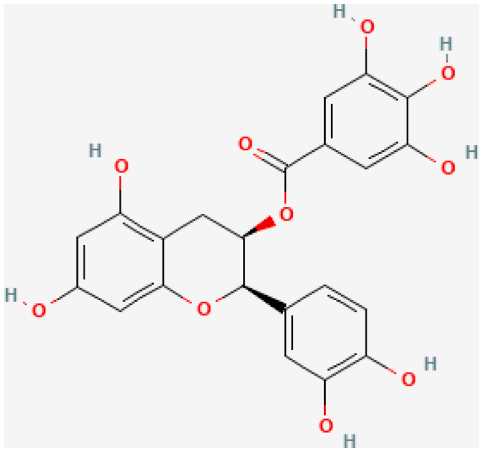
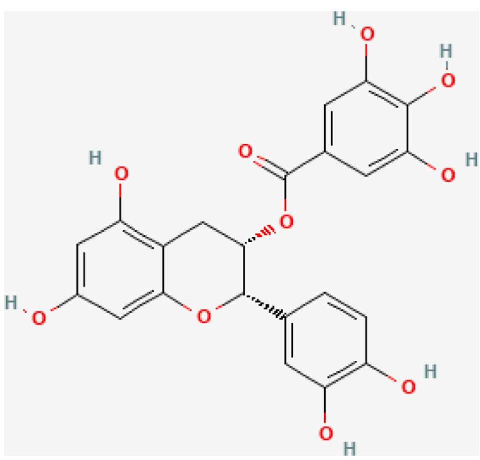
Table 1 (*continued*)

Compound	Structure	Astringency mechanism
(−)-epicatechin gallate		Not clearly mentioned in the literature
(+)-Epicatechin-3-gallate		Not clearly mentioned in the literature

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consumer fractions with adults mostly preferring tannin-containing beverages such as tea. Humans consume tannins (natural or synthetic) via various food sources. According to diet analysis, the daily tannin intake in India ranges from 1500 to 2500 mg (Sharma et al, 2021). Spices contribute a large portion of the tannin content in the diet. The safe limit of daily tannin consumption ranges between 1.5-2.5 g, and ingestion above this range is accountable for inadequate iron absorption from a daily diet (Rao and Prabhavathi, 1982). Tannins should be used within permissible and safe limits for therapeutic purposes, according to regulatory body guidelines. Natural tannin sources can be consumed without concern for a healthy life due to their insignificant risk facet and beneficial effect (Ghosh, 2015).

With explanations on responsible components, most recognized and elucidated structure of action between these components encompasses interaction between accountable polyphenols and salivary proteins leading to the formation of a protein-astringent complex (Fig. 1). The progress of astringency sensation is ascribed to this complex owing to the precipitation of lubricating salivary proteins such as α-amylase, proline-rich

Table 1 (*continued*)

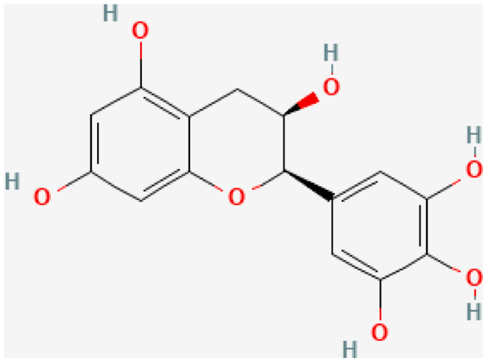
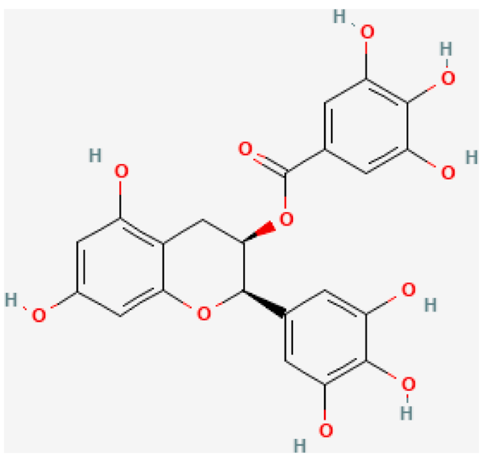
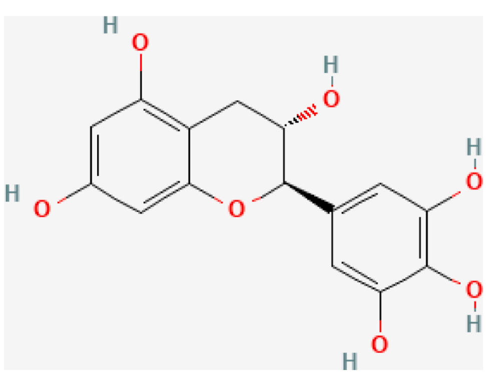
Compound	Structure	Astringency mechanism
(-)-Epigallocatechin		Not clearly mentioned in the literature
(-)-Epigallocatechin gallate		Epigallocatechin gallate (EGCG) provides the highest astringency perception compared to other catechins. Cationic valences and ionic strengths will affect saliva's lubrication behavior in several ways, while EGCG will further enhance astringency.
(+)-Gallocatechin		Not clearly mentioned in the literature

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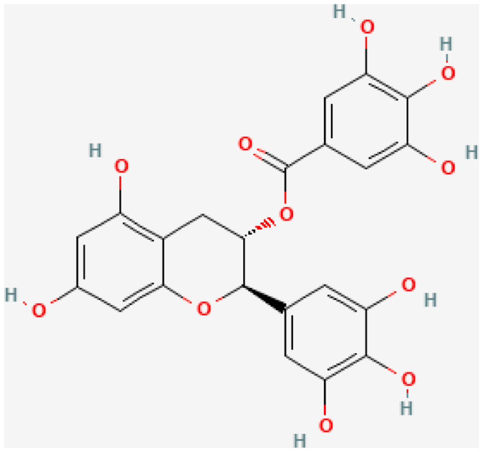
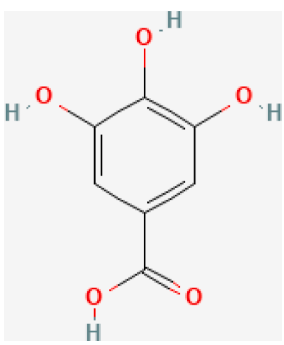
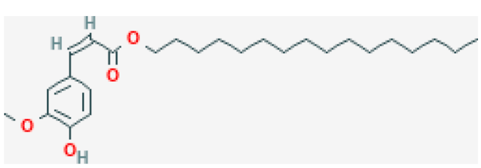
Table 1 (*continued*)

Compound	Structure	Astringency mechanism
(+)-Gallocatechin gallate		Not clearly mentioned in the literature
Gallic Acid		Not clearly mentioned in the literature
Hexadecyl (E)-ferulate		Not clearly mentioned in the literature

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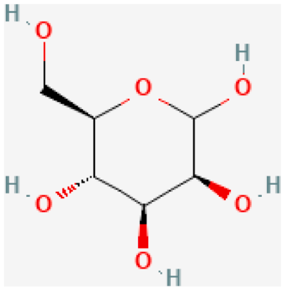
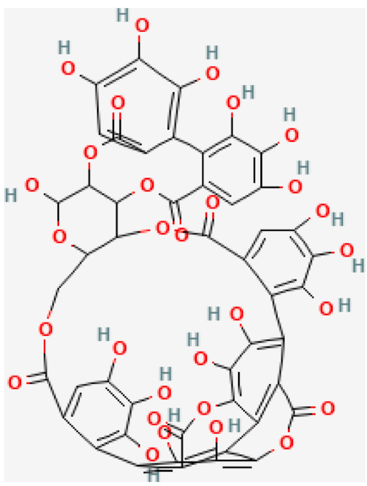
proteins etc. This interface instigates protein aggregation and precipitation, ensuing in the sensation of dryness and astringency (Ma et al., 2016). This combination usually refers to the hydrogen bonding between hydrophobic aromatic rings and hydrophilic hydroxyl groups of tannins and many hydrophobic groups present in salivary proteins. Other components, such as polysaccharides and acids, can also cause astringency; their presence is known to positively influence this sensation, or some may interrupt the tannins and protein combination (He et al., 2015).

Metal ionic salts like zinc salts is pronounced to have higher level of affinity towards the hydroxyl and sulfhydryl groups of protein fractions forming complexes with ammino acids and in turn with proteins. When these interactions operate a position in the lubrication part, there is the development of the proposed sensation (Liu et al., 2022). The level of astringency development is also dependent on the anionic portion of the salt with levels according to the properties of these substitutions. Different acid groups are also proposed to exhibit a similar interaction

Table 1 (*continued*)

Compound	Structure	Astringency mechanism
D-Mannose		Not clearly mentioned in the literature
Punicalagin		Not clearly mentioned in the literature

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with the hydroxyl groups forming a stable hydrogen bond with the protein. The projected stable protein moiety will be in a way consuming the lubricating protein developing astringency sensation in mouth (Zhao et al., 2023).

Scientists who studied astringency found various mechanisms behind it. The different astringent compounds undergo various channels for imparting their effects. It may be due to the difference in their chemical structure. Studies on the mechanisms behind astringency are not much available to date but among the studies conducted the interaction between the astringent compounds and the salivary proteins is highly pronounced. More specifically it is the oral friction that creates the sensation of astringency. The above said interaction reduces the lubrication of saliva and develops friction, which ultimately results in the puckering feel called astringency (Fig. 2) (Upadhyay et al., 2016; Pires et al., 2020).

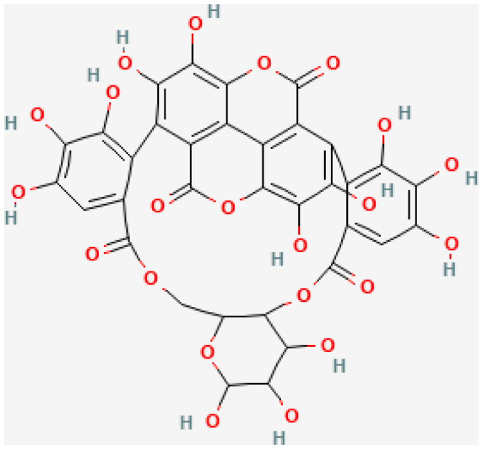
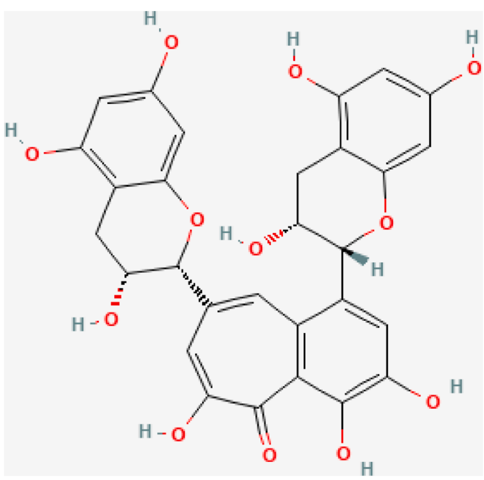
3. Common non-alcoholic beverages and foods rich in astringency

The acceptability of any food item primarily depends on its taste than its nutritional and health value. Since, astringency impacts taste, the presence of astringent compounds in any food item plays a significant role in determining its economic importance and popularity. That is., even though numerous fruits, vegetables and beverages are nutritionally rich, the presence of astringent compounds hinders its consumer acceptability (Soares et al., 2020), hence a thorough knowledge on the astringent compounds in these food items is necessary. The major astringent compounds in foods and beverages are illustrated in Table 2.

3.1. *Astringent-rich fruit fractions*

Incidence and development of astringency in grapes is majorly ascribed to the condensed tannin fractions present in their seed and skin

Table 1 (*continued*)

Compound	Structure	Astringency mechanism
Punicalin		Not clearly mentioned in the literature
Theaflavin		Not clearly mentioned in the literature

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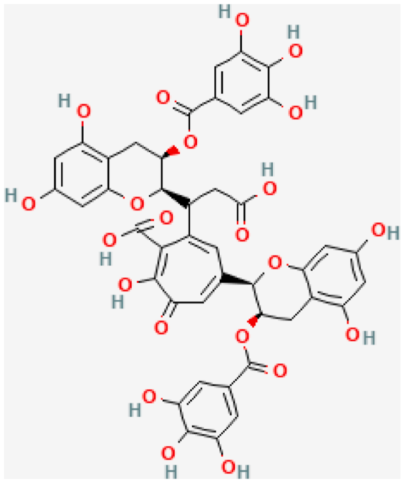
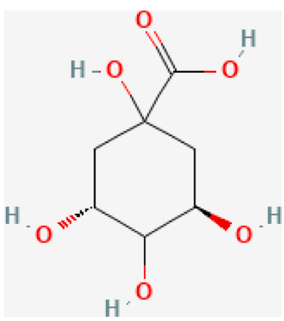
(Pascual et al., 2016). Oligomers of catechin found in seed and skin fractions attributes a greater degree of polymerization and a higher percentage of galloylation which in turn influences the formation of astringency sensation. Seed fraction proanthocyanidins with a greater degree of galloylation are more operative in astringency formation than skin proanthocyanidins (Pascual et al., 2016). Likewise, the condensed fractions of tannins including epigallocatechin and/or (+)-gallocatechin associated with some (-)-epicatechin and/or (+)-catechin were found to be responsible for astringency in cashew apple. Contrary to this, reports by Talasila and Shaik (2015) elucidates the possibility of contribution of other phenols, unknown oily substance (3%) and anacardic acids towards the developed astringency of fruits. On the other hand, limonoid aglycones, limonoid glucosides, and polymethoxylated flavones are the compounds found responsible for bitterness in orange juices (Glabasnia et al., 2018). Likelihood of changes in the astringency responsible components with changes in variety, maturity etc needs to be studied in detail to conclude on this behalf (Wu et al., 2022).

Addition to the condensed fractions of tannins, hydrolyzable fractions also contribute proportionately to the development of this sensation. Hydrolysable fractions like punicalagin which is found in higher

Table 1 (*continued*)

Compound	Structure	Astringency mechanism
Thearubigins		Not clearly mentioned in the literature
Quinic acid		Not clearly mentioned in the literature

amounts and others like gallic acid, ellagic acid and punicalin which are found in smaller amounts are responsible in development of astringency in pomegranate (Mayuoni-Kirshinbaum and Porat, 2014). The astringency in persimmons is attributed to water-soluble condensed tannins present in the tannin cells of fruit flesh and peel. Water-soluble condensed tannins are converted into insoluble compounds during ripening leading to lesser astringency. Among different varieties of persimmon Mopan from Northern China and Hachiya are highly astringent (Yaqub et al., 2016). In addition to this elucidations and studies on the correlation between the astringency development and the part of the plant under consideration is also important and needs more explanation. The main phenolic compound present in astringent persimmons are tannins and their concentration is found to be higher in pulp than in peel portion. This will lead to higher phenolic concentration and antioxidant activity of pulp (He et al., 2015).

The astringency of different products is not only a problem affecting the consumption of fresh fruit but also influences the juice processing industry. As per the authors, juice extracted from arils of unripe pomegranate fruit had a high level of hydrolysable tannins and astringency than compared to fruit juice from ripened arils. Peel with higher hydrolysable tannins with hydrophilic properties and seeds with phenolic compounds can also be introduced into the juice that will lead to astringency affecting consumer satisfaction (Mayuoni-Kirshinbaum and Porat, 2014). Like this astringency of the juice fractions of cashew apple was also reported by Talasila and Shaik (2015). Authors mentioned the presence of tannins, other phenols and unknown oily substance in the skin as a reason for development of this sensation.

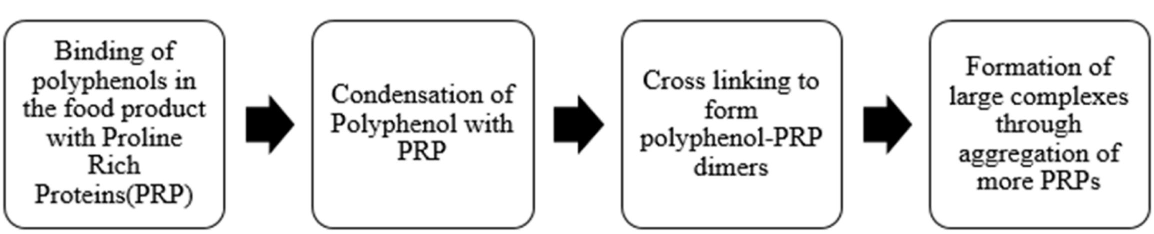


Fig. 1. Interaction between polyphenol and salivary proteins (Huang and Xu, 2021).

3.2. Different astringent-rich vegetables

Duggan et al. (2020) notes and records the incidence of astringency in one of the common vegetable potatoes. Author accounts the presence of compounds like α-solanine and saponins α-chaconine which are identified as the responsible components for the development of astringent off-tastes in potato tubers. In addition to that, the study also speculates about the possibility of different fatty acids and fatty acid oxidation products like *E*-9, 10, 13-trihydroxy-octadec-11-enoic acid etc and some other compounds like hexadecyl (*E/Z*)-ferulate, octadecyl (*E/Z*)-ferulate etc as the inducers of bitter and astringent off-taste. Similarly, there are reports on the prevalence of this unpleasant bitter and astringent taste in potato chips and other related products due to the presence of free amino acids. Certain components in foods are found to be acting as an influential factor in the development of this sensation. An example for similar condition is in case of some cultivars of potato owing to the presence of a higher amount of tyrosine induces the accumulation of homogentisic acid that results in this unpleasant taste (Sato et al., 2019).

Mabuchi et al. (2019) testifies the presence of O-phosphoethanolamine responsible for astringency in six different Japanese cabbage varieties. Possibility of change in tannin content and episode of astringency development according to the variance in variety of vegetable is stated and this opens the new possibility or need of studies in the field. Ogbede et al. (2015) reports the variation in tannin content of different varieties of cabbage. According to the studies, *Brassica oleracae* var. capitata L. tannin content is 2.84 mg/100 g which is higher compared to green cabbage (1.50 mg/100 g), red cabbage (1.57 mg/100 g) and Chinese cabbage (1.57 mg/100 g). These tannins are responsible for astringency that negatively affects the palatability of food. These compounds are having anti-nutritional properties thereby suppressing the availability and utilization of nutrients. Likewise, the astringency of cucumber varieties is attributed to a range of catechins like catechin gallate (CG), gallocatechin (GC), epicatechin (EC) etc present in the vegetable.

3.3. Coffee and tea

Among different varieties of tea infusions available in the global market, green tea is one the prominent and healthy option perceived by the customers. Flavonol glycosides and catechins were the compounds responsible for the bitterness and astringency of green tea infusions (Zhang et al., 2016). The former fractions are known to induce velvety

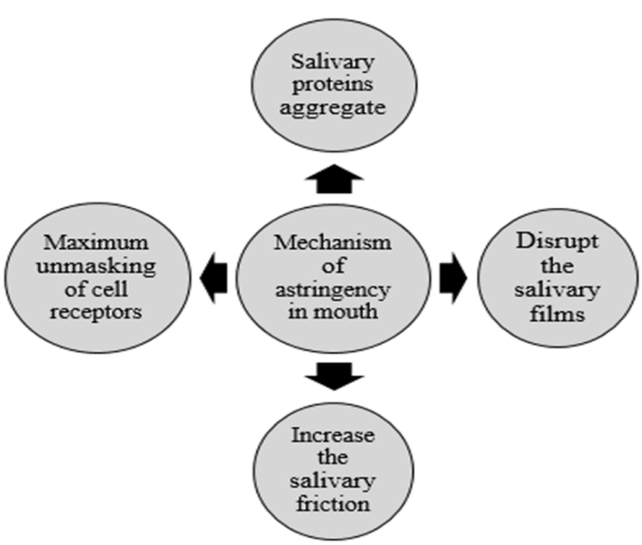


Fig. 2. Various functions of astringent compounds in the oral cavity on developing a sensation of astringency.

Table 2
The major compounds that cause astringency in foods and beverages.

Food or beverage	Scientific name	Astringent compounds	References
Grapes	*Vitis vinifera*	Catechin Epicatechin Epicatechin-3-gallate	Pascual et al. (2016)
Pomegranate	*Punica granatum L.*	Punicaligin Gallic acid Ellagic acid Punicalin	Mayuoni-Kirshinbaum and Porat (2014)
Cashew apple	Anacardium occidentale	Anacardic acids Water soluble condensed tannins	Talasila and Shaik (2015), Abdullah et al. (2020)
Persimmons	Diospyros kaki	Water soluble condensed tannin	He et al. (2015), Yaqub et al. (2016)
Cucumber	Cucumis sativus	Catechin Catechin gallate Gallocatechin Epicatechin Epigallocatechin Epicatechin gallate Gallocatechin gallate Epigallocatechin gallate	Xu et al. (2019)
Cabbage	*Brassica oleracea L.*	O-phosphoethanolamine	Mabuchi et al. (2019)
potato tubers	*Solanum tuberosum L.*	Saponins α-chaconine Saponins α-solanine Hexadecyl (*E/Z*)-ferulate Octadecyl (*E/Z*)-ferulate Homogentisic acid	Duggan et al. (2020), Sato et al. (2019)
Black tea	*Camellia sinensis assamica*	Caffeine Theaflavins Thearubigins Catechin Epigallocatechin gallate	Jolvis Pou (2016)
Green tea	*Camellia sinensis*	(−)-epicatechin (−)-epigallocatechin (−)-epicatechin gallate (−)-epigallocatechin gallate (+)-catechin (−)-gallocatechin (−)-catechin gallate (−)-gallocatechin gallate Caffeine Flavonol glycosides	Wu et al. (2012), Xu et al., 2018
Coffee	*Coffea arabica*	Cholorogenic acid Lipids Quinic acid Mannose Quinide	Kreuml et al. (2013); Wei et al. (2014)

astringency of green tea and the latter were found to provide puckering astringency (Xu et al., 2018). Presence of caffeine is not trivial as it strengthens the astringency of EGCG and thereby controlling the whole process (Xu et al., 2018). In detail the component catalogue ranges between epicatechin and non-epicatechins including epigallocatechin (EGC), epicatechin gallate (ECG), epigallocatechin gallate (EGCG), catechin (C), gallocatechin (GC), catechin gallate (CG) and gallocatechin gallate (GCG) (Wu et al., 2012). While evaluating other tea fractions, Jolvis Pou (2016) reports the peculiarity of astringency in black tea. The developed astringency of these infusions is classified as tangy or non-tangy type. Tangy astringency is denoted as a sharp and puckering sensation with a diminutive aftertaste and non-tangy sensation is tasteless mouth drying and coating sensation which lingers for a long period of time. Compounds like caffeine in presence of polyphenols like theaflavins, catechin and epigallocatechin gallate are necessary for reasonable levels of tangy astringency in black tea. Like the component fractions influencing the astringency development, certain processes concerned change in astringency in tea infusions. The process of decaffeination of these black tea fractions results in the conversion of non-tangy astringency to tangy type thereby changing the nature of astringency (Jolvis Pou, 2016).

Flavour development in coffee that stimulate chemical reactions like Maillard and Strecker reactions, degradation of polysaccharides, proteins, trigonelline, and chlorogenic acids remain obliged to the roasting process. Chlorogenic acid (CGA) is a phenolic fraction that is accountable for astringency, coffee pigmentation and aroma formation. Coffee robusta is known for its bitter sensation and astringency while coffee Arabica has a fine acidity, bitterness, and more intense aroma (Kreuml et al., 2013). According to Wei et al. (2014), components like lipids, mannose, quinic acid, and quinide contribute towards the development of this sensation whereas presence of chlorogenic acids, malate, citrate, arabinose, trigonelline, and galactose negatively affects the process. Correspondingly, astringency might be strongly related to the pH of the coffee because while roasting of coffee beans occurs, its colour changes from lighter to darker, its pH increases, acidity decreases and astringency increases. Lowered pH or added acid was found to influence the development of astringency sensation of phenolic compounds. pH reduction will dissociate the phenolic molecules increasing their affinity to salivary proteins via hydrogen bonding and thereby strengthening the sensation (Pires et al., 2020).

4. Methods to reduce astringency

To augment the consumer acceptability of these products it is imperative to control the development or elimination of the developed astringency in foods. Among the methods to mask astringency currently blending, encapsulation and fermentation technology are widely used. Blending operation involves the incorporation of polysaccharides like carboxymethyl cellulose (CMC), guar gum, xanthan gum, and Arabic gums in combination and are effective in reducing the astringency in chokeberry, green tea, and walnut. Instead of polysaccharides certain operations involve the use of phenolic extracts and pectin from citrus fruits for this purpose. Complex coacervation by gelatin and κ-carrageenan or Arabic gum can be applied for encapsulation of cinnamon extract with astringency (Huang and Xu, 2021). In the case of micro-encapsulation, polyphenol material is wrapped up using polymeric material which helps to mask the taste, allows slow liberation of the phenolic material and improves drug stability (Paulo and Santos, 2021). Cyclodextrin inclusion incorporates the phenolic material using the hole of β-cyclodextrin to materialize a stable complex substance (Boonchu and Utama-ang et al., 2015). Lactic acid fermentation using *Lactobacillus plantaru* can be applied to reduce astringency in pomegranate juice (Pontonio et al., 2019) and *L. bulgaricus* and *S. thermophiles* based fermentation is used in xuan mugua fruit (Shang et al., 2019).

According to Wan et al. (2021) modification of pH to 4.9 can help to mask the astringency of tea polyphenols solutions. In the case of persimmon fruit, astringency removal was carried out using high CO_2, ethanol, cold storage, and hot water. The commercial application of CO_2 as dry ice or gas enables us to obtain non-astringent fruit within a short span of 1 to 3 days. The use of ethanol to reduce astringency is not applicable commercially as it takes 10-day time period at room temperature to produce non-astringent fruit even though the final product is firm and of high quality. Reports also states that combination of certain food products and astringency reduction technique effects the product quality. Firmness of fresh-cut persimmon fruit is found to be better in case of hot water application than ethanol treatment technique at 80% of CO_2 for a storage period of 6 days (Ozdemi et al., 2020). According to Das et al. (2021), hot water, microwave and steaming methods with different temperatures and time conditions are used to reduce astringency in cashew apple fruit.

Deliberation about the different de-astringency techniques employed in different food and beverage industries comprises method of chemical precipitation also. The process includes flocculants or physical adsorption engaging carbon active sources. Regardless of the mechanisms and additives, these methods employ the removal of polyphenols and tannins from different food products and thereby plummeting the astringency sensation. A matter of concern related to the removal of these polyphenolic fractions is that they are recurrently allied with a food product's health benefit. Hence their removal may result in nutritional loss and product value jeopardy. There is a growing need for the development of an effectual de-astringency procedure that does not compromise nutrient value or change the flavour or physical properties of the food. To avoid undesirable precipitation or product separations during the discussed process in wines and juices having strong astringent flavour, agents like water-soluble colloids should be added as a safer alternative. One of the reported methods is the addition of Oxidised Starch Hydrogel (OSH) as a new de-astringency procedure to microencapsulate the responsible components in food (Xiaodan Zhao, 2020). The process of microencapsulation is expected to hinder the communication between salivary proteins and polyphenols in oral cavity hindering the development of astringency sensation. The advantage of this process is that it helps in retaining the bioavailability owing to the digestion and release of OSH in the gastrointestinal tract. Another possibility for astringency reduction is the treatment of food products with carbon dioxide. Salvador et al. (2008) have proposed the treatment with CO_2 as the most operative way in removing the astringency sensation from persimmon fruit retaining the firmness of the fruit. Result of this study encourages the feasibility of particular de-astringency method in the handling of 'Rojo Brillante' persimmon at the industrial level. The standard considered in the handling of these fruit fractions includes 95% CO_2 for 24 hours at 20 degrees Celsius.

5. Thermal methods for astringency reduction

The thermal methods of astringency removal include hot water treatment, steam treatment, microwave treatment and so on. Steam treatment is the most popular method for astringency removal which is performed using autoclaves. Microwave treatment is the most expensive thermal treatment compared with hot water and steam treatment (Vidal et al., 2017).

5.1. Hot water treatment (HWT)

As the name suggests, this treatment involves the processing of food in the hot water for a constant period at a regulated temperature. Generally, the HWT set-up is made using a stainless-steel material with an insulated lid and a thermostat to check the temperature level. This treatment helps in the destruction of microorganisms and softens the food improving the colour and reduces the astringency in fruits (Sui et al., 2014).

There are mainly three types of HWT systems; batch system, continuous system, and drainage system with major components including the treatment tank, water circulation system, heat exchanger unit, and temperature controller. In the batch system, the fruits are dipped in a container at a specific temperature for a particular time. Similarly, in the continuous system, the fruit taken in a conveyor belt is allowed to pass through a hot water container. Whereas, in the drainage system, the fruit is positioned in a conveyor and water at high temperature is drained into it. The duration of the treatment is decided based on the internal temperature of the fruits and hence it is fruit-specific. All these systems are fitted with a sensor to ensure that uniform temperature is maintained throughout the process (Fallik & Ilić, 2018).

As already reported, soluble tannins are mainly responsible for astringency and these types of tannins are extensively available in many fruits. When the soluble tannin-containing fruits are treated with hot water, a new compound, acetaldehyde, is formed. This acetaldehyde converts soluble tannin to insoluble tannin polymer, which causes the reduction of astringency in fruits (Ozdemir et al., 2020). A HWT study conducted in cashew apple juice using a thermostatic water bath (water temperature 100ºC for about 25 minutes) observed a reduction in the tannin content from 199 to 28.7 mg/100 mL. Authors also reported that the tannin reduction was directly proportional to the exposure time (Das et al., 2021). Similarly, another study on cashew apple juice observed that the HWT showed better effectiveness in the removal of tannins as compared to many other treatments (Emelike et al., 2016).

Correspondingly, another research on the HWT of persimmon fruits reported that a maximum astringency reduction was witnessed when treating the fruit at 40°C for 5 hours. Also, the treatment time can be further reduced to 20°C if the persimmon fruit is treated with 80% CO_2 (Ozdemir et al., 2020). However, all these studies also stated a significant decline in the ascorbic acid content and total sugar content when the fruits are subjected to HWT for a longer duration (Das et al., 2021). Therefore, the application of HWT is not recommended as a viable technique for mitigating astringency, as this method exerts a discernible influence on the nutritional composition of the product.

5.2. Steaming treatment (ST)

The steam treatment is done using an autoclave having superheated steam where the heat rises its temperature above saturation point and provides high pressure in the system. Along with the effectiveness in controlling the astringency development, it also helps to reduce microbial loads, spores, mycotoxin, and odours. The major disadvantages of it are high capital cost, the complexity of the equipment and the high temperature of processed products (Alfy et al., 2016; Sezdi & Yoleri, 2014).

A study conducted by Das et al., 2021 reported an astringency reduction of 39 to 56 % in cashew apple juice when it is treated with steam at 121°C for 2 mins. Similar to HWT, a reduction in ascorbic acid, upto 73%, was observed for ST as well. Owing to the high heat transfer rate of steam, there is higher reduction in total phenols and sugar content as compared to other thermal processes (Jafari et al., 2017).

5.3. Microwave treatment

The microwave system consists of centrally slotted rectangular waveguides and two magnetrons fed with different power levels. The generated microwave energy vibrates the molecules present in food and heat will be produced in it (Guo et al., 2017). The major benefits of using microwave treatments are shrinkage reduction of products, optimized quality, and fast removal of moisture. The major disadvantage of this process is the high operation cost, toughening of the products and massive flux of vapour towards the products (Ekezie et al., 2017).

Das et al. (2021) used a microwave oven having 2465 MHz is used for microwave treatment of cashew apple juice at different power levels (180 W, 360 W, and 480 W) and exposure times (30, 60 and 90 s). The study reported a total tannin reduction of up to 30% with an ascorbic acid reduction of only up to 11%. The total phenolic content reduced from 17.3 to 40.3% within an exposure time of 30 to 90 minutes at 180 to 540°C (Das et al., 2021). The tannin reduction was lower in microwave-treated samples compared with other treatments. The microwave treatment in lentils also shows the lowest reduction in tannin content (Prommajak et al., 2020). These results prove that the microwave is the most effective thermal treatment for the reduction of tannin content, the astringent compound, from food products.

6. Non-thermal methods of astringency removal

Non-thermal methods that are widely incorporated include high-pressure processing (HPP) (Subasi & Alpas, 2017), ultrasonication (Bhargava et al., 2021; Mehta et al., 2019), pulsed electric field (PEF) (Arshad et al., 2020), thermosonication (Abid et al., 2014), irradiation (Ajibola, 2020), cold plasma (Pankaj et al., 2018; Thirumdas et al., 2015), membrane filtration (Abdullah et al., 2022a; 2022b) and so on. Non-thermal methods like HPP, the addition of a clarifying agent that removes tannins and clarifies the juice, filtration, coagulation, etc., can reduce astringency without lowering the quality and nutritional property of the final product. The non-thermal methods used are summarised in Table 3.

6.1. High pressure processing

High-pressure processing (HPP) is an inventive technique in which the food product is subjected to very high pressure for a short period of time to preserve the sample and achieve microbial safety. During the process, transformation occurs in the cell wall of the product, directing to both enzymatic and non-enzymatic reactions. Only a limited study was conducted exploring the possibility of astringency reduction using HPP. Vázquez-Gutiérrez et al. (2013) studied the combined effect of HHP and refrigerated storage (4°C) on the tannin extractability of persimmon cubes (*Diospyros kaki* L.f.). Here Persimmon samples subjected to a pressure of 200 MPa for time intervals of 3 and 6 min were analysed after 7, 14, 21, and 28 days of storage at 4°C. The structural changes of the sample increased with increase in treatment time. Tissue degradation of permissions was found to be influenced by storage time. HHP treatment facilitated the precipitation of tannins, thereby decreasing astringency. This method also favours the extraction of bioactive compounds. Storage had a more pronounced effect on tannin content than the treatment time. An evident decrease in tannin content was found after a storage period of 7 days under both treatment times. Another study was conducted on HPP of persimmon juice and found that the pre-treatment of persimmon juice with HPP could significantly improve its quantity, quality and shelf life, and reduces its turbidity and astringency (Xu et al., 2021). Similarly, Hernández-Carrión et al. (2014) also reported that HPP and pasteurization has a synergetic impact on astringency reduction in Persimmon fruit.

6.2. Clarification

The application of *Moringa oleifera* seed powder as a clarifying agent to eliminate tannins and other colloidal particles present in cashew apple juice has been studied by Ugwuoke et al., (2020). The whitish seeds of *M. oleifera* were sun-dried, crushed and ground to obtain the powder and was used for the clarification of 250 ml of cashew apple juice. The process was done using 5 g, 10 g, 15 g, and 20 g of *M. oleifera* seed powder and was performed using filter paper for 1 hr to get the clarified juice. Atomic absorption spectroscopy (AAS) was performed to analyse the clarity of juice and best clarity was detected with 10 g of powder. The clarified juice also retained nutrients like vitamin C, zinc, copper, magnesium, and calcium. The sensory analysis results indicated moderate ratings for the aroma of the treated sample and superior ratings for flavour, colour, and overall acceptability. Dried okra pod powder (DOP) and dried drumstick seed powder (DDSP) were used as bio coagulants in cashew apple juice (Das et al., 2021). The particle size of the coagulant considered was 150 and 1000 μm, and concentration was 0.1-0.5% and the settling time was between 0.5-1.5hrs. The use of DOP at a concentration of 0.3%, and a settling time of 0.5 hr gave the best result in reducing astringency along with a high sensory score of 93%.

Besides the use of bio-coagulants, enzymatic clarification is also a better option. The increasing requirement for biocatalysts in the juice industry has accelerated the development of enzymes from various sources. The Tannase enzyme is responsible for the hydrolysis of tannins (hydrolysable). It hydrolyses the ester bonds present in tannic acid and produces gallic acid and glucose. *Aspergillus, Rhizopus, Penicillium* and *Bacillus* can be used for the production of tannase (Prommajak et al., 2020; Rout & Banerjee, 2006). Tannase enzyme was found to reduces the tannin content and thereby the bitterness reduce the bitterness in pomegranate juice (Rout & Banerjee, 2006; Prommajak et al., 2020).

6.3. Ethanol vapours

The use of ethanol for removing astringency is not a common technique. The basic principle behind the reduction of astringency in this method is that the fruit surface absorbs the ethanol vapours. It is converted to acetaldehyde within the cell by the action of alcohol dehydrogenase (naturally found in cashew). The enzyme acts reversely as well; this property balances the concentration of ethanol and acetaldehyde (Tezotto-Uliana et al., 2018). The disadvantage of the treatment is the cost, and could also lead to quality deterioration (Das & Eun, 2021).

A study conducted by Tezotto-Uliana et al., (2018) aimed to identify the accurate dose of ethanol vapour and the exposure time to reduce astringency without causing fermentation in cashew apples. Cashew apples were exposed to ethanol concentration of 1.75, 3.50, 7.00 and 14.00 mL/kg of cashew for 12 hrs in first condition and for an exposure time of 24 hrs under same concentrations in the second condition. For a storage period of 16 days, both set of treated samples were kept at 5°C at 90% RH. The concentration of acetaldehyde, ethanol, proanthocyanidins and total phenols of cashew apples were affected by the dose, but exposure time did not cause many effects. The exposure using 3.50 mL/kg was found to reduce tannins to the lowest levels. The highest doses caused fermentation, and changes in colour along with weight loss. The use of 3.50 mL/kg for 12 hr was found to be the most appropriate without compromising postharvest quality.

A similar study using ethanol has been done on astringent persimmon fruit. Non-astringent and astringent ('Rojo Brillante'-pollination variant astringent (PVA)) variety of persimmons are available. The astringent variety can be consumed after the removal of astringency. Ethanol treatment of the fruits was done by dipping them in 0%, 10%, 20%, and 40% ethanol. Ethanol concentration at 20% and 40% rendered better results compared to lower concentration. The firmness of fruits weighing 1.5-2.5kg was obtained when the fruits were packed in PE bags or treated with 20% ethanol (Hejazi et al., 2019).

6.4. CO_2 treatment

This approach is effectual in controlling the development of astringency sensation because it causes anaerobic respiration in fruits, which results in the development of acetaldehyde. Incidence of acetaldehyde in the system leads to interactions of the compound with soluble tannins. As a result of these interactions, tannins become insoluble and lose their astringent properties (Fathi-Najafabadi et al., 2021).

Fathi-Najafabadi et al. (2021) studied in detail about the possibilities and positives of traditional CO_2 treatment using 95% CO_2 at 20°C for 24hrs over wax and plastic film incorporation to the system of storage. Author states clearly about the suitability of carbon dioxide treatment in controlling the astringency development and retaining the quality characteristics. Similarly, the most common method stated by another study for removing astringency in persimmons is to expose the fruit to 95–98% CO_2 at 20°C and 90% RH for 24 hours (Besada & Salvador, 2018). Although the utility of this de-astringency technique has been extensively researched, a high treatment concentration harms the parenchyma structure, producing cell membrane disintegration and subsequent loss of flesh firmness (Fathi-Najafabadi et al., 2021). In addition, retention of quality parameters was significantly superior in fruit that had received treatment at the end of storage. Chance of internal browning was observed in CO_2-treated fruit after 30 days of storage and shelf-life (Fathi-Najafabadi et al., 2021). Studies have shown that the application of CO_2 to persimmons for de-astringency purposes can lead to a notable decrease in quality. This is primarily attributed to the development of flesh browning when the fruit is stored in cold conditions for extended periods. Additionally, the cost associated with this treatment method is another drawback that needs to be taken into consideration. (Das & Eun, 2021; Fathi-Najafabadi et al., 2021).

Table 3
Non-thermal methods for astringency removal.

Method	Product	Results	References
High hydrostatic pressure (HHP)	Persimmon	HHP treatment facilitated the precipitation of tannins, thereby decreasing astringency.	Vázquez-Gutiérrez et al. (2013)
Clarification using *Moringa oleifera* seed powder	Cashew apple juice	• The best clarity was detected in juice clarified with 10g of powder. • The clarified juice also retained nutrients like vitamin C, zinc, copper, magnesium, and calcium.	Ugwuoke et al. (2020)
Clarification using Dried okra pod powder (DOP) and dried drumstick seed powder (DDSP)	Cashew apple juice	The use of DOP at a concentration of 0.3%, settling time of 0.5hr gave the best result in reducing astringency along with a high sensory score of 92.7 ± 1.6%.	Das et al. (2021)
Ethanol vapours	Cashew apple	• The exposure using 3.50mL/kg was found to reduce tannins to the lowest levels. • The highest doses caused fermentation, and changes in colour along with weight loss. • The use of 3.50 mL/kg for 12hr was found to be the most appropriate without compromising postharvest quality.	Tezotto-Uliana et al. (2018)
Carbon Dioxide	Persimmon	• Fruit quality was significantly higher in fruit that had received the novel treatment (wax + film) at the end of storage. • Internal browning was observed in CO_2-treated fruit after 30 days of storage and shelf-life; however, this abnormality was not observed in waxed fruit	Fathi-Najafabadi et al. (2021)
Freezing temperature	Persimmon	• Simple and cost-effective method keep fruit in better condition. • In fruits stored at -20°C, soluble tannin content was reduced from 4.59 to 3.52 mg/g DW, and for -80°C the soluble tannin reduced from 4.18 to 3.34mg/g DW when compared to the control sample there was a considerable reduction. • There was also a reduction in the proanthocyanidin content.	Das and Eun (2021)

(continued on next page)

Table 3 (*continued*)

Method	Product	Results	References
Fermentation	*Xuan Mugua*	The tannin content of fresh *Xuan Mugua* can be reduced by up to 78% using lactic acid bacteria fermentation-like incubation.	Shang et al. (2019)
	Coffee	The astringency experience was minimized in Mundo Novo inoculated with CCMA 0543 and CCMA 0684 treatments, respectively.	Ribeiro et al., (2017)

6.5. *Freezing*

The effect of storage periods at freezing temperatures of -20°C and -80°C in astringency reduction in Persimmon fruits was studied by Das & Eun, 2021. Study involves the fruits packed in airtight Ziplock packages, and stored at -20 and -80°C for a storage period of 15 to 60 days. Freezing temperature treatment significantly reduced the soluble tannin content and increased the insoluble tannin content; this in-solubilisation of soluble tannins causes a reduction in astringency. In fruits stored at -20°C, soluble tannin content was reduced from 4.59 to 3.52 mg/g DW, and for -80°C the soluble tannin reduced from 4.18 to 3.34 mg/g DW when compared to the control sample there was a considerable reduction. There was also a reduction in the proanthocyanidin content. A notable increase in insoluble tannin content was also observed. This is a low-cost storing method that keeps the fruit in excellent condition.

6.6. *Fermentation*

The tannin content of banana stems and leaf silage was found to be reduced by *Lactobacillus plantarum*. Plant nutrients were reduced, and new metabolites were generated by these bacteria (Li et al., 2014). This study focuses on the use of lactic acid bacteria fermentation-like incubation to reduce the astringency of *Mugua* fruits by lowering tannin content (Singh et al., 2019). To decrease the tannin concentration in *Xuan Mugua*, the work focussed on natural methods. For fermentation-like incubations, lactic acid bacteria (*L. bulgaricus* and *Streptococcus thermophiles*) were utilised to reduce the astringency of the fruit. The fruits were collected and stored in a refrigerator at 4°C, and they were washed and cut into pieces. The ability of bacteria to decompose tannin is dependent on the culturing time. The experiments were conducted at different time intervals of 3 hrs, 8 hrs, and 34 hrs. *Lactobacillus* content of 0.1 g and 1.0 g were selected at incubation temperatures of 26°C, 38°C and 40°C. The fruit (10 g) was immersed in 15 mL water (pH-5.0), then 20 mL of various concentrations of *Lactobacilli* solution were added. The mixture was kept at multiple incubation temperatures. *Mugua* pieces were collected from the incubation chamber and dried in a 40°C oven until the water content in each sample was less than 5%, and tannin extraction was done. The tannin content of fresh *Xuan mugua* can be reduced by up to 78% using lactic acid bacteria fermentation-like incubation. However, following fermentation, the active components of the extracts, such as polysaccharides and triterpenes, and their antioxidant activity diminished. Compared to the control group, the flavour components remained nearly the same, but the content changed slightly (Shang et al., 2019).

A study on the controlled fermentation of coffee beans was investigated by Ribeiro et al. (2017). The sensory analysis of coffee beans was performed to evaluate their quality. Two varieties of coffee, Ouro Amarelo and Mundo Novo, were inoculated with three strains of the yeast *Saccharomyces cerevisiae* CCMA 0200 and CCMA 0543 and *Torulaspora delbrueckii* CCMA 0684. The application of strains CCMA 0543 and CCMA 0684 improved the beverage sensations of both coffee samples. The acidity and nuts sensations were enhanced in Ouro Amarelo inoculated with CCMA 0543, while the astringency experience was minimized in Mundo Novo inoculated with CCMA 0543 and CCMA 0684 treatments, respectively. The inclusion of CCMA 0543 starting culture enhanced the acidity of the coffee, resulting in improved sensory outcomes for both coffee kinds. The employment of two sensory analysis approaches (cup taste and temporal dominance of sensations analysis) allowed for a more descriptive and comparative investigation of the treatments' sensory properties.

7. Conclusion & future prospective

The sensation that causes puckering, wrinkling feeling, shrinking, drying out, or stretching in the mouth is astringency. Attributed to the presence of tannins, polyphenols, metal salts and ascorbic acid, a wide variety of food products are known for the incidence of this sensation. Elucidations have aided in understanding how well the incidence of astringency sensation can be allied with the sensory experience of beverages. With different types of compounds accountable for the sensation, weightage has been given to tannin compounds majorly. The importance and incidence of tannins in different types of food were widely studied. But still the learnings lack elucidation on the underlying mechanism and there are different studies instigated to understand the mechanism to a certain extent. In the case of components other than tannins, the comprehension of the causal mechanisms is in a very embryonic stage. The correlation between underlying mechanisms and components present in food samples underscores the significance of these inherent interaction perceptions. Future advancements in the field are anticipated to encompass detailed studies on different components within these food groups and their synergistic interactions. Such research endeavors will contribute to a clearer understanding of the underlying mechanisms. Additionally, the effectiveness of discussed de-astringency techniques will be more justifiable with the manifestation of the synergistic effects among these liable components and their interactions. This holistic approach is essential for advancing our comprehension of astringency in non-alcoholic beverages and refining strategies to mitigate its effects.

CRediT authorship contribution statement

M Anjaly Shanker: . **Reshma Krishnan:** Writing – original draft. **Gopika S Kumar:** Writing – original draft. **Thasniya Mohammed:** Writing – original draft. **Arunima Suresh Hymavathi:** Writing – original draft. **Rosamma:** . **Nivedya Ragesh:** Writing – review & editing. **Sony George:** Writing – review & editing. **Sandeep Singh Rana:** Writing – review & editing. **S Abdullah:** Conceptualization, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that there is no competing interest.

Data availability

No data was used for the research described in the article.

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