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A review on coconut testa: Nutritional attributes, physical properties, biological activities, and product innovation

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ABSTRACT

Coconut testa (CT) is the brown color outer skin of the coconut flesh, a by-product of the coconut processing industry. It is often discarded or used to extract low-grade oil and the remaining residue is utilized for animal feed preparations. CT is a substance rich in phyto-nutrients such as polyphenolics, flavonoids, tannins, anthocyanins, etc. These phytochemicals are responsible for a variety of biological properties of CT, such as antioxidant, anti-hyperglycemic, anti-microbial and anti-inflammatory activities. Owing to these reasons, there has been a growing interest among researchers in utilizing CT for the production of value-added ingredients with health benefits. When CT is mildly dried and subjected to cold-press oil extraction, coconut testa oil (CTO) is produced with an edible grade residue. CTO is found to possess a fatty acid profile similar to that of regular coconut oil, but the level of specific fatty acids such as lauric, palmitic, oleic and linoleic acid showed differences. The studies on the defatted oil cake indicated that the main constituents of coconut testa flour (CTF) are carbohydrates (42–59 %), followed by protein (23–32 %) and fat (7–23 %). The de-fatted CT left behind in the oil extraction can be ground into flour and has been shown to be useful for developing novel product formulations. In recent times, different research groups have investigated many different aspects of CT and CTF. In this review, we intended for an in-depth analysis of research findings on CT, CTO and CTF.

1. Introduction

Coconut (*Cocos nucifera* L.), also known as kapruka in Sri Lanka, has been associated with human life and civilization for thousands of years. Almost all parts of the coconut tree find some beneficial uses for mankind. Its fruits are directly consumed fresh, both by humans and animals or converted into processed products. The most precious component of the coconut fruit is its flesh, which is usually covered by a thin brown outer layer called testa. As coconut testa (CT) tends to impart a brown color on processed products, it is customarily removed prior to production (Rushdha et al., 2022). The loss incurred by the removal of the testa from the coconut could be considerably high when considering the total economic value of the coconut. Based on a rough estimate, 6500 kg CT may be generated out of 100,000 nuts (Marikkar and Musthafa, 2022). In the local scenario, the CT is undervalued and used for the extraction of inferior quality oil and the remaining defatted residue is sent for the production of animal feed. There has been a myth prevalent for a long time in society, saying that CT might be unsafe for human consumption, as it serves as a protective layer, and it might contain toxic metal elements or any other harmful substances. Nonetheless, by taking into consideration bioactive compounds and nutritional attributes, the actual commercial value of CT is enormous. This alone would be sufficient for agricultural by-products like CT to be utilized for high-value end-products through innovative technologies. Uptill now, there has been a renewed interest in agricultural by-product utilization because of the availability of various bioactive compounds with potential health-promoting effects. Hence, the aim of this review is to present an overview of the recent advances in scientific knowledge regarding the food safety of CT and its exploitation for novel products.

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2. Physiological and structural characteristics of the testa

In nature, several seeds and nuts exist with an outer pericarp called the seed coat, which is meant to protect the inside kernel and embryo from injuries or microbial attack (Adekola *et al.*, 2017). In the case of coconut, CT serves the very purpose of protecting the white flesh against risks by microbial attack from outside (Commey *et al.*, 2021). As the CT is a living organ, it may undergo physiological and biochemical changes when the coconut fruit matures. Previous research confirmed that progressive changes take place in the composition of flesh as well as the oil component (Marikkar and Madhurapperuma, 2012). CT looks pale white in its tender stage, but tends to become pale-brown to dark-brown when the fruit reaches its full maturity. The changing nature of color could be partly due to respiration and other metabolic processes. Metabolic activities within the plant tissues are known to alter texture, color, flavor, taste, aroma, and phytochemical compositions. CT could become firmer due to the hardening effect of plant tissues, especially by structural polysaccharides. Nonetheless, studies strictly focused on compositional changes by polysaccharides are rarely reported. Apart from this, changes may also be influenced by factors like agronomical traits and cultivar differences and extrinsic factors like temperature, light, atmospheric pressure and relative humidity.

For the purpose of converting coconut into products or extracting the milk for culinary uses, they are usually harvested at 9–10 months of maturity (Mathes and Marikkar, 2004). Meanwhile, immature nuts are harvested at the age of 6–8 months of maturity for drinking as a beverage (Marikkar and Madhurapperuma, 2012). These are done according to practical experience without deriving information through systematic studies. Prior to manufacturing products like coconut milk powder and desiccated coconut, the CT within the coconut will be peeled off from the flesh (Fig. 1). Since it is tightly attached to the coconut shell, CT needs to be relaxed through a period of seasoning about 5 - 6 weeks by keeping it in an open yard. This is again done according to practical experience rather than deriving information through systematic studies. Removal of CT from fully-matured coconuts would become relatively easy when compared to immature coconuts. Immature nuts, which are composed of soft spongy tissues due to high water content at the tender stage, are the main reason, while the CT of the mature coconut would have a lower content of moisture. This phenomenon would make the recovery of CT from the flesh of the tender nut more difficult than that of the mature coconut.

3. Nutritional attributes and food safety

3.1. Proximate composition

Over the years, efforts have been underway to compile the proximate composition of the fresh coconut flesh and copra kernel through various studies (Appaiah *et al.*, 2014; Marikkar and Madurapperuma, 2012). Nonetheless, studies on the proximate compositions of CT, either in its tender form or mature form, are limited. According to Table 1, some reports compiled the composition of the whole CT while others reported the composition of defatted CT. Some recent studies showed that the major nutrient constituents of the CT were fat (65.63 %), followed by crude fibre (16.00 %), protein (8.11 %), carbohydrates (7.89 %) and ash (1.54 %) (Kumari et al., 2024) (Table 2). Nevertheless, a slight difference in composition was previously reported by Appaiah et al. (2014), where the dried CT was found to possess fat (59 %), carbohydrate (26.3 %), protein (9.3 %), crude fibre (11.6 %) and ash (1.4 %). The observed differences in the proximate composition of CT could be due to geographical variations and varietal differences. Unlike other nuts and kernels, the proximate compositions of the coconut flesh might tend to vary across the different sub-sections (Nathaniel, 1966). Based upon this observation, the composition of CT might be different from that of the whole kernel, mainly due to the unique structure of the mature coconut flesh; the oil content of the layer closest to the water cavity was higher (~56.3 %) than that of the layer nearest to CT (~75.4 %) (Nathanael, 1966). Nonetheless, this pattern of distribution does not have any implications for the nutritional safety of CT.

Outer pericarps and seed coats are very common in beans, rice, wheat, etc. They mainly serve as protective layers for these foodstuffs (Adekola *et al.*, 2017). Owing to the unique structure of coconut flesh, the proximate compositions of CT are remarkably different from those of either wheat bran or rice bran (Table 2). For instance, the fat content of CT is remarkably higher than that of rice bran, wheat bran, etc. When considering carbohydrates, the content in wheat brans is much higher than that of either CT or rice bran. Despite this, somewhat similar carbohydrate contents were noticed in rice bran and defatted CT. Since CT

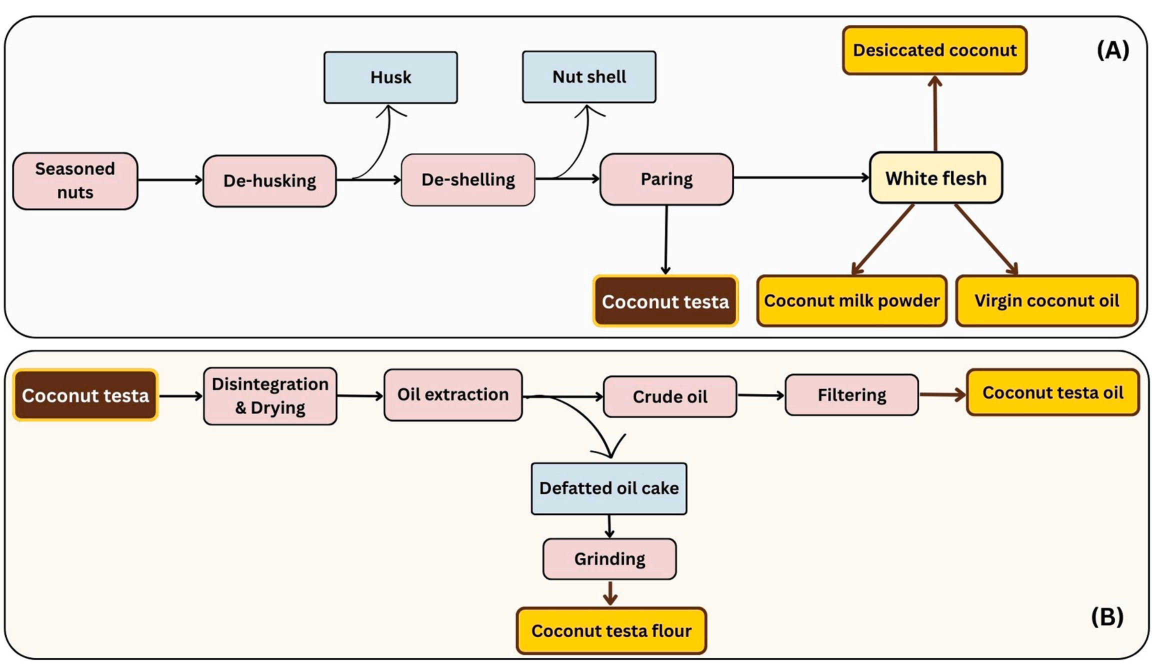

Fig. 1. Process of manufacturing coconut testa (CT), coconut testa oil (CTO) and coconut testa flour (CTF).

Table 1
Studies on nutritional composition, phyto-nutrient distribution, functional and biological properties of coconut testa.

Sample	Sample pre-treatment/ Extraction methodology	Analysis type	Major findings	Reference
Phytochemical composition and biological activities				
Defatted residue of Gon Thambili, Ran Thambili, San Raman, Tall × Tall and commercial hybrid (Country of origin: Sri Lanka)	Sequentially extracted with hexane, ethyl acetate and methanol	TPC, TFC, DPPH radical scavenging activity, FRAP, anti-hyperglycemic assays; α- amylase & α- glucosidase inhibitory assays	Methanol extract of all tested cultivars is rich with polyphenols, flavonoids and has the highest antioxidant and α-amylase inhibitory activities. Hexane and ethyl acetate extracts showed the highest α-glucosidase inhibitory activity	Gunarathne *et al.* (2022)
Dried CT; Variety: not specified (Country of origin: Malaysia)	70 % ethanol-water	TPC, TFC, flavonoid and phenolic acid analysis, antioxidant assays; DPPH, RPA, ABTS, anti-hyperglycemic assays; α-amylase, α- glucosidase inhibitory assay	CT extract was rich in phenols and flavonoids and has high antioxidant and anti- diabetic potential.	Adekola *et al.* (2017)
Dried CT; Variety: not specified (Country of origin: India)	Sequential extraction with 1. Petroleum benzene 2. Chloroform 3. Ethyl acetate 4. Methanol 5. Aqueous	Phytochemical screening, TPC, TFC, TTC, antioxidant assays; DPPH, ABTS, phosphomolybdate assay, metal chelating, RPA, CUPRAC assay, antimicrobial, anti-inflammatory assay	CT contains a wide range of phenolic and non-phenolic antioxidants and compounds with potent antimicrobial and anti-inflammatory properties.	Ojha et al. (2019)
Dried and defatted CT; Variety: West Coast Tall cultivar (Country of origin: India)	Acetone, acidified acetone, acetone 80 %, acidified acetone 80 %, ethanol, acidified ethanol, ethanol 80 %, acidified ethanol 80 %, methanol, acidified methanol, methanol 80 %, acidified methanol 80 %, water, acidified water.	TPC, TFC, analysis of flavonoid and phenolic acid profile and composition, antioxidant assays; DPPH, RPA, ABTS, CUPRAC assay	CT is rich in various phenolic acids and flavonoids with strong antioxidant activity. Hence, it has the potential to be a natural antioxidant source.	Arivalagan *et al.* (2018)
Wet CT, copra CT; Variety: not specified (Country of origin: India)	Extracted with hexane to separate the CTO	Fatty acid and triacylglycerols compositions, phenolic acid analysis, and phytosterols contents	CTO contained higher natural antioxidants and monounsaturated and polyunsaturated fatty acids compared to the coconut kernel oil	Appaiah *et al.* (2014)
Wet CT, copra testa, copra testa cake, wet coconut whole and copra whole; Variety: not specified (Country of origin: India)	Ethanol	Phytochemical screening, TPC, TFC, phenolic acid analysis, tocopherols and tocotrienols, antioxidant assays; DPPH, RPA	Wet CT extracts had higher phytochemicals and showed strong antioxidant activity compared to the other forms of CT extracts.	Appaiah *et al.* (2016)
CT; Variety: not specified (Country of origin: India)	Phenolic concentrates from CT	*In-vivo* analysis of high-fat-fed C57BL/6 mice. Parameters such as blood glucose, serum advanced glycation, serum glucose and lipid profile, atherogenic index, serum insulin contents, antioxidant enzyme activities and glucose tolerance were tested.	Phenolic concentrate of CT possesses hypolipidemic activities.	Kumar *et al.* (2021)
Dried CT; Variety: not specified (Country of origin: Malaysia)	Cold extraction with 70 % ethanol-water	The in-vivo anti-diabetic effect of CT extracts on streptozotocin-induced diabetic Sprague-Dawley rats. Fasting blood glucose levels and blood parameters (total protein, cholesterol, creatinine, urea, bilirubin, aspartate transaminase, and alanine transaminase) were tested.	CT possesses a strong potential to be used in anti-diabetic food applications.	Adekola & Marikkar (2022)
Nutritional composition and functional properties				
Defatted residue of Gon Thambili, Ran Thambili, San Raman, Tall × Tall and commercial hybrid (Country of origin: Sri Lanka)	Extraction of crude polysaccharide: CTF was defatted with hexane and extracted with hot water, followed by de-proteinization.	Degree of hydrolysis in artificial human gastric juice, prebiotic activity on *Lactobacillus* sp	Crude polysaccharides extracted from CTF exhibited promising prebiotic properties.	Gunarathne *et al.* (2024a)
Dried CT; Variety: not specified (Country of origin: Sri Lanka)	Grinding in a mixer to prepare creamed coconut testa	Proximate analysis: moisture, crude fat, crude proteins, ash, crude fiber and total carbohydrate contents	Creamed CT is a rich source of crude fibers and has the potential to be used as a substitute for coconut milk.	Kumari *et al.* (2024)
Defatted residue of Gon Thambili, Ran Thambili, San Raman, Tall × Tall and commercial hybrid (Country of origin: Sri Lanka)	CTF was used as it is for analysis	Proximate analysis: moisture, crude fat, crude proteins, ash and carbohydrate contents. Fatty acid and macro-mineral compositional analysis	CTF is a nutritious food source rich in macro and micronutrients	Marasinghe et al. (2019)
Defatted residue of Gon Thambili, Ran Thambili, San Raman, Tall × Tall and commercial hybrid (Country of origin: Sri Lanka)	CTF was used as it is for analysis	Physical and functional properties: particle size, bulk density, swelling capacity, water absorption capacity, emulsion activity, emulsion stability, foam capacity, foam stability, least gelation concentration	CTF possesses beneficial physical and functional properties, which could be useful in partial substitution of wheat flour in different food applications	Marasinghe et al. (2021)

Table 2
Macronutrient distribution of creamed coconut testa, defatted coconut testa, rice bran and wheat bran.

Macronutrient	Content (%, w/w)			
	Creamed coconut testa[a]	Defatted CT[b]	Rice bran[c]	Wheat bran[d]
Fat	65.63	7.93–23.49	12.03–18.68	4.25
Protein	8.11	23.82–32.22	12.04–15.20	15.60
Ash	1.54	3.70–5.30	6.19–10.50	5.79
Carbohydrate	23.89	42.55–59.24	48.46–58.00	64.50

[a] Kumari *et al.* (2024).
[b] Marasinghe *et al.* (2019).
[c] Wisetkomolmat *et al.* (2022).
[d] Li *et al.* (2023).

is predominantly an oil-rich material, it is generally subjected to oil extraction and the leftover residue is used as animal feed. In CTF, carbohydrates (42.55–59.24 %) were the most dominant component, followed by protein (23.82–32.22 %) and fat (7.93–23.49 %) (Marasinghe et al., 2019). This changing pattern is not a rare phenomenon, but a similar effect on proximate composition has been seen in defatting of the seed kernel of *Terminalia catappa* (Fahmidha et al., 2024).

3.2. Micro mineral distribution

Comparing mineral distribution in foodstuffs is important for many reasons. Although they are generally required in minute quantities, they play a vital role in the body's metabolic processes. As shown in Table 3, various studies on the micronutrient distribution of CT have been performed in many parts of the world. Both wet coconut testa and copra testa are rich sources of minerals such as K, Na, *Ca*, Fe, and Zn (Appiah *et al.*, 2014). K and Na were identified as the most abundant minerals in both types of testa. Between them, the amount of K was higher in copra testa (120.3 mg/100 g) than wet coconut testa (107.8 mg/100 g). In contrast to this, Na content in wet coconut testa was higher (29.8 mg/100 g) than that of copra testa (22.4 mg/100 g). In the case of CTF, Mn was the most prevalent mineral (73.71 - 94.1 mg/ kg), followed by Zn (29.65 to 57.34 mg/kg) and Cu (29.94 – 45.14 mg/kg) (Marasinghe et al., 2019). In addition, Marasinghe et al. (2019) also confirmed the presence of minerals including Ni, Zn, Cr, Co, Cu, Fe, Ba, and Mo in CTF. The changing pattern in mineral distribution could be due to the effect of defatting, or inter-varietal and geographical differences. According to some other studies, the whole coconut kernel was known to possess minerals such as Fe, Cu, Mn and Zn (Yalegama et al., 2013). Although the occurrence of toxic elements in food has been a major concern, toxic metals like cadmium and arsenic were rarely reported in CT.

Table 3
Mineral and phyto-constituents of coconut testa.

Category	Constituent	References
Minerals	Ni, Zn, Mn, Cr, Co, Cu, Fe, Ba, Mo, K, Na & Ca	Appaiah *et al.* (2014); Marasinghe *et al.* (2019)
Phenolic acids	Chlorogenic acid, gallic acid, cinnamic acid, caffeic acid, ferulic acid, hydroxybenzoic acid, vanillic acid, syringic acid, p-coumaric acid, protocatechuic acid, ellagic acid	Appaiah *et al.* (2016); Jamaluddin *et al.* (2016); Adekola *et al.* (2017); Razak *et al.* (2016); Geetha *et al.* (2016); Gunarathne *et al.* (2022a)
Flavonoids	Epigallocatechin gallate, catechin, epicatechin, epigallocatechin, quercetin, kaempferol, rutin, leteolin, apigenin, naringenin, hesperetin	Adekola *et al.* (2017); Arivalagan *et al.* (2018); Gunarathne *et al.* (2022a)
Other	Myristin, umbelliferone	Arivalagan *et al.* (2018)

3.3. Fatty acid distribution

Evaluation of fatty acid compositions has been done for several plant oils and fats. As shown in Table 3, a number of studies on fatty acid compositions of CT have been reported from many parts of the world. CT is generally found to possess saturated fatty acids (88.75 – 91.23 %) and unsaturated fatty acids (8.76 – 11.19 %). As a common feature in many studies, lauric acid was the dominant fatty acid (42.65 – 45.97 %), followed by myristic acid (19.69 – 21.46 %) and palmitic acid (9.42 – 10.24 %). According to Zhang et al. (2015), CTO consisted of lauric (42.28 %) as the predominant fatty acid, followed by myristic (18.99 %)- and palmitic (11.57 %) acids. In another study, Marikkar and Nasyrah (2012) observed that the proportion of fatty acids in CTO followed the order of lauric>myristic> palmitic acids. Despite this, some differences were observed in the proportional distribution of fatty acids in the oils of copra testa and wet-coconut testa; they took the order of lauric>myristic> oleic acids (Appaiah et al., 2014). Safety-wise, some fatty acids are known to be toxic or harmful to human health, especially when consumed in excess. Although CTO is composed of a greater portion of saturated fatty acids, they are mostly shorter- and medium-chain, which are relatively harmless and do not pose risks leading to cardiovascular disease. The commonly known undesirable fatty acid, like erucic acid, was rarely detected in CTO.

3.4. Food safety aspects

Enzymatic and non-enzymatic reactions are thought to be responsible for the browning phenomenon in most food systems. The majority of tropical fruits are susceptible to enzymatic browning, especially when exposed to atmospheric oxygen. This phenomenon is believed to occur due to the polyphenol oxidase activity in fruits such as apples, bananas and strawberries (Soliva-Fortuny and Martin-Belloso, 2003; Nicolas *et al.*, 1994). However, removal of CT from the coconut flesh hardly causes enzymatic browning. However, such information on the action of polyphenol oxidase in CT is scantily reported in the literature. The browning phenomenon might also possibly occur in CT as a result of non-enzymatic reactions, such as either the Maillard reaction or caramelization. As shown in Fig. 1, removal of CT by peeling off the flesh is required to disintegrate CT into medium-sized particles; disintegrated CT particles are usually wet and have a moisture content of 40 to 47 % and therefore dehydration by high temperature is required. This would usually lead to non-enzymatic reactions, such as either the Maillard reaction or caramelization. The Maillard reaction, as it occurs between amino acids and sugars, might lead to the formation of a pigment called melanoidins. In the intermediary step of the malanoidin reaction, the formation of acrylamide, which is a potential carcinogen, might be possible. On the other hand, caramelizations occurring in CT are essentially carbon-back and are nontoxic. However, it might negatively impact the visual appeal or cause losses in vitamin C content.

4. Biological activities of testa

4.1. Phyto-nutrients

Research studies on CT were not merely limited to macronutrients, but they went further to explore secondary metabolites. Table 1 shows the compilation of studies on phyto-nutrients in CT and the assessment of their biological activities by various research groups. Phytochemicals of CT generally include simple phenolics to polyphenols like flavonoids, anthocyanins, tannins, etc. (Gunarathne *et al.*, 2022a; Ojha et al., 2019; Arivalagan *et al.*, 2018; Jamaluddin *et al.*, 2016). The major constituents of CT are polyphenols and flavonoids, which act as anti-oxidative agents. These are generally considered safe for human consumption due to their ability to protect human cells against free radical-induced damage. To date, evidence for any adverse side effect of CT on the liver using *in vivo* animal models is rarely reported.

Profiling of phyto-nutrients is a crucial step in dietary assessments of food systems. Phyto-nutrient compositions of plant foods are generally found to vary based on factors like geographical origin, soil types, varietal differences, climatic conditions, etc. This holds true in the case of CT, as evidenced by variations reported across studies from different regions. The phyto-nutrient compositions of CT reported from countries such as India (Appaiah *et al.*, 2016), China (Zhang *et al.*, 2016), Malaysia (Adekola *et al.*, 2017), and Sri Lanka (Gunarathne et al., 2024b) bear witness to this. Nonetheless, these studies hardly paid any attention to food safety issues associated with CT. For instance, focusing on anti-nutrition factors is vitally important. Phytate and trypsin inhibitors are common anti-nutritional factors of concern in foods of plant origin. Phytate has long been known to bind with minerals such as zinc and interfere with its absorption (Balogun et al., 2019) while trypsin inhibitor is well recognized to reduce protein digestibility in the body.

Quantification of TPC is one of the important initiatives in the assessment of phyto-nutrients in plant foods. According to multiple reports, the occurrence of polyphenols would bring several beneficial effects on health and well-being. Adekola *et al.* (2017) reported the TPC of CT (TPC of CT was 44.61±0.56 mg GAE/g) using 70 % ethanolic as the medium of extraction. Nevertheless, the findings of Appaiah *et al.* (2014) indicated something different; in this report, TPC of wet CT was found to be a little higher (6.3 ± 0.3 g GAE/100 g) than that of dried CT (1.3 ± 0.1 g GAE/100 g). TPC of the methanolic extract of CT was found to be 16.36 mg GAE/g. Among the phytonutrients, gallic acid, chlorogenic acid, caffeic acid, ferulic acid, hydroxybenzoic acid, and cinnamic acid were found to emerge in dried CT, while constituents like vanillic and syringic acids were detected only in wet CT (Appaiah *et al.*, 2016). A reinvestigation carried out by the same authors previously indicated that vanillic acid was not present in wet CT (Appaiah *et al.*, 2014). A separate investigation reaffirmed that vanillic was absent in the phenolic concentrates of CT; nevertheless, p-coumaric and protocatechuic acids were shown to be present in the phenolic concentrate of CT (Geetha *et al.*, 2016). In contrast to these findings, p-coumaric acid was reported in both dried CT and wet CT, but was absent in dried CT, as stated previously by Appaiah *et al.* (2016).

Multiple reports indicated the influence of extracting media on the efficacy of phytochemical extraction (Table 1). The fact of the matter is that the polarity of solvents often found to affect the extractability of phyto-chemicals in CT (Arivalagan *et al.*, 2018; Gunarthne *et al.*, 2022). Particularly, the effect of acidification of the extracting media has already been seen on the changing distribution of TPC in CT extracts (Table 1). As per reports, the highest TPC was recovered by acidified 80 % acetone (167 ± 1.1 mg GAE/g of dry defatted testa sample), followed by acidified 80 % methanol (118 ± 4.9 mg GAE/g of dry defatted testa). Of the several solvent systems tested, the least TPC recovery was detected in acetone (Arivalagan *et al.*, 2018). The geographical origin of the sample is yet another factor influencing the TPC content of CT. An Indian study involving some Indian coconut varieties reported twelve flavonoids, including three flavan-3-ols (catechin, epicatechin, and epigallocatechin), three flavonols (myristin, quercetin, and kaempferol), one flavonol glycoside (rutin), two flavones (leteolin and apigenin), two flavanones (naringenin and hesperetin) and one coumarin derivative (umbelliferone). Nonetheless, a study conducted using a testa sample of Sri Lankan origin has indicated somewhat different results; the list of compounds included caffeic acid, vanillic acid, ellagic acid, chlorogenic acid, p-coumaric acid, quercetin, epigallocatechin gallate (EGCG), and rutin in all cultivars (Gunarathne et al., 2022a) (Table 1). Among the constituents, chlorogenic acid was the most predominant phenolic acid in all cultivars investigated. As a notable feature, compounds, namely, epicatechin and kaempferol, were not present in any of the five cultivars in this study. In contrast to the study reported from India, epigallocatechin gallate, chlorogenic and caffeic acids were detected as additional phenolic constituents in dried CT (Adekola *et al.*, 2017). Further search of scientific literature elaborated two other studies on phytochemical profiling in Malaysia by Jamaluddin *et al.* (2016) and Razak *et al.* (2016). As reported by Jamaluddin *et al.* (2016) and Razak *et al.* (2016), the TPC of CT was reported as 0.9 ± 0.06 mg GAE/g and 0.78 ± 0.12 mg GAE/g, respectively. Protocatechuic and hydroxybenzoic acids were detected in non-fermented CT (Jamaluddin *et al.*, 2016; Razak *et al.*, 2016). Other than these, vanillic and gallic acids were also found to be present in CT (Jamaluddin et al., 2016).

The estimates of TPC and TFC were also undertaken in the oil of CT as well; TPC contents of copra testa oil and wet CT oil were 1.9 ± 0.12 mg GAE/100 g and 0.5 ± 0.02 mg GAE/100 g, respectively (Appaiah *et al.*, 2014). According to Zhang *et al.* (2016), the TPC of the oil component of CT was 68 mg/g of the extract. Based on the results of the phytochemical profiling of this study, caffeic acid, ferulic acid, gallic acid, catechin, epicatechin and p-hydroxybenzoic acid were enlisted as phenolic constituents present in CT.

4.2. *Antioxidant properties*

The majority of the plant materials are known to exhibit antioxidant activities due to their secondary metabolites (Mahdi-Pour *et al.*, 2012). In the case of coconut, antioxidant activities exhibited by CT are due to various phytonutrients. Geetha et al. (2016) previously stated that the phenolic concentrate of CT has had strong antioxidant activity in terms of DPPH radical scavenging activity. This finding was reaffirmed in CT in terms of FRAP, DPPH and ABTS (Adekola et al., 2017). More recently, the existence of antioxidant activities of CT was found to stand true even on partially defatted CT (Gunarathne *et al.* 2022a). Significantly higher antioxidant activities were observed for the methanolic extracts of five local coconut cultivars (Table 1); the methanolic extract of the Gon Thambili cultivar exhibited the strongest antioxidant activity when compared to those of other cultivars. This finding is in agreement with previous findings reported by Marasinghe *et al.* (2020) (Table 1).

Several past investigations have dealt with the influences of processes on the anti-oxidative capacity of plant foods. Jamaluddin *et al.* (2016) observed that the DPPH radical scavenging activity and the ferric reducing power of CT were significantly ($p < 0.05$) increased when it was subjected to solid-state fermentation using *Monascus purpureus*. Separately, Razak *et al.* (2016) observed the effect of fungal solid-state fermentation on the antioxidant activity of CT extracts. Based on these two studies, fermentation of CT with a single culture of *Aspergillus oryzae* and *Rhizopus oligosporus* tended to increase the DPPH radical scavenging activity and the FRAP value of CT extracts.

Although investigations on the biological activities of CT as a whole are numerous, explorations on the antioxidant potential of CTO are limited. When compared to ordinary coconut oils, CTO has been shown to have higher tocopherol content and an increased level of phenolic constituents (Narayanakutty *et al.*, 2022). It should be noted that tocopherols are well-known for their protective action against peroxidation. According to some recent studies, CTO extracted by different methods varied in antioxidant capacity, as they have impacted TPC and TFC contents differently (Illengarathna et al., 2025). The DPPH radical scavenging activity of CTO was strongly influenced by the proportion of antioxidant extractability in terms of TPC. Based on the studies of Illengarathna et al. (2025), the TPC of CTO by dry process was found to be lower than that of wet-centrifuge methods. The results of the *in vitro* studies demonstrated its effectiveness in scavenging peroxide. Further analyses have revealed that the extracts of CTO were found to contain elevated levels of phenolic acids and flavonoids, highlighting the nutritional and pharmacological significance for applications (Narayanakutty *et al.*, 2022). According to Zhang *et al.* (2016), an estimated 49.81 ± 3.10 % hydrogen peroxide scavenging activity was detected in CTO at a concentration of 2.5 mg/mL. They noticed a slight increase in the scavenging activity of hydrogen peroxide with higher concentrations of CTO. Furthermore, a negative correlation was found between the oxidation of linoleic acid in CTO and the antioxidant capacity within the reaction time; they observed a drastic decline in the antioxidant activity from 56.82 % to 31.70 %, within the initial 80 min

(Zhang *et al.*, 2016).

4.3. Anti-microbial properties

Exploring anti-microbial activities of plant extracts has been a general focus among researchers engaged in phytochemical studies. This aspect is critically important due to the growing threat of anti-microbial resistance (AMR) and the potential of plants to provide new and effective anti-microbial agents. Ojha et al. (2019) investigated several anti-microbial activities of CT with reference to extracting media such as petroleum ether, chloroform, ethyl acetate, methanol and water (Table 1). It is interesting to note that the aqueous extract of CT had the highest anti-bacterial activity among all extracts, with a maximum zone of inhibition (17.33 ± 2.08 mm) against *S. aureus.* Concurrently, the methanol extract of CT had the highest anti-bacterial activity with a maximum zone of inhibition (17.66 ± 1.15 mm) against *E. coli.* In the case of anti-fungal activity, the methanolic extract of CT had the highest activity with a maximum zone of inhibition (24.66 ± 0.57 mm) against *C. albicans* (Ojha et al., 2019). When compared to other extracts, methanol, chloroform and petroleum ether extracts of CT were found to exert anti-microbial activity against the tested pathogens. The overall findings of this study revealed that the anti-microbial activity of CT is influenced by the solvent type used.

4.4. Anti-inflammatory properties

The anti-inflammatory activity of CT was scantily reported in the scientific literature. Nonetheless, exploring the anti-inflammatory activity of plant materials is crucial for identifying potential natural remedies for inflammation-related diseases. Ojha et al. (2019) evaluated the anti-inflammatory activity employing heat-induced hemolysis, hypotonic-induced hemolysis, and heat-induced albumin denaturation assays for different extracts of CT obtained with petroleum ether, chloroform, ethyl acetate, methanol and water. According to the outcome of the study, water extract of CT had the highest anti-inflammatory activity, followed by chloroform extract, which had the lowest EC_{50} values for all tested assays. The anti-inflammatory activity of CT was strongly dependent on the solvent type employed in the extraction process.

4.5. Prebiotic characteristics

The prebiotic properties of food materials are investigated as they can influence the colonic microbiota, giving beneficial effects on human gut health. Gunarathne *et al.* (2024a) recently assessed the prebiotic characteristics of crude polysaccharides isolated from defatted CT (CTF) of five locally grown cultivars. In fact, the crude polysaccharides isolated through the hot-water extraction of CTF were found to have β-glucan possessing β−1,4 glycosidic bonds. The occurrence of this peculiar bonding structure has been attributed to the crude polysaccharides of CTF, which display high resistance to hydrolysis in human stomach conditions (94 % - 97 % resistance). This was a favorable feature when considering CTF as an ingredient for the development of anti-diabetic foods. According to the findings of this study, the crude polysaccharides isolated from CTF were capable of stimulating *Lactobacillus* sp. probiotics to proliferate, which is a beneficial characteristic of functional foods.

4.6. Enzyme inhibitory activities

Pancreatic alpha-amylase and alpha-glucosidase are crucial digestive enzymes that are responsible for a spike in postprandial blood glucose. It is said that the partial inhibition of these enzymes might offer potential benefits to individuals with type 2 diabetes to control the postprandial spike in blood glucose (Tundis *et al.*, 2010). According to Adekola *et al.* (2017), CT extract at a concentration of 200 μg/mL was found to show 24.83 % inhibitory activity against alpha amylase. Based on a follow-up *in vivo* study, the extract of CT proved its anti-hyperglycaemic effect on Streptozotocin-induced diabetic rats (Adekola and Marikkar, 2022). This finding was reaffirmed by Gunarathne *et al.* (2022a), who observed the inhibitory effect of partially defatted CT on alpha-amylase and alpha-glucosidase. Methanol (MeOH) extracts of all cultivars were found to exhibit strong inhibitory activity against alpha-amylase, while hexane extracts exhibited relatively weaker activity, along with some of the ethyl acetate (EtOAc) extracts. Additionally, Gunarathne *et al.* (2024b) observed that all crude extracts from different cultivars exhibited inhibitory activity against alpha-glucosidase, with the strongest activity noticed in the hexane extract (IC_{50}: 8.38 ± 0.52 ppm).

Tyrosinase and elastase are identified as the enzymes primarily accountable for skin pigmentation and wrinkle formation in the human body, respectively. Scientists look into inhibitory activity against tyrosinase as the predominant strategy for discovering novel skin-lightening agents. Meanwhile, inhibiting elastase stands as a method to safeguard against skin aging (Razak *et al.*, 2016). Some studies were carried out to see the effect of solid-state fermentation of CT on tyrosinase and elastase inhibitory activity. Previously, Jamaluddin *et al.* (2016) noticed the high tyrosinase inhibitory potential of CT when subjected to solid-state fermentation (SSF) by *Monascus purpureus*. Likewise, the same researchers observed a significantly high inhibitory activity of CT against elastase when CT was subjected to solid-state fermentation by *Monascus purpureus*. The authors suggest that the biochemical alterations taking place throughout the fermentation process could be attributed to these biological activities. In a separate study, Razak *et al.* (2016) evaluated the effect of solid-state fermentation with a single culture of *Aspergillus oryzae* and *Rhizopus oligosporus* on the inhibitory activity against tyrosinase and elastase. Comparatively, the inhibitory activity of CT against tyrosinase gets increased after fermentation with *A. oryzae* (12.39±2.72 %), while no activity was detected for the sample fermented with R. *oligosporus.* In the case of elastase inhibitory activity, they didn't observe any activity for unfermented CT. However, a significant improvement in the elastase inhibitory potential was noticed after fermentation with *A. oryzae* (15.83 ±0.07 %), with no activity after fermentation with *R. oligosporus.*

5. Products of coconut testa

5.1. Testa oil and defatted oil cake

Owing to the growing demand for vegetable oils, much interest is currently being focused on the possibilities of exploiting newer and underutilized plant resources for the production of oils (Fahmidha et al., 2024; Raihana *et al.*, 2015). Coconut testa can be one of the potential novel sources of edible oil to strengthen the effort taken for food security, as it is found to be rich in oil (≈65 %) (Kumari et al., 2024). Nevertheless, CTO is undervalued in the oil trade and business as industrial-grade oil (Gunarathne et al., 2022b). This undervaluation of CTO may be attributed to myths prevailing in society suggesting its use is unfit for human consumption. For this, high acidity and toxic compounds like aflatoxins were attributed to the industry. Microbial growth in CT is the most probable factor due to delays, leading to the deterioration of the quality parameters of CTO. High acidity in CTO might occur if there are delays in processing the testa after its removal from the coconut flesh. If industries can take swift action to utilize CT immediately after its removal from the flesh, issues related to the quality deterioration of CTO can be eliminated. CTO can be produced by various methods. As illustrated in Fig. 1, the dry process might yield edible-grade oil and defatted residue. The use of the cold-press extraction method could help recover good-quality CTO and defatted oil cake.

The constituent fatty acids of CTO are somewhat different from those of ordinary coconut oils (Gunarathne et al., 2022b; Nasyrah and Marikkar, 2012). When compared to ordinary coconut oil (48.5 - 52.6 %), CTO used to possess a lower amount of lauric acid (35 - 40.9 %)

(Appaiah *et al.*, 2021), but slightly higher amounts of oleic and linoleic acids (Nasyrah and Marikkar, 2012). A similar pattern of fatty acid distribution was reported from two other studies by Zhang *et al.* (2016) and Ramesh et al. (2022). Previously, Appaiah *et al.* (2014) compared the fatty acid composition of CTO obtained from copra testa with that obtained from wet-coconut testa. When we compared the findings from various reports, the order of dominance of the fatty acid distribution was roughly similar, with lauric acid as the most dominant fatty acid, followed by myristic acid, but the third-highest fatty acid was oleic. As an additional feature, a wider difference was noticed in the proportions of lauric acid in copra testa (40.9 %) and wet-coconut testa (32.4 %) (Appaiah *et al.*, 2014). Ramesh et al. (2022) determined the fatty acid composition of CTO obtained from six Indian coconut genotypes, West Coast Tall (WCT), Federated Malay State Tall (FMST), Chowghat Orange Dwarf (COD), Malayan Yellow Dwarf (MYD), and Dwarf × Dwarf (*D* × *D*), Cameroon Red Dwarf (CRD) × Ganga Bondam Green Dwarf (GBGD) and MYD × Chowghat Green Dwarf (CGD). In conformity with previous reports, lauric acid (26.66–32.04 %) was the dominant fatty acid in CTO, followed by myristic (18.41–19.60 %) and palmitic (13.43–15.75 %) acids.

Apart from fatty acid composition, other physical properties of CTO were also important for quality assessment. Several physico-chemical properties of CTO obtained from six Indian coconut genotypes were found to display significant differences (Ramesh et al. 2022). With regard to the degree of unsaturation, the highest iodine value was noticed for COD (13.58 ± 0.37 g I_2/100 g). Among all six coconut genotypes, genotype FMST exhibited the highest saponification value (258.00 ± 1.00 mg KOH/ g). Based on a study conducted in Sri Lanka, the iodine value (IV) of CTO was found to range between ~15–18 g I_2/100 g (Marikkar and Nasyrah, 2012). The IV for CTO was somewhat different from that of ordinary coconut oils. Among the genotypes, the highest acid values were observed for COD and MYD × CGD (~0.93 mg KOH/g), denoting the higher degree of hydrolysis of oils, while the highest peroxide value was noticed for COD (~2.60 meq O_2/ kg), indicating the higher level of auto-oxidation.

Studies on the melting and crystallization behaviors of CTO would be beneficial for a variety of reasons. Frequently, differential scanning calorimetry (DSC) is employed to determine thermal transitions associated with various oils and fats (Marikkar, 2015). Although DSC has been extensively used for thermal property determination of a host of oils and fats, DSC thermal profiles of CTO have not been frequently reported. Compilation of DSC thermal curves of CTO obtained from different local coconut cultivars was a new initiative taken forward for the authentication of CTO (Gunarathne et al., 2022b). Based on the findings of this study, CTO is composed of a variety of triacylglycerols, which exhibit closely similar melting characteristics, causing them to melt or crystallize within a narrow temperature range. This could later on become a reference data set for investigations leading to the detection of adulterations in CTO. Despite apparent similarities in the pattern of the DSC curves of CTO of coconut cultivars, slight differences were noticed among them due to compositional differences. For instance, some close similarity in the DSC melting points of coconut cultivars, namely TT (24.6 $^{\circ}$C), SR (24.5 $^{\circ}$C) and COM (25.4 $^{\circ}$C) was evidently seen.

The de-fatted oil cake obtained after oil extraction was reported to have less than 15 % oil content (Marasinghe et al., 2019). As the texture of the residue of de-fatted oil cake was found to be crunchy, it facilitated grinding it into a powder form. The resulting coconut testa flour (CTF), however, might not be uniform in particle size distribution. Owing to this reason, it needs to be sieved using a sieve shaker in order to get it to a usable form (Marasinghe et al., 2021). As mentioned previously by Wang and Flores (2000), the particle size distribution of any flour is of particular concern because the particle size distribution would influence different physicochemical properties. The type of grinding machine used for the flour-making process would have some influence on the particle size distribution (Suntharalingam and Ravindran, 1993). This could probably be because the sieving process would be affected by flour constraints and sieve constraints, such as aperture opening, direction of movement of the sieve, sieve cloth, etc. Regarding flour attributes, particle size, bulk density, and water absorption capacity are three main determinants of non-cereal flours. The physical characteristics, along with the proximate composition of the flours, might have some influence on the quality indices and subsequent product formulation. Based on the findings of Marasinghe et al. (2021), no significant differences were detected in the particle size distribution of CTF produced from different coconut cultivars for particle size ranges of 63–150 μm and 150–297 μm, but a significant difference was noticed for the particle size range of 420–500 μm.

Water holding capacity (WHC) and oil holding capacity (OHC) of non-cereal flours are key performance characteristics in food applications. These two are significantly influenced by the composition of the flour, including fat and proteins. Based on the findings of Marasinghe et al. (2021), WHC of CTF flour of different coconut cultivars was found to range from 194.33 % to 320.00 %, with the highest and the lowest WHCs for San Raman and Ran Thambili cultivars, respectively. OHC, on the other hand, is the physical retention of oil, which is related to taste and texture. In fact, both of these are desirable properties for retaining the flavor and tenderness. Based on the findings of Marasinghe et al. (2021), OHC of CTF flour of different coconut cultivars was found to range from 85.67 % to 142.67 % with the highest and the lowest OHCs for Ran Thambili and Commercial Hybrid cultivars, respectively. The swelling capacity is the maximum volume a flour sample can occupy as a result of water absorption. According to a previous report, the swelling capacity of a flour is generally affected by particle size and processing methods (Chandra and Samsher, 2013). Based on the findings of Marasinghe et al. (2021), the swelling capacity of CTF flour of different coconut cultivars was found to range from 20.67 % to 35.00 % with the highest and the lowest swelling capacities for Ran Thambili and Commercial Hybrid cultivars, respectively.

5.2. Finished food products

Transformation of agro-byproducts into value-added products is trending globally as a part of sustainable agriculture (Marikkar and Musthafa, 2022). Although CT is an edible bio-product, it is not yet fully exploited as an ingredient for staple food preparations. Past studies indicated that approximately 6750 kg of CT can be generated by processing 100,000 nuts. This is actually indicative of a high wastage of CT as a by-product. Some initiatives were taken recently to maximize the potential of CT as a food ingredient. Converting CT into a cream is an initiative beneficial to the culinary preparation sector as a substitute for fresh coconut milk. Countries like Sri Lanka experience a significant surge in coconut prices in the local market due to various challenges, including a dry spell. Consequently, the cost of fresh coconut in the form of milk would escalate due to an imbalance in supply and demand. In fact, a lot of coconut wastage happens in Sri Lankan households due to the manual hand-squeezing of grated coconuts for milk production. When CT is converted into a cream, it can be diluted to use as a medium for cooking in place of coconut milk. Some recent reports indicated that CT cream can be diluted into a nine ratio (CT: water=1:9) to become an acceptable form of medium in the preparation of a potato curry (Kumari *et al.*, 2024).

Utilization of the defatted residue of CT could be a beneficial way to maximize the waste by-product. The most attractive feature of the defatted residue of CT is its high content of soluble and insoluble fibre. CTF might have a fair amount of non-digestible carbohydrates, such as dietary fiber, based on the report by Rushdah *et al.* (2022). Analysis of 100 g of CTF flour yielded the total dietary fibre content of 68.74–72.87 %, out of which the insoluble dietary fibre content was 53.18–55.85 % while the soluble dietary fibre content was 13.65–18.05 % (Rushdah *et al.*, 2022). Based on this compositional distribution, CTF is found to possess good water-holding capacity, a feature that helps ease bowel movement and overcome constipation among adults. Generally, drugs that are heavy in nature would cause the human stools to become dry and harder, leading to constipation. Increased intake of water, adapting to physical exercises, and consuming fiber-rich foods are sometimes recommended to avert constipation.

A number of initiatives were continued to incorporate defatted CT into wheat flour, which can bring benefits to the coconut sector. For instance, CTF was incorporated with wheat to formulate fibre-rich cookies (Marikkar et al., 2020) and staple food formulations (Rushdah *et al.*, 2022). These suggested its suitability in formulating low-calorie snacks and breakfast foods for diabetes patients. According to Marikkar *et al.* (2020), substituting WF up to 30 % of CTF will not compromise the overall acceptability of the cookies. When the substitution of CTF level increased, the fiber and protein contents of the cookies also increased. Nonetheless, the hardness of cookies tended to decrease owing to the decline in amylose content. Some effort was also made to see the effect of incorporating CTF into string hopper formulations by mixing CTF with white rice flour (RF) in four different ratios (15 %, 20 %, 25 % and 30 %) (Rushdah *et al.*, 2022). This research study also investigated the flat-bread (rotti) formulations by mixing CTF with wheat flour (WF) in four different ratios (10 %, 20 %, 30 % and 40 %). Based on the sensory evaluation, the best overall acceptability and other sensory attributes were attained for composite flour mixtures containing 25 % CTF in rice flour for string hoppers (idiyappa) and 20 % CTF in wheat flour for flat-bread (rotti) (Rushdah et al., 2022). Subsequently, Pathirana *et al.* (2023) re-assessed the consumer acceptance of three roti samples prepared by incorporating CTF into WF in different ratios (10 %, 20 % and 30 %). Based on the findings of this study, CTF can be incorporated into CTF up to 20 % to enhance the nutritional value of roti, without causing undesirable textural changes.

6. Future perspectives

CT has been a valuable agro-bio material that holds significant potential for novel product development in the food, nutraceutical, and cosmetic sectors. Owing to its rich nutritional composition, CT flour is a promising alternative to wheat flour. This review highlights the incorporation of CT flour in various food preparations, demonstrating its wide applications and its ability to enhance the nutritional profile of foods. CT can also be incorporated into the development of various nutrient-dense, gluten-free food products. In line with emerging health trends, CT offers opportunities for creating products tailored to specific consumer needs, such as gluten-free formulations, energy bars, and fiber-rich foods.

An array of phyto-nutrients, including phenolic acids, flavonoids, anthocyanins, sterols, terpenoids, steroids and alkaloids, etc., have been discovered in CT by various research groups. The phenolic acids and flavonoids present in CT are nontoxic but display potent antioxidant capacity. The brown colour of the CT is probably due to some pigments or phytochemical constituents, which are not harmful. Oil extracted from CT might contain more natural antioxidants, which might aid in better health benefits. Hence, CT demonstrates strong potential as a functional ingredient for health promotion, particularly through its application in the development of supplements and nutraceuticals. Nonetheless, some knowledge gaps pertaining to CT still prevail, which calls for further research to support this aspect. Furthermore, the bioactivities of CT, including tyrosinase and elastase inhibition, underscore its potential applications in the cosmetic industry, particularly as an anti-aging and skin-lightening agent.

Despite its great potential for innovation, existing knowledge gaps and technological barriers continue to hinder the industrial uptake of CT. Generally, fruit ripening is marked by a sharp rise in both respiration rate and ethylene release. Nevertheless, very little is known about the physiological changes taking place in CT along the ripening process, particularly if CT is affected by the said metabolic processes. In contrast to climacteric fruits, the fruit ripening process in the coconut would not cause softening of the CT or coconut flesh. The tissues of CT are matured by metabolic processes, including respiration, during the time the coconut is still in the bunch, prior to harvest. There is hardly any information on whether these metabolic processes are terminated once the coconut fruit is harvested. Other than this, experimental data on the physiological changes taking place in CT during postharvest storage are rare. In addition, organic acids and volatile compounds in the CT also might have undergone considerable changes during the progressive growth of the coconut or in the ripening stage. Information on the type of changes taking place in CT is also rare due to compositional changes in sugars during the different stages of maturity. On the other hand, as a by-product of the coconut industry, delays in processing CT can promote microbial growth and lipid oxidation, leading to quality deterioration and loss of bioactivities. The effect of drying on CT remains poorly understood. As drying can alter the phytochemical profile and thereby influence its bioactivities, establishinhg a standardized drying protocol is essential. Therefore, studies to optimize proper drying conditions are needed. The classification of protein types dominating in CT, along with amino acid profiling, will need further investigation. In this regard, research could employ protein separation methods if we are interested in developing any protein concentrates. Investigation of anti-nutritional factors is of great concern in most plant foods. It is also worthwhile to pay some attention to these aspects. Although explorations on macro and micro minerals have already been done, investigations regarding vitamins in CT are scanty, whether they are water-soluble or organic solvent-soluble. Comparative analysis of the rate of hydrolysis of CTF and wheat flour is worthwhile in understanding the occurrence of resistant starches. Further studies addressing these aspects are essential to fill existing knowledge gaps and support the establishment of standardized extraction and preparation protocols for CT flour and oil. Such advancements would help overcome current barriers to its industrial application.

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Data availability

Data will be made available on request.

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