

REVIEW

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Nutritional composition and bioactive properties of tropical coconut palm fruit with functional food applications

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Abstract

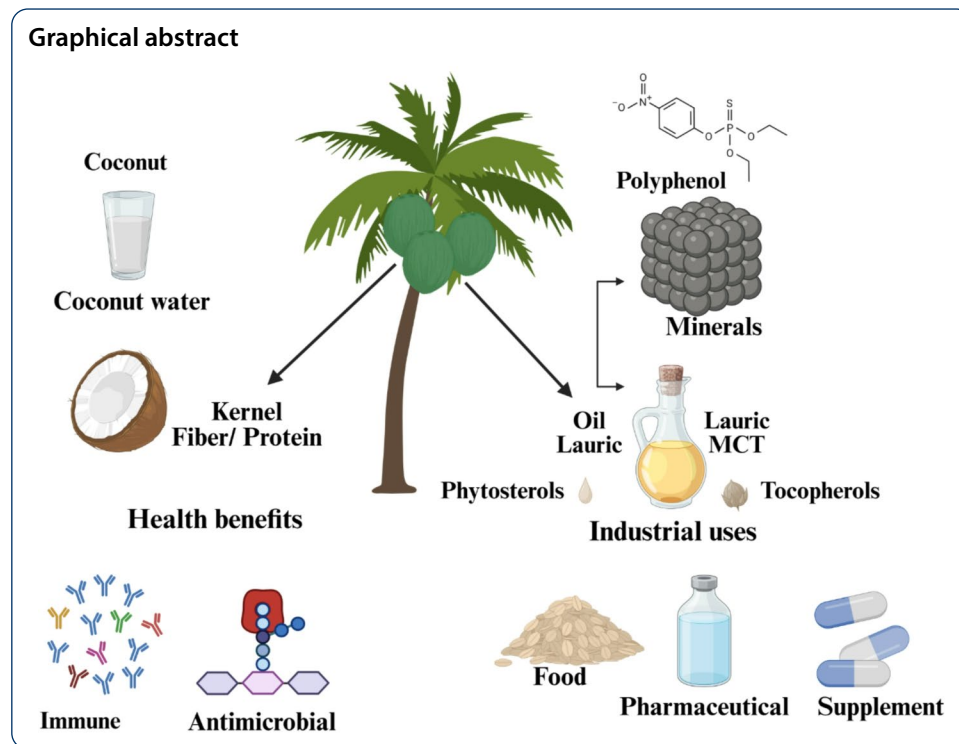
Coconut palm (*Cocos nucifera* L.) is a versatile fruit crop recognised for its diverse nutritional and bioactive compounds found in its kernel, water, and byproducts. Despite its potential, coconut fruit remains underutilized in functional food and biopharmaceutical development. This review critically examines the nutritional composition and bioactive properties of coconut fruit and its main components (water, kernel, oil), focusing on their applications. It synthesizes recent findings on coconut derived nutrients, highlighting phytochemical diversity across different parts, and includes a comparative analysis with other functional fruits and an overview of traditional and contemporary uses. Coconuts are rich in polyphenols, mineral, protein, dietary fiber, and medium -chain fatty acids (e.g., lauric acid), contributing to a wide range of biological activities, including immune boosting and cardioprotective effects. Additional phytochemicals like phytosterols, tocopherols, and alkaloids further enhance its bioactivity. The review documents the increasing scientific focus on coconut water, kernel, and virgin coconut oil in food, health and biopharmaceutical industries. By integrating current evidence on its nutritional and therapeutic potential, this review aims to stimulate further research, promote broader utilization, and support the commercialization of coconut based products to meet consumer demand for natural, health promoting foods.

Highlights

- Coconut fruit offers significant nutritional and bioactive potential for functional food and health.
- This review synthesizes the composition, bioactivities, and health benefits of coconut water, kernel, and virgin coconut oil.
- Coconuts are rich in polyphenols, fatty acids, fiber, vitamins, and minerals, providing antioxidant, anti-inflammatory, and cardioprotective effects.
- Comparative analysis and document traditional/moderns use underscore coconut's value as a nutraceutical resource.
- The review identifies key knowledge gaps and future research directions for broader coconut product utilization.

Keywords Bioactive compounds, Functional foods, Nutritional properties, Virgin coconut oil





1 Introduction

Fruits are essential for global well-being, valued for their nutritional content and bioactive constituents [1, 2]. Their significance in promoting public health is undeniable, especially with increasing global demand for health enhancing foods [3]. This demand has spurred extensive research into the bioactivity and nutraceutical properties of various fruits. Studies revealed a positive correlation between fruit intake and reduced mortality from chronic illnesses [4]. Researchers attributed these benefits to their rich composition of vitamins, minerals, enzymes, amino acids, and other beneficial compounds [5].

The coconut fruit is a vital crop commercially grown in Asia, South America, Africa, and the Neotropical islands in the Atlantic Ocean (Fig. 1) [6]. In 2020, global per capita coconut consumption reached 3.01 kg, with Sri Lanka (60.9 kg), Comoros (58.8 kg), and Papua New Guinea (45.7 kg) leading consumption. This high demand underscores the importance of coconuts as dietary staples in tropical regions and highlights their potential as versatile ingredients for global health and economic growth [7]. These three countries significantly exceeded the global average, highlighting their strong cultural and dietary preferences for coconuts compared to the rest of the world. Climatic factors such as temperature, rainfall (precipitation), wind direction, land shape, cloud cover, and humidity significantly influence the development and growth of coconut species [8]. These variables alter the crop's behavior, phenology, physiology, and ecological interactions, leading to faster-than expected impacts on production [9].

Coconut palms distinguish themselves from other palm species through their exceptional stability in flowering and fruit production, which they sustain over several months, years, and even decades. Coconuts play a crucial role in agrarian communities, where agriculture is the primary source of livelihood and economic activity [10]. They offer a dual benefit by providing affordable dietary options and energy sources, which

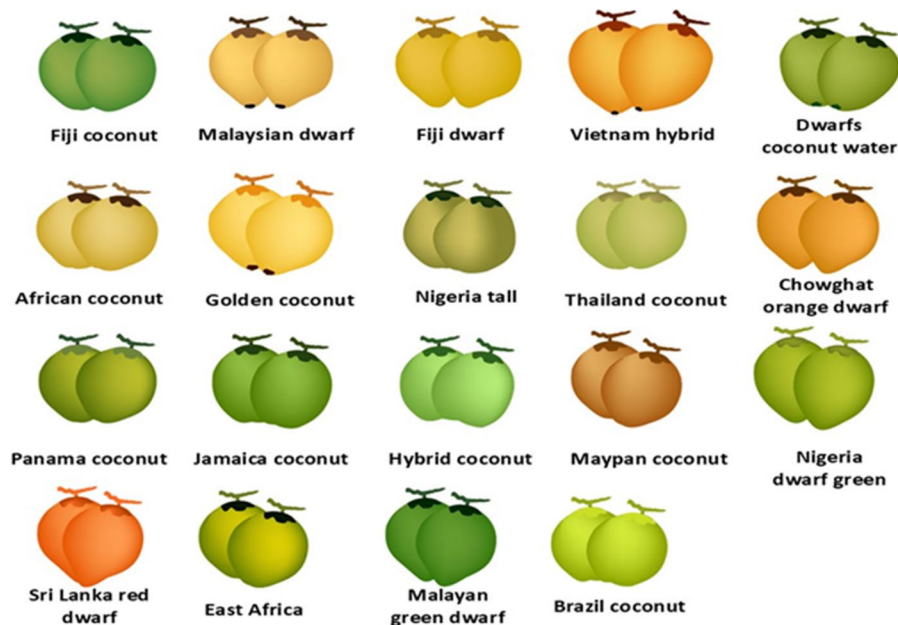


Fig. 1 Varieties of *Cocos nucifera* L. (coconut) fruit

contributes to the growth of local economies, enhances food security, and promotes sustainability [11]. Coconuts promote healthy living by providing essential natural nutrients and micronutrients [12]. They are rich in polyphenolic components, including protocatechuic acid, 4-hydroxybenzoic acid, tocopherol, caffeic acid, catechin, ferulic acid, quercetin, epicatechin, rutin, and myricetin [13]. These bioactive phenolic constituents have demonstrated a broad spectrum of beneficial properties, encompassing antitumor, antibacterial, anti-inflammatory, antioxidant, antiviral, antifungal, and analgesic effects [14].

Beyond polyphenols, *Cocos nucifera* contains natural functional dietary fibers such as glucomannans, lignin, hemicellulose, galactomannans, cellulose, and uronic acid [15, 16]. The diverse microflora in the human large intestine metabolizes these fibers, producing significant amounts of short-chain fatty acids (SCFAs), mainly propionate, acetate, and butyrate. These SCFAs play a pivotal role in modulating serum cholesterol levels, contributing to the potential therapeutic benefits associated with *Cocos nucifera* consumption [15].

A bibliometric analysis on lens.org reveals that between 2015 and 2024, a total of 620 peer-reviewed scholarly works were published on coconut fruit and its bioactive compounds (Fig. 2A). Among these, coconut water was the most popular subject, followed by studies on coconut kernel and virgin coconut oil (VCO) (Fig. 2B). Research on coconut components predominantly originates from the disciplines of Food Science, Biology, and Chemistry (Fig. 2C), with significant contributions from researchers in India, Brazil, China, United States, Malaysia, Turkey, Egypt, Iran, France, Mexico, Italy, Indonesia, and Nigeria (Fig. 2D). Many of these publications focused on the bioactive constituents present in coconut water, VCO, and kernel (meat), with particular emphasis on medium-chain fatty acids (MCFAs), especially lauric acid, as well as phenolic compounds and phytosterols [14, 17]. Recent reviews, such as Chen et al. [18], have provided comprehensive examinations of coconut protein, while earlier works (e.g., Yong et al. [19]) have focused on coconut water and oil, respectively.

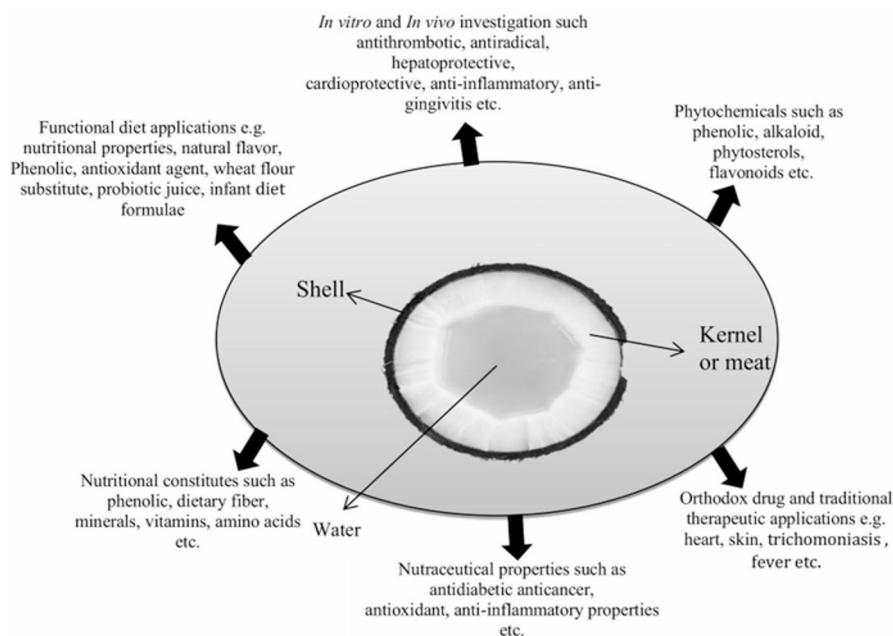


Fig. 3 . Multifunctional benefits of coconut components in nutrition, health, and therapeutics uses

ranged from 59.5 to 527 $\mu\text{g}/100\text{ ml}$ and in MYD from 135 to 694 $\mu\text{g}/100\text{ ml}$ [23]. Other reported CW sugar contents include cellobiose (1.08 mg/100 ml), xylose (0.15 mg/100 ml), sucrose (0.96 mg/100 ml), fructose (1.20 mg/100 ml), and glucose (1.20 mg/100 ml) [24]. Coconut sugar offers nutritional advantages over other common sugars due to its lower glycemic index and trace minerals. While sorbitol enhances starch digestibility when blended with wheat flour, palm and coconut sugars show comparable, slightly lower digestibility [25]. Coconut sugar is notable for its nutrient content, including essential elements like potassium, calcium, zinc, and iron, and vitamins B1, B2, B3, and B6. It also contains short-chain fatty acids, polyphenols, and antioxidants, potentially offering anti-diabetic, antioxidant, and cardioprotective benefits [26, 27].

Coconut cultivation spans diverse countries, each contributing unique varieties to the global gene pool (Table 1). For example, Malaysia cultivates Malayan Tall and various Malayan Dwarf types, while India grows Bengal Tall and Gangabondam Green Dwarf. This varietal diversity highlights the agricultural richness and cultural significance of coconuts, with each variety offering distinct flavors, textures, and uses for culinary, industrial, and traditional applications. Coconut farming plays a pivotal role in sustaining livelihoods and local economies. The sugar and amino acid (AA) content of CW varies significantly with the maturity stage and variety of *Cocos nucifera* [35, 36]. CW is a rich source of essential AAs, contributing to its nutritional value. Saker et al. [35] detected and quantified thirteen free AAs in CW. These AAs enhance flavor and serve as precursors for flavor molecules. Cystine, arginine, serine, and alanine levels in CW are higher than those in cow's milk [35, 36]. Six-to-eight-month-old CW showed higher levels ($>0.052\text{ g}/100\text{ ml}$) of serine, glutamic acid, histidine, and valine compared to four-month-old CW.

Shen et al. [37] analyzed CW from 8-month-old national coconut germplasm nursery, identifying 13 amino acids as differential metabolites, suggesting potential amino

Table 1 Location and varieties of some coconut fruits

Origin	Coconut varieties	References
Malaysia	Malayan tall; Malayan Dwarf (Red, Green, Yellow, Orange, golden) × Rennell tall × West African tall (PB121+); Malayan dwarf	[20, 28]
Nigeria	Nigeria Tall, Nigeria Dwarf Green, Nigeria Tall, Nigeria Dwarf Green	[29]
Côte d'Ivoire	West African tall; West African dwarf	[28]; [30]
Equatorial Guinea	Equatorial Guinea Green Dwarf; East Africa tall; West African tall	[31]
Cameroon	Cameroon Red dwarf; West African tall; East African tall	[32]
Vietnam	Ta; dau; Sap; Ta ben luc; Tarn Quan; Eo; Xiem	[32]
Brazil	Green coconut; Green dwarf Brazil, Brazil tall coconut	[32]
Thailand	Mu si sum; Pathiu; Thung Kled; Nam Horn; Nali-ke; Nok Koom; Kalok; Toddy; Maphaeo; Thalai Roi; Chumphon; Pak Chok; Tap Sakae	[28]
Indonesia	Nias yellow & green dwarf; Bali yellow & green dwarf; Jombang yellow & green dwarf; Sagerat orange dwarf; Raja dwarf; Bali tall; Tenga tall; Beji tall; Lubuk Pakam tall, Palu tall; Wusa tall; Sea tall Sawama tall; Jepara tall, Wulung, Kebumen Entog Dwarf	[20, 33]
India	Arsikere tall; Nylor gading, Bengal tall; Mysore tall; Gon thembili; Gangabondam green dwarf; Spicata; Navasi; Bombay tall; West coast tall; Chowgat orange dwarf; Chitta Gangapani dwarf; Uddha; Kenthali orange dwarf Gangapani Semitall; Chowgat green dwarf	[28]
Sri Lanka	Yellow dwarf; Red dwarf; Green dwarf; Brown dwarf; Rathran thembili; Nawasi thembili; Dikiri; Bodiri; Kamandala; Ran thembili; Pora Pol; Nawasi Gon thembili; Sri lanka tall	[34]
Philippines	Hijo tall; San Ramon tall; Orange dwarf; Green dwarf; Baybay tall; Zamboanga; Tagnanan	[32]

acid biosynthesis during storage. Proteinaceous amino acids like L-phenylalanine, L-histidine, L-methionine, L-asparagine, L-threonine, L-serine, and L-proline were upregulated in samples stored for 35 days compared to fresh samples. Another study reported arginine content in CW from fresh aromatic coconuts (3.14 mg/100 ml), fresh ripe coconuts (2.02 mg/100 ml), and canned CW (1.85 mg/100 ml) [38]. Both tall and aromatic coconut varieties contain arginine. Yong et al. [19] identified the non-proteinogenic amino acid gamma-aminobutyric acid in CW, along with trace amounts of histidine, pipercolic acid, dihydroxyphenylalanine, and hydroxyproline [39].

CW contains higher concentrations of mineral elements like magnesium (Mg) and potassium (K) than extracellular fluids (ECF), making CW an excellent electrolyte source. Calcium (Ca) concentrations in CW are also slightly elevated compared to ECF levels. A study on fresh tender CW (6–7 months maturity) found potassium at 2163 µg/ml, sodium at 302.3 µg/ml, and calcium at 117 µg/100 ml [40]. Coulibaly et al. [41] noted differences in calcium and phosphorus concentrations among CW from street markets (CWS), tree dwarf (CWD), and tree tall (CWT) varieties. Potassium ion (K⁺) content in young CW from Kebumen Entog Dwarf and Nias Yellow Dwarf varieties varies with maturation [42]. Hikmawandari and Ratman [43] reported potassium contents of 162 µg/ml and 154 µg/ml, respectively. The phytochemical profile of CW changes with maturity, with potassium levels decreasing as the fruit ripens. CW also contains various vitamins, including pyridoxine (B6), niacin (B3), pantothenic acid (B5), riboflavin (B2), thiamin (B1), biotin, folate, and nicotinic acid, all present in varying concentrations [44]. These vitamins are crucial for energy metabolism, red blood cell formation, and nervous system development. Additionally, CW provides vitamins C and E, which serve as essential dietary antioxidants [45]. The nutritional composition of CW, mainly its high mineral and vitamin content, suggests potential health benefits. Regular consumption

of CW by nursing mothers may help meet the calcium requirements of their infants, potentially preventing nutritional rickets [20]. However, vitamin C levels in CW can vary depending on fruit maturity and harvest location.

Coconut kernel, commonly called coconut meat, is the edible portion of the *Cocos nucifera* fruit. This meat has high market value and is rich in coconut oil (CO), widely used in baking, cream production, coconut milk, and cooking [45]. On a dry basis, coconut meat (CM) consists of approximately 4.08% protein, 37.3% fat, 11.3% carbohydrates, 1.03% ash, and 3.4% crude fiber [46]. In contrast, unripe coconut meat has reported compositions of about 0.6% ash, 6.3% carbohydrates, 1.4% fat, and 0.9% protein per wet mass [47]. Variations in the nutritional composition of different coconut varieties can be attributed to factors such as cultivation practices, harvesting periods, source, and fertilizer type [48]. CM is a rich source of mineral nutrients, including potassium (98 µg/ml), sodium (18.82 µg/ml), calcium (2.74 µg/ml), magnesium (10.30 µg/ml), and zinc (1.07 µg/ml) [47]. It also contains trace amounts of iron, crucial for human nutrition as a component of myoglobin, hemoglobin, and enzymes, supporting healthy blood and overall vitality [49]. Total phenolic compounds (TPC) in CM range from 6.28 to 10.01 mg GAE/100 g [50]. Appaiah et al. [45] found fresh CM contained polyphenols ranging from 18.5 to 24.8 mg GAE/100 g, along with amino acids, minerals, and tocopherols. Major phenolic acids identified in CM include p-coumaric acid, caffeic acid, gallic acid, and salicylic acid. Observed variations in phenolic content may result from differences in coconut maturity or varietal distinctions.

During early maturation (up to 190 days after pollination), phenolic compound synthesis increases due to the plant's natural defense mechanisms. However, at 225 days after pollination, antioxidant capacity and TPC decline, possibly due to shifts in metabolic priorities or enzymatic activities. CM exhibited higher antioxidant activities and TPC than CW [50], highlighting its potential nutritional and antioxidant benefits.

Coconut milk, a white oil in water emulsion extracted from CM, is a notable ingredient in food processing [51, 52]. The extraction method involves grating fresh coconut flesh, steeping it in boiled water, and filtering the mixture. It is known by various names globally, such as "wara agbon" (Nigeria), "gata" (Philippines), and "santan" (Indonesia and Malaysia). Its composition primarily includes water (50%), fat (23.8%), protein (2.3%), and carbohydrates (6%) [53]. A detailed analysis reveals approximately 0.7 g ash, 23.8 g fat, 2.9 g protein, 2.2 g dietary fiber, 5.5 g carbohydrates, and 2.3 g sucrose per 100 g, providing 230 kcal [54]. Coconut milk is rich in essential minerals: calcium (16 mg/100 g), sodium (15 mg/100 g), phosphorus (100 mg/100 g), potassium (263 mg/100 g), and magnesium (37 mg/100 g) [55]. Trace minerals like manganese (2330 mg/l), iron (149 mg/l), zinc (71 mg/l), and copper (2.5 mg/l) are also present [54]. The milk also contains substantial amounts of vitamins C and E, known for their antioxidant properties [56]. These vitamins and antioxidants contribute to detoxification, promoting kidney and liver health [57]. Notably, coconut milk, extracted from mature coconut flesh, has higher antioxidant potential than soy and cow's milk [51]. A distinctive feature is its high proportion of medium-chain saturated fatty acids (SFAs), which can act as monolaurin, an antibacterial and antiviral agent supporting overall health and heart well-being [58].

Coconut oil (CO) is characterized by high SFA content, with lauric acid (45–52%) being predominant, followed by caprylic acid (5–10%), stearic acid (2–4%), capric acid (4–8%), palmitic acid (7.5–10.2%), and myristic acid (16.8–21%). Trace amounts of

palmitoleic acid are also present. Unsaturated fatty acids include linolenic acid (0–0.2%), linoleic acid (1–3%), and oleic acid (5–10%) [59, 60]. Gas chromatography consistently identifies lauric acid as the primary SFA across cultivars, with myristic acid as the second most abundant [59–62]. Arachidic and butyric acids also contribute to CO's complex fatty acid profile [63, 64].

CO's SFA content has led to its classification alongside palm oil, butter, and other animal fats, which nutritional guidelines generally recommend limiting [19, 65]. However, CO's unique composition, particularly its high lauric acid content, has generated significant interest for its nutritional benefits and oxidative stability [66, 67]. Lauric acid, the predominant fatty acid, converts to monolaurin in the body, a bioactive compound with notable antiviral and antibacterial actions [66, 67]. Monolaurin has shown inhibitory effects against various pathogens and may decrease triglyceride and cholesterol levels, potentially lowering cardiovascular disease risk [68]. Despite concerns about its high saturated fat content, recent research explores the potential benefits of SFA-rich dietary oils, including CO, in preventing inflammatory and thrombotic conditions [69]. However, CO's impact on cardiovascular health remains debated [70]. CO's unique fatty acid profile, especially its high lauric acid content, offers potential health benefits, but its high saturated fat content requires careful dietary consideration. In-depth studies are needed to fully elucidate CO's complex effects on human health and establish evidence-based dietary guidelines. Future research should focus on comprehensive genetic, nutritional, and functional profiling of coconut varieties; standardization and documentation; addressing variability; exploring underutilized resources; evaluating socioeconomic and sustainability aspects; and expanding biotechnological and industrial applications. This will provide a stronger scientific basis for the conservation, improvement, and utilization of coconut diversity worldwide.

2.2 Dietary fiber content

Beyond its rich profile of polyphenols, *Cocos nucifera*, is also a significant source of natural functional dietary fiber (DF). This include glucomannans, lignin, hemicellulose, galactomannans, cellulose and uronic acid [15, 16]. These diverse fiber play a crucial role in gut health. They are metabolized by the varied microflora in the human large intestine, leading to the production of significant amounts of short chain fatty acids (SCFAs) The primary SCFAs produced are propionate, acetate, and butyrate. These SCFAs are pivotal in modulating serum cholesterol levels, thereby contributing to the potential therapeutic benefits associated with *Cocos nucifera* consumption [15]. The presence of these functional fibers underscores coconut's role not only as a source of essential nutrients but also as a contributor to gut health and systemic metabolic regulation.

2.3 Phytochemical contents of coconut fruits

Phytochemicals are bioactive compounds found in fruits and plants that have a variety of physiological effects, and some offer therapeutic value when consumed as part of a daily diet or used as medicinal agents [71]. Researchers identified a diverse array of bioactive constituents in coconuts, including carotenoids, polyphenols (primarily tannins, flavonoids and phenolic compounds), and sterols, each present in varying quantities [72]. For instance, an analysis of polyphenolic compounds in CW samples revealed that those from coconut tree dwarf varieties contained higher levels of total flavonoids and

phenols compared to coconut tree tall and coconut water street samples. Specifically, the total flavonoid content was measured at $0.381 \pm 0.010 \mu\text{g/mL}$ QE, while the total phenol (TPC) was $0.177 \pm 0.001 \mu\text{g/mL}$ GAE [41]. Recent studies have further elucidated the phytochemical profile of coconut and its various components. For example, an investigation of coconut cotyledons identified cardiac glycosides as the primary secondary metabolite; methanol extracts showing higher yields of total phenolic content ($30.35 \pm 0.94 \text{ mg TAE/g dw}$) compared to chloroform extracts [73]. The total alkaloid fraction was also higher in chloroform extracts ($19.7 \pm 0.32 \text{ mg CE/g dw}$) than in methanol extracts [73]. The phenolic composition of CO has also been a subject of recent studies.

2.3.1 Factors influencing phytochemical composition

Several key factors significantly influenced the concentration and proportion of phytochemicals in coconuts, including the fruit's maturity stage, specific coconut variety, harvesting time, and the geographic region of cultivation [74]. These intrinsic and extrinsic factors contribute to the observed variability in the phytochemical profile across different coconut products. Furthermore, the choice of extraction methods and subsequent processing techniques critically determines the yield and composition of various bioactive compounds. Studies consistently show that the solvent used and the extraction parameters (e.g., heat percolation vs. cold percolation) can significantly impact the recovery of phenolic compounds, alkaloids, and other phytochemicals [17, 48, 50, 57, 73, 75].

91, 109]. For instance, the total phenolic content (TPC) in coconut oil can vary considerably based on whether wet or dry extraction methods are employed [17]. Similarly, the yield of total alkaloid content is dependent on the specific extraction parameters [73]. These observations underscore the importance of optimizing and standardizing extraction and analysis protocols to ensure accurate comparisons and to maximize the recovery of beneficial compounds for research and industrial applications [75].

2.3.2 Phenolic compounds

Phenolic compounds, comprising both non-flavonoids and flavonoids, significantly contribute to the antiradical properties of coconuts [76]. Researchers categorize Flavonoids into subclasses such as anthocyanidins, flavonols, and flavones, while they classified phenolic acids as hydroxybenzoic and hydroxycinnamic acid derivatives [77]. Scientists identified a diverse array of phenolic constituents in coconuts, encompassing gallic acid, m-coumaric acid, salicylic acid, catechin acid, and p-coumaric acid. The presence of these polyphenolic compounds associates with various physiological effects, including anti-inflammatory, antibacterial, antiradical, chemoprotective, and anti-hepatosteatotic properties [77].

Researchers investigate soluble phenolic compounds, including flavonols, hydroxycinnamates, and hydroxybenzoate, have been investigated in the coconut fruit testa [57]. They observed additional compounds such as syringic acid, epigallocatechin, caffeic acid, p-hydroxybenzoic acid, epicatechin, and ferulic acid in coconut fruit oil [50]. The coconut fruit husk reportedly contain approximately 492.2 mg of catechin equivalent per gram of condensed tannins, also known as proanthocyanidins [78]. A recent study analyzed the phenolic profiles of three types of coconut milk (domestic, liquid, and powdered), revealing that the phenolic substances across these three preparations were

present in similar quantities [51]. This finding suggests a consistent phenolic composition across different coconut milk products, despite variations in processing methods. Additional investigations are warranted to elucidate the specific roles of individual phenolic constituent in coconut and their potential health benefits.

2.3.3 Alkaloids

Alkaloids, a significant class of naturally occurring nitrogen-containing organic compounds, most of which are derived from amino acids, are present in the coconut cotyledon [73, 79]. These phytochemicals demonstrate potential in treating intestinal inflammatory disorders through their antioxidant properties. Researchers typically classify alkaloids based on their carbon skeletons [80], biochemical precursors, or the plant families from which they are derived. Common alkaloid classes include pyridines, pyrrolidines, pyrrolizidines, tropanes, isoquinolines, indoles, and quinolones [81]. A recent study investigated the alkaloid content in coconut cotyledons using both cold and hot percolation methods. The results revealed that the total alkaloid content varied depending on the solvent and extraction method employed. In chloroform extracts, the total alkaloid content was 16.68 ± 0.42 mg/g for hot percolation and 19.7 ± 0.32 mg/g for cold percolation. Methanol extracts yielded 5.74 ± 0.37 mg/g for cold percolation and 5.01 ± 0.57 mg/g for hot percolation [73]. Further investigations are warranted to elucidate the specific alkaloid profiles in coconut fruits and their prospective therapeutic effects, particularly in relation to intestinal inflammatory disorders and antioxidant activity.

2.3.4 Phytosterols and phytoestrogens

Phytosterols, a class of phytochemicals found in the lipid-soluble fraction of coconut fruits [82], are commonly used to assess oil quality and detect alterations in vegetable oils. In oils, phytosterols generally exist in their esterified forms [83]. Both copra oil and VCO contain phytosterols [12], with VCO exhibiting a higher proportion compared to copra oil [58]. Researchers have utilized these oils for various health benefits for decades.

Studies revealed the sterol content of crude coconut oil (CO) to be 100 mg/100 g [48]. Comparative studies have consistently shown that CO has the lowest sterol content among common edible vegetable oils. For instance, CO contains 114 mg/100 g of sterols, whereas virgin olive oil, sunflower oil, corn oil, soybean oil, and contain 256 mg/100 g, 451 mg/100 g, and 871 mg/100 g, respectively [84]. The primary phytosterols identified in coconuts include stigmasterol, campesterol, β -sitosterol, Δ^5 -avenasterol, and cycloartenol [85]. Additionally, researcher detected various phytoestrogens such as isoflavones, lignans, and coumestrol in coconut fruit [86].

Despite the lower overall sterol content, β -sitosterol stands as the major sterol in CO, constituting 70.4% of the total sterol fraction [87]. Studies support this finding, reporting that among the sterols present in coconut oil, β -sitosterol is the most abundant, with a concentration of 45 mg/100 g, higher than the amounts of other individual sterols measured in CO [84]. Multiple studies have demonstrated the capacity of β -sitosterol and stigmasterol to inhibit cancer cells in prostate, colon, breast, ovarian, and esophageal tissues. The high concentration of β -sitosterol in CO contributes to understanding the potential anti-cancer properties of coconut oil.

2.3.5 Phenolic acids and other bioactive compounds

Phenolic acids are important aromatic secondary plant metabolites characterized by hydroxyl functional groups attached to aromatic benzene rings and one or more carboxylic acid groups [88]. Researchers identified salicylic acid, p-coumaric acid, ferulic acid, and gallic acid as examples of phenolic acids in coconuts [50, 89, 90]. In addition to phenolic acids, coconuts also contain other significant bioactive compounds with antioxidant properties. Scientists identified catechin and epicatechin, classified as flavonoids, in various coconut products, including coconut haustorium [89, 90]. Ascorbic acid (Vitamin C), an important organic acid, also contributes to the overall antioxidant potential of coconuts. The presence of these diverse compounds underscores the complex phytochemical profile of coconuts.

Further investigations revealed a diverse array of phenolic acids in coconut products. For instance, researchers detected p-coumaric acid, ferulic acid, catechin, and gallic acid in coconut haustorium (CH), with ferulic acid being the most prevalent (2035.58 ± 0.91 $\mu\text{g/g}$, dry basis) [89, 90]. These constituents are also present in CW and CM, suggesting that CH may accumulate bioactive substances from these sources during germination.

2.3.6 Flavonoids

Flavonoids, a significant class of polyphenolic secondary metabolites derived from plants, possess antioxidant properties that can help prevent cardiovascular diseases and chronic illnesses [88, 91]. Investigations on coconut cotyledons have revealed flavonoid contents ranging from ~ 12 to 24 $\mu\text{g QE/g DW}$ [73]. Researcher identified catechin (6.4 – 3451 $\mu\text{g/g}$), apigenin (33.0 – 3881 $\mu\text{g/g}$), and kaempferol (1187 – 9271 $\mu\text{g/g}$) as the major flavonoids in coconut testa during the analysis of flavonoid content and composition [57]. The presence of these flavonoids in coconuts further confirms their role as antioxidants. Recent studies have provided additional insights into the flavonoid content and antioxidant activity of various coconut products. For instance, coconut water extract has been reportedly contains a total flavonoid content of 0.53 ± 0.02 mg/g QE , which contributes to its scavenging capacity against ABTS and DPPH radicals in vitro [92]. Furthermore, the total flavonoid content of water from mature coconut and fresh coconut meat was reported as 11.90 ± 1.81 $\mu\text{g/mL}$ and 51.84 ± 1.02 $\mu\text{g/g FW}$, respectively [93], highlighting the potential of different coconut parts as sources of antioxidant. Future studies on flavonoids in coconut products should focus on comparative analyses of different cultivars, comparisons with other fruits, optimization of extraction methods, in vivo studies to assess health benefits, investigations of synergistic effects with other nutrients, and examinations of developmental dynamics to fully understand their antioxidant properties and potential applications.

2.3.7 Tocopherols and tocotrienols

Tocotrienols and tocopherols (tocols) are lipid-soluble natural antioxidants found in most vegetable oils [94]. They belong to the vitamin E group and are essential due to their antioxidant potential [95]. Through their scavenging activities, tocols can protect the components of biological membranes [98]. Watson and Preedy [96] observed that tocotrienols offer greater health benefits than α -tocopherol. Additionally, they protect edible oils against reactive oxygen species (ROS), contributing to their stability. Tocols are more effective than the synthetic free radical scavengers dibutylhydroxytoluene [97].

The content of tocopherols varies among different vegetable oils [83], and different homologs of tocopherols (alpha, beta, delta, and gamma) are present in vegetable oils [98]. In coconut oil (CO), α -tocotrienols have been reported at 5 mg/L, δ -tocotrienol at 19 mg/L, and γ -tocotrienol at 1 mg/L [99]. Oils extracted from wet coconut testa as well as copra testa exhibit higher tocotrienol concentrations than other CO samples, such as copra whole, copra white kernel, and wet coconut white kernel [100]. Researchers also detected α -tocopherol, another form of vitamin E, in coconut fruit oil [84]. The α -tocopherol content in VCO ranges from 40 to 44%, which is higher than that of palm oil (18–20%) [101, 102]. However, coconut oil has the lowest α -tocopherol content (0.32 mg/100 g) compared to other oils, such as corn oil (66 mg/100 g), sunflower oil (63 mg/100 g), extra virgin olive oil (26 mg/100 g), and olive oil (18 mg/100 g) [99]. Additionally, researchers reported CO to contain the lowest amount of tocopherol (1.7 mg/100 g) among various vegetable oils. Despite its lower α -tocopherol content, coconut oil has demonstrated various beneficial properties, including its ability to soothe hair and skin, prevent air oxidation, and potentially exert anticancer effects [61, 103].

2.3.8 Bioactive peptides

Bioactive peptides (BPs) are protein fragments with potential physiological effects beyond their fundamental nutritional value. Recent studies identified several BPs derived from coconut cake albumin (CCA) with promising bioactivities. Zheng et al. [104] isolated three novel peptides from CCA hydrolysates: KAQYPYV, KIIINYN, and KILLYG, with molecular masses of 867.45, 762.47, and 705.44 Da, respectively. These peptides exhibited potent ACE-inhibitory activity (IC₅₀: 37.06–58.72 μ M) and hydroxyl radical scavenging capacity (IC₅₀: 70.84–95.23 μ M). They also demonstrated high Fe²⁺ + chelating activity and considerable superoxide radical scavenging action. Furthermore, the peptides reduced intracellular endothelin-1 content and protected vascular endothelial cells from ROS-mediated damage, suggesting potential antihypertensive effects. Li et al. [105] identified two antioxidant peptides from defatted CCA hydrolysate: Pro-Gln-Phe-Tyr-Trp (739.84 Da) and Val-Val-Leu-Tyr-Arg (648.81 Da). These peptides exhibited potent non-competitive ACE inhibition with IC₅₀ values of 0.104 \pm 0.012 and 0.244 \pm 0.026 mg/ml, respectively. They also showed relatively good stability against gastrointestinal enzyme digestion and demonstrated the ability to suppress endothelin-1 content and protect vascular endothelial cells from oxidative damage. Wang and Ng [106] isolated the peptide EQCREEEDDR from coconut using ion exchange chromatography and FPLC. This peptide showed the ability to lower HIV-1 reverse transcriptase activity, suggesting potential antiviral properties. These findings highlight the diverse bioactivities of coconut-derived peptides, including antihypertensive, antioxidant, and potential antiviral effects.

3 Bioactivities of coconut fruit

Coconuts (*Cocos nucifera* L.) are notable for their diverse bioactive constituents, including phenolic compounds, various flavonoids (such as catechins), tannins, alkaloids, and steroids, which contribute to their recognized nutraceutical potential. These compounds, found in varying concentrations across different coconut parts and influenced by extraction methods, are associated with health-promoting effects such as

anti-diabetic, antibacterial, anti-inflammatory, and antioxidant activities. The section details these benefits and the factors influencing their composition.

3.1 Anti-inflammatory effects

Virgin coconut oil (VCO) has demonstrated notable anti-inflammatory activity across various experimental models. Intahphuak et al. [107] reported that VCO significantly reduced arachidonic acid-induced paw edema and ethyl phenylpropionate-induced ear edema in rats, indicating its efficacy in acute inflammatory responses. Additionally, VCO exhibited moderate analgesic and antipyretic effects, which were associated with decreased serum alkaline phosphatase, reduced transudative weight, and inhibition of granuloma formation. These findings were corroborated by Roopan et al. [108], further supporting the anti-inflammatory potential of VCO. Extracts from different fractions of coconut husk fiber also demonstrated anti-inflammatory effects. Silva et al. [109] observed that doses ranging from 10 to 100 mg/kg inhibited cell migration induced by subcutaneous carrageenan injection, suggesting a mechanism involving the modulation of cellular inflammatory responses.

Undiluted coconut water (CW) has shown promise in mitigating inflammation in diabetic models. Zulaikhah et al. [110] found that CW, administered at 8 ml/200 g body weight, lowered levels of pro-inflammatory cytokines, including Interleukin-6 (IL-6), Interleukin-1 (IL-1), and Tumor Necrosis Factor-alpha (TNF- α), in nicotinamide and streptozotocin-induced diabetic rats. This indicates CW's potential to exert significant anti-inflammatory effects by modulating systemic inflammatory markers. Further evidence supports the anti-inflammatory potential of other coconut-derived products. Methanolic extracts of coconut haustorium (CH) reduced lipopolysaccharide (LPS)-induced production of pro-inflammatory cytokines (IL-1, IL-6, TNF- α) and inhibited nitric oxide synthesis in macrophage cells [111]. These effects are attributed to CH's rich antioxidant content and its ability to upregulate the Nrf2/HO1 pathway, enhancing cellular antioxidant defenses and providing cytoprotective benefits. Hydrolyzed virgin coconut oil (HVCO) exhibited significant anti-inflammatory activity *in vitro* using the RAW 264.7 macrophage cell model. Upon LPS stimulation, HVCO treatment markedly reduced the expression of pro-inflammatory cytokines (TNF- α , IL-1 β , IL-6) and inflammatory mediators (iNOS, COX-2) [112]. Cell viability assays confirmed HVCO's non-cytotoxicity at effective concentrations, suggesting its potential as a natural anti-inflammatory agent. Cultured coconut oil (CCE), rich in medium-chain fatty acids, was evaluated for its anti-inflammatory activity in LPS-induced RAW264.7 macrophage cells. CCE (15.625–62.5 μ g/mL) significantly reduced nitric oxide (NO) production and intracellular inducible nitric oxide synthase (iNOS) levels. Additionally, CCE at 62.5 μ g/mL significantly decreased IL-6 and TNF- α levels [113]. These findings indicate that CCE suppresses inflammatory responses in macrophages by targeting key inflammatory mediators. Collectively, these studies highlight the diverse anti-inflammatory properties of coconut-derived products. However, further research, particularly human clinical trials, is required to elucidate precise mechanisms of action and validate their therapeutic potential in inflammatory conditions. Detailed analyses of active phytochemical structures and comprehensive mechanistic studies are warranted.

3.2 Antioxidant properties

Antioxidants play a crucial role in both food processing and human health by inhibiting or delaying oxidative damage caused by free radicals and ROS [114]. These harmful molecules are implicated in various diseases, including cancer, diabetes, atherosclerosis, and neurodegenerative disorders [113]. In food processing, ROS and free radicals contribute to lipid oxidation, leading to toxic reaction products and undesirable off-flavors [115]. While synthetic antioxidants have been traditionally used, concerns regarding their potential carcinogenicity have driven interest in natural alternatives [116]. Coconuts are an excellent source of natural antioxidants, containing diverse bioactive constituents such as polyphenols, alkaloids, tannins, and sterols [72]. Mansor et al. [102] identified α -tocopherol and γ -tocotrienol as key antioxidants in coconut oil. These tocopherols, precursors of vitamin E, offer significant antioxidant potential for food preservation and human health. Natural antioxidants, including those from coconut, can inhibit lipid oxidation through oxygen scavenging, free radical neutralization, and antioxidant regeneration, often outperforming synthetic counterparts [117]. Coconut components like cotyledon, coconut oil (CO), and coconut water (CW) exhibit significant antioxidant properties due to their phenolic compounds, tocopherols, and other bioactive metabolites (Fig. 4) [73, 118–120].

Moreover, natural antioxidants demonstrate enhanced stability at elevated temperatures, making them effective during food processing methods. Despite these advantages, some natural antioxidants may have lower individual radical scavenging abilities compared to synthetic alternatives, potentially requiring higher quantities for equivalent effects [121, 122]. This necessitates further research to optimize their application in food systems and fully delineate their mechanisms and health benefits.

Antioxidant activities in coconuts vary based on factors such as cultivar, geographical origin, type, growing conditions, climate [12], and maturity stage [50]. Studies have documented the antioxidant abilities of various coconut varieties. Santos et al. [123]

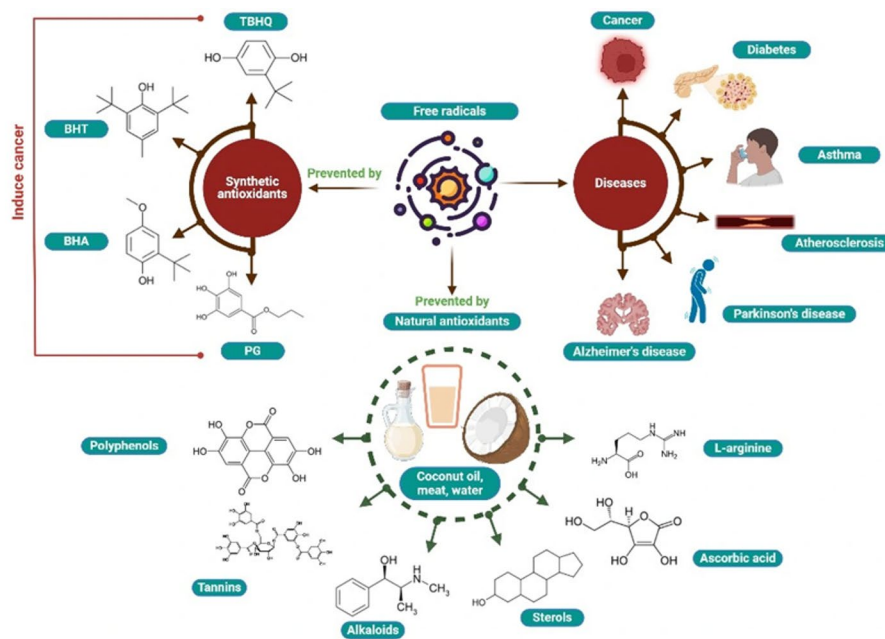


Fig. 4 Antioxidant effects and specific mechanisms of action

compared four coconut water varieties, demonstrating their effectiveness in eliminating DPPH and nitric oxide, with the green dwarf variety showing particularly potent activity. Coconut water's micronutrients support the body's antioxidant defense, as CW administration to rats restored antioxidant enzyme activity and reduced lipid peroxidation [124]. CW is rich in L-arginine (30 mg/dl), which reduces free radical generation [125, 126], and ascorbic acid (15 mg/100 ml), which decreases lipid peroxidation [127]. Mahayothee et al. [50] reported that coconut meat exhibited higher antioxidant abilities than coconut water, with extracts showing superior DPPH and ABTS free radical scavenging. Virgin coconut oil (VCO) consistently demonstrates elevated antioxidant capacity compared to other oils. Mulyadi et al. [128] identified protocatechuic acid, syringic acid, and vanillic acid as key phenolic compounds responsible for VCO's antioxidant characteristics. Unrefined VCO, particularly hot-extracted and fermented variants, exhibits higher inhibition and radical scavenging bioactivity [129]. Unlike conventional coconut oil, VCO increases antioxidant enzyme activity while reducing lipid peroxidation [87]. Rahim et al. [130] showed that VCO enhanced glutathione peroxidase and superoxide dismutase activity in brain homogenates of LPS-challenged rats (Fig. 5). Further research is needed to explore the effects of various factors on coconut's antioxidant content and to investigate the mechanisms by which coconut-derived antioxidants exert their health benefits in humans.

3.3 Anticancer properties

Recent studies highlight the potential anticancer actions of coconut-derived metabolites, particularly lauric acid, the predominant fatty acid in VCO. In vitro experiments demonstrate the efficacy of coconut oil (CO) extracts in inhibiting the proliferation of various cancer cell lines, including colon, mammary, liver, lung, and oral cancers [129, 131].

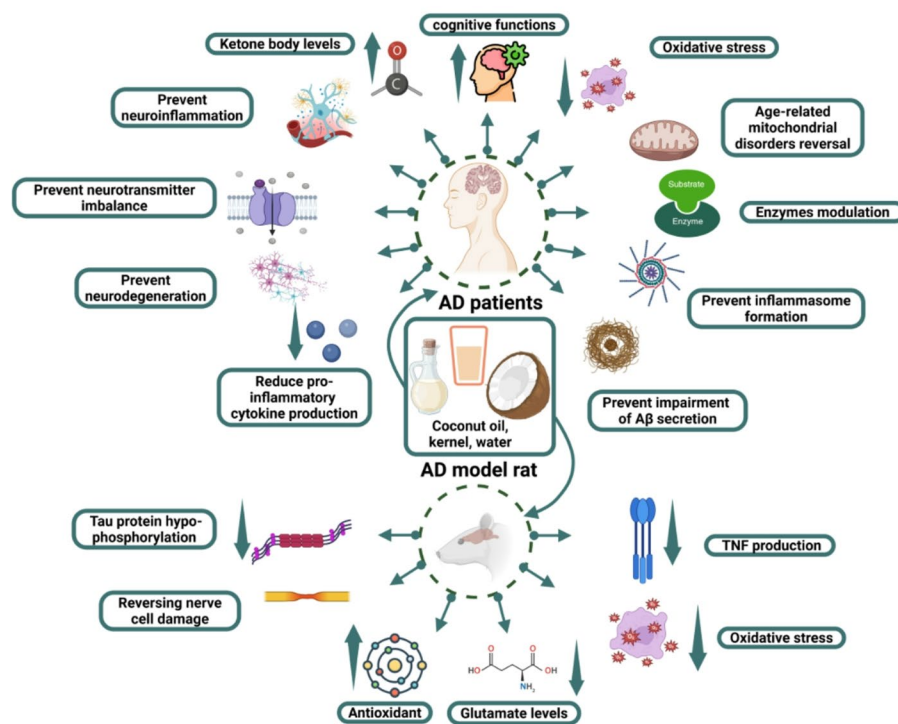


Fig. 5 Neuroprotective effects and specific mechanisms of action

Lauric acid induces apoptotic changes in endometrial, colorectal, and breast cancer cells, mediated ROS generation [132]. The mechanism involves activation of the EGFR/ERK/AP1 signaling pathway, leading to the upregulation of p21Cip1/WAF1 in a p53-independent manner. Additionally, lauric acid modulates cancer-associated microRNA expression, suppressing oncogenic miRNAs and upregulating tumor suppressor miRNAs [133]. Pruseth et al. [134] reported the anti-cancer effects of VCO, demonstrating VCO-induced apoptosis in HepG2 liver cancer cell lines and noting its safety for consumption. Both in vitro and in silico experiments also showed lauric acid's cytotoxicity towards murine macrophages, HepG2 (human hepatocellular carcinoma), and HCT-15 (human colon cancer) cells. Verma et al. [135] reported the efficacy of fractionated and processed CO in treating oral and liver cancer cells. Furthermore, Radhakrishnan et al. [136] suggested that polyphenolic extracts from coconut kernel may prevent colon cancer growth by modulating apoptotic machinery through mitochondrial ROS production. Tender coconut water (TCW) inhibits cancer cell viability by reversing epithelial-to-mesenchymal transition (EMT) in HepG2 cells and affecting various cancer cell lines (breast, colon) without harming normal cells [137]. Metabolomics analysis identified specific anticancer components in TCW, such as 3-hydroxy-1-(4-hydroxyphenyl)propan-1-one, indole-3-carboxaldehyde, and caffeic acid. Coconut kernel extract (CKE) demonstrates chemopreventive potential against carcinogen-induced skin cancer by reducing oxidative stress and inhibiting C-MYC proto-oncogene expression [138]. Additionally, coconut water vinegar exhibits in vitro and in vivo antitumor effects against 4T1 breast cancer cells by inducing apoptosis and delaying metastasis, while promoting antitumor immunity [139]. Amrisha Pavithra E and Santhy K.S [140]. reported that dodecanoic acid, a phytoconstituent from coconut sprouts, exhibited promising drug-likeness and ADME properties. Molecular docking analysis revealed its strong binding affinity to the acute myeloid leukemia-associated protein PTPN11. These results suggest *C. nucifera* sprouts as a natural source of anticancer agents, with dodecanoic acid showing potential as a PTPN11 inhibitor. While these findings are promising, most studies are in vitro or animal models. Comprehensive clinical trials are essential to validate anticancer activities in humans. Future studies should elucidate precise molecular mechanisms, optimal dosing, and potential synergistic effects with existing cancer therapies.

3.4 Anti-diabetic properties

Recent research highlights the potential of natural plant extracts in diabetes management. Coconut water and VCO are promising candidates due to their rich bioactive compound profiles and demonstrated antidiabetic properties. Coconut water contains L-arginine, ascorbic acid, phenolic compounds, and cysteine, all potential antidiabetic agents [141]. In diabetic rat models, mature coconut water reduced glycated hemoglobin and blood glucose levels while improving plasma insulin concentrations. It also normalized liver enzyme markers and improved blood urea, serum creatinine, and albumin levels [142]. VCO supports blood glucose regulation and reduces hyperglycemia, attributed to its phenolic constituents inhibiting dipeptidyl peptidase-4 (DPP-4) and the polyol pathway [141]. In vivo studies show CW improves antioxidant status in diabetic rats, increasing catalase, glutathione, vitamin C, and vitamin E levels [143]. Both tender and mature CW exhibit antioxidant properties that may mitigate diabetes complications. Rahmawati et al. [144] found that both VCO and its emulsions significantly reduced

blood glucose levels and improved lipid profiles in diabetic animal models, evidenced by decreased total cholesterol and triglyceride levels. These findings indicate that coconut-derived products may have significant biomedical potential for diabetes management. However, further clinical investigations are needed to fully elucidate their safety and efficacy in human subjects.

3.5 Antimicrobial properties

The antimicrobial properties of natural compounds have garnered significant attention as a result of their potential in combating resistant pathogens, offering advantages such as lower costs and reduced side effects compared to synthetic alternatives [147]. Lauric acid (C12:0), particularly in its monoglyceride form (monolaurin), has been identified as the primary component responsible for the antimicrobial actions of coconut oil [67]. The mode of action involves the disruption of bacterial cell membranes, leading to leakage of cellular contents and inhibition of bacterial growth. Monolaurin has demonstrated broad-spectrum activity against various bacteria, viruses, and fungi, including *Staphylococcus aureus*, *Candida albicans*, and herpes simplex virus [67]. Further research is warranted to explore the full spectrum of antimicrobial activity of coconut-derived compounds and to investigate their potential as natural alternatives to conventional antimicrobial agents in various applications, including food preservation and pharmaceutical development.

3.6 Cardioprotective properties

Epidemiological studies indicate that increased concentrations of high-density lipoprotein (HDL) cholesterol might confer protection against cardiovascular diseases, including stroke, myocardial infarction, and ischemic heart disease [145]. Multiple investigations have reported the potential cardioprotective actions of coconut and its derivatives (Fig. 6).

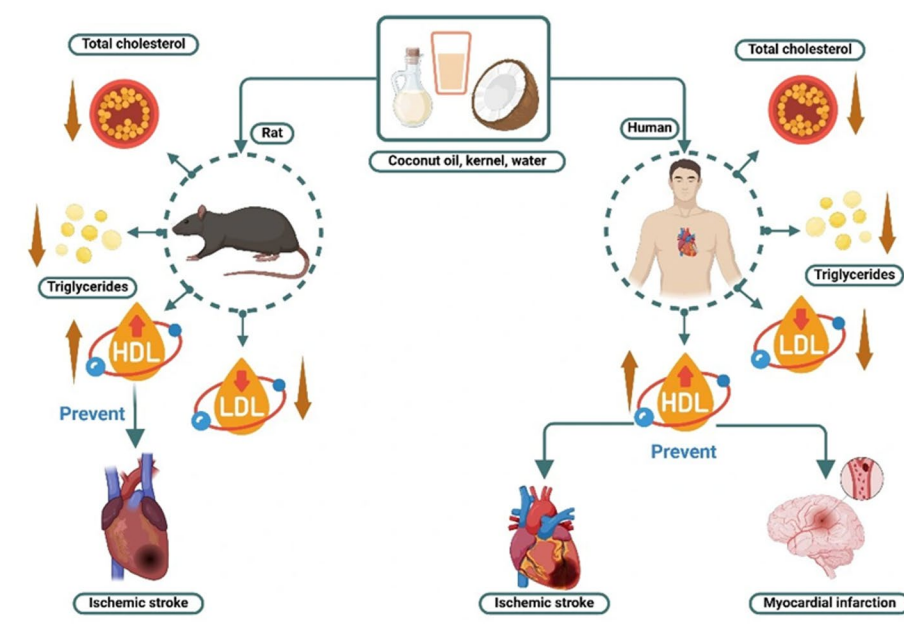


Fig. 6 Cardioprotective effects and specific mechanisms of action of coconut fruits

Anurag and Rajamohan [146] demonstrated the cardioprotective actions of CW in an experimental model of myocardial infarction induced in rats. Similarly, Lima et al. [72] found that tender CW administration protected against isoproterenol-induced myocardial infarction and reduced mitochondrial lipid peroxidation in a rat model. These findings suggest that CW might mitigate cardiac damage through antioxidant and anti-ischemic mechanisms. A randomized controlled trial involving 96 participants compared the effects of unsalted butter, VCO, and extra virgin olive oil (50 g/day for 1 month) on lipid profiles. The study observed that LDL-cholesterol levels were remarkably lower with coconut oil than with butter (difference of 0.42 mmol/L, 95% CI: 0.19 to 0.65), with no significant differences between olive oil and coconut oil [147]. Additionally, coconut oil elevated HDL-cholesterol compared to olive oil (0.16 mmol/L, 95% CI: 0.03 to 0.28) and butter (0.18 mmol/L, 95% CI: 0.06 to 0.30) [147]. These results indicate that VCO can favorably modulate lipid profiles, potentially reducing cardiovascular risk factors. Rajamohan and Kurup [148] conducted a study on human subjects, reporting that ingesting coconut kernel (55.8 g/day) along with coconut oil (38 g/day) led to a favorable lipid profile, including higher HDL cholesterol, lower total cholesterol, a reduced LDL/HDL ratio, and decreased triglyceride levels. The authors concluded that incorporating CO and coconut kernel into a regular diet did not negatively impact serum lipid levels. A preclinical study by Nevin and Rajamohan [149] examined the effects of VCO produced through a wet process. Daily consumption of 30 mL of VCO showed advantageous effects on lipid profiles compared to copra oil, lowering phospholipids, cholesterol, total triglycerides, VLDL, and LDL cholesterol levels while increasing HDL cholesterol in tissues and serum. These findings collectively support the potential of coconut and its derivatives in promoting cardiovascular health through lipid regulation and antioxidant effects.

3.7 Anti-obesity properties

Coconut oil, particularly its medium-chain fatty acid (MCEFA) content, has garnered attention for its potential role in weight management and anti-obesity effects. Unlike long-chain fatty acids, MCFAs are rapidly absorbed and metabolized, leading to increased energy expenditure and reduced fat accumulation. Assunção et al. [150] demonstrated that dietary coconut oil reduced abdominal obesity in women, leading to a decrease in waist circumference and an increase in HDL cholesterol levels. This effect is attributed to the thermogenic properties of MCFAs, which promote fat oxidation and energy expenditure. Furthermore, a meta-analysis by St-Onge and Jones [151] concluded that consumption of MCTs, abundant in coconut oil, leads to greater energy expenditure and fat oxidation compared to long-chain triglycerides (LCTs). This suggests that incorporating coconut oil into the diet may contribute to weight loss and improved body composition. The anti-obesity effects of coconut oil are primarily mediated by its influence on satiety, thermogenesis, and lipid metabolism, making it a promising dietary component for obesity prevention and management. However, further large-scale clinical trials are needed to confirm these findings and establish optimal dosages for weight management.

3.8 Other bioactivities

Beyond the well-studied properties, coconut fruit and its derivatives exhibit a range of other significant bioactivities such as:

- i. *Antifungal Activity*: Coconut oil has demonstrated potent antifungal activity, particularly against *Candida albicans*, a common opportunistic fungal pathogen. This effect is primarily attributed to lauric acid and capric acid, which disrupt the fungal cell membrane, leading to cell lysis and inhibition of growth [152].
- ii. *Antiviral Activity*: Monolaurin, a monoglyceride derived from lauric acid, has shown antiviral properties against various lipid-enveloped viruses, including herpes simplex virus, influenza virus, and measles virus. Its mechanism involves solubilizing the lipid envelope of these viruses, thereby inactivating them and preventing viral entry into host cells [153].
- iii. *Wound Healing*: Studies have indicated that VCO can accelerate wound healing. This is attributed to its antioxidant properties, which reduce oxidative stress at the wound site, and its ability to promote collagen synthesis and re-epithelialization [154]. VCO also exhibits antimicrobial properties that help prevent wound infections.
- iv. *Bone Health*: Emerging research suggests that coconut oil may play a role in improving bone health. Animal studies have shown that VCO can enhance calcium absorption and reduce bone loss, potentially benefiting individuals with osteoporosis. This effect is linked to its antioxidant capacity and ability to modulate bone metabolism [155].

These diverse bioactivities underscore the broad therapeutic potential of coconut fruit, extending beyond its nutritional value to various health applications. Further research is needed to fully elucidate the mechanisms and clinical relevance of these properties.

4 Applications of bioactive constituents of coconut in in vivo and in vitro studies

Extensive studies have been performed to ascertain the pharmacological bioactivities of coconut in both in vitro and in vivo models (Table 2). For example, Preetha et al. [156] investigated the antithrombotic agent of MCW in diabetic rats. The study found that rats fed MCW exhibited higher nitric oxide synthase activity in the liver, increased plasma arginine concentrations, and elevated urinary nitrite levels compared to the L-arginine-treated group. The observed L-arginine-mediated effects suggest a potential mechanism for mitigating metabolic alterations in lipids, profiles of blood glucose as well as coagulation factors through enhanced nitric oxide production.

Zhang et al. [157] reported the anti-cataract actions of CW treatment in induced diabetic rats, demonstrating that CW reduced the rise in malondialdehyde levels and mitigated the decline in activities of glutathione peroxidase and superoxide dismutase caused by diabetes mellitus. Additionally, Zhang et al. [158] revealed that CW had anti-retinopathy effects in diabetic Sprague Dawley rats treated with streptozotocin (STZ) at 60 mg/kg. Lakshmanan et al. [159] carried out a comprehensive investigation into the protective actions of tender coconut water (TCW) on rat hepatocytes using an in vitro sepsis model. The study revealed that TCW effectively mitigated pro-inflammatory gene expression and attenuated hepatocyte damage associated with increased inflammatory

Table 2 Potential therapeutic and biological applications of coconut components: insights from in vitro and in vivo study

Coconut part	In vivo and in vitro experiment	Model system	Dosage	Trial duration	outcomes	Refs.
MCW	In vivo (rat model)	Alloxan-induced diabetic male Sprague-Dawley rats	MCW (4 mL/100 g BW/day) + L-arginine (7.5 mg/100 g BW/day)	45 days	. ↓ Blood glucose (32% reduction) and HbA1c (28% reduction) ↑ Plasma insulin (1.8x higher vs. diabetic control). ↑ L-arginine levels in liver/plasma (2.5x higher). ↑ Nitric oxide synthase (NOS) activity ↓ Platelets (40%), fibrinogen (35%), WBC (25%) ↑ Prothrombin time (1.5x longer) and ↓ Factor V activity (50%)	[156]
CW	In vitro	Rat lens epithelial	5% and 10% CW in culture medium	48 h	Reduced LECs apoptosis; improved antioxidant markers (lower MDA, higher SOD/GSH-Px)	[157]
CW	In vivo	STZ-induced diabetic SD rats	STZ injection: 60 mg/kg in citrate buffer (pH 4.5).	20 wks	Reduced fasting blood sugar - Decreased retinal thickness - Lowered VEGF expression - Comparable effects to glibenclamide	[158]
Tender coconut water	In vitro	Sepsis model (IL-1 β -stimulated hepatocytes)	Fresh/commercial TCW (equally effective)	30 min pretreatment + cytokine exposure	Inhibited NO ₂ ⁻ production. - Heat-stable active compounds. - Commercial TCW matched fresh TCW efficacy.	[159]
Coconut Testa Oil (CTO)	In vitro	RAW 264.7 murine macrophages	15–30 μ g/mL	24 h pretreatment + LPS exposure	Reduced IL-1 β , IL-6, TNF- α ($p < 0.05$). Enhanced intracellular antioxidants (SOD, CAT).	[13]
Virgin Coconut Oil	in vivo	Streptozotocin-diabetic + gentamicin-induced nephrotoxicity (rats)	10 mL/kg BW (oral)	4 weeks	Normalized serum creatinine/urea. - Reduced oxidative stress (↓MDA) and inflammation (↓IL-6, TNF- α). - Enhanced renal antioxidant defenses (↑SOD, CAT).	[160]

Table 2 (continued)

Coconut part	In vivo and in vitro experiment	Model system	Dosage	Trial duration	outcomes	Refs.
VCO, copra oil (CO), olive oil (OO), sunflower oil (SFO)	In vitro	Male Sprague-Dawley rats	8% of total diet (by weight) for all oils	45 days	VCO PF showed strongest inhibition of ADP-induced aggregation (35% vs. 10–25% for other oils). Reduced coagulation factors: Factor V, fibrin, fibrinogen, and thromboxane B ₂ by 25–40% vs. CO.	[161]
VCO	In vivo	Alloxan-induced diabetic male Sprague-Dawley rats	10% of total diet (by weight)	3 weeks	↓ Blood glucose (180 vs. 320 mg/dL*); ↑ renal SOD/CAT; ↓ MDA levels	[162]
Coconut kernel protein (CKP)	In vivo	Male Wistar rats	50 mg/100 g body weight (oral)	45 days	CKP reduced ISO-induced elevation of Serum CPK (↓52%), LDH (↓48%), and AST (↓45%). ↑ SOD (89%) and catalase (72%) activity in cardiac tissue ($p < 0.05$). ↑ Reduced glutathione (GSH) by 2.1-fold; ↓ lipid peroxidation (MDA) by 58%.	[163]
Haustorium (methanol extract)	In vitro (cell culture)	Intestinal epithelial cells (IEC-6 line)	10–40 µg/mL CHE (methanolic extract)	24-hour pre-treatment + 6-hour NaF exposure	Normalized GSH biosynthesis enzymes (GCL, GS). ↓ Lipid peroxidation (TBARS ↓ 50%, conjugated dienes ↓ 60%). ↑ Glutathione (GSH) levels (2.5× increase vs. NaF-only group). Restored catalase activity (84.37 → 42.15 U/mg protein)	[165].
Young coconut inflorescence	In vivo (rat model)	Alloxan-induced diabetic rats	20% w/w in diet	30 days	↓ Fasting glucose (52–58%) and HbA1c (25–28%) ↓ Gluconeogenic enzymes: Glucose-6-phosphatase (↓62%), fructose-1,6-diphosphatase (↓55%). β-cell regeneration: ↑ Islet cell mass. Restored hepatic glycogen (2.3× higher).	[166, 167]

Table 2 (continued)

Coconut part	In vivo and in vitro experiment	Model system	Dosage	Trial duration	outcomes	Refs.
Coconut oil	Clinical trial (human subjects)	60 adolescents (16–18 years) with plaque-induced gingivitis	5 mL coconut oil swished daily for 10–15 min	30 days	Reducing plaque adhesion and gingival inflammation.	[168]
FCW	In vitro (agar diffusion)	<i>Listeria monocytoses</i> , <i>Escherichia coli</i> and <i>Staphylococcus aureus</i> and <i>Salmonella typhimurium</i>	Probiotic CW sample with 2.3×10^7 CFU/mL	24 h	Inhibited <i>Listeria monocytoses</i> (9.23 mm). Minimal effect <i>S. aureus</i> (2.43 mm)	[169]

TCW tender coconut water, VCO virgin coconut oil, CO coconut oil, CKP coconut kernel protein, CH coconut haustorium, CTO coconut testa oil, FCW fermented coconut water

cytokines and enhanced nitric oxide synthesis. Narayanankutty et al. [13] recommended consuming coconut testa oil (CTO) to reduce free radical-mediated cell injury and lipid peroxidation-mediated cytokine production. Famurewa et al. [160] demonstrated the protective actions of VCO against diclofenac-induced nephrotoxicity in female Wistar albino rats. The antithrombotic activity of the VCO diet against ADP-induced platelet aggregation in male rats indicated that VCO significantly inhibits platelet activation and coagulation factors compared to other tested oils [161]. Akinnuga et al. [162] studied the ameliorative actions of a VCO diet on antioxidant enzymes, blood glucose, as well as renal tissue in diabetic rats, showing that VCO can alleviate oxidative stress and hyperglycemia, as well as improve renal tissue enzyme function.

Additionally, studies have revealed that diets containing coconut kernel protein (CKP) exhibit cardioprotective [163], hypolipidemic, antioxidant, and anti-inflammatory effects [164] against myocardial infarction, further affirming CKP as a medicinal food. Methanol extracts from coconut haustorium have been shown to alleviate cell death induced by fluoride toxicity [165]. Young coconut inflorescence has been reported to protect against alloxan-induced pancreatic cytotoxicity and severe hyperglycemia, promoting the repair and rejuvenation of the residual β -cell population in diabetic rats [166, 167]. Peedikayil et al. [168] reported the anti-gingivitis properties of CO in plaque-induced gingivitis among a total of 60 age-matched adolescents. These outcomes reinforce the potential of CO as a nutraceutical agent and its application for functional purposes. Extending these benefits to fermented coconut products, Ajibola et al. [169] reported *Lactococcus lactis* fermented unpasteurized (UPW) and pasteurized (PW90) coconut water extracts inhibited foodborne pathogens (*L. monocytogenes*, *S. aureus*, *S. Typhi*, *E. coli*), primarily via organic acids (~0.90% titratable acidity) with synergistic polyphenolic effects.

5 Functional food applications of coconut palm

Owing to the recognized health advantages linked to diverse constituents of coconuts, several studies on their applications are detailed in this section, as indicated in Table 3. For instance, Hossain et al. [170] documented the incorporation of coconut flour (CF) into wheat flour for plain cake production. The results indicated that substituting 20% of wheat flour with CF increased the levels of crude fiber, ash content, carbohydrates, protein, and fat and significantly enhanced moisture content. This remarkable improvement

Table 3 Functional application of coconut in food products

Coconut component	Food product	Result	Conclusion	Refs.
CF	Cake	Incorporation of 20% coconut flour (CF) in cake significantly increased crude fiber (173%), fat (68.44%), ash (9.68%), protein (8.92), and moisture content (3.95%) compared to the control, while reducing carbohydrate content (30.63%)	The addition of 20% CF to cake formulations improved both nutritional and physical quality	[170]
Defatted CF (10%)	Masa	Incorporation of 10% DCF in masa significantly enhanced protein (102%), fiber (12%), ash (6%), fat (6%), while reducing carbohydrate content (12%) compared to the control, and produced a highly acceptable product	Inclusion of DCF in nixtamalized maize flour enhanced nutrients, dietary fibre, protein, and antioxidants; masa with 10% DCF had comparable acceptability to control, supporting its use in managing protein-energy malnutrition and promoting coconut residue utilization	[171]
CF powder	Gluten-free baked cookies	CF increased ash (320%), protein (150%), fat, and moisture in cookies compared to rice flour; blends (\leq 50% CF) improved flavor and taste, but $>$ 50% CF led to high moisture and poor texture.	Rice-CF blends can be used for gluten-free cookies, with optimal proportions (\leq 50% CF) recommended for best quality and shelf life	[79]
CF	Potato starch gluten-free cookies	Incorporation of CF (at 10% replacement of potato starch) significantly increased the protein (from 4.82% to 6.21%), lipid (from 11.01% to 15.77%), and reduced carbohydrate content (from 69.10% to 53.91%) in the cookies compared to the standard formulation.	CF at 10% replacement enhances the nutritional profile and acceptability of gluten-free cookies, offering a healthy alternative for celiac and health-conscious consumers.	[172]
CH	Feed for extrusion	CH is nutrient-rich, containing 33.8–47.1% soluble sugars, 8.2–10.2% ash, 5.2–9.2% protein, and notable potassium (4.1–4.7%); addition to feed improves nutritional value	CH is a rich natural source of phenolics and flavonoids with potent antioxidant capacity, making it a valuable alternative to synthetic antioxidants in food and feed applications.	[57]
VCM	Cake (5–20% substitution)	Hardness increased (exact % not specified), moisture up 61% (10.67% to 17.23%), fat up 77% (18.51% to 32.79%), protein up 21% (5.91% to 7.14%), fiber up 2511% (0.09% to 2.35%), carbohydrate down 38% (64.43% to 39.83%); sensory acceptability maintained up to 15% substitution	VCM (5–20%) in cakes increases nutritional value and hardness while maintaining sensory acceptability up to 15% substitution, demonstrating its potential as a functional ingredient in bakery products	[173]
CW	Edible coating on minimally processed carrots	Improved <i>L. acidophilus</i> LA3 viability: loss reduced from $>$ 4.0 log to $<$ 0.6 log cycles in 7 days (effectively $>$ 85% more viable cells retained); sensory acceptability increased, and purchase intention rose from $<$ 50% (control) to 84% (coated sample) after 14 days	CW in alginate coatings preserves probiotic viability and enhances sensory quality of minimally processed carrots, increasing consumer acceptance and product shelf life.	[174]

Table 3 (continued)

Coconut component	Food product	Result	Conclusion	Refs.
VCO	Mayonnaise	Increased phenolic content (61% vs. Soya bean oil), higher anti-oxidant activity (19% ABTS), lower texture firmness, larger droplet size (144%), lower sensory acceptability due to strong aroma	VCO in mayonnaise boosts phenolic content and anti-oxidant activity but reduces texture firmness and sensory acceptability due to its strong aroma, making it a promising health-enhancing ingredient with potential for further optimization	[175]
MCW	Fermented probiotic beverage	Fermentation with <i>L. lactis</i> IO-1 increased viable cell counts, antioxidant activity (TPC: up to ~68 µg/mL GAE; FRAP: ~68%; DPPH: ~63%), antibacterial activity, non-toxic, improved sensory with honey and coconut flavor	Fermentation of CW with <i>L. lactis</i> IO-1 produces a probiotic beverage with improved antioxidant and antibacterial activities, non-toxicity, and high sensory acceptability, suitable as a functional drink for diverse consumer groups	[177]
VCO	Filled milk and infant food	Good fat source for infant food and filled milk formulae	VCO serves as an excellent fat source for infant food and filled milk formulations, supporting essential nutritional requirements for healthy growth.	[180]

CF Coconut flour, CH coconut haustorium, VCM virgin coconut meal, VCO virgin coconut oil, MCW mature coconut water, TP Total phenolic, FRAP Ferric Reducing/Antioxidant Power, DPPH 2,2-diphenyl-1-picrylhydrazyl, ABTS 2,2'-Azino-bis(3-ethylbenzothiazoline-6-sul

in nutritional values suggests that coconut flour could serve as a functional food supplement. Additionally, gluten-free cookies with a pleasant flavor and taste were developed using blends of rice flour and coconut flour [171]. The nutritional characterization of *Cocos nucifera* L. flour makes it an excellent candidate for adding value to baked goods. Replacing 50% of rice flour with coconut flour increased the moisture content (6.65%), fat (2.15%), protein (2.55%), and ash (0.38%) in the final product. Incorporating coconut flour into potato starch for gluten-free cookie production enhanced nutritional value and improved physicochemical properties despite a slight reduction in energy and carbohydrate content [172]. Job et al. [165] demonstrated that incorporating 20% coconut haustorium (CH) into a composite mixture containing 30% maize and 50% rice yielded extrudates with favorable nutritional profiles and sensory attributes. This formulation was deemed suitable for producing nutritious and palatable extruded products, as evidenced by comprehensive biochemical analyses and sensory evaluation studies.

Incorporating virgin coconut meal (VCM) into cake formulations (5–20%) increased hardness while reducing gumminess and chewiness. Among the tested formulations, cakes with 10% VCM achieved the highest acceptability score (9) from sensory panelists. The study revealed that cake mixtures with up to 15% VCM replacement could be utilized without compromising food quality [173]. Considering the escalating consumer interest in functional and health-oriented food products, coconut presents promising potential as a nutraceutical ingredient for developing innovative culinary formulations. Processed carrot obtained from fermented coated carrot using *Lactobacillus acidophilus* LA3, coated with sodium alginate and coconut water, achieved a considerably high viable cell count throughout 21 days of cold storage [174]. This product was recommended as a nutritional supplement in the food sector. According to Muhialdin et al.

[175], VCO was compared to soybean oil in the development of mayonnaise. This study's outcomes strongly support VCO's utilization as a viable option for producing innovative mayonnaise formulations with additional beneficial properties. Furthermore, Moraes et al. [176] investigated the dietary incorporation of coconut cake, a coconut oil production byproduct, in Japanese quail nutrition, revealing significant improvements in laying rate, egg mass production, feed conversion efficiency, and eggshell quality during the laying phase.

Mature coconut water (MCW), which has less commercial value, was used to produce a coconut beverage concentrate through lactic acid fermentation with 0.5% *Lactococcus lactis* IO-1 for 48 h to maximize beverage yield. The resulting beverage contained 41.12 ± 0.73 g/L total sugar, 15.42 ± 0.02 g/L reducing sugar as well as 6.7 ± 0.29 g/L total soluble solids, making it suitable for probiotic beverage production [176]. Probiotic beverages derived from coconut fruit water, fermented using lactic acid bacteria, demonstrated potential health benefits for specific dietary populations, including vegetarians, lactose-intolerant individuals, and those with milk product allergies [177]. The incorporation of *lactis* IO-1 in coconut juice remarkably elevated the antiradical power and total phenolic content (TPC) of the probiotic beverage compared to the control.

VCO exhibits valuable chemical properties and physicochemical characteristics that make it suitable as an edible oil. It is high in lauric acid and demonstrates stability, providing various health benefits [178]. Its content of SFAs combined with an abundance of bioactive constituents (such as tocopherols, polyphenols, carotenes, and phytosterols that possess anti-radical and other health-promoting properties) contribute to its high resistance to oxidative rancidity [179]. Therefore, VCO can be utilized as cooking oil without refining, serving as frying or seasoning oil, and as a good fat source in the production of infant food and filled milk formulations [180].

6 Conclusion

Overall, coconut palm (*Cocos nucifera* L.) and its fruit components-particularly the kernel, water, and oil-represent valuable sources of bioactive and nutritional compounds with considerable potential for use in functional foods, nutraceuticals, and biopharmaceuticals. The rich presence of polyphenols, vitamins, minerals, amino acids, medium-chain fatty acids, and dietary fiber in coconut contributes to a broad spectrum of health advantages, including antioxidant, anti-inflammatory, immune-modulating, and cardioprotective effects. Additionally, phytochemicals such as phytosterols, tocopherols, flavonoids, and alkaloids further enhance the bioactivity profile of coconut, supporting both traditional and modern food and medicinal applications. Despite this promise, coconuts remain underutilized as functional ingredients in many regions, and their full potential in health-promoting product development has yet to be realized.

7 Research gaps and future directions in coconut fruit bioactivity

Despite growing interest in coconut fruit's nutritional and medicinal potential, significant research gaps persist, hindering its full therapeutic and functional food application. Future investigations should prioritize:

Comprehensive Characterization and Standardization: Beyond identified compounds, a need exists for detailed chemical profiling across diverse cultivars and maturity stages using advanced analytical techniques (e.g., metabolomics). This includes standardizing

extraction and processing methods to ensure consistent product quality and understanding genetic/environmental influences on compound biosynthesis.

Elucidation of Mechanisms of Action: While bioactivities are observed (e.g., anti-inflammatory, antioxidant), precise molecular mechanisms remain largely undefined. Future research must identify specific cellular targets, delineate signaling pathways, and investigate synergistic effects among coconut compounds.

Clinical Validation and Human Studies: The current literature is heavily reliant on *in vitro* and animal models. Robust human clinical trials are crucial to validate efficacy and safety for specific health conditions, determine optimal dosing and formulations, assess bioavailability and metabolism in humans, and investigate long-term health outcomes.

Exploration of Underutilized Components and Byproducts: Beyond the well-studied water, kernel, and oil, underutilized parts (e.g., husk, shell, roots) may harbor novel bioactive compounds. Research should focus on identifying these and developing value-added products, promoting a circular economy.

Comparative Studies and Dietary Interactions: Further comparative studies are needed to assess coconut's efficacy relative to other functional foods. Additionally, research should explore how coconut consumption interacts with other dietary components and lifestyle factors for personalized nutritional approaches.

Addressing these gaps will advance the understanding of coconut fruit's health benefits, facilitate evidence-based product development, and maximize its contribution to global health and sustainable development.

Abbreviations

CW	Coconut Water
CM	Coconut Meat (also referred to as coconut kernel)
CO	Coconut Oil
VCO	Virgin Coconut Oil
DF	Dietary Fiber
SCFAs	Short-Chain Fatty Acids
TCW	Tender Coconut Water
MCW	Mature Coconut Water
DCCP	Defatted Coconut Cake Powder
CF	Coconut Flour
CH	Coconut Haustorium
CCA	Coconut Cake Albumin
BPs	Bioactive Peptides
CKP	Coconut Kernel Protein
VCM	Virgin Coconut Meal
CCE	Cultured Coconut Oil
TPC	Total Phenolic Compounds/Content
AA	Amino Acid(s)
LCTs	Long-Chain Triglycerides
MCTs	Medium-Chain Triglycerides
MCFAs	Medium-Chain Fatty Acids
SFA	Saturated Fatty Acids
IL-6	Interleukin-6
IL-1	Interleukin-1
TNF- α	Tumor Necrosis Factor-alpha
iNOS	Inducible Nitric Oxide Synthase
COX-2	Cyclooxygenase-2
VLDL	Very Low-Density Lipoprotein
HDL	High-Density Lipoprotein
LDL	Low-Density Lipoprotein
ABTS	2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (used in antioxidant assays)
DPPH	2,2-diphenyl-1-picrylhydrazyl (used in antioxidant assays)
ROS	Reactive Oxygen Species
QE	Quercetin Equivalent (measurement unit in flavonoid content)
TAE	Tannic Acid Equivalent (used for phenolic content quantification)
CE	Chloroform Equivalent (measurement for alkaloid content)
GAE	Gallic Acid Equivalent (used to express phenolic content)

FPLC Fast Protein Liquid Chromatography
CKE Coconut Kernel Extract
CTO Coconut Testa Oil

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Olaide Olawunmi Ajibola: Conceptualization, Writing Original draft, visualization, writing Review & Editing, Software.

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Data availability

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Declarations

Ethics approval and consent to participate

Not applicable. This study is review and does not involve human participants or clinical trials.

Consent for publication

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Competing interests

The authors declare no competing interests.

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