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REVIEW ARTICLE

A comprehensive review of virgin coconut oil: Extraction methods and diverse applications

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Abstract

The extraction of virgin coconut oil (VCO) is a critical process that yields premium oil from fresh coconut meat. Renowned for its numerous health benefits and wide-ranging applications in the food, cosmetics, and pharmaceutical industries, VCO has attracted a lot of interest. Traditional cold-pressing methods coexist with modern techniques such as centrifugation and enzyme-assisted extraction. Each method has its own benefits and drawbacks that influence the quality of the end product. To optimize VCO production and maintain its superior quality, it is crucial to understand the extraction procedure, including key factors like acidity, colour, scent, moisture content, and fatty acid composition. Rich in medium-chain fatty acids (MCFAs), particularly lauric acid, VCO exhibits potent antibacterial and antioxidant properties, offering significant health and wellness benefits. VCO has diverse industrial applications. It serves as an active ingredient in pharmaceutical formulations, a base oil in cosmetics, a cooking oil, and a component in various food products. It unique combination of nutritional and functional qualities makes it an ideal choice for manufacturers seeking natural and sustainable ingredients. This review focuses on the production methods, physiochemical properties, health benefits, and industrial applications of VCO extraction.

Keywords

extraction methods; medium-chain fatty acids; pharmaceutical formulations; virgin coconut oil

Introduction

Virgin coconut oil (VCO) is an edible oil derived from the milk of both young and mature kernels of the coconut (*Cocos nucifera* L.) (1). Recently, Western medicine has renewed its interest in this versatile tree, renowned for its numerous nutritional and therapeutic benefits. Various parts of the coconut, such as tender coconut water and kernel, are believed to possess therapeutic properties, including immune system stimulation, a low glycemic index, and antioxidant, antiviral, antifungal, and antibacterial properties (2). As a dietary fat, coconut oil ranks among the most significant edible oils worldwide. It is widely used in the culinary sector for baking, confectionery, and cooking purposes (3).

VCO, the latest and most premium coconut product, is highly sought after for its functional food properties and human nutraceutical advantages.

The demand for VOC is rapidly increasing worldwide. VCO is a traditional substance with a long history of ethno pharmacological use. Extracted at lower temperature from fresh coconut flesh without the addition of chemicals, it has demonstrated anticancer potential, including inhibiting colon carcinogenesis and mammary tumors in animal studies (4–6). Renowned as the finest type of coconut oil, VCO is characterized by its natural coconut flavour and aroma. It solidifies at low temperature and becomes as clear as water when liquefied (1, 7).

VCO is extracted from the fresh, mature coconut kernels through mechanical or natural methods, without applying heat or employing chemical processes such as refining, bleaching, or deodorising. Unlike refined-bleached-deodorized (RBD) oil, VCO preserves the physiologically active substances often lost during conventional extraction process (Table 1) (8-12). Wet processing techniques for VCO extractions are specifically designed to retain its high levels of vitamins, minerals, and antioxidants (13, 14). Physicochemically, VCO shares similarities with regular coconut oil, including moisture content, saponification value, and iodine value. Both oils exhibit nearly identical fatty acid profiles (13).

The production of VCO, primarily conducted at household, micro, or village scale, is growing quickly. It has the potential to increase coconut farmers' earnings by 5–8 times compared to traditional practices such as production of copra or selling fresh nuts (13). The primary methods of VCO production include centrifugation (CEN), fermentation with or without heat (FWH), and expeller (EXP) processes. While small-to medium-scaled enterprises dominate VCO manufacturing, demand for its use in edible and cosmetic industries continues to rise (1).

VCO is distinguished by its clear appearance and pronounced coconut aroma. It can be produced from fresh coconut meat, coconut milk, or by-products from coconut milk processing (14). Compared to copra oil, VCO increases high-density lipoprotein (HDL) cholesterol while reducing total cholesterol, triglycerides, phospholipids, low-density lipoprotein (LDL), and very low-density lipoprotein (VLDL) cholesterol levels in blood and tissues. Additionally, VCO administration has been shown to decrease lipid peroxidation and enhance antioxidant enzyme activity (15). Unlike long-chain triglycerides (LCT), VCO is rich in medium-chain triglycerides (MCT), which are metabolized and digested differently by the human body (16).

The study aims to explore the nutritional and therapeutic benefits of VCO extracted from fresh coconut kernels by highlighting its unique composition, extraction method, and functional properties. It evaluates the impact of VCO on cholesterol levels, lipid metabolism, and antioxidant activity while also assessing its potential as a sustainable economic opportunity for coconut farmers in response to growing global demand.

VCO composition and their role

The composition of VCO may exhibit slight variations depending on factors such as coconut variety, growing environment, and processing techniques. A comprehensive overview of VCO's composition is mentioned in Table 2 (1, 7, 17, 18).

VCO offers a unique and pleasant taste while retaining the natural flavour and aroma of coconuts. It is crucial to note that individual responses to dietary lipids may vary, and research on the composition and health benefits of coconut oil, particularly VCO, is on-going. While VCO is associated with numerous health advantages, excessive intake of saturated fatty acid may lead to cardiovascular issues. Therefore, it is always advisable to consult medical specialists for specific recommendations depending on needs about nutrition and state of health (19). Among the diverse health benefits of VCO, notable ones include its ability to enhance antioxidant enzyme activity and inhibit LDL lipid oxidation. Furthermore, VCO differs from crude coconut oil (CCO) samples in its higher content of total polyphenol, antioxidant activity, tocopherols, phytosterols, monoglycerides, and diglycerides (13). The primary fatty acid in the VCO is lauric acid, which accounts for about 48.40 % to 52.84 % of its composition. The metal concentrations in VCO

Table 1. Comparison of VCO, copra oil, and RBD oil: Production methods, nutritional content, and health benefits (8-12)

Features	Virgin coconut oil	Copra oil	RBD oil
Production method	Cold or wet processing extraction like cold pressing, hot extraction, fermentation, or enzymatic methods without chemicals.	Dry processing method produced by drying coconut kernels (copra) and extracting oil through mechanical pressing.	Refining, bleaching, deodorizing undergoing chemical refining to remove impurities, bleaching for clarity and deodorizing to remove odour.
Nutritional content			
MCTs	~61.1 %	~60.5 %	~59.8 %
Vitamin E	Contains moderate amounts of vitamin E (tocopherols- 10-40 mg/kg)	Low vitamin E content (tocopherols-1-10 mg/kg)	Very low vitamin content due to refining
Total phenolic content (Gallic acid equivalents -GAE)	11.15 ± 0.22 mg GAE per kg of oil	4.74 ± 0.33 mg GAE per kg of oil	-
Health benefits			
Antioxidant capacity by DPPH (2, 2-diphenyl-1picryl-hydrazyl) radical scavenging assay	910.02 ± 22.75 mg/mL	702.47 ± 15.33 mg/mL	-
Anti-inflammatory by protein denaturation inhibition activity (mg/mL)	444.11 ± 6.76 mg/mL	350.39 ± 0.74 mg/mL	-

Table 2. VCO composition (1, 7, 17, 18)

S. No.	Component	Description
1	Fatty acid	Saturated fats make up the fatty acids in VCO. The most prevalent is lauric acid, which is followed by capric and caprylic acids.
2	Medium-chain triglycerides	MCTs, which the body can readily metabolise, are abundant in VCO.
3	Polyphenols	Polyphenolic substances with antioxidant qualities are present in VCO.
4	Vitamins and minerals	VCO's antioxidant qualities may be aided by trace levels of vitamin E.
5	Phytosterols	VCO contains phytosterols, plant-derived compounds with potential health benefits.

fall within the acceptable limits recommended by the Asia-Pacific Coconut Community (APCC). Moreover, its total phenolic content and DPPH radical-scavenging activity (IC50) range between 1.16–12.54 mg gallic acid equivalents (GAE)/g and 7.49–104.52 mg/mL, respectively. These findings underscore the high quality and safety of VCO (20).

Chemical properties and fatty acid composition of VCO

Among VCO samples, no significant variation was observed in lauric acid concentration, which ranged between 46.64 and 48.03 %. The major triacylglycerol identified in these oils were LaLaLa, LaLaM, CLaLa, LaMM, and CCLa, where La represents lauric acid, C represents capric acid, and M represents myristic acid. The iodine value ranged from 4.47 to 8.55, indicating a low occurrence of unsaturated bonds. The saponification value ranged from 250.07 to 260.67 mg KOH/g of oil, while peroxide value (0.21–0.57 mequiv oxygen/kg) demonstrated good oxidative stability. The anisidine value varied between 0.16 to 0.19. Furthermore, the relatively low free fatty acid content (0.15–0.25) indicated high-quality VCO. All chemical compositions conformed to the codex standards for edible coconut oil. Additionally, VCO samples exhibited significantly higher total phenolic content (7.78–29.18 mg GAE/100 g oil) compared to refined, bleached, and deodorised coconut oil (7).

VCO extraction methods and its effects

VCO, a premium and highly refined variant of coconut oil, is widely known for its functional food properties and numerous health benefits. The extraction process of VCO from coconut kernels is crucial for its commercialization. Several extraction techniques are employed, including cold and hot extraction, low-pressure extraction, fermentation, CEN, and enzyme-assisted extraction. These methods yield VCO with distinct physicochemical characteristics, with hot and cold extraction being the most commonly used.

Hot extraction involves pressing fresh, clean, crushed coconuts to obtain coconut milk, which is then subjected to high temperature to extract valuable micronutrients. Conversely, the cold extraction process employs methods such as CEN, enzymatic treatment, fermentation, cooling and thawing, or other non-thermal techniques to destabilise the coconut milk emulsion without applying heat, thus preserving the oil's natural bioactive components (21). Lauric acid, a key bioactive component of VCO, is well-documented for its antibacterial and anti-inflammatory properties, which enhance the oil's therapeutic value and appeal in health and wellness applications (22). Choosing the appropriate extraction method is crucial, as it significantly influences the quality and properties of the final product. A detailed overview of VCO extraction methods is provided in Fig. 1.

Cold extraction processes

The process involves separating coconut oil from coconut milk by breaking the mixture into components without applying heat. Coconut milk, known for its exceptional emulsion stability, undergoes three steps of destabilization:

Phase separation: Gravitational force separates the cream into two phases: An aqueous layer at the bottom and a creamy layer on top.

Flocculation and clustering: This stage involves the grouping of oil droplets without the rupture of the surrounding interfacial film.

Final Destabilization: The most critical stage, leading to the extraction of oil (17, 23).

Centrifuge method

The CEN method is an effective cold process for extracting VCO. At 40 °C, optimal production of VCO was achieved through CEN. Studies investigating the demulsification of coconut milk at speeds ranging from 6,000 to 12,000 rpm for durations of 30 to 105 min revealed a faster demulsification process compared to fermentation, yielding higher-quality VCO (24). Fresh dry and fresh wet CEN techniques, which employ two and three phases of CEN respectively, are commonly used to achieve de-emulsification of the coconut milk emulsion, resulting in high-quality VCO (15, 25, 26).

Fermentation method

Fermentation is a popular cold process method for extracting VCO (27). In this method, coconut milk is left to ferment naturally, or induced fermentation is carried out using probiotic culture, such as bacteria *Lactobacillus plantarum* 1041 IAM (27). Various factors, including coconut kernel-to-water ratios (1:1 to 1:3), fermentation temperatures (30-70 ° C), and durations (2–6 hr), influenced the yield of VCO (28). Induced fermentation using probiotics, such as *Lactobacillus acidophilus,* and *L. plantarum* under suitable pH, temperature, inoculums percentage and aerobic/micro-aerobic conditions yield higher VCO. It was found that the

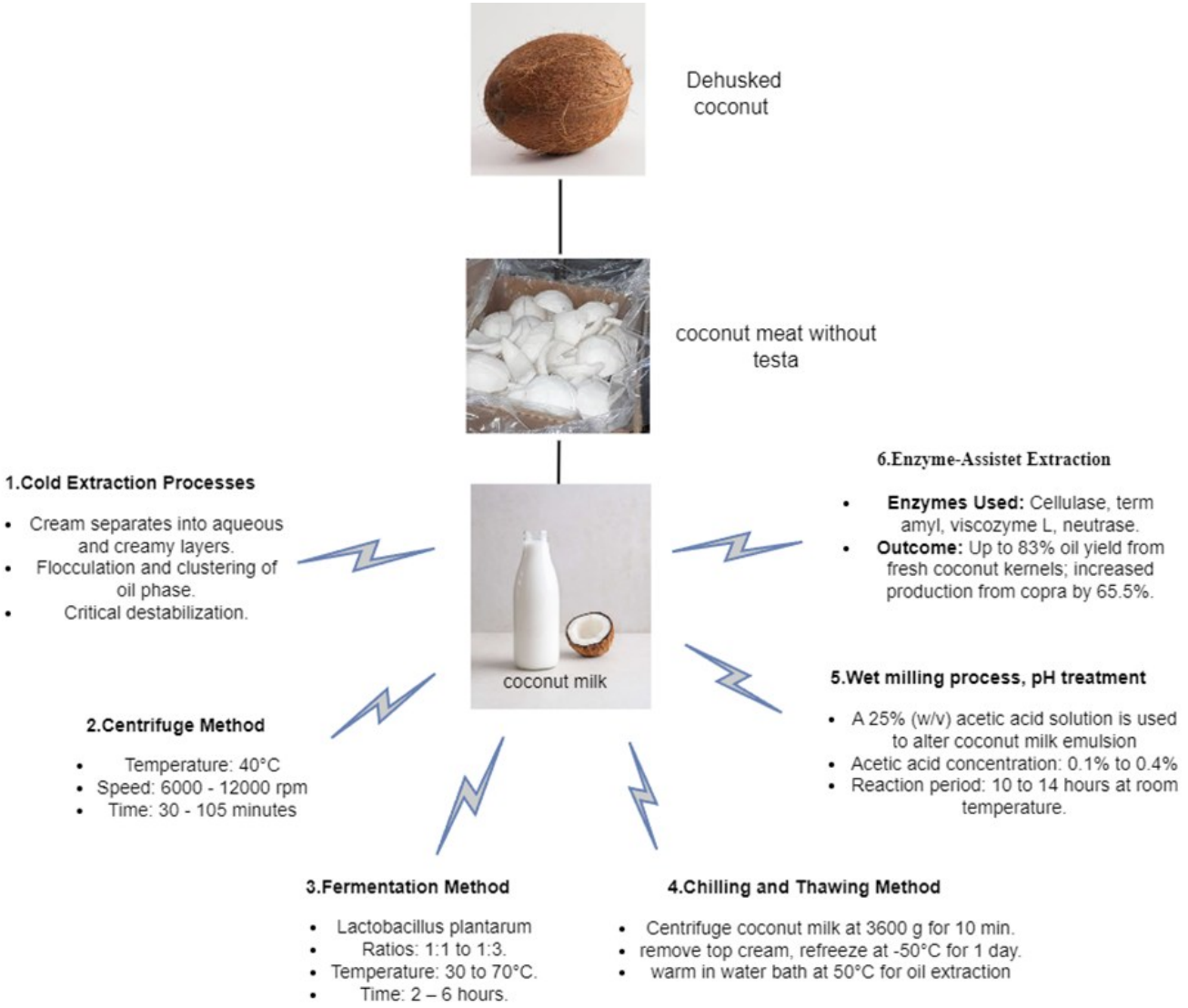

Fig. 1. Different methods of VCO extraction.

temperature of 45 ± 1 ℃, pH of 5 ± 0.1, inoculum concentration of 2 %, fermentation duration of 48 hr under anaerobic conditions has been shown to produce higher VCO yields (28).

Chilling and thawing method

This process involved an initial CEN step, where the cream layer is separated after spinning coconut milk at 3,600 g for 10 min. The cream is then frozen at -50 ℃ for a day, followed by gradual warming in a water bath at 50 ℃ to extract the oil. This process is repeated in batches and aids in the removal of undissolved materials post-extraction (29, 30). The total phenolics content (TPC) of VCO extracted using the chilling and thawing method is notably higher (68.12 mg GAE/100mL oil) compared to other methods such as fermentation (61.98 mg GAE/100mL oil), enzyme-assisted extraction, and RBD oil (37.42 mg GAE/100mL). The low temperature approach of this method contributes to the higher recovery of phenolic compounds, enhancing the oil's quality and antioxidant properties (31).

Wet milling process, pH treatment

Fresh coconut meat is used to extract coconut milk, and the oil is subsequently separated using various techniques including heating, fermentation, or enzymatic processes (1). A 25 % (w/v) acetic acid solution was used to modify the coconut milk emulsion. Results showed that treating the emulsion with 0.1 to 0.4 % acetic acid and allowing a reaction period of 10–14 hr at room temperature resulted in 58.3 to 60.3 % oil recovery with improved quality (32).

Enzyme-assisted extraction

The use of enzymes facilitates the breakdown of coconut cell walls, thereby enhancing oil extraction. High-quality coconut oil (83 %) was obtained through several stages (as depicted in Fig. 1) by using a combination of enzymes, including cellulase, endoamylase ((termamyl), viscozyme L, neutrase, and alcalase (protease), to extract oil from fresh coconut kernels (33). The production of coconut oil from copra was increased by up to 65.5 % by employing an aqueous solution containing protease, α-amylase, cellulase, hemicellulase, and pectinase enzymes (34). VCO is a versatile and valuable product in daily life. The modern industry has developed various techniques for extracting oil from coconuts, including CEN, fermentation, freezing and thawing, humid extraction, low-pressure extraction, cold extraction, hot extraction, enzymatic extraction, and supercritical fluid carbon dioxide extraction. These methods yield VCO with varying levels of lauric acid and purity, influencing their applications.

Addressing the challenges industries face in extracting coconut oil is essential for advancing extraction technology and optimizing downstream processing (35).

In this study, VCO was produced using fresh-dry (grated coconut), chilling and thawing, enzymatic (Fig. 2), and fermentation methods. All VCO samples met the physicochemical standards set by the Codex Alimentarius Commission and APCC. Lauric acid content ranged from 46.36 % to 46.42 %, making it the predominant fatty acid (FA). The main triacylglycerol (TAG) component, LaLaLa (La: Lauric), accounted for 17.94 % to 19.83 % of the overall TAG. Tocopherol analysis indicated low levels of beta, gamma, and delta tocopherols, with no significant differences across the extraction methods (36).

A comparative analysis was conducted on VCO derived from three distinct phases of coconut maturity: over-mature coconuts (OMC), mature coconut (MC), and immature coconut (IMC). The VCO from OMC exhibited the highest recovery (95.64 %) (p<0.05), followed by MC (84.40 %), and IMC (61.06%). All VCO samples appeared water-like and contained MCFA, with lauric acid (C12:0) accounting for the majority at 49.74–51.18 g/100 g. Myristic acid (C14:0) was present at 18.70–19.84 g/100 g. Low levels of lipid hydrolysis and oxidation were observed across all VCO samples, indicating stable oxidative properties regardless of maturity stage Table 3 (20, 37-39).

Four extraction methods, including enzymatic, dry, fermentation, and freezing and thawing were used to produce VCO, which then assessed for fatty acid content, physicochemical characteristics, and antioxidant activities. The results were compared with commercially available refined, bleached, and deodorised coconut oil (RBD-CO). The physical and chemical properties of the extracted VOCs were as follows:

The yield ranged from 54 to 72 %; moisture contents ranged from 0.12 to 0.16 %; refractive index was 1.45; viscosity was 48 to 51 cP; free fatty acid content was 0.16 to 0.2 g/100 g; iodine value was 4.17–7,13 g I2/100 g of oil; and peroxide value was 147–259 meq O_2/kg of oil. Lauric acid was the most abundant fatty acid in all the VCO samples, ranging from 47.95 to 48.08 %. The total phenolic content (TPC) ranged from 37.42 to 68.12 mg GAE/100 mL, while DPPH radical-scavenging activity (IC50) ranged from 205.15–248.16 mg/mL (31).

Fermentation techniques significantly influence the characteristics of VCO. This study aimed to examine the physicochemical properties of VCO produced using different

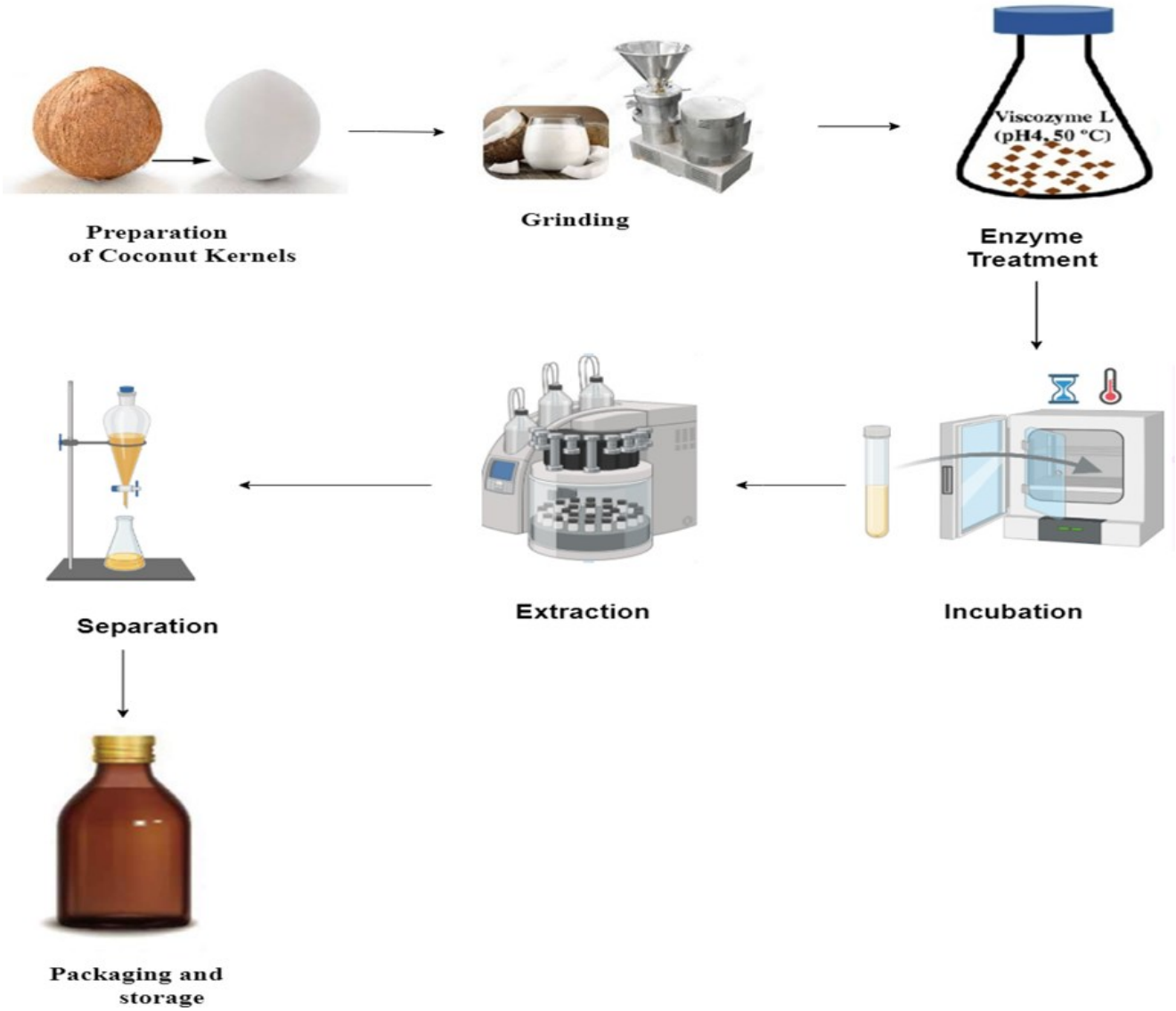

Fig. 2. Steps involved in production of VCO by enzyme-assisted extraction.

Table 3. Comparison of fatty acid composition of VCO with virgin olive oil, and virgin avocado oil (20, 37-39)

Fatty acid composition	Lauric acid (C12:0)	Myristic acid (C14:0)	Palmitic acid (C16:0)	Stearic acid (C18:0)	Oleic acid (C18:1)	Linoleic acid (C18:2)	Linolenic acid (C18:3)
Virgin coconut oil	48.40 - 52.84 %	16-20 %	8-10 %	2.00 - 3.00 %	5.00 - 7.00 %	1.00 - 2.00 %	0.50-1.00 %
Virgin olive oil	-	-	10.12 - 15.31 %	1.61 - 2.61 %	64.81 - 76.06 %	5.53 - 14.41 %	0.61 - 1.11 %
Virgin avocado oil	-	0.10–0.14 %	12.79–17.50 %	0.63–2.15 %	59.46–67.69 %	10.50–15.15 %	0.80–1.30 %

cultures, including *Rhizopus oligosporus*, *L. plantarum*, and *Saccharomyces cerevisiae*. Fermentation was conducted in two phases, with VCO fermented at 35 ℃ for 24 hr during the first phase. VCO produced using *Saccharomyces cerevisiae* exhibited lower moisture content, acid value, and iodine number compared to other types, while density, viscosity, and peroxide values were nearly identical. All physicochemical characteristics complied with the standards set by Standar Nasional Indonesia and APCC (40).

VCO health benefits, applications and uses

VCO has emerged as functional food oil due to its wide range of biological activities that are beneficial to human health. The presence of phenolic compounds in VCO contributes to its pharmacological properties, such as immunomodulatory, anti-inflammatory, anti-hyperlipidemia, anti-cancer, antidiabetic, anti-bacterial, and neuroprotective effects (41). VOC, produced from fresh coconut flesh, milk, or residue, is highly valued for its health benefits and nutritional profile. Its growing popularity is supported by numerous studies demonstrating its positive health effects. Research has explored the pharmacological characteristics of VCO, including anti-inflammatory, analgesic, antipyretic, antioxidant, anti-stress, and antibacterial properties (42).

Health benefits of lauric acid

Coconut and its derivatives have been used for centuries in food, cosmetics, and medicine. VCO is gaining recognition as a functional food due to its purported health benefits. It contains medium-chain triglycerides (MCTs), which are metabolized by the liver to produce energy rather than being stored as fat. Besides its strong antioxidant profile, coconut oil exhibits antibacterial and hypolipidemic properties (16). VCO is particularly rich in MCFAs, with lauric acid comprising about half of its total fatty acid content. Lauric acid is widely used as an antibacterial agent against bacteria, viruses, and fungi. The fatty acid profiles of coconut oil and breast milk are notably similar. MCFAs in coconut oil are rapidly metabolized in the liver to provide immediate energy, bypassing storage in adipose tissue (43).

Lauric acid is especially recognized for its antimicrobial properties, which stem from its amphiphilic structure. This structure, consisting of a hydrophobic alkyl chain and a hydrophilic carboxylate group, enables effective interaction with bacterial cell membranes. Upon contact, lauric acid integrates into the lipid bilayer, increasing membrane permeability and causing leakage of essential intracellular components, which compromises bacterial viability. Lauric acid is particularly effective against gram-positive bacteria, which have simpler membrane structures compared to gram-negative bacteria. The outer membrane of gram-negative bacteria acts as a barrier, limiting the access of lauric acid to inner cell layers (44). *Clostridium difficile* is a leading cause of antibiotic-associated diarrhea in hospitals worldwide. Previous studies have demonstrated the antibacterial activity of VCO. This research highlights how the lipid components of VCO regulate the growth of *C. difficile*. Results indicate that lauric acid exhibited the most significant growth-inhibitory effect ($p < 0.001$), as evidenced by a reduction in colony-forming units per milliliter. Capric and caprylic acids also inhibited bacterial growth, albeit to a lesser extent. While bacterial cells exposed to 0.15–1.2 % lipolyzed coconut oil experienced growth inhibition, VCO itself did not significantly affect the growth of *C. difficile* (45).

VCO and weight management

A study was conducted to evaluate the safety and efficacy of VCO in promoting weight loss among obese but otherwise healthy Malay volunteers. Anthropometric parameters, lipid profiles, and organ function tests were measured one week before and after VCO consumption. Differences were analyzed using paired *t*-tests.

The results showed a significant reduction in waist circumference (WC), with a mean decrease of 2.86 cm or 0.97 % from baseline measurements ($p = 0.02$). The reduction in WC was particularly pronounced in males ($p < 0.05$). However, no significant changes were observed in lipid profiles. Minor reductions in alanine transferase and creatinine levels were noted. The findings indicate that VCO is safe for human consumption and effective in reducing WC, particularly in men (46).

Wound healing and skin health

The primary component of VCO is medium-chain fatty acids, particularly lauric acid, which is readily absorbed, accelerates cell metabolism, hydrates wounds, and exhibits anti-inflammatory properties. Partial hydrolysis of VCO produces monoglycerides, diglycerides, and free fatty acids, with lauric acid and monolaurin being particularly notable for their antibacterial properties. Hydrolyzed VCO treatments

demonstrated the fastest healing rate (12 days), followed by partially hydrolysed VCO at 35 % (15.5 days), VCO at 0 % (17.3 days), and bioplacenton ® (18.1 days). In comparison, the untreated/negative control group exhibited the slowest healing time (23.5 days). Greater degrees of VCO hydrolysis were correlated with faster burn wound healing in rabbits (47).

VCO-treated wounds demonstrated higher levels of essential skin components and shorter periods for full epithelization, indicating significantly faster healing. Pepsin-soluble collagen was markedly increased in VCO-treated wounds, reflecting enhanced collagen cross-linking. Elevated collagen turnover was also associated with increased glycohydrolase activity. By the tenth day post-injury, VCO-treated wounds showed heightened antioxidant enzyme activity, decreased glutathione levels, and reduced malondialdehyde levels, signifying lower oxidative stress. By the fourteenth day, the treated wounds exhibited signs of returning to normal. Lipid peroxide levels were reduced in treated wounds, and histopathological analysis revealed increased fibroblast proliferation and neovascularization compared to controls (48).

MCFAs in VCO are recognized for their metabolic and therapeutic benefits in skin healing. They are rapidly absorbed and converted into energy by the liver, enhancing energy availability crucial for skin repair. MCFAs also reduce oxidative stress on skin cells and possess anti-inflammatory properties by modulating pro-inflammatory cytokines such as tumor necrosis factors (TNF-α), and interleukins ((IL-6), (IL-8)). This action alleviates chronic skin conditions like atopic dermatitis and psoriasis, characterized by inflammation and impaired skin barrier function. Moreover, MCFAs enhance skin barrier integrity by promoting the synthesis of structural proteins like filaggrin and involucrin, which maintain hydration and prevent water loss. They also stimulate aquaporin-3 (AQP-3), further supporting skin hydration (48).

Cardiovascular health

Numerous studies have examined how die try components can improve cardiovascular (CV) health. VCO has gained popularity due to its CV benefits. Unlike its copra-derived counterpart, VCO is considered healthier because of its chemical composition and unique production process. Evidence suggests that dietary interventions, either alone or combined with exercise, can reduce the burden of cardiovascular disease (CVD). VCO is of particular interest for its cardioprotective properties, which challenge traditional views on the role of saturated fatty acids in CVD risk (49).

Applications in medicine, cosmetics, and nanotechnology

VCO, sometimes known as the "mother of all oils," is processed differently from commercial coconut oil. It is rich in vitamins, minerals, and antioxidants, making it a valuable food-grade product with diverse applications in the food, medicine, cosmetics, and nanotechnology industries. VCO versatility has led to its classification as a highly valuable oil. Various manufacturing techniques for VCO have been documented, producing liquid and solid by-products with applications in multiple fields (50).

VCO is rich in phenolic compounds, such as ferulic acid and p-coumaric acid, which contribute to its strong antioxidant properties. These compounds protect the skin from oxidative stress and signs of aging. Recent research highlights the potential of solid lipid particles (SLPs) in delivering VCO for skincare. SLPs enhance the absorption of active ingredients, improving their efficacy. Advanced techniques like ultrasonication optimize SLP size and stability, creating formulations ideal for skin application.

Solid lipid nanoparticles (SLNs), ranging in sizes from 50 to 1000 nm, provide an effective means of encapsulating VCO's beneficial compounds. This small particle size enhance penetration through the skin barrier and enables controlled release, making it ideal for advanced cosmetic applications. Evaluating the effectiveness of VCO-SLPs involves analysing particle size distribution, zeta potential, and entrapment efficiency to ensure stability and performance. Nanotechnology has revolutionized the delivery of VCO through the skin barrier, with studies demonstrating that smaller particles significantly improve skin absorption (51).

Stress reduction and antioxidant effects

Atopic dermatitis (AD) is a chronic inflammatory skin condition characterized by intense itching and eczematous lesions. The physiochemical properties of VCO, particularly its MCFAs and triglycerides, remain intact, making it a safe and effective topical treatment for AD. Studies have shown that VCO exhibits antibacterial, anti-inflammatory, moisturizing, and antioxidant properties, all of which are essential for managing AD (52).

VCO is rich in MCFAs and polyphenols, which contribute to its therapeutic potential. *In vivo* studies on stress-induced damage in mice have highlighted the anti-stress and antioxidant effects of VCO. Using the forced swim test and chronic cold restraint stress models, researchers found that VCO reduced the duration of immobility in mice and mitigated oxidative stress. Mice treated with VCO exhibited decreased brain 5-hydroxytryptamine levels, increased brain antioxidant levels, and reduced adrenal gland weights. Furthermore, these mice showed lower blood levels of corticosterone, glucose, triglycerides, and cholesterol. These findings suggest that VCO has potential as a functional oil for stress reduction (53).

The broad spectrum of biological functions exhibited by VCO, including antioxidant, anti-inflammatory, antibacterial, and antiviral properties, positions it as a promising therapeutic agent for managing various chronic degenerative diseases. Among these, its antioxidant activity is particularly noteworthy and is largely attributed to its phenolic compounds and MCFAs (9). VCO's bioactive compounds, especially lauric acid and monolaurin, are well-recognized for their anti-inflammatory effects. Research indicates that VCO interacts with key enzymes involved in inflammatory pathways, such as cyclooxygenase (COX) and lipoxygenase (LOX). By inhibiting these enzymes, VCO reduces the production of pro-inflammatory molecules like prostaglandins and leukotrienes, which are pivotal in driving inflammation. Additionally, VCO modulates cytokine levels and other inflammation-related markers. These combined

mechanisms underscore the potential of VCO as a natural anti-inflammatory agent, offering therapeutic value for managing inflammation-related health conditions (44).

Future prospects

Interestingly some food processing industries are introducing coconut as a viable substitute to palm kernel oil, which has faced negative perceptions among consumers. In this context, it is crucial to conduct comprehensive studies to evaluate the environmental and social impacts of this sector, particularly in Asia, which serves as the primary production region. The rapidly expanding market for specialized health-food products, such as coconut water and VCO, is driving significant growth in the industry. Future research should focus on developing innovative and sustainable technologies that preserve both the nutritional and functional properties of coconut-based products.

The "extensive" approach to cultivating coconut palms aligns well with the demand for new health-oriented products like VCO and supports their strategic market positioning. It is crucial to identify the coconut varieties best suited for emerging opportunities within this sector. Once identified, these varieties should be carefully characterized and considered for replanting programs, genetic selection, or improvement strategies aimed at developing high-yield coconut hybrids for the future. Such efforts will ensure that the recent surge in demand for coconut products' remains sustainable and contributes to improving the livelihoods of millions of people living in the tropical regions.

Conclusion

In summary, the extraction methods and applications of VCO underscore its immense potential as a valuable resource across diverse industries. VCO can be effectively extracted using both traditional methods, such as cold-pressing and contemporary methods like CEN and enzyme-assisted extraction, each of which has unique benefits in terms of yield and quality. The overall quality and stability of VCO are influenced by its physicochemical characteristics, including its fatty acid composition, moisture content, acidity, colour, and aroma.

Lauric acid, a medium-chain fatty acid abundant in VCO, imparts it with antibacterial, anti-inflammatory, and antioxidant properties, making it particularly beneficial for health and cosmetic applications. The well-documented health benefits of VCO include enhancing skin and hair care, promoting cardiovascular health, and supporting weight management. Its versatility renders it suitable for a wide range of commercial applications, including as a cooking oil, an ingredient in food products, a base oil in cosmetics, and an active component in pharmaceutical formulations.

Despite significant progress in VCO extraction methods and its numerous applications, continued research and innovation remain essential. Future research efforts should prioritize refining extraction techniques to enhance efficiency and product quality, exploring novel applications of VCO in emerging sectors, and addressing environmental concerns associated with its production. This analysis underscores the potential of VCO as a highly versatile and valuable product through a comprehensive understanding of its extraction processes and applications. Leveraging its nutritional and functional properties, VCO holds significant promise as a natural and sustainable ingredient that meets the needs of producers and consumers in an increasingly health-conscious and environmentally aware market.

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Authors' contributions

TGB wrote original manuscript. MK conceptualized the manuscript and reviewed the manuscript. SG and JS reviewed the manuscript. VV reviewed and edited the manuscript. All authors read and approved the final version of the paper.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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