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REVIEW ARTICLE

Unveiling the bioactive potential of cashew nut testa shell (*Anacardium occidentale* L.): a despised by-product

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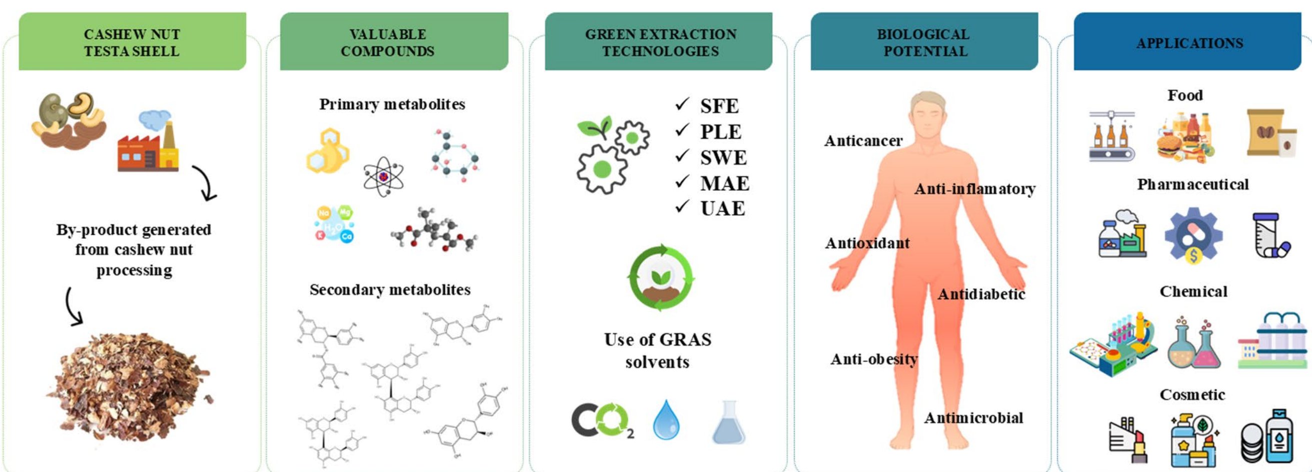
Abstract

Cashew nut (*Anacardium occidentale* L.) processing generates several by-products that are mostly not managed sustainably and can have environmental and economic impacts. Among these by-products, cashew nut testa shell (CNTS) stands out as an underutilized material despite being a rich source of primary and secondary metabolites. To recover the compounds with bioactive potential present in CNTS, efficient extraction methods aligned with the principles of sustainability are essential. This review explores the paradigm shift towards emerging extraction techniques, aiming to add value to CNTS. Evidence from recent studies highlights that CNTS is particularly rich in polyphenols, tannins, flavonoids, and lipid compounds, which exhibit strong antioxidant, antimicrobial, and anti-inflammatory activities. Alternative methods such as supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), subcritical water extraction (SWE), microwave-assisted extraction (MAE), and ultrasound-assisted extraction (UAE) have demonstrated high selectivity and efficiency compared to traditional methods. Nonetheless, the scalability, cost-effectiveness, and regulatory approvals for food and pharmaceutical uses remain a challenge for the alternative methods. This review synthesizes the current knowledge on CNTS valorization, highlights the potential of green extraction technologies, and points out the main gaps for industrial applications.

Graphical abstract



Keywords By-product valorization · Green alternatives · Biocomponents · ODS

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Introduction

Cashew (*Anacardium Occidentale* L.), a member of the *Anacardiaceae* family, originates from the tropical regions of South America, and is widely cultivated in several countries across Asia, West Africa, and Central America [1] The fruit consists of two main parts: the nut, which accounts for approximately 10% of its weight, and the apple, which makes up the remaining 90% [2]. The nut itself is composed of three components, the kernel or nut, the testa, and the shell [3].

The cashew processing generates several by-products, depending on the part of the fruit used (cashew apple or cashew nut). For instance, large-scale cashew nuts processing generates significant amounts of solid waste, the cashew nut testa shell (CNTS), which has gained increasing attention from due to its high potential as a source of bioactive compounds [4]. According to the *Food and Agriculture Organization* data from 2023, cashew production is mainly concentrated in tropical regions of Africa, Asia, and South America. Côte d'Ivoire leads the global cashew nuts shell production, with approximately 1.04 million tons, followed by India (782,000 t), Viet Nam (347,600 t), Benin (203,800 t), and the United Republic of Tanzania (189,100 t). Regarding cashew apple production, Brazil stands out as the leading producer with about 1.06 million tons, followed by Mali (179,900 t) and Madagascar (77,200 t) [5]. The *Instituto Brasileiro de Geografia e Estatística* (IBGE) reported in 2023 that Brazil produced approximately 127,931 tons of cashew nuts, and indicates Ceará State as the top Brazilian producer [6]. Considering that CNTS represents 1% to 3% of the total nut weight [7], the Brazilian cashew nut processing generated in 2023 between 1,279 and 3,838 tons of CNTS. This significant volume accentuates its potential use as a source of valuable components.

Although it has been reported that CNTS is rich in phytochemicals and nutrients, this by-product is often overlooked and inadequately managed, as commonly discarded in open environment, incinerated, or used for animal feed [8, 9]. Occasionally, partial composting or anaerobic fermentation are also carried out, although associated with only partial use of the biomass [4, 10]. Nevertheless, the recovery of bioactive compounds from CNTS should be improved considering environmental guidelines from the Sustainable Development Goals (SDGs) and principles of green chemistry.

The CNTS is rich in bioactive compounds, such as fatty acids, carotenoids, and phenolic compounds [7, 11]. The potential of these compounds has sparked considerable interest in their extraction, as they hold the key to innovations in pharmaceuticals, cosmetics, and functional foods. However, the conventional methods for extracting these compounds come with environmental concerns and efficiency limitations. The need to use eco-friendly techniques to recover bioactive compounds requires technological innovation. Cutting-edge technologies that have potential for revolutionizing CNTS research and applications include the extractions of supercritical fluid (SFE), pressurized liquid (PLE), subcritical water (SWE), microwave-assisted (MAE), and ultrasound-assisted (UAE) [12, 13]. These techniques align with the principles of green chemistry, aiming to minimize the environmental footprint while maximizing yield and purity. Green extraction involves a variety of innovative methods that use alternative solvents, moderate operating conditions, and advanced technologies to maximize the extraction of bioactive compounds in CNTS [9].

This review investigates the potential of CNTS as a source of novel bioproducts, recovered through the application of green extraction technologies, which highlights the limitations and drawbacks of conventional extraction methods and underscores the urgent need to adopt environmentally sustainable alternatives, in line with the United Nations SDG-12 (Responsible Consumption and Production), and SDG-9 (Industry, Innovation, and Infrastructure). This novel approach provides a comprehensive overview of advanced green extraction approaches for efficiently recovering high-value bioactive compounds from CNTS. Furthermore, the review discusses the bioactivity and functional properties of these compounds and outlines future perspectives for its industrial applications in chemical, pharmaceutical, cosmetic, and food sectors, emphasizing the integration of ecological responsibility with technological innovation.

Search methodology

An extensive literature search was conducted to explore the composition profile of the phenolic compounds from CNTS, and their dependence with the extraction techniques use to recover this bioactive fraction. The primary objective was identifying and assessing relevant studies on the above topics. The aim was to gain insights into the phenolic compound content and characteristics of CNTS and investigate the effectiveness of various extraction methods. A search within peer-reviewed journals from 2000 to 2025 (SCOPUS database) was conducted in October, 2025 considering the keywords "Cashew AND (testa OR husk)", and resulted in 142 documents. The selection criteria for this search were restricted to articles focusing on CNTS, written in English, and published in scientific journals. From the initial 142 papers, more than 100 documents were published since 2015, which only 22 refer to bioactive compounds (polyphenols) with the Booleans "Cashew AND (testa OR husk) AND (polyphenols OR bioactive)". The lack of scientific research about this subject suggests the relevance for further investigation on bioactive components from CNTS useful for food, pharmaceutical, and cosmetic applications.

CNTS: a by-product

The processing of the cashew is divided in two different lines. The processing of the cashew apple for the production of juice, beverages, drinks, and sweets, generating the cashew bagasse (CAB). The second is related to the cashew nut processing, which generates various by-products. For instance, the raw material (cashew nut) undergoes drying, steaming, and cooling, followed by cutting and separation to obtain cashew nut shell (CNS). Rich in oil, the CNS is submitted to pressing extraction to produce the cashew nut shell liquid (CNSL) and generating the press cake as by-product [8, 14]. Once the cashew nut shell is removed, the nuts are covered in a reddish-brown skin called the cashew nut testa shell (CNTS). Following this, the nuts undergo drying and cooling to facilitate CNTS removal, another by-product which is typically discarded due to its bitter taste. Subsequently, after the CNTS removal, the nuts are grading and packaging, with intact nuts slated for commercial sale, while damaged kernels are either discarded or processed into cashew nut meal (CNM), a by-product commonly utilized as animal feed flour or in the use of product development with lower market value (Fig. 1) [4].

Although the relevance of CNTS components has been detected, this biomass represented by a thin reddish-brown layer covering up to 3% of the cashew nut is still underestimated [7, 15, 16]. The CNTS separation from the nut may result in material losses during mechanical peeling, providing a by-product with high content in bioactive components, which requires proper storage conditions to maintain the biomass quality and stability. These considerations highlight the importance of optimizing processing steps to efficiently utilize this valuable material [17].

The literature has reported CNTS as a source of considerable amounts of primary (like carbohydrates, lipids, proteins and fibers) and secondary metabolites (bioactive compounds) such as phenolic compounds. The centesimal composition from CNTS indicates moisture values of 9.50 and 7.05 g 100 g^{-1}, lipids content of 21.00 and 20.10 g 100 g^{-1}, ash values of 1.71 and 2.02 g 100 g^{-1}, fiber of 9.67 and 10.30 g 100 g^{-1}, protein values of 11.71 and 19 g 100 g^{-1}, and carbohydrate content of 51.05 and 39.08 g 100 g^{-1}, as presented by Oliveira [18] and da Costa [19], respectively.

The fatty acids content from CNTS was reported by Trox et al. [7], which presented a comparative study of fatty acids profile from cashew nuts with and without CNTS. The main fatty acids reported are unsaturated, including oleic (18:1) and linoleic (18:2) acids, and saturated fatty acids (e.g., stearic acid). Although the protein content from CNTS is lower than that of cashew nut and cashew nut shell, they are important for several metabolic functions. High carbohydrate content suggests relevant presence of natural sugars [20]. The primary minerals from CNTS are magnesium (0.58 g 100 g^{-1}), calcium (0.56 g 100 g^{-1}), phosphorus (0.19 g 100 g^{-1}), and potassium (0.15 g 100 g^{-1}) [16].

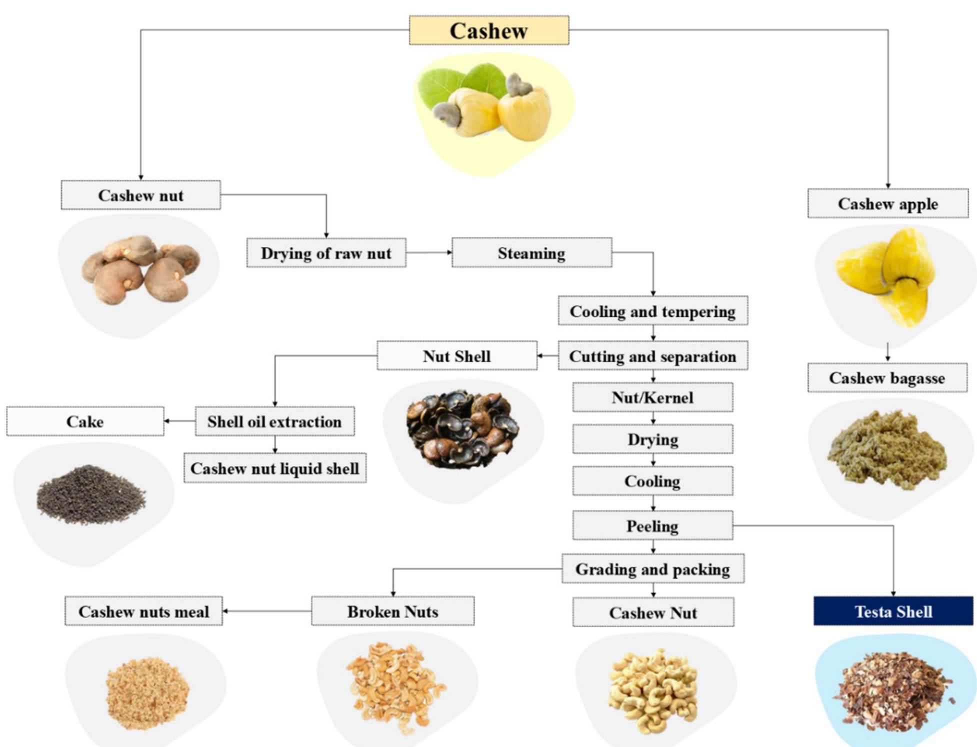

Fig. 1 Cashew processing and obtaining CNTS. **Source**: Adapted from Dhanushkodi, Wilson and Sudhakar [14].

The CNTS was related as a source of important carotenoids, such as β-carotene, α-carotene, lycopene, and lutein, which are the common carotenoids present in fruits and vegetables, and part of human diet. Research conducted by Trox et al. [7] with cashew samples from Indonesia indicates that cashew nut with and without CNTS contain levels of β-carotene of 21.80 and 8.96 µg 100 g^{-1}, and for lutein of 52.50 and 29.20 µg 100 g^{-1}, respectively. These results confirm the importance of CNTS, contributing to the presence of valuable natural antioxidant colorants.

Agricultural by-products typically serve as rich sources of secondary metabolites, and often present significant quantities of different bioactive compounds. The abundance of bioactive compounds holds promising potential for their utilization in various processing industries, especially for foods, pharmaceuticals, and cosmetics [21]. These metabolites are categorized into distinct groups based on the presence of phenol rings and their stabilization. Phenolic compounds occur in various functional forms, including methyl esters, esters, and glycosides. They are often found in conjugation with poly- and monosaccharides, wherein one or more phenolic compounds are bonded to these sugars [22]. The classes of phenolic compounds predominant in the CNTS include phenolic acids, flavonoids, and tannins [7, 11].

CNTS: A potential source of bioactive compounds

Several organic compounds are produced from plants as secondary metabolites, either as part of the regular metabolic processes, or in response to specific environmental factors such as injuries, temperature fluctuations, UV radiation exposure, and infections [23]. These metabolite components are categorized into distinct clusters based on the presence of phenol rings in their structures and the structural motifs that anchor these rings. Thus, the main phenolic compounds present in CNTS can be classified as phenolic acids or flavonols, as illustrated in Fig. 2.

Phenolic acids are defined by at least one aromatic ring linked to one or more hydroxy substituents, where their structure can extend from simple phenolic molecules to complex polymers with substantial molecular weights [24]. This class of components is classified in two primary groups: hydroxybenzoic acids (C6–C1 structure with an aromatic ring attached to a carboxylic group) and hydroxycinnamic acids (have a C6–C3 structure with an unsaturated side chain) [25]. Chandrasekara and Shahidi (2011b) reported that the main phenolic acids present at the CNTS are gallic acid, syringic acid, and p-coumaric acid, respectively with values of 0.36, 2.51, and 0.52 mg g^{-1} of defatted CNTS. The significance of these contents of phenolic acids in CNTS lies in their health-promoting benefits, including antioxidants, anti-inflammatory, antimicrobial, and antiradical properties [7, 11, 16, 26].

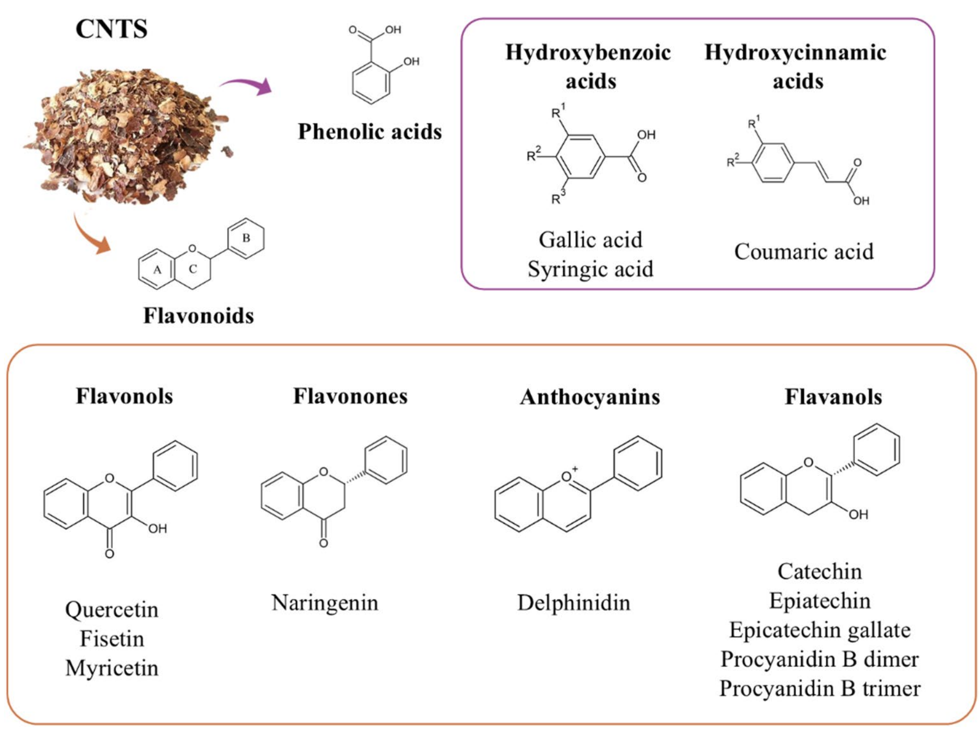

Fig. 2 Main phenolic acids and flavonoids present in CNTS. **Source**: Prepared based on Chandrasekara; Shahidi [26], Donkoh et al. [16]. , Sruthi; Roopavathi; Madhava Naidu [11] and Trox et al. [7].

The flavonoids group presents components that share a common structure, comprising two aromatic rings designated as A and B, linked to a 3-carbon atom chain, forming an oxygenated heterocycle referred to as ring C [27]. Flavonoids are further categorized into six subclasses based on the type of heterocycle (C6-C3-C6) involved. These subclasses include flavonols, flavones, isoflavones, flavanones, anthocyanins, and flavanols [21, 28]. Flavonoids have garnered considerable attention for their functional and therapeutic potential [27].

Flavonols stand out as the most commonly occurring flavonoids in vegetable materials, with key representatives including quercetin, kaempferol, and myricetin. Significant variations in its concentration can be observed among different vegetables and its by-products [28, 29]. For instance, flavones, primarily comprising glycosides of luteolin, apigenin, and chrysin, are less prevalent in vegetables compared to flavonols [30]. Ukoha, Ejikeme and Maju [31] identified quercetin, myricetin, and fisetin as the main flavonols present in the fraction extracted using ethyl acetate from CNTS.

Isoflavones exist as phytoestrogens owing to their affinity for estrogen receptors [32]. Even though they are non-steroids, they contain OH^{-} group at positions 7 and 4' in a configuration similar to estradiol [21]. The fundamental distinction between isoflavones and other flavonoids lies in positioning of benzene ring B at C3 place. This has important implications in structure, biological function and metabolic activity [33]. Flavonones are also categorized within the flavonoid group, distinguished primarily by their glycosylation at position 7 with a disaccharide [34]. Sruthi, Roopavathi and Madhava Naidu [11] identified naringenin in hydrolyzed free phenolic fraction from CNTS.

Anthocyanins consist of an aglycone unit (a degradation product of the flavylium ion) linked to heterosides [35]. The differences among various anthocyanins primarily lie in factors such as the positioning of these bonds, the types and quantity of sugars attached, the presence of aliphatic or aromatic carboxylates connected to the sugar molecules, and the number of hydroxyl groups in the aglycone [36]. Anthocyanins can manifest in various forms, including aglycones, esterified with diverse organic acids, glycosylated with glucose at position 3, and bound to phenolic acids. They maintain stability by forming complexes with other flavonoids [37]. Ukoha, Ejikeme and Maju [31] identified cyanidin and delphinidin as the main anthocyanins present in the fraction extracted using ethyl acetate from CNTS.

Flavanols are monomers, such as catechins and epicatechins, and in polymerized forms, are known as procyanidins [38]. The A ring of the monomer undergoes multiple levels of hydroxylation at the 5 and 7 positions, while the B ring undergoes similar hydroxylation at the 3′, 4′, and 5' positions. The position 3 of the C ring is either esterified with gallic acid or contains a hydroxyl group [39]. Flavanols discovered in food typically lack glycosylation, a feature commonly observed in other flavonoids. Procyanidins, also known as condensed tannins, are diverse flavonols linked by C–C bonds at either 4–6 or 4–8 positions, such as B-type procyanidins [39]. In a study conducted by Sruthi, Roopavathi and Madhava Naidu [11], catechin, epicatechin, and epicatechin gallate as the main flavanols found in the raw material. Chandrasekara and Shahidi [26], Trox et al. [7], and Van Thanh et al. [40] quantified the catechin content found in CNTS, reporting values of 47.28, 7.70, and 207 mg g^{-1}, respectively. Chandrasekara and Shahidi [26] and Trox et al. [7] also reported values for epicatechin of 28.29 and 4.46 mg g^{-1}, respectively. These flavan-3-ols are the significant polyphenols of CNTS. Sruthi, Roopavathi and Madhava Naidu [11] reported free, esterified, and bound phenolic compounds were detected from different fractions of CNTS. (+)-catechin, (-)-epicatechin and epicatechin gallate were detected in all the phenolic forms. Nevertheless, few compounds, like (-)-epigallocatechin, procyanidin B1, (epi)-Gallocatechin-(epi)-catechin gallate, procyanidin dimers, procyanidin trimer, were restricted only in the free fractions. Sruthi, Roopavathi and Madhava Naidu [11] also identified the presence of procyanidin B1, procyanidin B2, and procyanidin B3 in the free fractions of CNTS. These compounds exhibit diverse biological potentials, including antimicrobial (p-coumaric acid, catechin, and epicatechin gallate), antioxidant (catechin, quercetin, and gallic acid), anti-inflammatory (quercetin, naringenin, and gallic acid), hepatoprotective (naringenin, syringic acid, and epicatechin), anti-obesity (kaempferol, delphinidin, and procyanidin B3), anticancer (quercetin, kaempferol, and epigallocatechin), and neuroprotective effects (fisetin, kaempferol, and procyanidin B2), as well as cardioprotective properties (catechin, epicatechin, and delphinidin) [28, 38].

CNTS has been increasingly studied within the biorefinery context because it represents a sustainable source of phytonutrients and valuable functional compounds. Instead of being discarded, CNTS can be integrated into a circular production chain, maximizing the use of biomass while minimizing the waste generation. The recovery of its bioactive compounds from CNTS adds economic value to the processing chain and supports the development of sustainable ingredients for food, pharmaceutical, and cosmetic industries. Therefore, the use of environmentally friendly extraction methods is essential to provide the adequate process yield, and sustainable products.

Extraction methods applied to CNTS for the recovery of valuable components

Solvent extraction is a common method across various industries to recover bioactive compounds. Conventional or classical extraction methods like Soxhlet, maceration, percolation, agitation, and centrifugation have been largely used to recover high-value-added compounds from various by-products [41]. The versatility of these methods, applicable for different matrices, can be enhanced by using different solvents and heating methods to facilitate the mass transfer [24]. Typically, water, ethanol and their mixtures are the primary solvents used to recover bioactive compounds. Nevertheless, toxic solvents are frequently involved in these methods, also known for their high energy, solvent and time consuming, and sometimes associated to low yields. Additionally, elevated process temperatures can be are applied depending of the solvent used, which can be associated to thermal degradation of heat-sensitive compounds [42]. Even though various studies have demonstrated the CNTS potential in small-scale processes, conventional extraction methods still face scalability challenges due to their above-mentioned drawbacks. Therefore, fully commercial applications remain rare, emphasizing the necessity of green/efficient strategies to enable industrial applications. The exemplify the CNTS relevance, Table 1 summarizes the studies involving several classical techniques that have been used to extract the bioactive compounds from CNTS, including agitation, percolation, maceration, and centrifugation with different solvents.

For instance, Mathew and Parpia [43] identified (+)-catechin and (-)-epicatechin as the predominant polyphenols from CNTS extracts obtained by aqueous acetone solution. Kamath et al. [44] recovered CNTS extracts by shaking with ethanol at 37 °C for 3 h, and obtained an extraction yield of 45%, and samples with total phenolic content of 243 mg g^{-1} of extract, and antioxidant activity in IC_{50} (concentration required to inhibit half-maximum) of 1.30 µg mL^{-1} in 2,2′-azino-bis (3-ethylbenzthiazoline-6-sulfonic acid) radical scavenging assay (ABTS assay). Epicatechin was detected in the extract as the main polyphenol. Nagaraja [20] observed the presence of tannins and phenols in CNTS methanolic extracts from different cashew varieties. Chaves et al. [45] evaluated CNTS extracts obtained by maceration with ethanol and reported values of 185.44 mg GAE g^{-1} of extract (Gallic Acid Equivalents). Furthermore, the CNTS extracts showed antioxidant capacity near 40% with extract concentrations of 250 µg mL^{-1} at DPPH (2,2-diphenyl-1-picrylhydrazyl) method. Ukoha, Ejikeme and Maju [31] obtained CNTS extracts using acetone/water solution (70:30 v v^{-1}) for the recovery of phenolics-rich fractions, and identified the presence of quercetin, catechin, epicatechin, myricetin, azaleatin, cyanidin, and delphinidin.

Trox et al. [7] extracted polyphenolics from CNTS using a methanol solution (40:60 v v^{-1}), 50 µL of formic acid, 3 min at 2500 g by centrifugation technique. Under these conditions, (+)-catechin and (-)-epicatechin with 5.70 and 4.46 g kg^{-1} DM (dry matter), respectively, were extracted. Chandrasekara and Shahidi [26] used a solution (80:20 v v^{-1}), 6 g:100 mL, 4000 g at 5 min, to extract the phenolic compounds of CNTS. These parameters resulted in the extraction of 269.05 mg GAE g^{-1} (gallic acid equivalent) of phenolic content and 23.89 mg CE g^{-1} (catechin equivalents) of proanthocyanidin content. In addition, obtained antioxidant capacity (ORAC Activity) of 54171.00 µmol TE g^{-1}. Oliveira [18] extracted phenolics, flavonoids, and

Table 1 Conventional extraction methods used for the recovery of bioactive compounds from CNTS

Sample preparation	Method	Solvent	Experimental Conditions	Yield	Bioactive compounds	Ref
CNTS dried	-	Acetone/water	Solution (50:50 v v^{-1})	42.5%	Polyphenols	[43]
CNTS dried and sieved	Agitation	Ethanol	1:5 (w/v) at 37 °C for 3 h	45.0%	Phenolics and antioxidants	[44]
CNTS defatted	-	Methanol	Acid solution (pH = 4)	-	Tannins and phenols	[20]
CNTS dried	Maceration	Ethanol	-	14.0%	Phenolics and antioxidants	[45]
CNTS dried	-	Acetone/water	Solution (70:30 v v^{-1})	-	Phenolics and tannins	[31]
CN with CNTS	Centrifugation	Methanol/water	Solution (40:60 v v^{-1}), 50 µl of formic acid, 3 min at 2500 g	-	Polyphenolics	[7]
CNTS defatted and sieved	Centrifugation	Ethanol/water	Solution (80:20 v v^{-1}), 6 g:100 mL, 4000 g at 5 min	42.9–44.2%	Phenolics, proanthocyanidin, and antioxidants	[26]
CNTS dried and sieved	Percolation	Ethanol/water	Solution (70:30 v v^{-1})	44.6%	Phenolics, flavonoids and tannins	[18]
CN with CNTS	-	Ethanol/water	Acid solution (80:20 v v^{-1})	-	Phenolics	[46]
Milled CNTS	Agitation	Milli-Q water	1 g: 10 mL, 1 h at 37 °C. Centrifuged 10.000 g for 1 min at 4 °C.	-	Antioxidants	[47]
CNTS powder	-	Ethanol/water	50 g: 150 mL	-	Phenolics, flavonoids, and antioxidants	[11]
CNTS dried and grounded	Centrifuge	Ethanol/water	Solution (70:30 v v^{-1}), 1 g:10 mL, and 30 min at 40 °C.	-	Phenolics and antioxidants	[48]

tannins in the CNTS using ethanol aqueous solution (70%) by percolation method. The results confirmed the presence of catechins, simple phenols, and flavanones.

Griffin and Dean [46] produced an extract of CNTS using an ethanol/water solution (80:20 v v^{-1}) and provided phenolics content of 301.0 mg GAE/100 g, procyanidin trimer of 1473.5 mg/100 g, and small molecule phenolics as epicatechin (1567.3 µg g^{-1}). In addition, the antioxidant capacity detected from the recovered extract was 25.2 mg TE g^{-1} (DPPH) and 4287.9 µg TE/100 g. According to Lee et al. [47], CNTS extracts obtained by agitation with water were incorporated into biodegradable packaging films, and the results show good antioxidant and antimicrobial activity and extremely high thermal stability.

Sruthi, Roopavathi and Madhava Naidu [11], reported that the majority of phenolic compounds present in CNTS were found in the free form followed by the bound and esterified fractions, with values of 62.5, 21.8, and 15.6%, respectively. The free phenolic fraction (FPF) exhibited the highest concentrations of total polyphenols and flavonoids. The FPF exhibited the greatest radical scavenging activity, with an IC_{50} value of 12.35 ± 1.48 µg mL^{-1} from the DPPH assay, 33.77 ± 1.04 µg mL^{-1} from the ABTS assay, and 62.89 ± 2.1 µmol from Fe^{2+} equivalent per gram of cashew nut testa (ferric reducing antioxidant power - FRAP). Sruthi, Madhava Naidu and Rao [48] showed that nano-complex powder extracts increased DPPH and ABTS radical scavenging activities due to their high polyphenol content, indicating potential food and agricultural applications.

A wide range of conventional extraction techniques has been successfully applied to CNTS for the recovery of bioactive extracts, which have demonstrated significant antioxidant potential due to the presence of valuable phenolics, flavonoids, and tannins. Hydroalcoholic mixtures in different concentrations are the most recurrent solvents used in CNTS, likely due to the wide polarity range and ability to solubilize phenolic acids and flavanols. Despite their effectiveness, these solvents may also co-extract non-target compounds such as pigments, lipids, or residual tannins, or other undesirable compounds which could interfere in antioxidant assays, or limit its direct use in food products. In addition, most studies rely on single-step extraction, although combining solvents of different polarities or performing sequential extraction could enhance the overall recovery of distinct classes of components. For instance, a first extraction with aqueous ethanol could target catechins and flavonols, followed by acetone or methanol to recover condensed tannins.

From the extraction method perspective, conventional techniques such as maceration and shaking are easy to implement and require minimal equipment. Still, they are time-, energy- and solvent-consuming, compared to emerging green extraction approaches. Therefore, a transition to more eco-efficient technologies is relevant for industrial applications, as a request to reduce environmental impact, while maintaining process efficiency and extract quality. Finally, considering that CNTS contains a complex mixture of phenolics and tannins, further purification or fractionation steps may be of interest to separate undesirable compounds such as the astringent tannins or other reactive components, often relevant for food or pharmaceutical applications.

Approach to the principles of green extraction

Green extraction principles describe the approaches and strategies for reducing the environmental impact of the extraction methods, while optimizing efficiency, safety, and quality of the final product. According to Chemat et al. [49], the green principles emphasize process sustainability by encouraging the use of renewable raw materials and eco-friendly solvents, optimizing energy efficiency, reducing waste generation, and obtaining non-denatured and biodegradable extracts. As illustrated in Fig. 3, green extraction concept compasses the compounds integrity, enhanced selectivity, and health and safety aspects, serving as a comprehensive roadmap for the development of sustainable and efficient extraction systems.

Aligned with the broader philosophy of green chemistry, these principles emphasize sustainability, resource efficiency, and waste reduction [50]. Therefore, the use of solvents that are renewable, biodegradable, non-toxic and environmentally safe is fundamental within the green principles. Water, for example, is highly favored due to its renewability and wide availability [51]. Supercritical carbon dioxide (CO_2) is an alternative to non-polar toxic solvents for obtaining bioactive compounds [52]. The use of ethanol is also an alternative to traditional organic solvents, providing effective extraction of polar compounds [53]. Chemat et al. [49]. highlighted the use of ethanol, glycerol, and d-limonene, which are renewable, biodegradable and non-toxic solvents. They also noted the potential of emerging solvents like ionic liquids and pressurized hot water for efficient and selective extraction across diverse compounds, as well as deep eutectic solvents (DES), as presented by Benvenutti et al. [54].

Green extraction techniques, driven by a commitment to energy efficiency and sustainability, minimize energy consumption through gentler operating conditions, reduce the carbon footprint, and aid the fight against climate change [55]. By optimizing operating conditions, these methods lower energy usage, benefiting the environment and leading to cost savings for industries [56]. Chemat et al. [49] emphasize that energy efficiency in green extraction can be achieved through process intensification and innovative

Fig. 3 Green extraction principles: guidelines and strategies. **Source**: Elaborated based on Irianto et al. [50].

technologies such as pressure-, ultrasound-, microwave-, and pulsed electric field-assisted methods.

Waste reduction is prioritized through enhanced efficiency, employing techniques that minimize solvent usage and extraction durations. By using a smaller solid: liquid ratio, these methods significantly reduce waste production and its environmental impact [57]. Shortening extraction times conserves resources and energy, increasing economic efficiency and aligning sustainability principles to lower waste management costs [58, 59].

Preserving the integrity of bioactive compounds is crucial, and this can be achieved by using moderate operating conditions to avoid high temperatures or extreme environments that cause degradation, preserving the stability of sensitive compounds [60]. This approach results in high-quality extractions, aligning with sustainability and improved efficiency [61].

The high selectivity of green extraction techniques is achieved by targeting desired compounds while minimizing the extraction of non-target components, increasing the extract purity and reducing further purification processes. Selectivity is achieved by a careful selection of the solvents, the process conditions, and the extraction methodology [62]. The adequate selection should result in the recovery of extracts rich in the target components, aligned with sustainability goals by minimizing resource-intensive post-extraction processing [63].

It is important to avoid hazardous solvents and conditions that could endanger health, and to ensure the well-being of workers, consumers, and the environment [64]. These methods favor less-toxic solvents and operate under milder conditions to reduce safety risks like fire or explosion. By minimizing toxic chemicals and generating minimal waste, green extraction methods align with sustainability and ethical resource use, ensuring the safety of all involved. The concept of "green extract" proposed by Chemat et al. [49] emphasizes sustainability throughout circular processing chain, from cultivation to recycling, ensuring minimal environmental impact, energy efficiency, and ethical handling. This approach provides a basis for developing international standards or eco-labels for sustainable extraction.

Trends for the green extraction of bioactive compounds

The recovery of bioactive compounds from CNTS adds value to the cashew industry, diversifying the processing chain and reducing waste management costs [9, 65]. The valorization of this by-product relies on replacing conventional extraction methods that use large volumes of hazardous solvents with cleaner, more efficient, and low-impact alternatives [66]. Consequently, innovative green technologies, such as supercritical fluid (SFE), pressurized liquid (PLE), subcritical water (SWE), microwave-assisted (MAE), and ultrasound-assisted (UAE) extractions have emerged as sustainable approaches to reduce waste, shorten processing time, and improve extract quality [9, 13, 67–69]. It is important to note that while green technologies such as PLE, MAE, and UAE offer sustainable approaches, they can also use a variety of solvents, non-necessarily GRAS (*Generally Recognized as Safe*). Therefore, the greenness of these techniques depends also on the selected solvent. Figure 4 summarizes recent non-conventional green extraction methods.

Supercritical fluids extraction (SFE) has gas-like viscosities and diffusivities, combined with liquid-like density. Above the critical conditions, small changes in pressure and temperature result in significant changes in the density of supercritical fluids [70]. The SFE is an environmentally friendly extraction process which normally uses carbon dioxide (CO_2) as solvent, with easy product separation and minimal alteration of the extracted products [52]. Besides, high-pressure CO_2 has been widely used in the extraction of lipids and carotenoids [71]. The main parameters that affect compounds extraction are pressure, temperature, CO_2 flow rate, extraction time, and co-solvent addition [72]. The higher diffusion coefficient and lower viscosity of the supercritical fluids, compared to liquid solvents, result in rapid

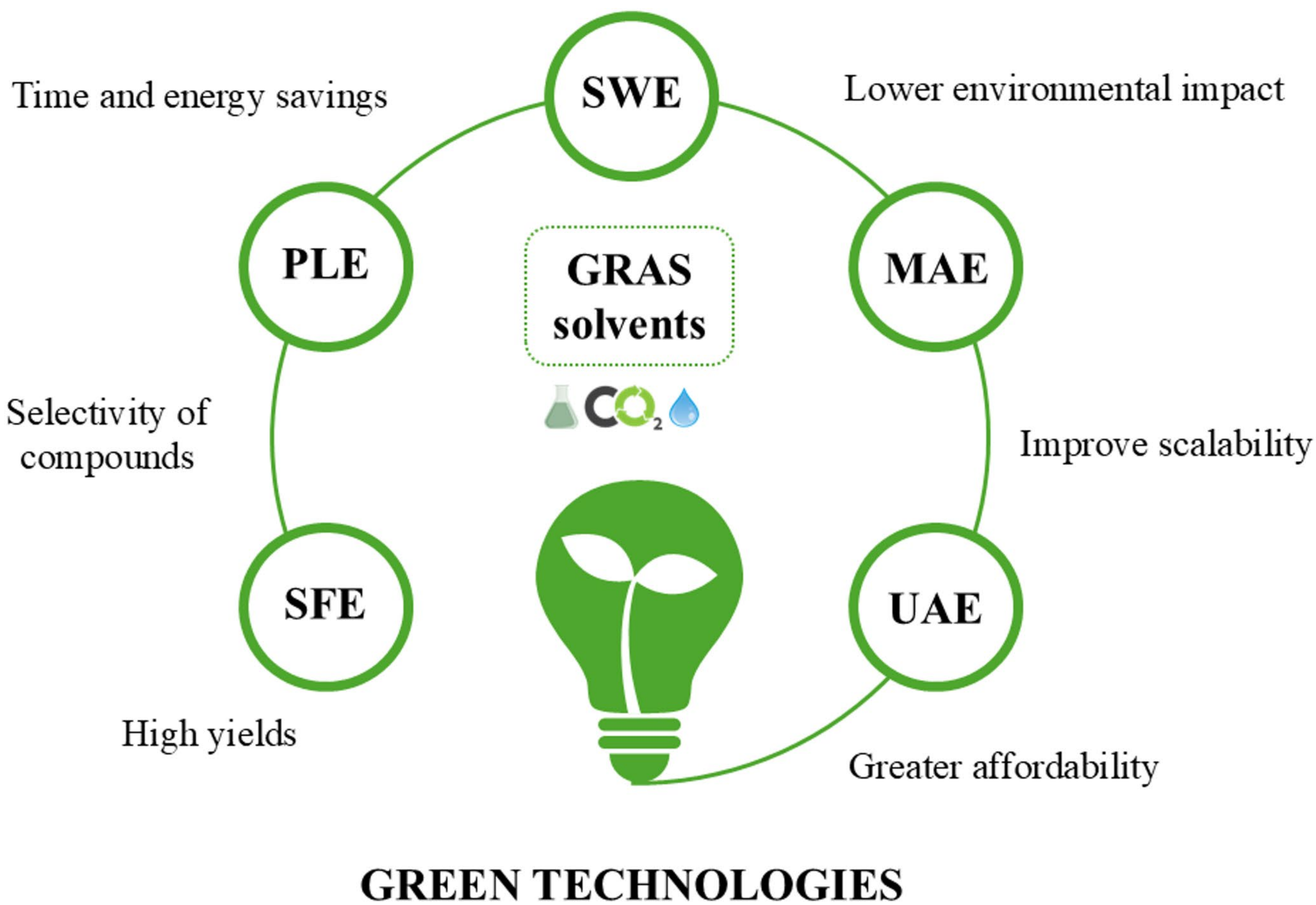

Fig. 4 Non-conventional green extraction for obtention bioactive compounds. *SFE - Supercritical fluid, PLE- Pressurized liquid, SWE – Subcritical water, MAE - Microwave-assisted, and UAE - Ultrasound-assisted extractions

penetration into the complex structures of plant matrices, providing high extraction yields. Also, due to the low process temperatures, the SFE is especially recommended to extract high purity thermolabile compounds [73].

Pressurized liquid extraction (PLE) is a technique that operates under different temperature and pressure conditions, which are maintained high enough to keep the solvents in their liquid state above the atmospheric boiling point [74]. These conditions promote fast and efficient extraction by enhancing diffusion, reducing viscosity, and decreasing the surface tension of the extraction solvent [75]. By adjusting pressure and temperature conditions, varying dielectric constants (which roughly indicate a solvent's polarity) can be achieved. This affects the solvation power and selectivity toward the target compounds [76]. PLE requires less solvent and shorter extraction times compared the conventional techniques using the same solvents. Additionally, PLE can be combined with the use of green solvents, enhancing the environmental sustainability of the process [56, 77].

Subcritical water extraction (SWE), also known as PLE with water at high pressure and high temperature, is an emerging technology for the recovery of bioactive compounds. It offers a rapid method with low energy and solvent consumption in comparison with time and solvent-consuming low-pressure methods [78, 79]. SWE uses water in a subcritical state as the solvent. The process operates at temperatures between 100 and 374 °C, with pressures typically ranging from 5 to 10 MPa to keep the water liquid [80, 81]. Water's physical and chemical properties change significantly with temperature variations, making it a viable and attractive solvent. Under subcritical conditions, water's dielectric constant decreases drastically, reducing its polarity and giving it a solvation ability like organic solvents (ethanol and/or methanol) [78, 82]. In addition to the decrease in dielectric constant, subcritical water also exhibits reductions in surface tension, viscosity, and density, along with an increase in its ionic product. These characteristics improved the extraction efficiency, and the technology demonstrates high scalability potential, reaching favorable Technology Readiness Levels [83–86].

Microwave-assisted extraction (MAE) improves extraction efficiency due to heating caused by dipole rotation and ions' conduction in the solute and the solvent [87]. This thermal effect, arising from dipole rotation and ionic conduction, significantly influences the solvent penetration and disruption of hydrogen bonds within the solid material, thereby enhancing the extraction [88, 89]. The extraction efficiency of MAE is influenced by several factors, including microwave power, irradiation time, the type and dielectric constant of the solvent, and the temperature of the extraction system [90]. In addition, MAE scale up for industrial application is still in initial stages, and it is largely limited to laboratory scale [91]. However, contemporary research highlights significant efforts and progress toward overcoming these limitations [92].

Ultrasound-assisted extraction (UAE) is a green technology that improves extraction efficiency by reducing time, energy, and solvent use compared to conventional methods with the same solvents [93]. UAE preserves heat-sensitive compounds while operating at lower temperatures and shorter times, minimizing environmental impact and ensuring operator safety [94, 95]. The technique uses sound waves (20 kHz to 100 MHz) to create cavitation, where microbubbles form, grow, and collapse, disrupting cell walls and releasing bioactive compounds [95, 96]. UAE is adaptable for various scales, making it suitable for industries like pharmaceuticals, nutraceuticals, and food production, offering a sustainable and efficient approach to extraction [97].

The opportunity to recover bioactive compounds from CNTS products to diversify and add value to the production chain and reduce the waste management costs associated with the disposal of large volumes of industrial waste is challenging [9]. Therefore, one of the possible best uses of these residues is the extraction of bioactive compounds because of their high commercial value and potential health benefits [11, 65]. Some studies have reported using non-conventional techniques to extract bioactive compounds from CNTS. Table 2 overviews of different green extraction methods and their respective conditions for extracting bioactive compounds from CNTS.

Da Silva et al. [12] evaluating the use of SFE with CO_2 for a selective recovery of liquid fatty acids from dry CNTS. The extracted oil was rich in palmitate, linoleic, stearic, oleic, behenic and erucic fatty acids, quantified by gas chromatography. Additionally, the ethanolic and aqueous extracts recovered by PLE and SWE, respectively, presented polyphenols such as catechin, epicatechin, and procyanidin, identified by ultra-performance liquid chromatography. These molecules are known for their high antioxidant potential and biological activities. The authors also observed that the sequential extractions applied to CNTS increased the process yield and enable the fractionation of the bioactive components from CNTS, compared to isolated extractions. For instance, the extractions conducted with polar solvents (ethanol and water) provided a fraction rich in phenolics. This study provides important insights for the sustainable development of this by-product, following a biorefinery approach with viable high-pressure methods for recovering bioactive compounds.

Da Silva et al. [13] optimized the use of microwave-assisted (MAE) and ultrasound-assisted extraction (UAE) for CNTS applying GRAS (generally recognized as safe) solvents, with results presented at Table 2. The extraction yields, total phenolic, flavonoid, and carotenoid contents,

Table 2 Green extraction methods and solvents used for bioactive compounds extraction from CNTS

Sample preparation	Method	Solvent	Experimental Conditions	Yield	Bioactive Compounds	Ref
CNTS dried	SFE	CO_2	40 °C, 25 MPa, and 1.2 kg.h^{-1}	12.3%	Fatty acids	
	PLE	Ethanol	60 °C, 10 MPa, and 4 mL.min^{-1}	28.0%	Polyphenols (phenolic and flavonoid compounds) and antioxidants	[12]
	SWE	Water	120 °C, 10 MPa, and 4 mL.min^{-1}	37.0%		
CNTS defatted	SFE-PLE	CO_2/Ethanol	40 °C, 25 MPa, and 1.2 kg.h^{-1} and 60 °C, 10 MPa, and 4 mL.min^{-1}	27.0%		
	SFE-SWE	CO_2/Water	40 °C, 25 MPa, and 1.2 kg.h^{-1} and 120 °C, 10 MPa, and 4 mL.min^{-1}	33.3%		
CNTS dried	MAE	Ethanol/water	Optimized conditions: 54 °C, 26% EtOH (v/v), 20 mL/g	30.2%	Polyphenols (phenolic and flavonoid compounds), carotenoids, and antioxidants	[13]
	UAE	Ethanol/water	Optimized conditions: 30 °C, 60% EtOH (v/v), 450 W	37.7%		
CNTS powder	SFE	CO_2 with ethanol as co-solvent	40 to 60 °C, 5 to 20% EtOH (v/v), 15 to 30 MPa, 30 to 120 min	-	Phenolics and antioxidants	[98]
CNTS powder	E-UAE	Water	Viscozyme L, 40 °C, 1:30 g: mL, 40 kHz, 30 to 60 min	-	Phenolics, flavonoids, catechin, epigallocatechin gallate, and antioxidants	[40]

and antioxidant capacity (measured by FRAP and DPPH assays) were evaluated, with the best values for MAE and UAE respectively, of: 30.23 and 37.73% for yield, 392.97 and 445.60 mg GAE g^{-1} of phenolics, 348.71 and 349.22 mg CAE g^{-1} of flavonoids, 4.27 and 5.01 mg β-CE g^{-1} of carotenoids, 2.95 and 3.21 mmol TE g^{-1} for FRAP and 5.39 and 4.37 mmol TE g^{-1} for DPPH. Catechin, epicatechin, and procyanidins were identified as the main compounds from the extracts obtained at optimized conditions for MAE and UAE. In addition, it was observed that the extracts effectively inhibited the digestive enzymes α-amylase and α-glucosidase, with values of 2.09 and 0.015 IC_{50} mg mL^{-1} for MAE and 2.71 and 0.017 IC_{50} mg mL^{-1} for UAE, respectively. This inhibition is possibly due to these polyphenol's presence, which can reduce blood sugar levels after meals, indicating potential health benefits.

Tai, Ha and Thanh [98] evaluated the extraction of CNTS with supercritical CO_2 using ethanol as co-solvent. The best extract results of phenolics and antioxidant activity were obtained using 15% (v/v) co-solvent, at 40 °C, 25 MPa, and an extraction time of 90 min. Under these conditions, the extract exhibited a phenolics content of 63.97 mg GAE g^{-1} and antioxidant activity (ABTS) of 1.52 mmol TE g^{-1} on a dry weight basis. The results indicated that increasing ethanol concentration within a certain range positively influenced the phenolics recovery and antioxidant activity. However, to increase the efficiency of polyphenol extraction, the authors recommend incorporating an additional pretreatment step, such as defatting, which has shown better extraction results, according to the literature [12].

Van Thanh et al. [40] applied ultrasound-assisted extraction (UAE) to recover bioactive compounds from CNTS, with results evaluated according to total content of catechin, flavonoids, and phenolics of the extracts, and the biological activity. In addition, the incorporation of an enzymatic assay improved the extraction process (E-UAE). The results showed that extract by UAE presented a phenolic content of 203 mg GAE g^{-1}, flavonoids of 177 mg RE g^{-1}, catechin of 139 mg g^{-1}, and epigallocatechin gallate of 37 mg g^{-1}, while E-UAE provided phenolics of 263 mg GAE g^{-1}, flavonoids of 249 mg RE g^{-1}, catechin of 207 mg g^{-1}, and epigallocatechin gallate of 95 mg g^{-1}. The CNTS extracts showed high antioxidant potential, enzyme inhibitory action, and anticancer activities, with E-UAE as the most effective method for the extraction of bioactive compounds.

Overall, combining different green extraction techniques can improve the recovery and selectivity of CNTS bioactive compounds. However, further optimization is still required to enhance scalability and ensure the purity of the extracts for commercial applications. For instance, raw material pretreatments and sequential extractions may represent promising strategies toward more efficient and sustainable valorization of this by-product. These compounds are known for their antioxidants, antimicrobial, anticancer, and antidiabetic properties, which will be further discussed in the following section. These properties are essential in protecting cells from oxidative damage and offer significant potential benefits for human health. They also contribute to developing functional products across various industries, including food, cosmetics, and pharmaceuticals.

Scalability and industrial potential of green extraction technologies

Although green extractions such as SFE, PLE, SWE, MAE and UAE, have shown promising laboratory-scale results, their scalability for industrial application still faces technical and economic challenges. Among them, SFE and PLE are already considered viable technologies for several industrial applications, providing reproducibility, solvent recovery efficiency, and adaptability to continuous operation under controlled high-pressure conditions [99].

The SFE is widely industrially used, mostly for food and pharmaceutical products, with high selectivity and purity, although high equipment costs associated to the use of high-pressures may limit its use in small and medium scales. Several worldwide companies have successfully implemented SFE for various industrial applications. For instance, the companies *SKW/Degussa* and *Lavazza* established the first large-scale SFE plants in Europe for decaffeination of tea and coffee, while *Flavex Naturextrakte* GmbH became a benchmark in high-pressure CO_2 extraction in Germany, among several other companies that uses SFE for various purposes. Finally, *NATEX* company from Austria has become a global supplier of industrial SFE systems for hops, hemp, and other natural products. Likewise, different studies have demonstrated the PLE scalability, reporting the semi-industrial-scale feasibility for different matrices, particularly using ethanol or water as green solvents. Such studies support the extraction efficiency and selectivity at upscaled conditions, enabling their integration into industrial biorefinery processes [69, 99–101].

Otherwise, MAE and UAE, while cost-effective and efficient at lab-scale, require refinement for large-scale consistency, such as in uniform energy distribution (microwave or ultrasound) and heat transfer control [102, 103]. MAE and UAE industrial scales are also being driven by sustainable chemistry and circular bioeconomy [92, 104, 105].

Biological potential of CNTS extracted compounds

The main bioactive constituents of CNTS and their biological potential and health effects are illustrated in Fig. 5.

CNTS is rich in polyphenols (catechin, epicatechin, and procyanidins) and carotenoids, such as β-carotene, astaxanthin, and lutein, which are potent antioxidants that effectively quench free radicals and reactive oxygen species (ROS) [106]. In addition to the importance of provitamin A, β-carotene has a protective function against both UV-light and oxidative stress through deactivation of singlet oxygen and by inhibition of lipid peroxidation [7, 107]. These compounds help shield cells and tissues from oxidative stress, promoting skin health, supporting vision, and enhancing immune function [108]. Some authors reported that CNTS extracts were tested for their antioxidant capacity by FRAP, DPPH, and ABTS methods [7, 11, 12, 109].

CNTS presents a wide range of natural compounds with antibacterial properties against pathogenic microorganisms. Sruthi, Roopavathi and Madhava Naidu [11] tested the antimicrobial activity of the phenolic fractions of CNTS against pathogens of food origin (*Bacillus cereus*, *Escherichia coli*, *Micrococcus luteus*, and *Staphylococcus aureus*). Lee et al. [47] evaluated the antimicrobial activity of a CNTS aqueous extract against two pathogens and observed that the CNTS extracts exhibited antimicrobial activity against gram-positive *Escherichia coli* and *Bacillus cereus*. All the phenolic fractions containing catechin, epicatechin, and procyanidins of the CNTS inhibited the growth of these pathogens.

The carotenoids present in CNTS are bioactive compounds of great importance for human health. In addition to acting as precursors of vitamin A, essential for adaptive immunity and the development of T and B cells, they are also recognized for their role in the prevention of chronic diseases, such as cancer and atherosclerosis [110]. In addition, they play a protective role against lipid peroxidation of membrane lipids, lipoproteins and storage fats [111]. Carotenoids are also capable of inducing apoptosis in tumor cells and modulating oncogenes. Various epidemiological studies have demonstrated that they are responsible for the low incidence of cancer in diets rich in vitamin E [107].

CNTS has been reported as a source of polyphenols (catechin, epicatechin and procyanidins). These compounds exhibit remarkable inhibitory effects on key human digestive enzymes, including α-amylase and α-glucosidase [38, 112–114]. Phenolic compounds, including phenolic acids and flavonoids, can form covalent bonds with α-amylase by reacting with nucleophilic groups on the enzyme molecule, thereby modifying its activity [115]. The CNTS extracts effectively inhibited carbohydrate hydrolysis by α-amylase and α-glucosidase, likely due to the presence of catechin, epicatechin, procyanidins, and catechin gallate. These compounds helped to reduce post-meal blood sugar levels within the digestive system [13]. Flavonoids have been widely studied for their strong potential to deactivate the binding sites of digestive enzymes through the formation of hydrogen bonds, π-π interactions, and various molecular interactions with enzyme amino acid residues [116].

Inflammation is a natural immune response to harmful stimuli; however, when it becomes chronic, it is associated with a range of long-term diseases, including cardiovascular disease, diabetes, and cancer [117, 118]. Polyphenols present in CNTS (catechin, epicatechin and procyanidins) can modulate inflammatory processes by inhibiting enzymes and molecules that promote inflammation [119]. Polyphenols can modulate inflammatory processes by inhibiting enzymes and molecules that promote inflammation [117]. They have demonstrated strong anti-inflammatory effects by reducing the production of inflammatory cytokines and enzymes. These compounds can help alleviate inflammation

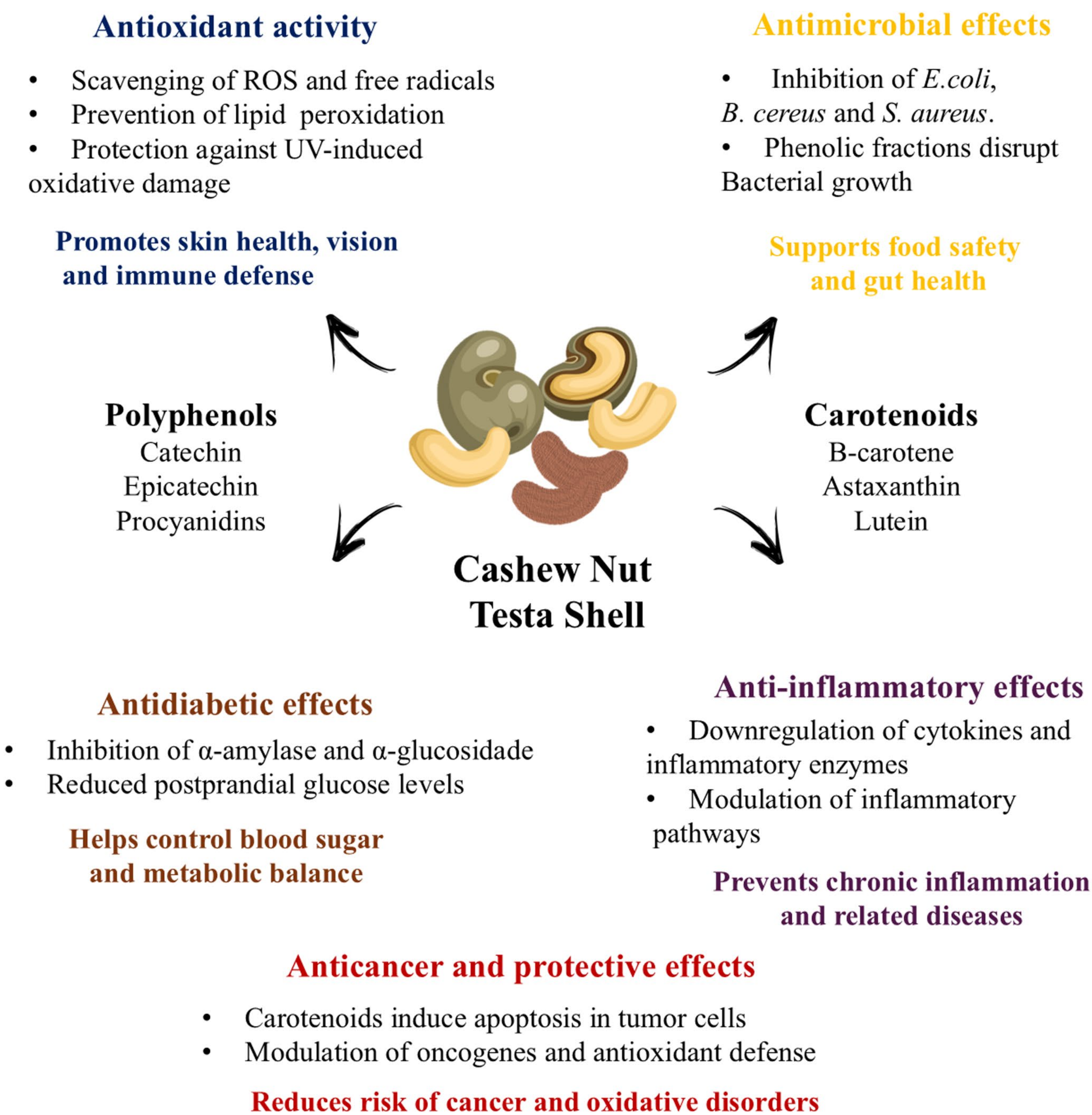

Fig. 5 Health-promoting bioactivities associated to CNTS

and may play a role in preventing inflammatory disorders [118].

Applications of bioactive extracts from CNTS

The use of CNTS extracts in food formulations can compromising the sensory acceptance of the product due to the bitterness taste or astringency sensation caused by the tannins. Nevertheless, polyphenols from the extract contribute to extend the foods shelf life because of their natural preservative properties. Then, encapsulation of the extract can contribute to overcome these challenges, masking undesirable flavors and improving bioavailability and stability of the extract to extend its application.

Sruthi et al. [120] used CNTS polyphenols in milk pudding formulation and evaluated their effect on physicochemical and functional properties, flavor profile, and microbiological and storage aspects. The results demonstrate the feasibility of the extract as functional ingredient, although its concentration must be optimized to balance bioactivity and acceptability. In general, phenolic compounds enhance the antioxidant activity and health benefits of food or beverage products, as observed in enriched drinks and cereal bars. The astringency of some polyphenols may be required in products such as alcoholic beverages, contributing to their characteristic sensorial profile. Nonetheless, stability issues, interactions with food components, and regulatory approvals remain relevant challenges to broader the application of novel ingredients.

Food packaging plays an important role in the preservation of food products throughout transportation and storage, maintaining safety and ensuring quality. Recently, active packages with antioxidants and antimicrobial agents and natural preservatives incorporated have been recognized for its ability to extend foods shelf life. Lee et al. [47] incorporated CNTS extract into a cellulose-based film prepared from sugarcane bagasse through interfacial assembly. The biofilm showed efficient antioxidant potential, good antimicrobial activity and high thermal stability (290 °C). Additionally, the pH-triggered release mechanism is caused by formation of hydrogen bonds between the cellulose and the CNTS extract. Biodegradable active packaging films are gaining popularity as an environmentally friendly alternative to conventional plastics. The CNTS polyphenols can enhance the antioxidant and antimicrobial properties of the films, and extend the product shelf life while align with environmental goals. However, the cost and scalability of these eco-friendly materials still need further evaluation before industrial implementation.

The antioxidant properties of the polyphenols prevent oxidative stress and cell damage by acting as chelating agents for reactive oxygen species, reducing its side effects [121]. Besides, long-term consumption of foods with antioxidants prevents/treats health problems including neurological disorders, diabetes, cancer, osteoporosis, cardiovascular diseases, and infections [122]. Nonsteroidal anti-inflammatory drugs are widely used to alleviate pain and reduce inflammation. The CNTS extract (polyphenols-rich) can be used as a natural bioactive source that inhibits cytokines and inflammatory reactions. However, the bioavailability, stability, and standardization of extracts are critical factors to ensure its efficacy. Nano formulations, particularly metal–phenolic networks (MPNs), have emerged as efficient strategies for controlled drug delivery and cancer therapy [123, 124], while safety and regulatory acceptance of MPNs remain areas for further disclosure.

Oxygen-reactive species cause oxidative damage to lipids, proteins, carbohydrates and DNA, contributing to skin aging [125]. Then, antioxidant components such as the polyphenols from the CNTS extracts, are powerful cosmetic tools, helping to neutralize this damage reducing and chelating ferric ions and inactivating radicals by transferring hydrogen atoms or donating an electron [126].

The natural ability of the polyphenols to enhance skin health, diminish aging signs, and protects against environmental stressors is highly valued for the cosmetics industry [127]. Polyphenols from CNTS, like flavonoids and tannins, present strong antioxidant properties, promoting collagen production, enhancing skin elasticity, and protecting against UV damage, helping to reduce oxidative harm in cosmetic formulations [38]. Health and cosmetic products containing phenolic compounds offer anti-inflammatory benefits, soothing irritated skin, reducing redness, and are effective against wrinkles, fine lines, and age spots [128]. Nevertheless, the stability of the cosmetic formulations must be addressed to ensure long-term performance.

Finally, although the bioactive compounds from CNTS exhibit great potential for food, pharmaceutical, and cosmetic products, most reported uses still require further studies for process optimization, safety evaluation, and cost–benefit assessment to enable large-scale and sustainable applications.

Challenges and futures perspectives

The recovery of bioactive compounds from CNTS by green extraction methods is challenging due to structural complexity and heterogeneity of the biomass. Achieving an optimal balance between selectivity and yield requires the use of advanced extraction strategies that minimize solvent use and preserve compound integrity. Recent approaches have explored hybrid and sequential processes, such as combining SFE, PLE, and SWE with methods like UAE and MAE to improve the recovery of target compounds (high selectivity). However, the high viscosity of some green solvents and difficulties in solvent recycling still limit large-scale applications.

The sustainability of extraction processes has been increasingly assessed using environmental metrics, solvent recyclability rate, and life-cycle assessment (LCA), which considers energy-efficiency, renewability of raw materials, GRAS solvents and other attributes to compare the greenness of the processes.

Emerging solvents such as DES and ionic liquids are promising alternatives to conventional organic solvents, combining low toxicity and tunable polarity. However, their toxicity, recyclability, cost and regulatory aspects are still in progressing studies. Therefore, future research should focus on process scalability, economic viability, and environmental safety to ensure the transition to industrial application.

Conclusions

A promising future lies in the application of green extraction methods to recover bioactive compounds from CNTS, guided by innovation and sustainable principles. Such eco-friendly approach not only enables the efficient recovery of bioactive molecules but also expand their applicability in food and beverage products, nutraceuticals, cosmetics and pharmaceuticals. This review demonstrates that CNTS extracts exhibit strong functional properties such as antioxidant, anti-inflammatory, antimicrobial and others, conferring to this underused material a wide spectrum of valuable applications. Furthermore, the review emphasizes the commercial potential of phenolic compounds from CNTS, which can be effectively utilized, contributing to the circular bioeconomy of the cashew nut processing chain, beneficing the local populations with an income, in attendance to the SDG from ONU.

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Data availability All data generated or analyzed during this study are included in this manuscript.

Declarations

Conflict of interest The authors declare no conflict of interest.

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